

Eocene extensional tectonics in the Amakusa region, northern Ryukyu arc

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ABSTRACT

Paleogene surface tectonics in Japan is not well understood because of the paucity of onshore Paleogene stratigraphic records except for those from accretionary complexes. Paralic Paleogene formations remaining in SW Japan are usually so thin that it is difficult to decipher the tectonics from them. However, the Eocene paralic sedimentary package with a thickness of kilometers indicates syn-depositional tectonic subsidence by a few kilometers in the Amakusa archipelago, west of Kyushu Island. Thus, we made a detailed geological map of the

Eocene formations in an area of ~50 square kilometers in the northwestern part of the archipelago. We identified NE-SW and NW-SE trending normal faults, most of which were recognized by previous researchers, and also discovered low-angle faults. NW-SE trending ones are known to be of the Miocene. NE-SW trending and low-angle normal faults are the oldest map-scale structures in the Eocene ones. It is not obvious within the above-mentioned area whether those normal faults are accompanied by growth strata. However, the significant southeastward thickening of the Eocene formations across the Amakusa archipelago suggests that they filled a large half graben with the basin margin fault along the eastern side of the archipelago. This basin model is consistent with the N-S to NW-SE transport directions of the low-angle and NE-SW trending normal faults. Since many NE-SW to EW trending Eocene grabens were formed in the offshore regions west of Kyushu Island and in the East China Sea, the Amakusa region was probably a northeastern branch of the rift system. The geologic structures and depositional ages of the Eocene formations indicate that the Eocene extensional tectonics removed the overlying strata to some extent for the high-P/T Takahama Metamorphic Rocks which crops out to the south of our study area.

1 INTRODUCTION

The eastern margin of the Eurasian plate experienced extensive rifting during the Paleogene (Ma & Wu, 1987; Ren et al., 2002; Cheng et al., 2022). Many NE-SW trending rift basins were formed at that time, i.e., those under the East China Sea (e.g., Lee et al., 2006; Cukur et al., 2011a, b; Zhu et al., 2019) and Yellow Sea (e.g., Yi et al., 2003; Yoon et al., 2010) (Figure 1). The framework of the Japanese archipelago was reshaped simultaneously by remarkable crustal deformations including the exhumation of the high-P/T Sambagawa Metamorphic Rocks (Figure 1) and the juxtaposition of the Sambagawa belt and the high-T/P Ryoke metamorphic belt (e.g., Miyashiro, 1961; Hasegawa et al., 2019; Nakamura et al., 2021). The absence of clasts from the Sambagawa belt in the Late Cretaceous Izumi Group along the Median Tectonic Line (MTL) suggests that they were juxtaposed to form MTL after the Late Cretaceous (Yabe, 1915, 1963; Kobayashi, 1941; Nagai, 1958; Miyashiro, 1972). The Sambagawa Metamorphic Rocks was exposed at the surface before the early Middle Eocene,

the depositional age of the Hiwadatoge Formation which rests unconformably on the rocks in Shikoku Island (Figure 1) (Hanzawa, 1959; Narita et al., 1999; Kusuhashi et al., 2022). Metamorphic geologists consider that extensional tectonics assisted the exhumation of the rocks (e.g., Wallis, 1995; Yagi & Takeshita, 2002).

However, early Paleogene surface tectonics remains poorly constrained because of the scarcity of onshore Paleogene strata in Honshu, except for those in the Shimanto belt. Eocene formations remain around MTL (Ozaki et al., 1996; Yamamoto et al., 2000; Suzuki et al., 2003; Yamasaki et al., 2021), but are too thin and sporadic to decipher Eocene tectonics.

In contrast, the following facts make Eocene formations in the Amakusa archipelago adjacent to Kyushu Island (Figures 1–3) to be clues to understanding the Paleogene tectonics of Japan. Despite the proximity to the Usuki-Yatsushiro Tectonic Line (UYTL), which is the surface trace of a major basement fault across Kyushu Island at the southwestern extension of MTL, the total thickness of the Eocene formations is greater than ~3 km in the Amakusa region (Nagao, 1926; Nōtomi, 1930; Miki, 1975; Takai et al., 1997). Since the amplitudes of eustatic sea-level changes in the Eocene Period were of the order of 10^1 m (e.g., Simmons et al., 2020), the kilometer-scale thickness and paralic depositional environments indicate that the sediment accommodation for the formations was formed by the syn-depositional ~~basement~~ tectonic subsidence with an amount comparable with the thickness. In addition, the recent elucidation of Neogene extensional and compressional tectonic deformations (Ushimaru & Yamaji, 2022, 2023a, b) gives us the opportunity to distinguish Paleogene deformations from the Neogene ones in the Amakusa archipelago.

The purpose of this paper is to describe the geologic structures of Eocene formations in the Amakusa region and to discuss their implications for the Paleogene tectonics of Japan. We examined the Eocene formations by geological mapping in the northwestern part of Shimoshima Island, the largest island of the Amakusa archipelago (Figures 2, 4). Three classes of map-scale structures have been known in the Eocene formations: Folds with NNE-SSW to NE-SW trending axes, NW-SE and NE-SW trending faults (Takai et al., 1997). The folding and the faulting along the NW-SE trending faults were found recently to be younger than Middle Miocene felsic magmatism in this region (Ushimaru & Yamaji, 2023a, b). In contrast, no evidence has been presented for the timing and sense of faulting along the NE-SW trending faults. However, we found in this study that they are normal faults and are the oldest among

the three classes. Thus, we restored the faults using the attitudes of surrounding strata to investigate their pre-folding attitudes and slip senses. We conclude that the Eocene formations in the Amakusa region were accumulated in a half graben involved in the rift system of the East China Sea Shelf Basin.

We use the Paleogene time scale of Speijer et al. (2020) and the Cenozoic subseries/subepochs of Head et al. (2017) in this paper. Formations and groups are abbreviated to Fm. and Gp. as usual (e.g., Hansen, 1991, p55) in a few figures.

2 TECTONIC SETTING AND STRATIGRAPHY

The Amakusa region is situated at the junction of the SW Japan and Ryukyu arcs (Figure 1), and behind the volcanic front of the latter arc. There are two large islands in the Amakusa region, called Shimoshima and Kamishima Islands (Figure 2). We mapped Eocene and Upper Cretaceous–Paleocene formations in the northwestern part of Shimoshima Island.

The Eocene formations rest unconformably on the Upper Cretaceous–Paleocene Himenoura Group and are overlain unconformably by Plio-Pleistocene deposits (Figure 2) (Takai et al., 1997), which do not crop out in our study area. After Early Cretaceous plutonism, the Amakusa region belonged to a forearc until the volcanic front stepped trenchward across the region in the early Middle Miocene (Shinjoe et al., 2000, 2019).

Previous researchers recognized NW-SE and NE-SW trending, map-scale faults in the Eocene formations (e.g., Takai et al., 1997; Saito et al., 2010) (Figure 4). The NW-SE trending ones are dip-slip normal faults formed between ~14 and ~12.5 Ma, and some of them were reactivated as tear faults during folding after 12.5 Ma (Ushimaru & Yamaji, 2023a). The folds have NE-SW to NNE-SSW trends with wavelengths of 1–15 km. The wavelength of the Ittyoda Syncline is 10–15 km (Figure 2).

2.1 The Himenoura Group

The Himenoura Group in Shimoshima Island has a total thickness of > 3.7 km (Takai et al., 1997), and is correlated with the Upper Cretaceous (e.g., Yamaguchi et al., 2008; Kojo et al., 2011). Based on molluscan fauna and old fission-track data, several researchers consider the uppermost part of this group to be the mid-Paleocene in age (Yoshida & Tashiro, 1983; Yoshida et al., 1985), but the data have not been verified.

The group rests on Early Cretaceous plutonic and low P/T metamorphic rocks (e.g., Saito et al., 2010) in Kamishima Island—the second largest island of the Amakusa archipelago (Figure 2). The group is separated by a low-angle normal fault (Moriyama & Yamamoto, 2005) from the Late Cretaceous high P/T Takahama Metamorphic Rocks (Saito et al., 2010) in western Shimoshima Island. The Takahama Metamorphic Rocks is the southern part of the Nagasaki Metamorphic Rocks (Figure 1), which is thought to be the western extension of the Sambagawa Metamorphic Rocks (Faure et al. 1988; Nishimura, 1998).

Only the uppermost unit of the group, “Hg,” (Takai & Satoh, 1982; Takai et al., 1997) crops out in our study area (Figure 4). The lower part of this unit is composed of sandstone-rich alternation of sandstone and siltstone, and the upper part is composed of alternating pebbly conglomerate, sandstone, and siltstone (Figures 5, S1). No age data has been reported from this unit in the study area.

2.2 The Amakusa Group

The Eocene succession in Shimoshima Island has a total thickness of 3.4–3.8 km, and is comprised of the Fukuregi, Shikiyama, Toishi, Ittyoda, Sakasegawa, Futae, and Oniike Formations in ascending order (Figures 2, 3) (Takai et al., 1997), but the Futae and Oniike Formations do not crop out in the study area. The Eocene formations consist of siliciclastic deposits with few volcanic materials. There is unfortunately no consensus among researchers about the grouping of the formations (e.g., Otsuka, 2011, Table 1). Here, for convenience, we refer to the Amakusa Group as all the Eocene formations to distinguish them from the older and younger units. This group shows a large lateral variation in the total thickness, which is detailed in Section 4.1.

The depositional age of the Amakusa Group in Shimoshima Island is correlated with the calcareous nannofossil zones CP13a–CP15a (Okada, 1992), which correspond to the interval from Chron 21n to 17n (Agnini et al., 2014) and further to ca. 37–47 Ma (Speijer et al., 2020). The Akasaki Formation, the lowermost unit of the Eocene succession, yielded an U–Pb age of 49.1 ± 0.4 Ma (Miyake et al., 2016) (Figure 3). This is consistent with the mammalian fossil age of this formation (Miyata et al., 2011). The Akasaki Formation crops out in the eastern Amakusa archipelago but does not crop out in our study area. The formations of the lower Amakusa Group in Kamishima and Shimoshima Islands have different names, and are

correlated by their lithology (Figure 3). The Akasaki and overlying Shiratake Formations are separated by a paraconformity with a time gap of ~2 m.y..

Sequence stratigraphy was applied by Iwata & Kameo (2001) to the transgression-regression cycles of the Amakusa Group (Nagao, 1933, Fig. 24): They recognized three third-order sequences in Shimoshima Island. The first one involves the Fukuregi and Shikiyama Formations which represent a lowstand to transgressive systems tract and a highstand systems tract, respectively. The second sequence involves the Toishi, Ittyoda, and Sakasegawa Formations which correspond to a lowstand, transgressive, and highstand systems tract, respectively. The third sequence which begins with the Futae Formation corresponds to a transgressive systems tract.

The lithologies of the five formations of the Amakusa Group in our study area (Figures 5, S2, S3) are summarized as follows.

2.2.1 Fukuregi Formation

The Fukuregi Formation unconformably covers the Himenoura Group, and is ~90 m in thickness in northern Shimoshima Island (Takai et al., 1997). This formation is in fault contacts with the Hg Unit, the uppermost unit of the Himenoura Group in our study area (Figure 4). The thickness of the Fukuregi Formation in the area is ~80 m (Figure 6), indicating that only the basal part of the formation is truncated by faults. The Fukuregi Formation consists mainly of fine- to coarse-grained sandstone (Figures 5, S2). The Hg Unit and the lower Amakusa Group have similar lithology. Frequent occurrence of Eocene molluscan fossils from the Fukuregi Formation (Nagao, 1926; Takai et al., 1997; Otsuka, 2011) helped us distinguish the group from the Hg Unit (Figure 4) (Figures S2f–h). The Fukuregi Formation was deposited in braided-river environments (Iwata & Kameo, 2001).

2.2.2 Shikiyama Formation

The Shikiyama Formation is ~370 m thick and comprised mainly of shallow marine mudstone and alternation of sandstone and siltstone in the study area (Figures 5, 6). The top of the Shikiyama Formation is a glauconite-rich sandy siltstone layer with a thickness of ~50 cm occurring abundant fossil bivalves (Figures S2a, b). The Shikiyama Formation was deposited in estuary, shoreface, and inner shelf environments (Iwata & Kameo, 2001).

2.2.3 Toishi Formation

The Toishi Formation is ~250 m thick and composed of alternating thick-bedded

sandstone and thin siltstone with coal seams (Figures 5, 6, S3), some of which were mined until the 1970s. This formation was deposited in meandering-river environments (Iwata & Kameo, 2001).

2.2.4 Ittyoda Formation

The Ittyoda Formation is the conspicuous bed with thicknesses of several to ten meters resting on the Toishi Formation (Nagao, 1926). The salience of this bed comes from its massive, glauconitic, and fossil-bearing lithology (Figures S3, S4), and the bed is interpreted as a ravinement lag deposit (Iwata & Kameo, 2001). This key bed is traceable across Shimoshima and in western Kamishima Islands (Figure 2) (Matsushita, 1951; Takai et al., 1997). The calcareous nannofossils from the sub- and superstrata indicate that the Toishi and Ittyoda Formations deposited sometime in the CP13b zone, i.e., 44–46 Ma (Figure 3). This is consistent with the youngest detrital zircon grain reported from the Ittyoda Formation, i.e., a U–Pb age of 47.3 Ma (Yoshida et al., 2022).

2.2.5 Sakasegawa Formation

The Sakasegawa Formation is composed mainly of sandy shale and thin-bedded sandstone and siltstone in the study area (Figures 5, 6, S3). The formation is ~900 m thick in northern Shimoshima Island (Takai et al., 1997). The lower part of this formation with a thickness of ~160 m crops out in the northern study area (Figure 4). Glauconitic sandstones are intercalated in the basal part of tens to a hundred meters thick of this formation (Takai & Bojo, 1963; Miki & Fukuoka, 1983) (Figure S5).

2.3 Intrusive rocks

The Himenoura and Amakusa Groups were intruded by various magmas in the Miocene. The felsic to intermediate intrusions were formed in the Middle Miocene, and basaltic ones in the Late Miocene (Shibata & Togashi, 1975; Nagao et al., 1992; Hamasaki, 1996; Yamamoto et al., 1997; Miura & Ohira, 2012; Ohira et al., 2012). The intrusive bodies of rhyolite, granodiorite, quartz porphyry, andesite, and diorite yielded K–Ar and fission-track ages of 14–16 Ma (Nagao et al., 1992; Hamasaki, 1996; Yamamoto et al., 1997; Miura & Ohira, 2012; Ohira et al., 2012). However, recent U–Pb data indicated that the felsic to intermediate rocks were formed at 14.5–14.8 Ma (Shinjoe et al., 2022). The basaltic dike and sill yielded the K–Ar ages of 7–11 Ma (Nagao et al., 1992). A contemporaneous basaltic lava remains around a

summit of a mountain in southern Shimoshima Island.

Felsic dikes and sills make a radiating pattern from the cluster of granitic and rhyolitic stocks around the Tomioka Peninsula (Figure 2). In areas far from the peninsula, the dikes make a parallel swarm which was formed under the extensional far-field stress with the N-S to NNW-SSE trending σ_3 -axis (Ushimaru & Yamaji, 2022), where compression is positive in sign ($\sigma_1 \geq \sigma_2 \geq \sigma_3$) in this paper.

3 MAP-SCALE GEOLOGIC STRUCTURES

The Amakusa Group in the study area is folded with NE-SW trending axes. Here, we call it the Shiki Anticlinorium. The Amakusa Group is inclined at 30–50° and 15–30° in the northwestern and southeastern limbs, respectively, between which minor gentle folds occur with wavelengths of ~1 km. We found no reverse or thrust fault in the study area. Instead, NW-SE and NE-SW trending normal faults and low-angle faults were mapped. The NW-SE trending ones were already described in our previous study (Ushimaru & Yamaji, 2023a). Thus, the other two classes of faults are described in detail in the following subsections.

3.1 Low-angle faults

We found two map-scale low-angle faults in the southern and northern parts of the study area (Figures 4, 7, 9). We call them the Toshikara and Kotsu-Fukae Faults, respectively.

3.1.1 Toshikara Fault

The Toshikara Fault separates the Hg Unit (Himenoura Group) from the Amakusa Group with a stratigraphic separation (Neuendorf et al., 2005, p633) greater than 100 m. We found an outcrop of this fault in the northern part of the map in Figure 7a, where the fault had a northeastward dip of 18° (Figures 8a, f). This fault did not crop out to the south of this site (Figure 8a), but the trace of the fault that separates the Hg Unit and the Amakusa Group indicates a dip angle of the fault smaller than ~10° (Figure 7a–c). The fault had a 50-cm-thick, foliated, cataclastic, fault core (Figures 8b, c). Slickenlines on the foliations clearly showed an NW-SE trend (Figure 8f). We observed slickensteps and ridge-in-groove lineations (e.g., Fossen, 2016, p224) both indicating the top-to-the northwest sense of faulting (Figures 8d, e).

In addition, the hinterland-dipping duplex indicates a consistent vergence (Figures 8b, c). The crosscutting relationship indicates that the Toshikara Fault is older than NW-SE and NE-SW trending normal faults (Figure 7).

3.1.2 Kotsu-Fukae Fault

The Kotsu-Fukae Fault is inferred as a low-angle fault separating the Shikiyama Formation from the older Fukuregi Formation around crest lines in the northern part of the study area (Figures 9a, S7). We have not found the outcrop of this fault, but its attitude and existence are confirmed from the attitudes and distribution of the formations. The Fukuregi Formation crops out with northwesterly dips of ~ 20 to 30° along valley floors, and the younger Shikiyama Formation is exposed from place to place with similar attitudes on the valley sides. Note that the formations in the western part of the map of Figure 9a have similar NNW-dips at $\sim 20^\circ$ and are juxtaposed in the strike direction. The lateral change of the depositional environments of the formations is unlikely to explain this configuration as follows. Both the formations of the north wing of the anticline in this area are ~ 150 m in thickness, which is about half the total thicknesses of those formations (Figure 6). It means that each of the formations of this part represents a time interval of the order of 10^4 – 10^5 years (Figure 3), and eustatic sea-level changes during this interval are estimated to be with amplitudes of several tens of meters (Simmons et al., 2020). The Fukuregi and Shikiyama Formations were deposited in fluvial and shallow marine environments, respectively, which could not be juxtaposed within distances of < 100 m during the sea-level fluctuations. Thus, the juxtaposition leads us to infer a low-angle fault. That is, we interpret that the Fukuregi Formation crops out in tectonic windows (Figures 9a–c). This interpretation is consistent with the fact that no angular unconformity has been reported between the formations. The transport direction and the precise displacement of the fault are uncertain, but the stratigraphic separation should be a few hundred meters.

Crosscutting relationship indicated that the Kotsu-Fukae Fault is older than the NE-SW and NW-SE trending map-scale normal faults (Figure 9a). The northern ends of the tectonic windows were demarcated by the segments of ENE-WSW trending normal faults which are the northeastern segments of the Reihoku Fault System (RFS, Section 3.2). In addition, a map-scale NW-SE trending normal fault cuts the Fukuregi Formation in the western window and

also cuts the Shikiyama through Sakasegawa Formations (Figures 4, 9a). Accordingly, the Kotsu-Fukae Fault is older than the normal faults.

The Kotsu-Fukae Fault is older than the folds in this area: The folds are younger than normal faults in the Amakusa region (Ushimaru & Yamaji, 2023b). Some of the normal faults cut the Kotsu-Fukae Fault. In addition, the following facts are consistent with this temporal order. The surface of this low-angle fault had a convex-upward shape roughly concordant with the anticline made by the strata around the tectonic windows (Figure 9a). It is certain that the fault is located under the floor of the Kotsu-Fukae River, because the succession from the Fukuregi Formation to the Shikiyama Formation was observed in the valley without discontinuity (Figures 9b, c). This location is consistent with the hypothesis that the fault surface was bent during the folding.

3.2 Normal faults

We mapped twenty-eight segments of NE-SW trending faults, and found outcrops of three segments among them (Figure 4, S6). Here, we refer NE-SW trending faults collectively to NNE-SSW to ENE-WSW trending faults. These segments were all normal in sense with the rake angles of slickenlines ranging from 50 to 80° (Figure 10a).

In our study area, the RFS has the largest displacement among the NE-SW trending normal faults, which typically have a displacement of several tens of meters and up to 200 m. The fault system. is composed of NE-SW to E-W trending segments that are truncated often by NW-SE trending faults (Figures 4, S6). The RFS runs along the northwestern wing of and oblique to the Shiki Anticlinorium in the western and northern parts of the study area, respectively (Takai et al., 1997). The RFS locally branches into two faults around Uchida, Hirayama, and Shiki (Figures 4, S6). The upper formations of the Amakusa Group are juxtaposed with the Himenoura Group by segments of this fault system, indicating the stratigraphic separation of > 700 m. The lower Shikiyama Formation is juxtaposed with the Sakasegawa Formation by the system in the northern study area, indicating a displacement of ~1 km.

3.3 Tilt-correction

The Toshikara and Kotsu-Fukae low-angle faults and NE-SW trending normal faults are always displaced by the NW-SE trending ones (Figure 4, S6) (Takai et al., 1997). These faults

are older than the NW-SE trending normal faults, which are younger than folds in the Amakusa region (Ushimaru & Yamaji, 2023a, b). Thus, unfolding is necessary to consider the tectonic implications of the faults.

The following observations indicate that the Kotsu-Fukae Fault was probably a listric normal fault before the folding. The fault has an upward-convex surface. The crest line of this surface is roughly parallel to that of the anticline made by the surrounding Shikiyama Formation, but the former is offset by 100–200 m to the north-northwest from the latter (Figures 9b, 9c). This offset is consistent with the fact that the angle made by the fault surface and its adjacent bedding plane decreases southeastward as the cross-sections show. Thus, the unfolding transforms the Kotsu-Fukae Fault into a listric normal fault (Figure 9d).

The vergence of the Kotsu-Fukae Fault is loosely constrained by the restored fault shape. The listric fault should have had an easterly to southerly dipping ramp, indicating the southeasterly vergence of the fault with an uncertainty of a few degrees. It is uncertain whether the fault is accompanied by growth strata (e.g., Serck & Braathen, 2019). Consequently, the fault is the oldest map-scale structure in Figure 9a, but the accurate timing of this faulting is uncertain.

We reconstructed the fault-slip data of the Toshikara Fault and NE-SW trending normal faults by the unfolding. We used the software “KUT” (Tomita & Yamaji, 2003) and “Fault and Stress Viewer version 1.10” (Sato, 2013) for tilt-correction and visualization of fault-slip data, respectively. The unfolding increases the rake angles of their slip directions. Without the tilt-correction, two of the NE-SW trending normal faults were dip-slip normal faults, but the segment of the Reihoku Fault System (RFS) had a northeastward vergence. In contrast, the attitudes and slip directions of the restored data (Figure 10b) are more Andersonian than the in-situ ones (Figure 10a) because the original slip directions were subparallel to their dip directions. The restored Toshikara Fault (Figure 8) also had a consistent northwesterly vergence (Figure 10b).

Just like the fold test of paleomagnetism, the tilt-correction of fault-slip data helps us judge the relative timing of faulting and folding (Yamaji et al., 2005). For this purpose, the in-situ and untilted data are shown in Figures 10c and 10d, which offer further support for the hypothesis that the NE-SW trending, map-scale faults and two low-angle faults were formed before the folding. The principal stress axes and the stress ratios in Figure 10c indicate the

optimal stress for the four data in Figure 10a calculated by the method of Yamaji et al. (2006). The ratio is defined as $\Phi \equiv (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$. The gray arrows in Figure 10c indicate the theoretical slip directions predicted by this optimal stress. The solid arrows (sub)parallel to the surrounding gray ones are said to be explained by the optimal one. It is obvious from Figure 10c that the slip direction of the Reihoku Fault System is not explained. That is, plural stresses are needed to explain all the in-situ fault-slip data in Figure 10a. In contrast, all the tilt-corrected data in Figure 10b are explained by a single stress, the principal axes and Φ value are indicated in Figure 10d. All the solid arrows in Figure 10d are parallel or subparallel to the surrounding gray arrows. The angles made by solid arrows and the gray ones are smaller than 20°. Thus, the faults dealt with in Figure 10 were formed before the folding. All the faults are explained by the extensional stress with the NNW-SSE trending σ_3 -axis (Figure 10d).

4 DISCUSSION

4.1 Eocene graben formation in the Amakusa region

It was found recently in the Amakusa region that three events took place one after another in the Middle to Late Miocene, i.e., magmatism, normal faulting along the NW-SE trending faults, and the folding (Figure 2) (Ushimaru & Yamaji, 2023a, b). The NE-SW trending normal faults and low-angle faults are the oldest map-scale structures that affected the Amakusa Group (§ Section 3). Except for this relative timing, the onshore geology of the Amakusa region has provided little evidence for the absolute age of the extensional tectonics represented by these oldest structures.

On the other hand, under the Amakusa Sea adjacent to Shimoshima Island (Figure 11), a NE-SW trending half-graben is filled with Eocene–early Oligocene deposits (Itoh et al., 1999, Figure 7). Seismic and gravity surveys indicate that this graben had a NE-SW trend (Figure 11, 12a) and was formed along a southeasterly dipping, low-angle fault (Itoh et al., 1999, Figure 1). The depositional age of the graben fill was determined at the Amakusa-Oki 1X well (Figure 11). Unfortunately, the borehole did not reach the lower horizons of the deposits, giving rise to uncertainty about the timing of rift initiation.

We speculate that the Amakusa Group was accumulated in a large half graben spanning the Amakusa Sea and the Amakusa archipelago (Figure 13a). This model is based not only on the approximate simultaneity of the graben formation under the Amakusa Sea and the

accumulation of the Amakusa Group (Figure 3) but also on the following facts. All of them are consistent with the Eocene NW-SE extension around the Amakusa region (Figure 12f).

First, the graben model in Figure 13a is consistent with the map-scale faults in the Amakusa region. The NE-SW trending normal faults are the oldest among map-scale faults in the Amakusa Group in the study area. In addition, their northwest- and southeastward vergence are consistent with the model (Figures 10b, 12b): The slip directions (Figure 10b) are roughly perpendicular to the trend of the graben under the Amakusa Sea and the inferred basin margin fault (Figure 11). The extensional tectonics probably gave birth to the graben and the low-angle Toshikara and Kotsu-Fukae Faults because their transport directions are also roughly perpendicular to the basin margin fault (Figure 12c). The extensional stress with the NNW-SSE trending σ_3 -axis (Figure 10 d) explains the slip direction of the Toshikara fault together with the slip directions of NE-SW trending, map-scale, normal faults if the fault-slip data from those are untilted (Figure 10b, 10d). It means that the Toshikara fault was probably activated together with the NE-SW trending ones.

Second, the following facts indicate that the kilometer-scale total thickness of the group (Figures 14a, b) should have been approximately equal to syn-depositional subsidence of the basement. The group accumulated paralic depositional environments, which means that the strata were accumulated near the sea level. In addition, the Eocene eustatic fluctuations had amplitudes of 10^1 m (e.g., Simmons et al., 2020), which are smaller than the total thickness by two orders of magnitude. Thus, it can be assumed that the sea-level stayed at the same height during the accumulation. At the same time, the paleoenvironments indicate that the surface of the sedimentary pile was kept approximately at this height.

The lateral thickness variation of the Amakusa Group is also consistent with the model. That is, the total thickness in northern Shimoshima Island is ~2.6 km (Figure 14a, Columns 1 and 2), whereas that in southern Shimoshima Island is ~3.6 km (Figure 14a, Column 8). These values were obtained in Areas 1 and 2 in the northern part and in Area 8 in the southern part (Figure 14c). The dashed line in Figure 12d is parallel to the straight line between them. It means that the total thickness significantly increases south-by-southwestward. Unfortunately, the top of the Amakusa Group is not exposed (Figure 14c), but the Oniike Formation, the uppermost formation of the group, in northern and southern Shimoshima Island has roughly the same age (Okada, 1992, Tables 1 and 2). Therefore, the lateral variation in the total

thickness indicates the south-by-southwestward basement tilting. This direction has uncertainty of ca. $\pm 90^\circ$ which is represented by the blue fan in Figure 12d. It means that the possible direction ranges from westward to east-by-southeastward.

The lateral thickness variation of the Fukuregi–Ittyoda Formations, i.e., the lower Amakusa Group (Figures 14a, b), suggests southeastward basement tilting. Note that the formations of the group are lithostratigraphic units, meaning that the formation boundaries do not necessarily coincide with isochronous surfaces. However, the Ittyoda Formation is a ravinement lag deposit (Iwata & Kameo, 2001). Mining geologists regarded the formation as the key bed traceable across Shimoshima Island (Figure 14). The deposition of this layer must have taken a much shorter time than the deposition of the lower Amakusa Group. The total thickness is ~ 0.7 km in our study area (Figure 6 and Column 1 in Figure 14a), but it is ~ 2.4 km in the southern part of Shimoshima Island (Column 8 in Figure 14a) and in Kamishima Island (Column 13 in Figure 14a), where the Shikiyama Formation is called the Kyoragi Formation (Miki, 1980). The lateral variation suggests the southeastward thickening of the strata in tandem with the southeastward basement tilting.

This tilt direction is consistent further with the fact that the graben fill is ~ 1 km in thickness under the Amakusa Sea (Itoh et al., 1999, Figure 7) west of Shimoshima Island. The Amakusa Group onshore is a few times thicker than it. The graben fill was correlated with the nannofossil zones CP15a through CP16c at the Amakusa-OkI 1X well (Iwata & Kameo, 2001, Figure 2), i.e., ca. 37.5–32.5 Ma (Agnini et al., 2014; Speijer et al., 2020). Thus, the uppermost part of the Amakusa Group that has been lost by erosion in Shimoshima Island remains under the Amakusa Sea. The southeastward-dipping, low-angle normal fault of the graben under the sea was probably an antithetic fault against the main basin margin fault that ran along the southeastern margin of the Amakusa archipelago (Figure 11). Itoh et al. (1999, Figure 1) identified a NE-SW trending basement high along the extension of the Nomo Peninsula which borders the Amakusa Sea (Figure 11). The Nagasaki Metamorphic Rocks is exposed extensively on the peninsula (Figure 11) and covered by the Eocene formations of ~ 500 m thick that are contemporaneous with the Amakusa Group (Yamaguchi et al., 2008). The horst that neighbored the graben under the Amakusa Sea was situated along the peninsula (Iwata & Kameo, 2001).

Third, very rapid subsidence in the Amakusa region also suggests the Eocene rifting. Not

only the thickness but also the depositional ages of the Amakusa Group have been well-constrained in the southern area of Shimoshima Island (Okada, 1992). Figure 15 shows the cumulative thicknesses versus the ages of the Eocene formations in this area. The accumulation rate during the deposition of the lower Amakusa Group (the Fukuregi through the Ittyoda Formations) was ~ 1 km/m.y., as rapid as that of the intra-arc rifting in Miocene Northeast Japan (Yamaji, 1990). In contrast, the rate during the deposition of the upper Amakusa Group (Sakasegawa, Futae, and Oniike Formations) was relatively slow at 0.17 km/m.y. (Figure 15). No compaction correction (e.g., Allen & Allen, 2005, p. 358) was made for the formation thicknesses in Figure 15 due to the paucity of porosity data, which were reported only from few localities in the Amakusa region by Hoshino & Inami (1975). That is, the porosities of sandstone and siltstone were 1.6–3.6% and 1.4%, respectively. Thus, the correction would increase the earlier accumulation rate by several tens of percents.

Fourth, the distribution of the Akasaki Formation, the lowermost unit of the Amakusa Group, is consistent with the model (Figure 12e). That is, the formation rests on the Cretaceous Himenoura Group along the southeastern margin of the Amakusa archipelago, but is absent in the western part of the islands (Figures 13, 14). Thus, Miki (1975) inferred that the Akasaki Formation filled an NE-SW trending narrow graben (Figure 13a). The formation includes boulder-sized clasts of granitic rocks and greenschist (Miki & Matsueda, 1974; Miki, 1975; Kawaji, 2001), which indicate the proximity of the steep slopes where such crystalline rocks were exposed.

Finally, the distribution of workable coal in the Amakusa archipelago is also consistent with the model. That is, there were coal mines in western Shimoshima Island (Figure 11), but were few workable coal elsewhere in the archipelago (e.g., Nagao, 1926; Inoue, 1962; Miki, 1975; Miki & Takahashi, 1980; Takai et al., 1997). This distribution is explained by the southeastward basement tilting (Figure 13a). The contemporaneous formation in Kamishima Island was deposited in shallow marine environments (Saito & Matsuda, 2003). The northwestern part of Shimoshima Island remained above sea level while southeastern areas in the archipelago were inundated.

4.2 Basin margin fault

The Amakusa Group filled probably a large half-graben with an NE-SW trending basin

margin fault, which ran under the Yatsushiro Sea. The following two observations led us to consider this location. First, there is no Paleogene formation on the southeastern side of the Sea except those in the Shimanto accretionary complex (Miyazaki et al., 2016) (Figure 1). Second, the metamorphic clasts in the Akasaki Formation were derived from the Kiyama or Manotani Metamorphic Rocks that is extant to the northeast of the Amakusa archipelago (Miki & Matsueda, 1974) (Figure 11). They are Carboniferous–Permian and Triassic–Jurassic high-P/T metamorphic rocks, respectively (e.g., Hoshizumi et al., 2004). The extant metamorphic rocks are located 30–40 km northeast of Amakusa, but the inclusion of boulder-sized metamorphic clasts in the Akasaki Formation (REF) indicates that the rocks were exposed at a steep slope in the vicinity of the formation and on the southeastern side of the basin margin fault (Figure 11).

The basin margin fault seems to terminate around the base of the Uto Peninsula (Figure 13). There is no Paleogene basin fill extant around the Kumamoto Plain (Figure 11). Eocene–Oligocene Miike Group and its contemporaneous strata under the Ariake Sea (Figure 11) have a total thickness greater than 1 km (Iguchi, 2016), but they do not show growth structures. These facts suggest that the width of the half graben decreased northeastward and that the basin margin fault was terminated somewhere around the base of the Uto Peninsula (Figure 11).

The fault represented by the Usuki-Yatsushiro Tectonic Line (UYTL) is unlikely for the basin margin fault. UYTL is a surface trace of a crustal-scale, northwest-dipping fault across Kyushu Island and separates metamorphic terrains (northwest side) from a Jurassic accretion complex with clear zonal structures (southeast side) (Hoshizumi et al., 2004; Saito et al., 2010). The southwestern extension of UYTL runs in the Yatsushiro Sea (e.g., Editorial Committee of Kyushu, Regional Geology of Japan, ed., 1992; Fukuda et al., 2015). The Kiyama and Manotani Metamorphic Rocks belong to the northwest side (Figure 11), and should have belonged to the footwall of the basin margin fault because the Akasaki Formation contains clasts derived from those metamorphic rocks (Miki & Matsueda, 1974; Miki, 1975; Kawaji, 2001). Therefore, the basin margin fault ran between UYTL and the Amakusa archipelago, though the fault could meet the UYTL fault at depth.

Miki and his coworkers suggested syn-depositional faulting based on the large difference in the thicknesses in the Shikiyama Formation in Shimoshima Island and the Kyoragi

Formation in Kamishima Island. The formations are synonymous with each other. They suggested syn-depositional differential subsidence brought by an inferred fault between the islands (Miki, 1975, 1980; Miki & Suzukawa 1980). However, there is no abrupt change in the thickness of these formations across the Hondo Strait between the islands (Figure 14a–c) where they assumed the fault.

The large graben was inverted in the Miocene to form folds with NE-SW trending axes (Figures 11, 13b) (Ushimaru & Yamaji, 2023b). Cretaceous crystalline basement and the Himenoura Group which underlies the Amakusa Group were uplifted and exposed along both the wings of the Ittyoda Syncline in Shimoshima Island (Figures 2, 13b) and southeastern parts of the Amakusa archipelago (Figure 11). The pre-Eocene basement rocks are exposed in several areas in the archipelago, indicating that the large half graben has been subject almost to the “total inversion” which is a term coined by Bally (1984) to refer to an inverted half graben whose basement was once tilted but returned to the original level.

4.3 Exhumation of metamorphic units

The Eocene extensional tectonics in the Amakusa archipelago was possibly coeval with the uplift of the Takahama Metamorphic Rocks, which is a Cretaceous high-P/T metamorphic unit comparable with the Nagasaki Metamorphic Rocks to the northwest of the Amakusa archipelago and, possibly, further with the Sambagawa Metamorphic Rocks (Faure et al., 1988; Moriyama & Yamamoto, 2005). The Himenoura Group and the Takahama Metamorphic Rocks are separated by a low-angle normal fault in western Shimoshima Island (Moriyama & Yamamoto, 2005). The activity of this fault may be involved in the extensional tectonics that created the accommodation of the Amakusa Group because the slip direction of this fault (Moriyama & Yamamoto, 2005) was approximately parallel to that of the NE-SW trending normal faults and of the Toshikara low-angle fault in the study area (Figure 10b). Thus, the Takahama Metamorphic Rocks was probably uplifted by the Eocene extensional tectonics. The timing of its surface exposure is a future issue because metamorphic clasts in the Himenoura and Amakusa Groups around the Takahama Metamorphic Rocks have not been petrologically examined.

4.4 A northeastern branch of the East China Sea rift system

Sakai (1993) suggested that the lower Amakusa Group was deposited in a sinistral pull-apart basin resulting from the oblique subduction of the Pacific Plate before the plate motion change by the Hawaiian-Emperor bend, but we consider this is unlikely. There is no evidence for Eocene strike-slip tectonics in the Amakusa Group. However, the plate motion change seems important because the age of the Hawaiian-Emperor bend at ~50 Ma (Sharp & Clague, 2006) was roughly simultaneous with the age of the lowermost formation of the Amakusa Group (Figure 3). The start of basin subsidence in the Amakusa region was one of the contemporaneous tectonic events around the Pacific (Stock, 2006) in relation to the global reorganization of plate motions (e.g., Vaes et al., 2019; Hu et al., 2022). However, the link between the basin subsidence in the Amakusa region and this global event is beyond the scope of this study.

Eocene backarc rifting has been documented in the East China Sea (e.g., Zhu et al., 2019). The Pacific Plate was subducting in front of the Ryukyu arc at that time (e.g., Liu et al., 2023). This rift system is thought to have its northeastern end to the west of northern Kyushu Island (e.g., Cukur et al., 2011a, b), but this end is unclear due to the superposition of the Neogene–Quaternary rifting that has made the Okinawa Trough (Shang et al., 2017). Many NE-SW or NNE-SSW trending deep grabens are filled with thick Eocene formations in the East China Sea. The graben that was filled with the Amakusa Group was probably involved in this backarc rifting. The inferred trend of the basin margin fault in the Amakusa region is roughly parallel to the grabens under the East China Sea (Cukur et al., 2011a, Figure 14).

The backarc rift system under the East China Sea branched into the Amakusa region in the Eocene time, but no other regions in northern Kyushu Island as follows. Eocene paralic formations are extant in the northern part of Kyushu Island (e.g., Matsushita, 1949, 1971), but they do not show significant syn-depositional tectonic deformations. Eocene–Oligocene strata in northern and northwestern Kyushu Island were affected by a number of NW-SE trending normal faults which were thought to be syn-depositional (e.g., Matsushita, 1951; Takahashi et al., 1971). However, the timing of these faults was recently reconsidered to be of the Middle Miocene (Ozaki, 2013; Ushimaru & Yamaji, 2023a). There are veneers of Eocene formations remaining around the Seto Inland Sea (Figure 1), but they show no graben structure. Thus, the

Amakusa branch may not have reached the Sea.

The Paleogene rift system under the East China Sea probably branched into the Amakusa region in the Eocene time. Now, the Taiwan-Shinji fold belt runs between the Amakusa region and the Paleogene rift system under the East China Sea, but the fold belt was formed in the Miocene (e.g., Itoh and Nagasaki, 1996). Another branch extended probably into the area behind SW Japan to create the Japan Sea backarc basin eventually in the Miocene (e.g., Yun et al., 2007; Cukur et al., 2015).

5 CONCLUSIONS

The geologic structures of the Eocene formations in the Amakusa region to the west of Kyushu Island were studied in this work. We made a geological map of the northwestern part of Shimoshima Island and examined the slip directions of map-scale faults. As a result, we found that the map-scale faults in the study area were mostly normal in sense and that the NW-SE trending normal faults cut NE-SW trending ones. In addition, we found two low-angle faults (the Toshikara and Kotsu-Fukae Faults). The NE-SW trending normal faults and low-angle faults are the oldest structures in the Eocene formations. The trends and vergences of those faults are concordant with the formation of a NE-SW trending, Eocene–Oligocene, half graben under the Amakusa Sea west of our study area. Thus, the oldest normal faulting was probably involved in the syn-depositional extensional tectonics that created a large half graben to accommodate the Amakusa Group with kilometer-scale thicknesses. This half graben was tilted southeastward by the NE-SW trending basin margin fault. This model is consistent with the southeastward thickening trend of the thickness of the Amakusa Group. This graben was a branch of the backarc rift system under the East China Sea.

AUTHORSHIP CONTRIBUTION STATEMENT

Kentaro Ushimaru: Data curation, Formal analysis, Funding acquisition, Investigation, Writing-draft. **Atsushi Yamaji:** Conceptualization, Investigation, Methodology, Supervision, Funding acquisition, Writing-review.

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FIGURES

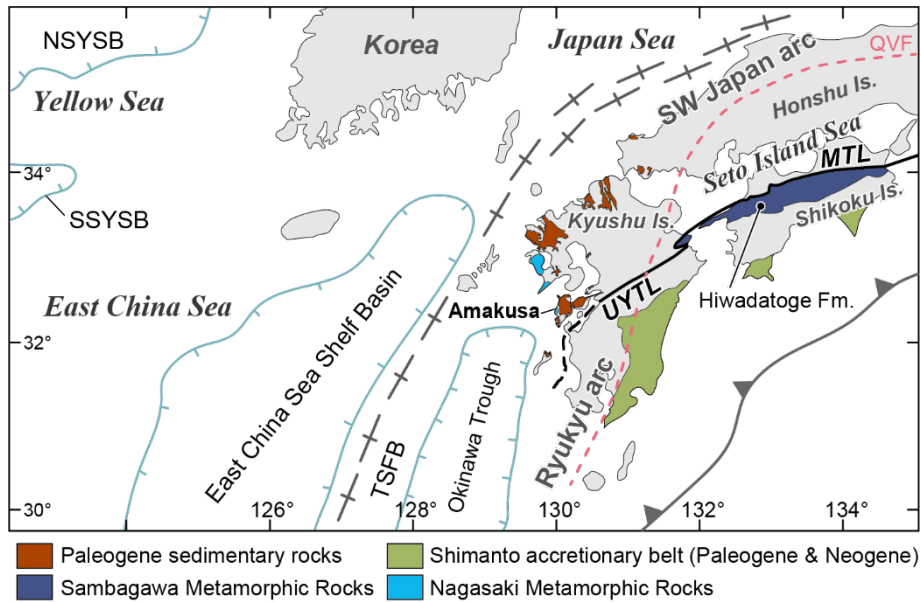


FIGURE 1: (a) Tectonic map around Kyushu Island. ECSSB, East China Sea Shelf Basin. NSYSB, Northern South Yellow Sea Basin. SSYSB, Southern South Yellow Sea Basin. TSFB, Taiwan-Shinji fold belt. MTL, Median Tectonic Line. UYTL, Usuki-Yatsushiro Tectonic Line. QVF, Quaternary volcanic front. The outlines of the NSYSB, SSYSB, and ECSSB are after Lee et al. (2006). The QVF is from Geological Survey of Japan (2013). Distributions of Paleogene sedimentary rocks, Sambagawa and Nagasaki Metamorphic Rocks, and Shimanto accretionary belt are simplified from the Seamless Geological Map version 2 (Geological Survey of Japan, 2023). The southwestern extension of the UYTL is from Editorial Committee of Kyushu, Regional Geology of Japan, ed. (1992). Is., Island.

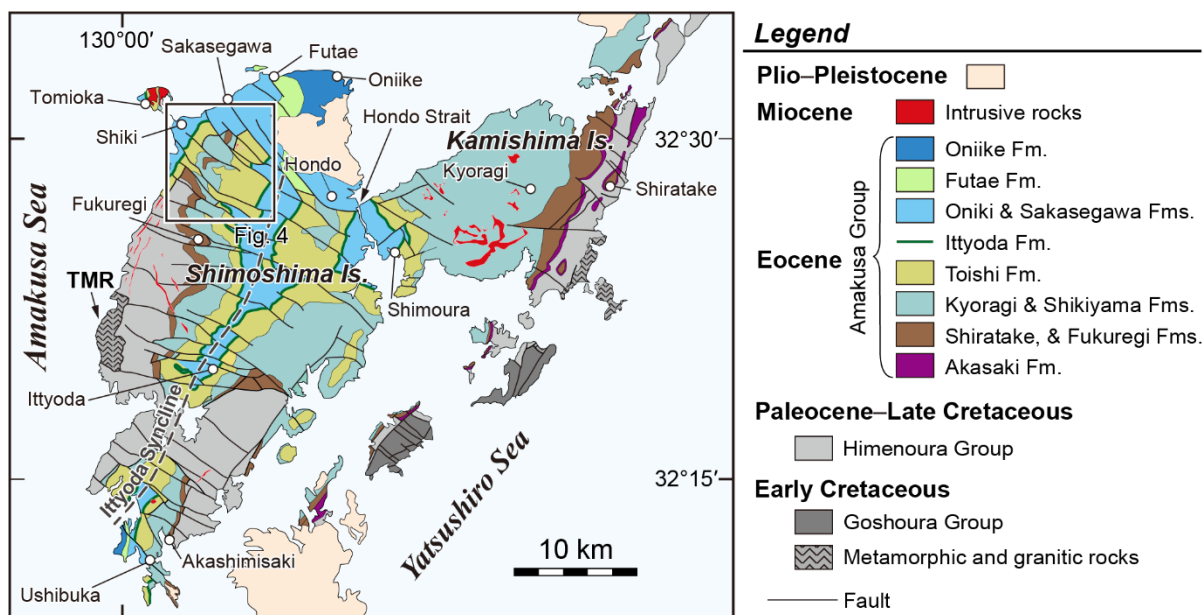


FIGURE 2: Geological map of the Amakusa region simplified from Saito et al. (2010). TMR, Takahama Metamorphic Rocks.

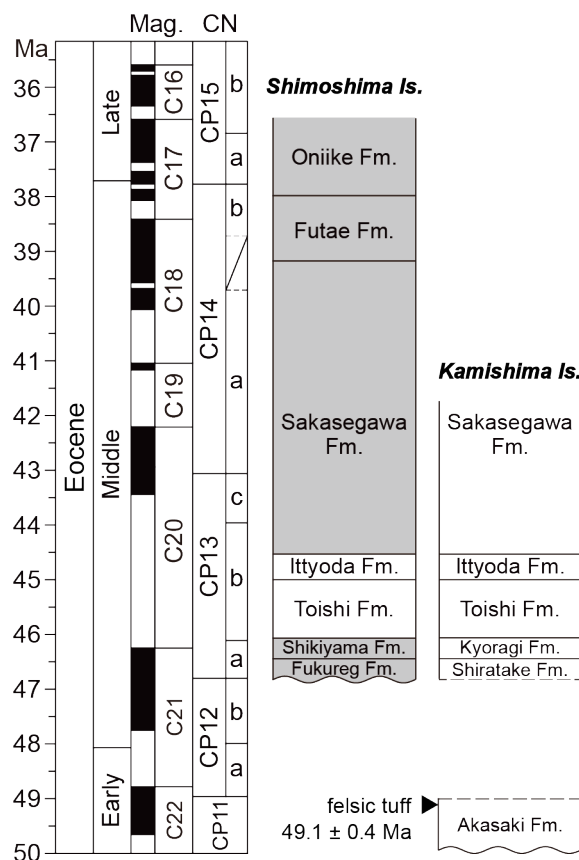
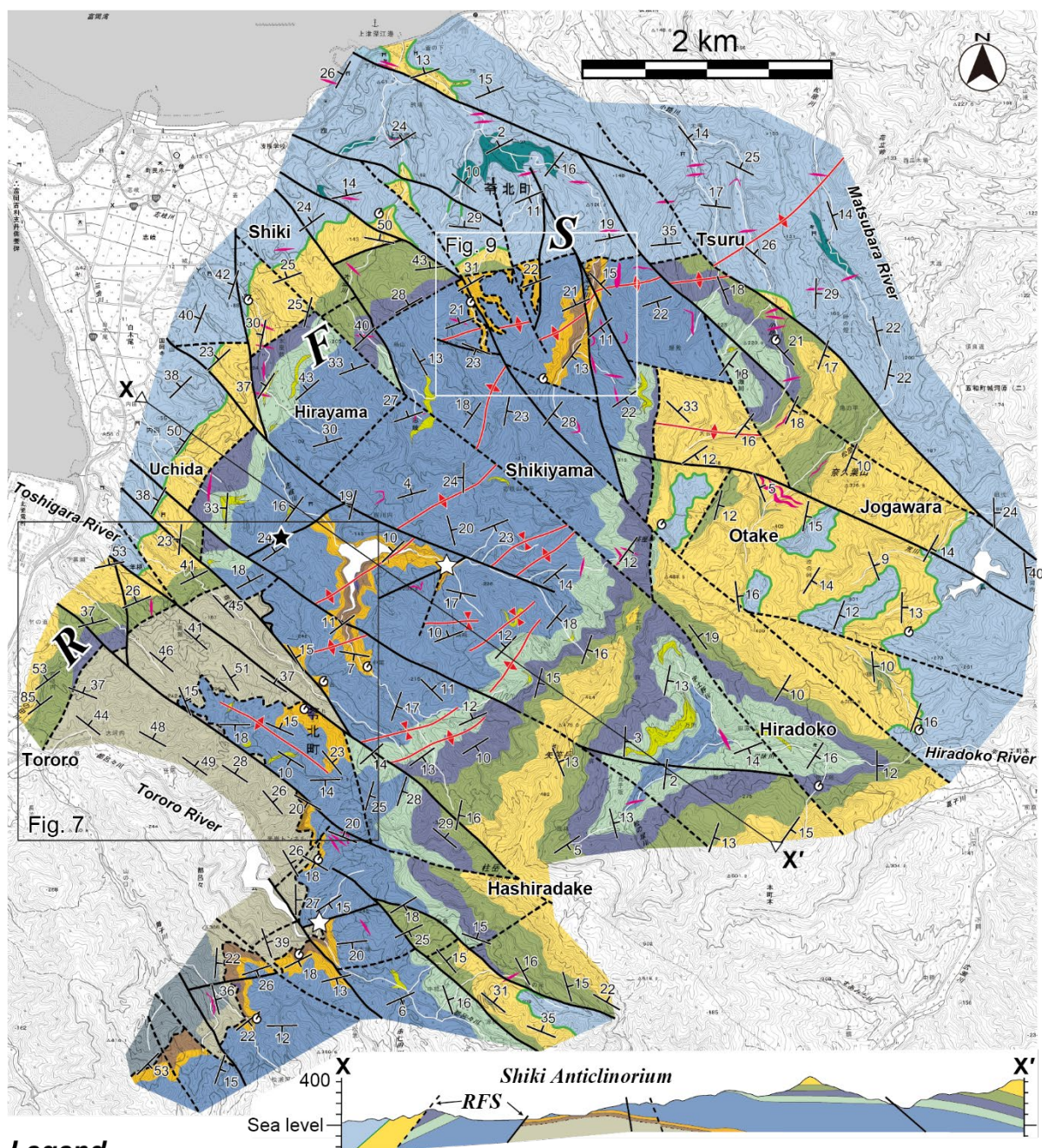


FIGURE 3: Depositional ages of the Eocene formations in the Amakusa region. Gray

956 backgrounds indicate the formations whose ages were constrained by calcareous nannofossils
957 by Okada (1992). The zircon U-Pb age of felsic tuff in the Akasaki Formation is after Miyake
958 et al. (2016). The ages of magnetic polarity and nannofossil zones after Speijer et al. (2020)
959 and Agnini et al. (2014).
960



Legend

Miocene	Amakusa Group	Intrusive rock	Rhyolite, dacite, and andesite	---	Fault (broken where inferred)
		Sakasegawa Fm.	Sandy siltstone	27	Bedding
		Ittyoda Fm.	Glauconite-bearing fine-grained sandstone	♦	Anticline
Eocene	Amakusa Group	Toishi Fm.	Medium- to coarse-grained sandstone and coal	⊕	Syncline
			Sandstone-rich alternation of sandstone and siltstone	○	Eocene molluscan fossils
			Massive siltstone		Fault outcrop with slickenlines
		Shikiyama Fm.	Fine-grained sandstone	☆	NE-SW trending
			Alternation of fine-grained sandstone and siltstone	★	Segment of RFS
Paleocene -Cretaceous	Himenoura Group (Hg Unit)		Siltstone-rich alternation of siltstone and sandstone		
		Fukuregi Fm.	Massive fine-grained sandstone		
			Bedded siltstone		
			Coarse- to very coarse-grained sandstone and siltstone		
			Alternation of pebbly conglomerate, sandstone, and siltstone		
			Alternation of sandstone and siltstone		

FIGURE 4: The geological map and cross-section around the northern Shiki Anticlinorium. No vertical exaggeration for the cross-section. The Reihoku Fault System (RFS) runs from Tororo in the southwestern part to Tsuru in the northern part of this map. The base map is by courtesy of the Geospatial Information Authority of Japan. Contour interval is 100 m.

Formation		Lithology	Thickness (m)
Sakasegawa		dark sandy shale sl-rich alternation of ss & sl	>160
Ittyoda		glauconite-bearing fine ss molluscan fossils	5–10
Toishi	Upper 	ss-rich alternation of ss & sl coal	250
	Lower 	sl-rich alternation of ss & sl	
Shikiyama	Upper 	massive & glauconite-bearing sl molluscan fossils	370
	Middle 	ss-rich alternation of ss & sl	
	Lower 	bedded sl sl-rich alternation of ss & sl	
Fukuregi	Upper 	fine ss molluscan fossils	>80
	Lower 	coarse to very coarse ss, sl molluscan fossils	
Hg Unit		pebble conglomerate, ss, & sl	>290
		ss-rich alternation of ss & sl	

FIGURE 5: Stratigraphy and lithologies of the Amakusa Group in the study area. The thicknesses of the Sakasegawa Formation, Fukuregi Formation, and the Hg unit are the lower limit values because the top or bottom of them are not exposed in the study area.

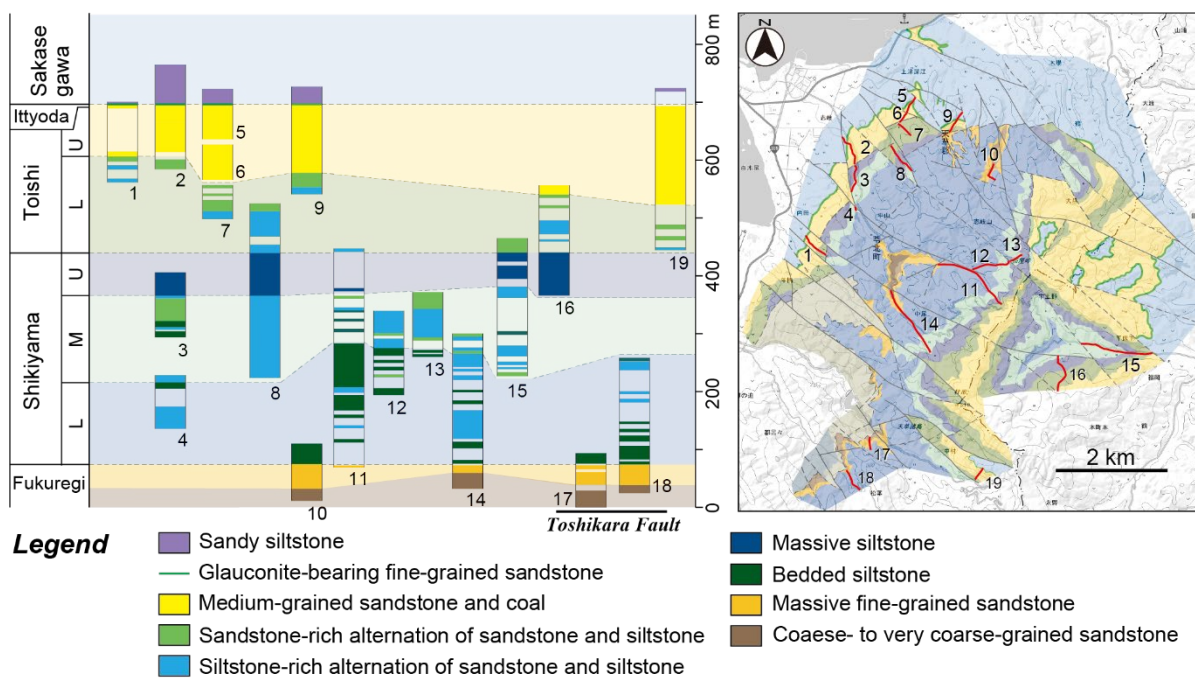


FIGURE 6: Route columnar sections of the Amakusa Group in the study area. See Fig. 4 for the legends of the geological map.

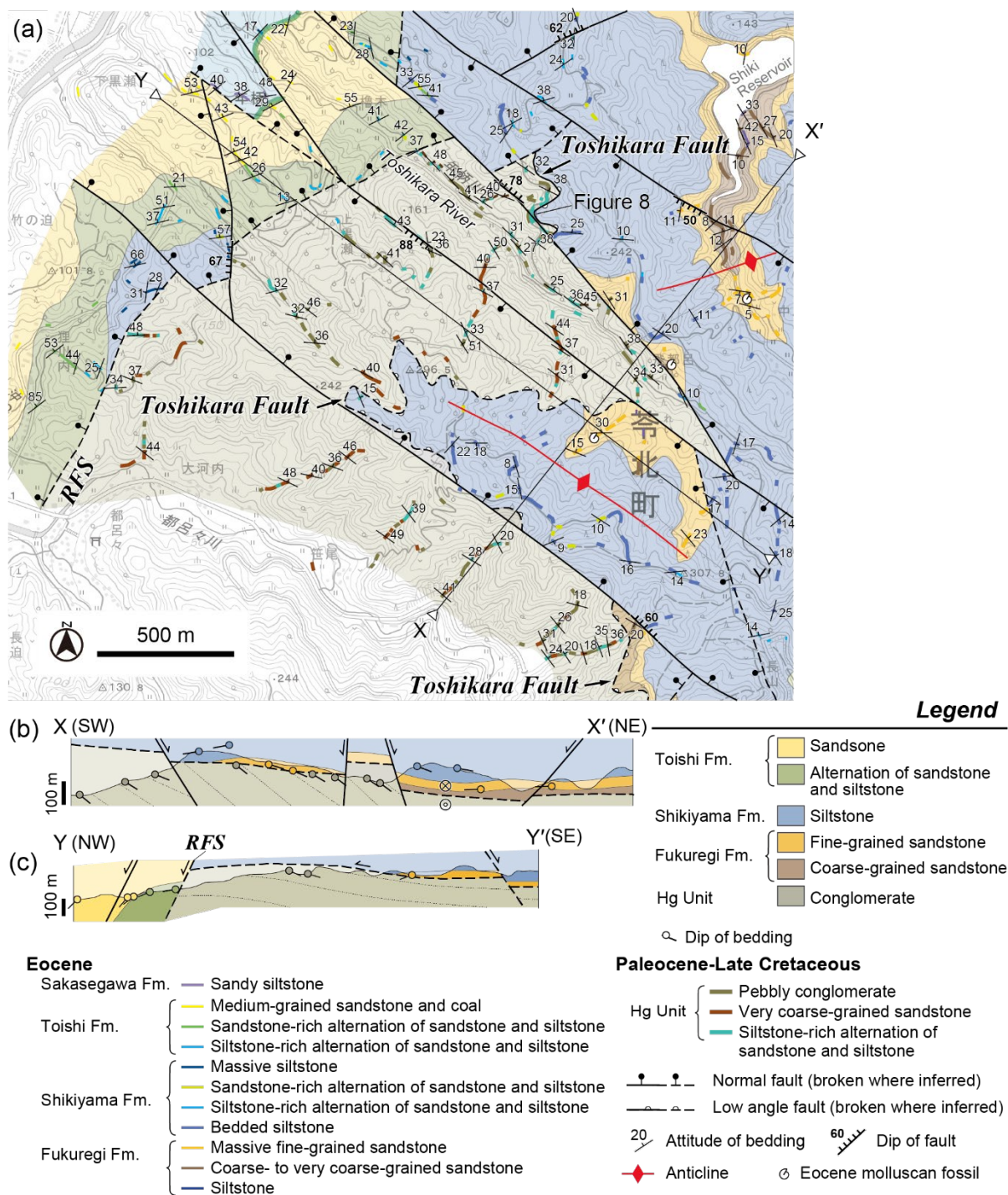


FIGURE 7: (a) The route map around the boundary between the Amakusa and Himenoura Groups and around the low-angle Toshikara Fault. The base map is by courtesy of the Geospatial Information Authority of Japan. Contour interval is 10 m. We observed an outcrop of this fault zone in the northern part of the fault (Figure 8). (b, c) The cross-sections along X–X' and Y–Y' without vertical exaggeration. The symbols, $\odot$ and $\otimes$, in (b) indicate the top-to-

the-NW sense of the fault.

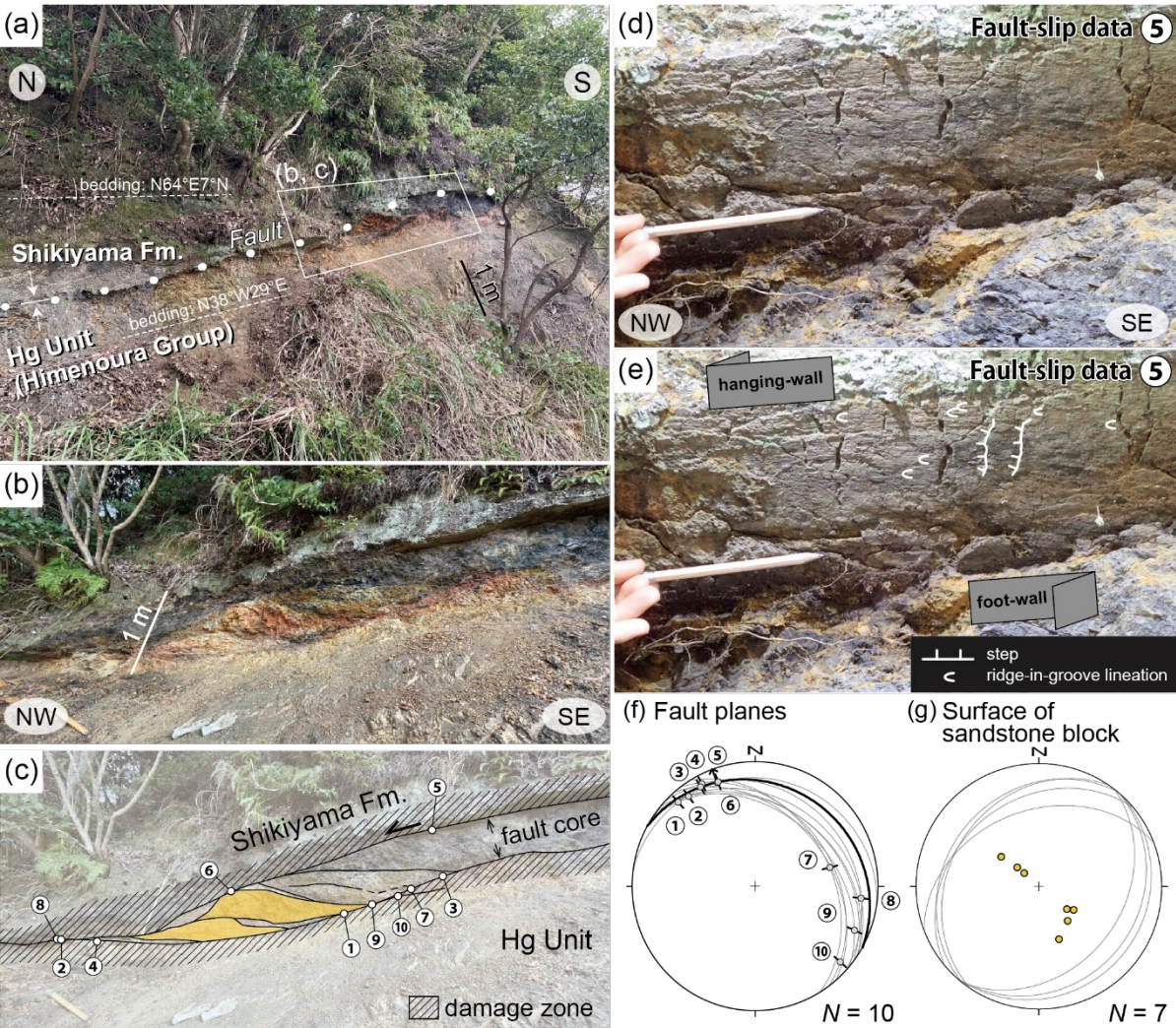


FIGURE 8: (a) The outcrop of the Toshikara Fault separating the Shikiyama Formation and the Himenoura Group. The shale of the Shikiyama Formation lies on the siltstone-rich alternation of sandstone and siltstone of the Hg Unit by a fault. The fault core involves duplexes, with which the fault zone has a pinch-and-swell structure. The locality of this outcrop is shown in Figure 7a. (b, c) An NW-vergent, hinterland-dipping duplex in the low-angle fault zone indicates top-to-the-NW sense of shear. Sandstone blocks involved with the duplex are colored yellow. The fault core pinches out leftward in this photograph. (d, e) Shear sense indicators at the top of the gouge zone showing sinistral oblique-normal faulting. The location of those photographs and the corresponding fault-slip datum are shown in (c) and (f), respectively. (f) Lower-hemisphere, equal-area projection showing the fault-slip data from the

outcrop. Bars indicate the orientations of slickenlines observed in the outcrop. Thick line indicates the main fault plane. (g) Lower-hemisphere, equal-area projection of poles to walls of sandstone blocks involved with the duplex in (b, c).

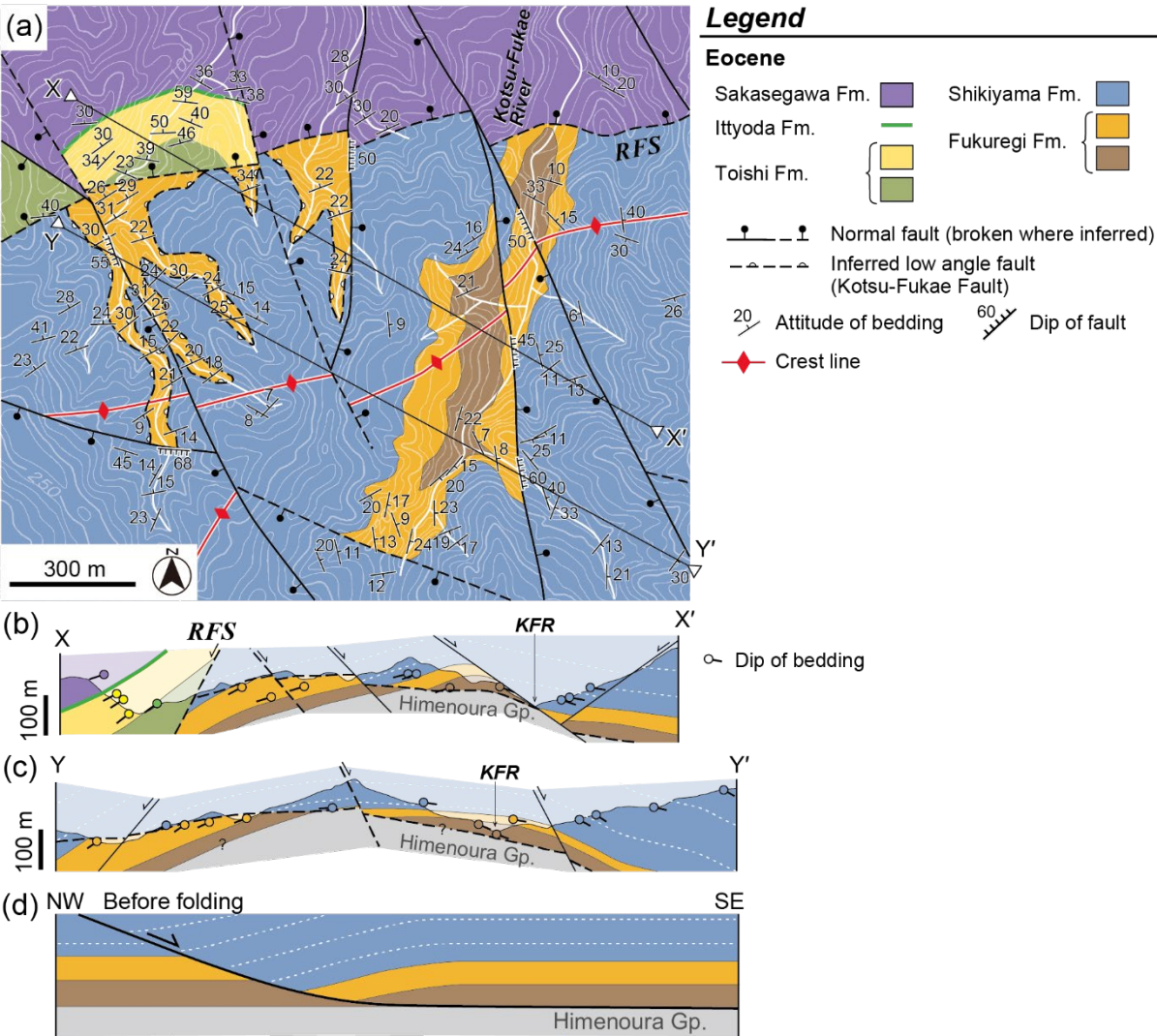


FIGURE 9: (a) The geological map around the low-angle fault in the northern part of the study area. Valley floors are depicted by bold white lines. RFS: Reihoku Fault System. The base map by courtesy of the Geospatial Information Authority of Japan. Contour interval is 10 m. The detailed outcrop data used to draw this map is available from Supporting Information (Figure S7). (b, c) The cross-sections along X-X' and Y-Y'. No vertical exaggeration. The Himenoura Group under the Fukuregi Formation is depicted by a grey color. KFR, Kotsu-Fukae River. (d) Schematic for the restored cross-section along Y-Y' before the folding.

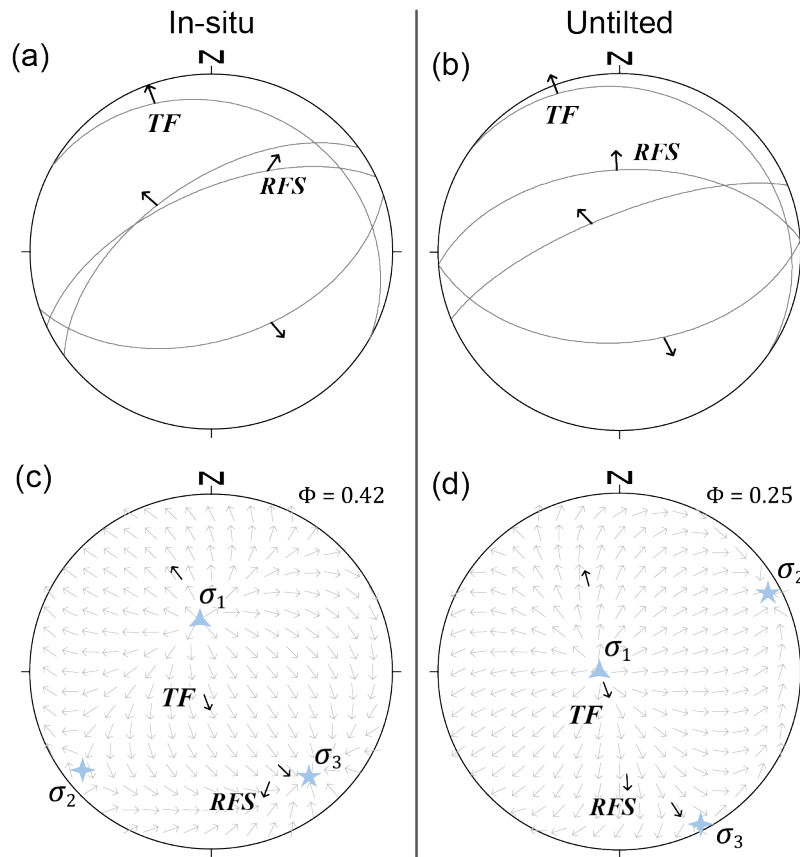


FIGURE 10: (a, c) In-situ and (b, d) untilted fault-slip data from NE-SW trending, map-scale, normal faults and the Toshikara Fault (the fault-slip data 5 in Figure 8f). (a, b) Lower hemisphere, equal-area projections. (c, d) Tangent-lineation diagrams. Solid arrows represent the data in (a) and (b). The position and direction of an arrow on a tangent-lineation diagram indicate the pole to a fault plane and the slip direction of the footwall, respectively. Gray arrows in (c, d) indicate theoretical slip directions calculated from the optimal stresses, the principal axes of which are depicted by blue stars. Their stress ratios are indicated on the upper right of each diagram. RFS, Reihoku Fault System. TF, Toshikara Fault.

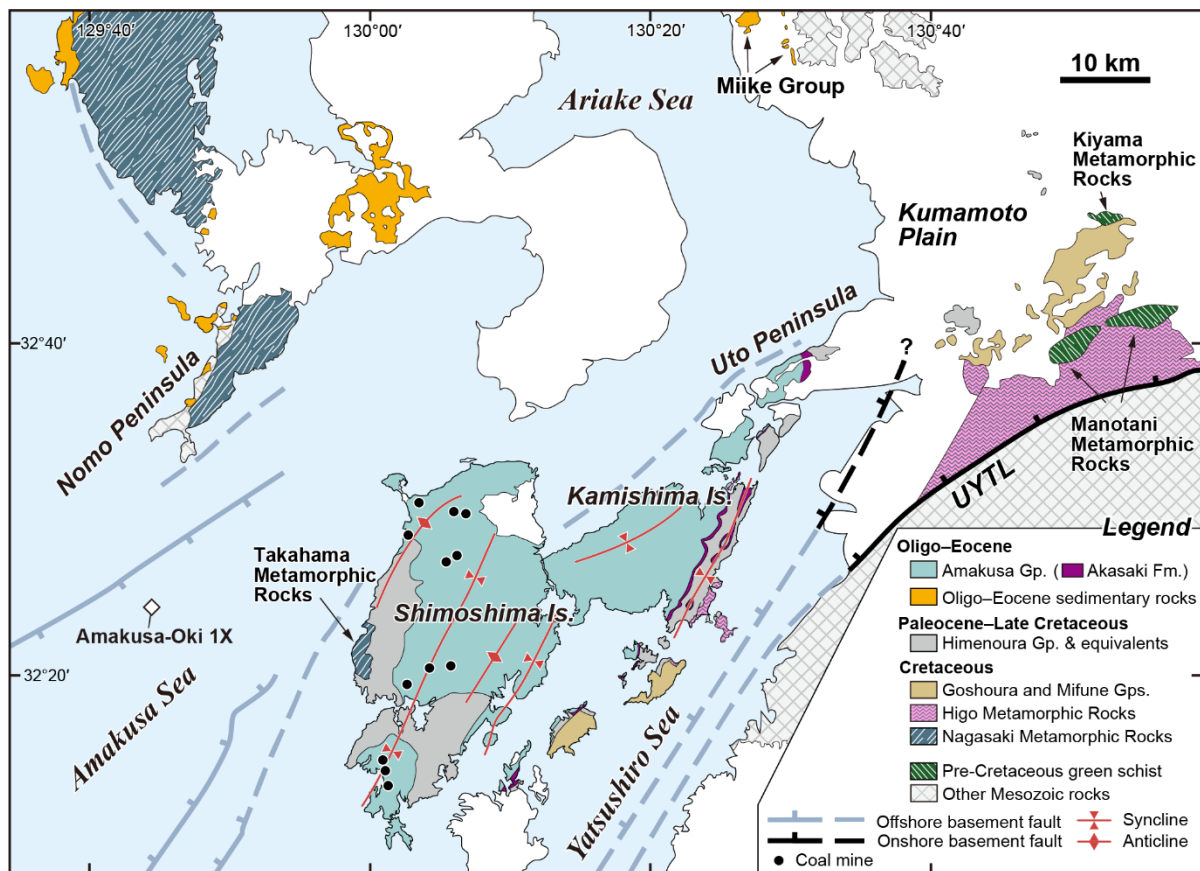


FIGURE 11: Tectonic map around the Amakusa archipelago. Onshore geological map is simplified from the Seamless Geological Map version 2 (Geological Survey of Japan, 2023). The offshore faults and the location of the Amakusa-Oki 1X well are from Iwata & Kameo (2001). The offshore and onshore faults are broken where inferred. Bars on fault lines indicate the dip directions of the faults. Locations of coal mines are after Miki (1975).

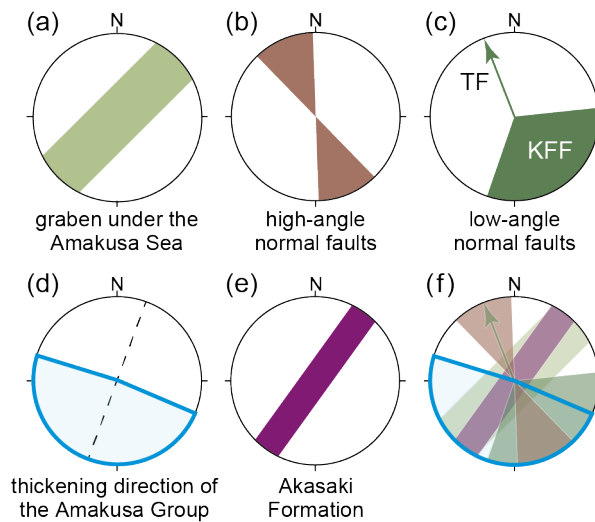


FIGURE 12: (a) The trend of the graben under the Amakusa Sea (Itoh et al., 1999, Figure 1). (b) Fans indicating the range of the slip directions of the hanging-walls of NE-SW trending, map-scale, normal faults (Figure 10b). (c) Those of the low-angle faults. TF, the Toshikara Fault; KFF, the Kotsu-Fukae Fault. The slip direction of the latter has a large uncertainty depicted by the fan. (d) Fan indicating the possible thickening direction of the Amakusa Group inferred from the total thickness of the group in the northern (Figure 14a, Columns 1 and 2) and southern (Figure 14a, Column 8) Shimoshima Island. This direction has the uncertainty of $\sim 180^\circ$ centered by the dashed line which shows the relative direction of Area 9 from Area 2 in Figure 14c. (e) The alignment of the Akasaki Formation in southeastern Amakusa archipelago (Figure 14c). (f) Superposition of (a)–(e).

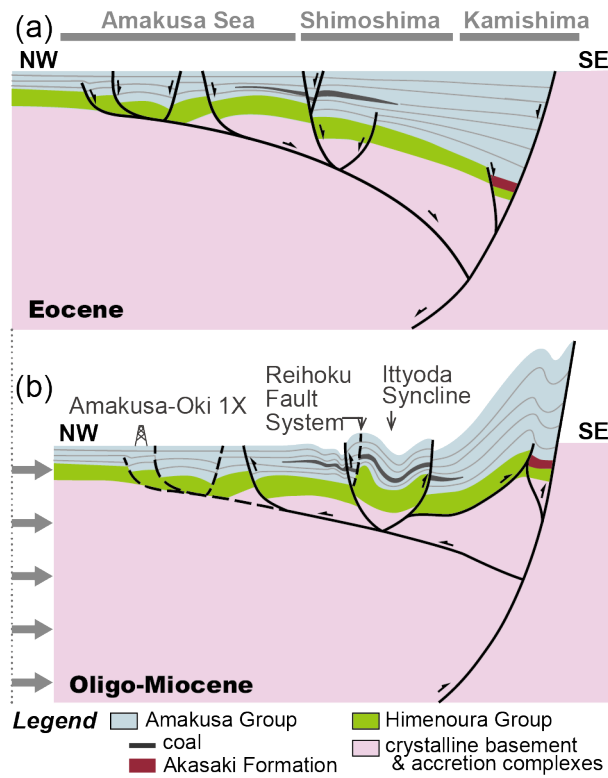


FIGURE 13: Schematic cross-sections across the Amakusa archipelago. Structures under the Amakusa Sea are simplified from Itoh et al. (1999). Not to scale.

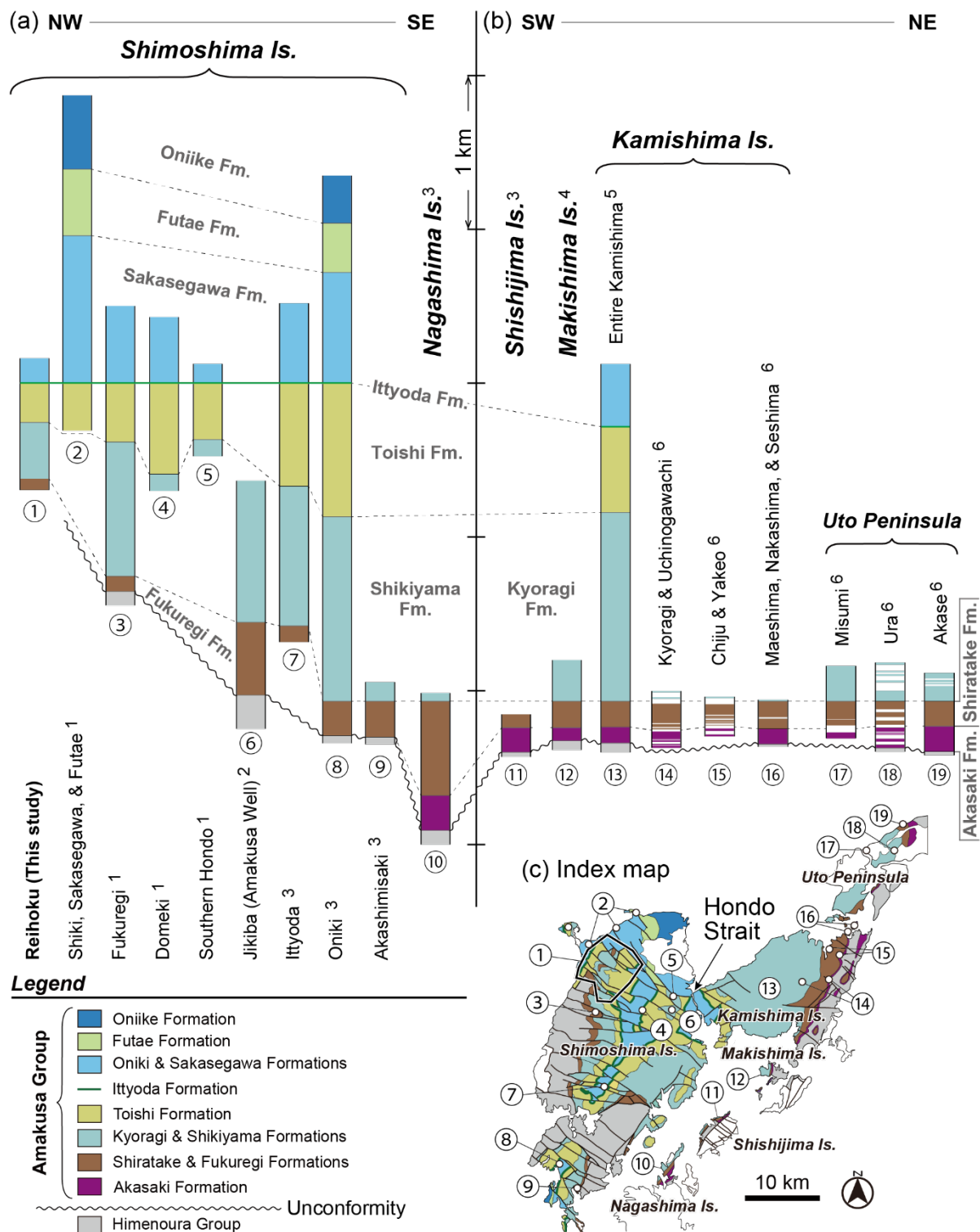


FIGURE 14: (a, b) Geologic columns of the Amakusa Group in (a) western and (b) eastern Amakusa region. Since the group is not interbedded with key tuff beds, we correlated those columns by the Ittyoda Formation which was interpreted as a ravinement plane (Iwata &

Kameo, 2001) or by the base of the Shikiyama & Kyoragi Formations for convenience. Data sources are: 1, Takai et al. (1997); 2, Atake, (1973); 3, Takai & Sato (1982); 4, Amano (1960); 5, Miki (1980); 6, Inoue (1962). (c) The locations of columns in (a) and (b) shown on the Geological map simplified from Saito et al. (2010). Miocene intrusive rocks are omitted, and Pliocene, Pleistocene, and Early Cretaceous rocks are not colored in the map.

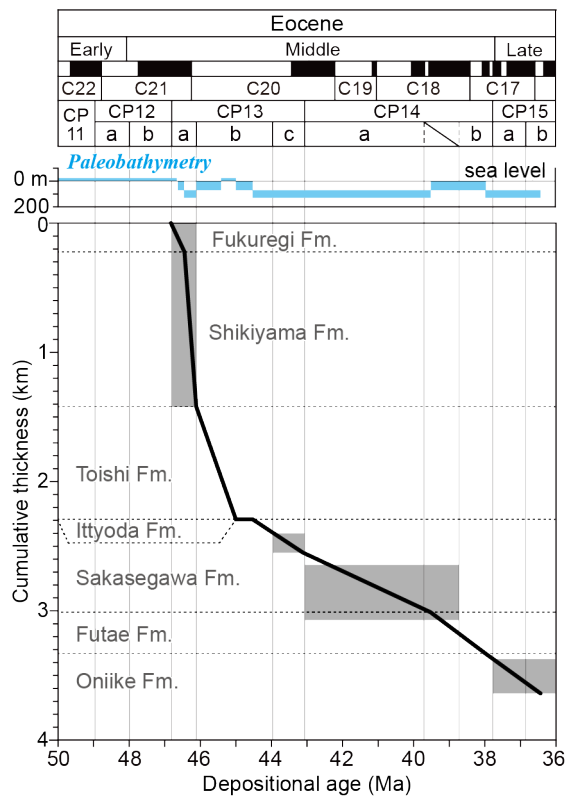


FIGURE 15: Sediment accumulation rates (Solid polyline) of the Amakusa Group in southern Shimoshima Island. Gray rectangles depict the error ranges of the lines. The widths of the rectangles indicate the possible ages compatible with the nannofossil zones reported from the group by Okada et al. (1992). For example, the Fukuregi and Shikiyama Formations yielded the nannofossils of the zone CP13a. Compaction correction is not made for the formations. The ages of magnetic polarity and nannofossil zones are after Speijer et al. (2020) and Agnini et al. (2014). The thickness is after Takai and Sato (1982) (Area 8 in Figure 14). The paleobathymetry is after Iwata and Kameo (2001).

SUPPORTING INFORMATION

- **FIGURE S1:** Photographs of the representative and notable outcrops of the Hg unit of the Himenoura Group.
- **FIGURE S2:** Photographs of the representative and notable outcrops of the Eocene Shikiyama and Fukuregi Formations.
- **FIGURE S3:** Photographs of the representative and notable outcrops of the Eocene Sakasegawa, Ittyoda, and Toishi Formations.
- **FIGURE S4:** Photomicrographs of the glauconite-bearing sandstone of the Ittyoda Formation.
- **FIGURE S5:** The boundary of the Ittyoda and Sakasegawa Formations at Shimoura, southwestern Kamishima Island.
- **FIGURE S6:** Tectonic map of the study area.
- **FIGURE S7:** Detailed outcrop data around the Kotsu-Fukae Fault.



FIGURE S1: Photographs of the representative and notable outcrops of the Hg unit of the Himenoura Group. (a) Alternation of siltstone and pebbly conglomerate of the Hg unit. (b) Alternation of conglomerate and sandstone of the Hg unit. Dashed line indicates the base of the channel. (d) Matrix-supported pebbly conglomerate of the Hg unit. (e) Alternation of sandstone and siltstone of the Hg unit.

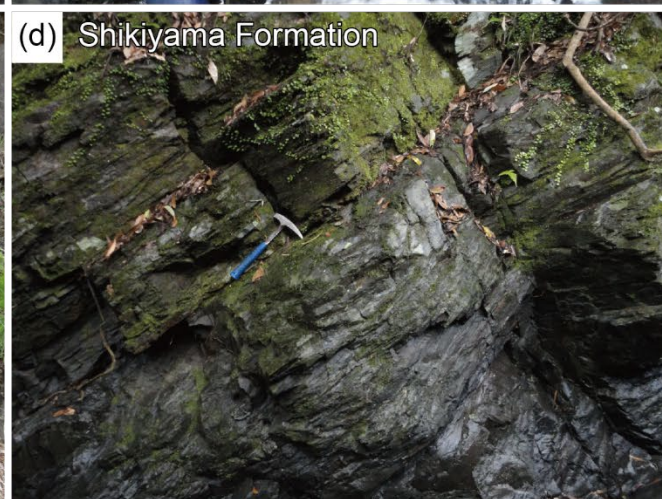


FIGURE S2: Photographs of the representative and notable outcrops of the Eocene Shikiyama and Fukuregi Formations. (a) Massive grey siltstone of the upper part of the Shikiyama Formation. (b) Bivalve fossils in the massive siltstone of the upper part of the Shikiyama Formation. (c) Well-stratified alternation of sandstone and siltstone of the middle part of the Shikiyama Formation. (d) Bedded dark siltstone of the lower part of the Shikiyama Formation. (e) Cross-bedded thick sandstone of the upper part of the Fukuregi Formation. (f) A fossiliferous horizon in the lower part of the Fukuregi Formation. (g) Molluscan fossils in the fossiliferous bed in the outcrop (f). (h) Molluscan fossils in the upper part of the Fukuregi Formation.

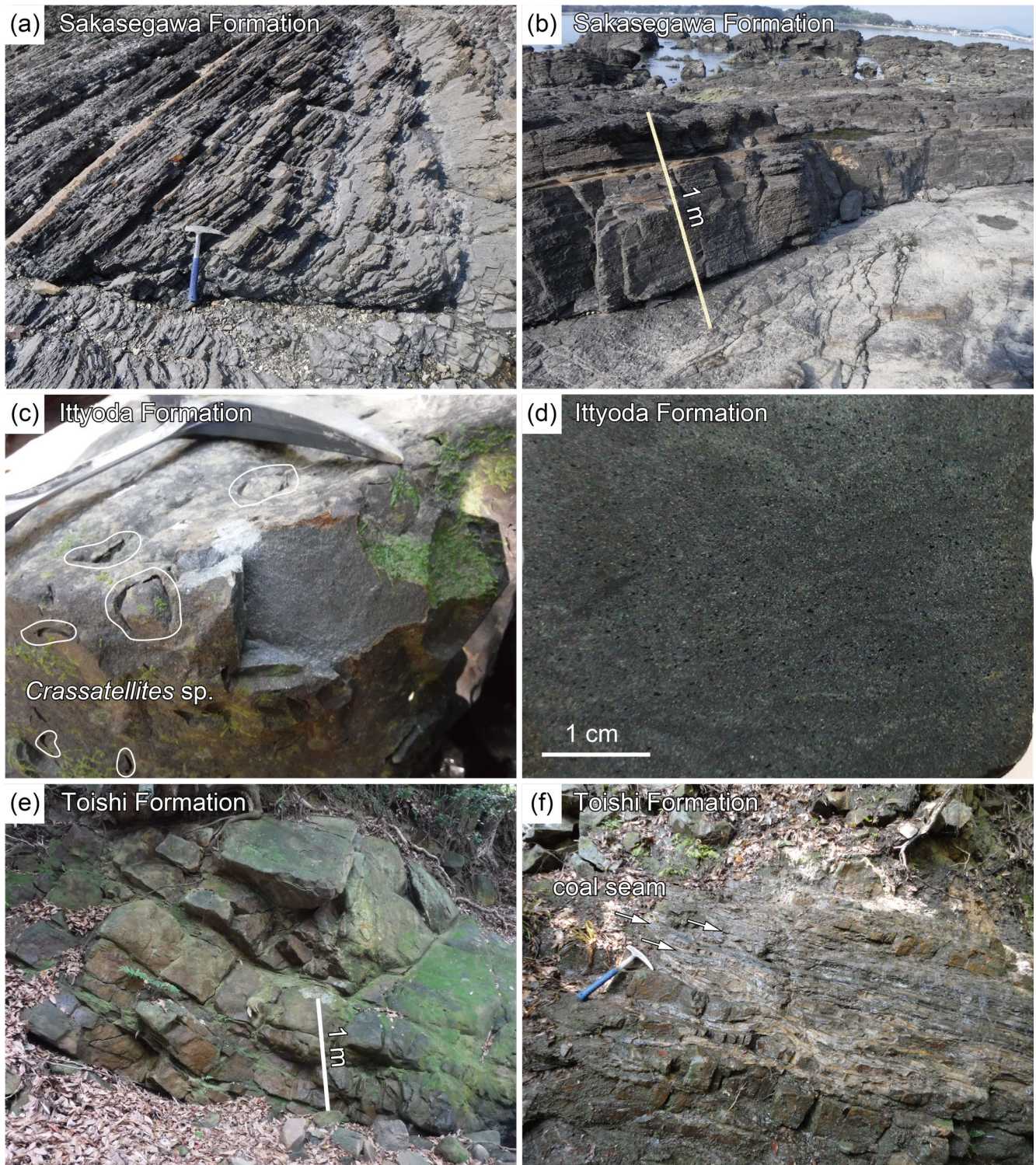


FIGURE S3: Photographs of the representative and notable outcrops of the Eocene Sakasegawa, Ittyoda, and Toishi Formations. (a) Well-stratified alternation of sandstone and siltstone of the Sakasegawa Formation. (b) Bedded sandy siltstone of the Sakasegawa Formation. (c) Glauconite-bearing, medium-grained sandstone of the Ittyoda Formation which contains fossil bivalves. (d) Cut section of the sandstone of the Ittyoda Formation. (e) Thick-bedded sandstone of the Toishi Formation showing undulatory bedding. (f) Thin coal seams interbedded with the alternation of sandstone and siltstone of the Toishi Formation. Arrows indicate the coal seams.

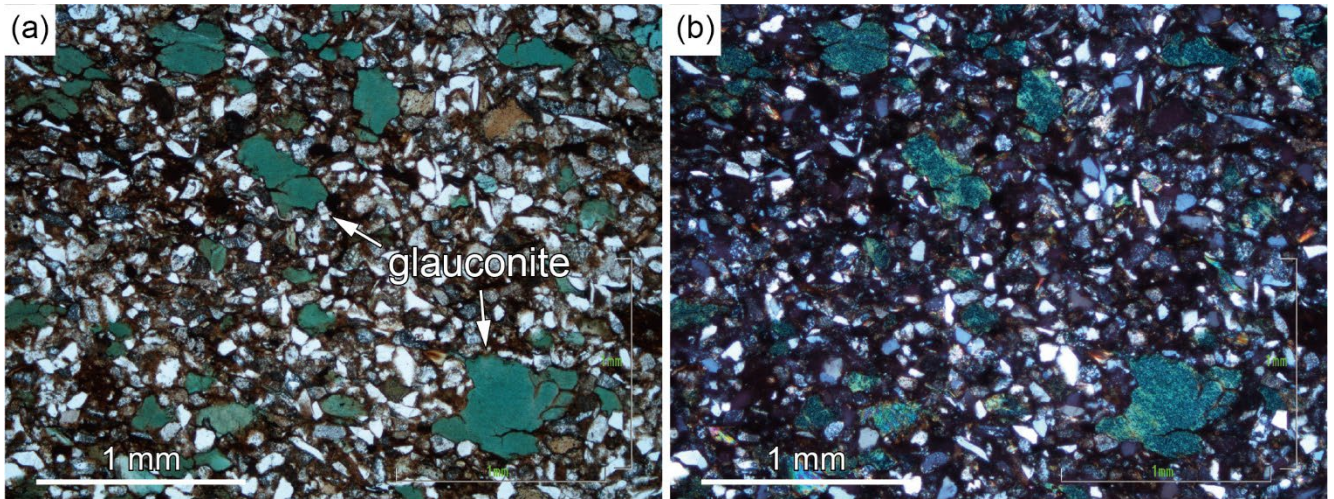


FIGURE S4: Photomicrographs of the Glauconite-bearing sandstone of the Ittyoda Formation. (a) plane- and (b) cross-polarized images.



FIGURE S5: The boundary of the Ittyoda and Sakasegawa Formations at Shimoura, southwestern Kamishima Island. The former is a glauconitic sandstone bed. The latter is composed mainly of shale, but a few glauconitic sandstone beds are intercalated in its basal part. The latitude and longitude of the outcrop are 32.4157°N and 130.2344°E, respectively.

