Styles of mesoscale brittle deformations associated with the Miocene folding of the Taishu Group, Tsushima, between the Japan Sea and East China Sea backarc basins

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Running Title *Folding of the Taishu Group, Tsushima*

Abstract The Taishu Group is a folded, Eocene–Lower Miocene, thick sedimentary package exposed widely on Tsushima Island between the Japan Sea and East China Sea. This location makes the strata important to understand tectonics and paleo-environments in the Far East, but the timing of the folding is controversial. We studied the styles of brittle deformations of the strata. It was found that flextural-slip folds were dominant. Mesoscale faults were classified into two groups: NE–SW trending reverse faults and NW–SE trending strike-slip faults. Members of both the groups showed movements largely perpendicular to the fold axes. The latter group consisted of sinistral and dextral faults. Accordingly, we interpreted that they were transfer faults activated during the folding. Consequently, mesoscale faults and flexural-slip faults evidence the map-scale plane strain of the Taishu Group in the plane perpendicular to the NE-trending fold axes. There were few transpressional deformations in the group. This is inconsistent with the transpression hypothesis for explaining the simultaneous folding and Japan Sea opening. Another hypothesis in which the folds in Tsushima are regarded as an onshore part of the Taiwan-Shinji fold belt is inconsistent with the timing of folding suggested by mining geologists to be consistent with and contemporaneous with this deformation. On the other hand, we found that dolerite dikes and sills were involved in the folding. Therefore, we conclude that the folding began during the late Early Miocene time and climaxed during the ore mineralization at around 15 Ma. We suggest that the folding in Tsushima was the easternmost manifestation of the compressional regime around the Yellow Sea and East China Sea in the Early to early Middle Miocene, and that the compression was brought about by the arrival of the Philippine Sea plate to initiate buoyant subduction under Kyushu.

Key words: flexural-slip fold, bedding-parallel fault, transfer fault, Taiwan-Shinji fold belt, Japan Sea opening

1 INTRODUCTION

The geology of Tsushima Island is a key to understand tectonic and climatic evolution of the Far East, because it is a large island rising in the straight between the Japan Sea and East China Sea backarc basins behind the Japan and Ryukyu island arcs (Fig. 1a). Folded Cenozoic strata, called the Taishu Group, are widely exposed in Tsushima (Fig. 1b). The folding may have led to the uplift of the straight that could affect the environments of the Far East (e.g., Chinzei, 1986; Kimura et al., 2004; Kitamura & Kimoto, 2006; Millien-Parra & Jaeger, 1999). However, the timing of folding is controversial.

Two hypotheses have been proposed for the timing. The first one attributes the folding to the inferred transpression at the southwestern end of the rapidly opening Japan Sea in the early Middle Miocene (Fabbri et al., 1996; Golozubov et al., 2017; Ishikawa & Tagami, 1991; Kim et al., 2008, 2010; Sakai, 1993). This hypothesis is consistent with the presence of the offshore Tsushima Fault System (Fig. 1a) along the western coast of Tsushima (Tomita et al., 1975), which was possibly a major dextral strike-slip fault during the Japan Sea opening (e.g., Jolivet et al., 1991). Folds in the island make, indeed, an echelon pattern with respect to the fault (Fig. 2a). The second hypothesis regards the folds as the onshore parts of the Taiwan-Shinji fold belt (Fig. 1a), which was formed mainly in the Late Miocene (Cukur et al., 2011; Gungor et al., 2012; Kong et al., 2000; Lee et al., 2006, 2011; Tai, 1973; Tanaka & Ogusa, 1981; Yoshioka et al., 2002).

However, the geologists of Taishu Mine in southern Tsushima (Fig. 1b) expressed another view based on their observations in the mine, where mesothermal veins were worked (e.g., Kiyosu, 1977; Shimada, 1977). Ikemi et al. (2001) obtained a K-Ar age of 15.4 ± 0.8 Ma (Ikemi et al., 2001) from an ore vein. Older ore veins were deposited on thrust faults with NW-vergence (Matsuhashi, 1967, 1968), and late Early to early Middle Miocene felsic sills were involved in the thrusting (Uehara, 1959; Uehara & Matsuhashi, 1961; Shimada, 1977). They considered that the Taishu Group was folded shortly before or simultaneously with the formations of older veins (e.g., Shimada, 1977). This seems consistent with the first hypothesis, above, in the timing of folding, but with the second one in the vergence. Unfortunately, the mine has been abandoned since 1973, so the validity of their opinion is uncertain.

The purpose of this paper is to describe mesoscale deformation structures observed at outcrops in the Taishu Group to verify the three hypotheses including the opinion of the mining geologists. That is, transpression of the first hypothesis should involve either (1) flextural-slip faulting oblique to the NE-trending fold axes (Tanner, 1998, Fig. 19) or (2) the intermingled distribution of folds, thrusts and strike-slip faults with similar trends (Figs. 2a, b) (e.g., Holdsworth et al., 2002; Jones et al., 2004; Tavarnelli et al., 2004) or (3) both. On the other hand, the second hypothesis expects the shortening of the crust that could be accommodated by flexural-slip faulting perpendicular to the fold axes and by reverse faulting with NW or NE vergence. We also investigated the relative timing of igneous intrusion and the deformations accompanied by the folding. However, it is beyond the scope of this paper to argue fully about the basin formation of the Taishu Group and about the opening or closure of backarc basins. We describe mesoscale tectonic deformations to test the three hypotheses.

2 GEOLOGICAL BACKGROUND

The Taishu Group is thought to be Eocene–Early Miocene in age. Deltaic to submarine slope or to basin settings are inferred for the depositional environments of the strata (Koga et al., 1988; Nakajo et al., 2006; Nakajo & Maejima, 1998; Ninomiya et al., 2009, 2010, 2020; Okada & Fujiyama, 1970). The folded Taishu Group is unconformably covered by Upper Pliocene sediments (Isomi & Nagahama, 1965). The group is composed of three informal units—the Lower, Middle and Upper Formations (Matsumoto, 1969) (Fig. 1b). The Lower and Upper Formations are composed of alternating sandstone and shale; the Middle Formation consists of massive mudstone and shale. Mudstones have locally incipient slaty cleavage (Fig. 3) (Oho *et al.,* 2007). The total thickness of the group is thought to be greater than 4 km, but is uncertain because of its controversial stratigraphy.

The stratigraphy of the group is a matter of debate (Miyata, 2010) owing to monotonous lithology, complicated structures and sparse inland outcrops. The Taishu Group has so complicated map- and mesoscale structures that bedding attitudes at neighboring outcrops are often discordant with each other and with uncertain stratigraphic relations. So, we did not draw geological maps, but dealt with mesoscale structures.

Radiolarian fossils indicate that the Lower Formation is Early Eocene in age (Nakajo & Funakawa, 1996). Pyroclastic rocks in the Middle Formation yielded the fission track ages of the mid Eocene (Sakai & Yuasa, 1998). Lower part of the Upper Formation yielded Early Miocene planktonic foraminifers (Ibaraki, 1994), but a middle horizon of the formation yielded Oligocene ones (Sakai & Nishi, 1990). In addition, Ninomiya et al. (2014) reported the U-Pb ages of ~18 and ~16 Ma from the tuffs that defined the boundary between the Lower and Middle Formations.

The Taishu Group is intruded by plagiophyre, quartz porphyry and granite with a minor amount of dolerite sheets and dikes. The granite was crystallized at a depth of 2–6 km (Shin et al., 2009). All those rocks yielded K-Ar and fission-track ages between 12 and 19 Ma (Ishikawa & Tagami, 1991; Karakida, 1987; Takahashi & Hayashi, 1985, 1987). Detailed geochemical study by Ikemi et al. (2001) showed with K-Ar thermochronology that the granite cooled down from 560 to 350°C in the period from

17 to 14 Ma and formed Pb-Zn deposits of the Taishu mine at ~15 Ma. Though various ages from 17 to 12 Ma were reported from the granite (Ikemi et al., 2001; Ishikawa & Tagami, 1991; Karakida, 1987; Kono & Ueda, 1966), the granite was emplaced probably at 17–18 Ma. Muscovite in an ore vein yielded a K-Ar age of 15.4 ± 0.8 Ma (Ikemi et al., 2001). The dolerite is thought to be as old as the felsic magmatism (Matsumoto & Takahashi, 1987). Felsic and mafic magmatism in Miocene Tsushima resulted probably from the same mantle upwelling event (Shin et al., 2009).

Offshore seismic survey near Tsushima showed that the Tsushima fault system was activated as a thrust system sometime in the Late Miocene or Pliocene (Minami, 1979), thereby the islands were uplifted. A seismic profile along a transect across the Taiwan-Shinji fold belt some 20 km to the northeast of Tsushima (Itoh & Nagasaki, 1996) visualized an anticlinorium involving Miocene and older rocks on the northeastern extension of the fold axes from Tsushima Islands, and showed the thinning of Pliocene-Quaternary offshore sediments toward the anticlinorium. The profile suggests an uplift of Tsushima by a few hundred meters after the Miocene. Marine terraces on Tsushima Islands evidence a slow uplift in the mid Pleistocene at a rate of 10^1 m/m.y. (Watanabe & Ikeda 1989). Offshore seismic profiles suggest that the Tsushima fault system is inactive (e.g., Tokuyama et al., 2001).

3 MESOSCALE DEFORMATION STRUCTURES

3.1 Fold geometry

There are map-scale and mesoscale folds in the Taishu Group, but thick vegetation hinders most of the hinge zones. Accordingly, we investigated the shapes and orientations of map-scale folds from bedding attitudes of neighboring fold limbs (Fig. 4). Slump folds are not rare in the group (Golozubov et al., 2017; Nakajo et al., 2006), but folds with tectonic origin were more abundant than slump folds. The tectonic origin was evidenced by the involvement of brittle deformations (Fig. 5). In each area in Tsushima, the orientations of fold axes were calculated from the orientation matrix of the poles to bedding (e.g., Scheidegger, 1965). That is, given bedding attitudes in neighboring limbs, the eigenvector corresponding to the minimum eigenvalue of the matrix was regarded as the fold axis. The intersections of the great-circles that indicate bedding attitudes made a small cluster around the eigenvector (Figs. 4a–k), meaning that the folds in the areas were cylindrical. In addition, the bedding attitudes had more or less two clusters in the stereograms, representing the planar limbs of chevron folds (Twiss & Moores, 2006). They had interlimb angles ranging from 50 to 150°, but isoclinal folds were found to the west of the Taishu mine. The orientations of axial planes were estimated to be roughly vertical from the bisector of the limb orientations.

The Osaki area (Fig. 1b) is one of the areas in Tsushima where short-wavelength folds were found, allowing us to recognize fold styles easily. Therefore, we made field survey mainly in the area. The Lower Formation in this area is composed of shale, massive mudstone and mudstone-dominant alternation of sandstone and mudstone. Complicated geologic structures impeded geological mapping. So, we present a geological route map of this area (Fig. 6). We recognized tens of fold hinge lines in the Osaki area with the wavelengths of 10^1–10^2 meters. Fig. 6a shows the orientations of 31 hinge lines of folds, indicating their mean orientation around 050°/20°. Bedding attitudes in neighboring limbs indicated that the folds were cylindrical in shape. This is evidenced by the great circles representing the bedding that intersect each other around a point in each of the stereograms in Fig. 4.

Folds had typical wavelengths of ~150 m along the northern coast of the Osaki area (Fig. 6b), but those folds did not extend southwestward along their trend into the western coast of the area around Cape Kottoi. There was no such short-wavelength fold there. This discontinuity suggests the presence of one or more map-scale transfer faults, low-angle faults or an angular unconformity between Kottoi and the northern coast, but thick vegetation hindered the boundary(s) and made geological mapping unattainable.

3.2 Bedding parallel faults

All the folds that we observed in the Taishu Group involved bedding-parallel faults (Figs. 7, 8). They were recognized by the offset or truncation of veins, faults, sole marks, etc., along bedding (Cloos, 1948; Fitches et al., 1986). Bedding planes with slickenside striations or slickenfibers were recognized as bedding-parallel faults as well. The sense of faulting was determined by a few criteria, i.e., the offset of those features intersecting the fault plane, the accretion steps of the fibers, the asymmetric striations made by ploughing particles (Petit, 1987).

Folds in the Taishu Group were formed by flexural-slip mechanism (Kim et al., 2008). There are two lines of evidence. First, the slip directions of bedding-parallel faults were roughly perpendicular to the fold axis that was determined by the bedding attitudes in neighboring fold limbs (Figs. 6, 8). Second, most of the faults upon which the sense was determined were reverse in sense, though the sense of movement was determined only on a small number of bedding-parallel faults. There were a few exceptions, which were nearly upright normal faults at Shiine (Fig. 4j). Since those faults were found in overturned strata, they may have been originally reverse faults overturned by folding. Arrows and bars on the stereogram in Fig. 8 show the slip directions and orientations, respectively, of bedding-parallel faults. Most of the symbols are drawn along the great- and small-circles with the pole that is parallel to the mean orientation of the fold axes. Therefore, bedding-parallel faults indicate nearly plane strain in the plane perpendicular to the mean orientation.

We found that ore veins near Taishu Mine were affected by the flexural-slip folding. That is, bedding surfaces coated by the quartz veins that bore sphalerite, pyrrhotite and magnetite (Fig. 9) had slickenside striations perpendicular to the general trend of the fold axes (Fig. 4). The ore veins of the mine were characterized by those minerals (Uehara, 1959).

3.3 Mesoscale faults cutting across bedding

We collected fault-slip data not only from bedding-parallel faults but also from mesoscale faults across strata. They had thin shear zones less than 1 cm in thickness. The sense of faulting was determined by the offsets of strata or by the asymmetrical minor structures on the fault surfaces, which were mentioned in the last subsection. To investigate syn-sedimentary tectonics Fabbri et al. (1996) and Kim et al. (2010) described such faults that were accompanied by soft-sediment deformations. However, we dealt only with brittle faults, because evidence for faulting involved in such deformations were rare, and because this paper aims at describing post-depositional deformations.

Figure 10 shows fault-slip data mainly from the Osaki area. The orientations of fault planes had a large variation, but their poles made two clusters. The mean orientation of fold axes is plotted in the figure as well. The most prominent cluster was made from NW–SE trending, nearly upright, strike-slip faults: Sinistral and dextral strike-slip faults were mixed in this group. Both the slip directions and fault planes were approximately perpendicular to the mean of the fold axes. That is, their tectonic transport directions were roughly the same with the trends of horizontal shortening by the flexural-slip folding. We interpreted that the faults were the transfer faults (e.g., McClay, 1992, p. 430) accompanied by the folding. This is supported by simultaneous activity of such strike-slip faults and bedding-parallel faults, evidenced by their crosscutting relationships (Fig. 11). Florez-Nino et al., (2005) reported pervasive, minor transfer faults in a fold and thrust belt in Bolivia.

The second prominent cluster appeared in the NW quadrant in the tangent-lineation diagram in Fig. 10. Most of the faults corresponding to this cluster were SE-dipping reverse faults. There were many faults with the symbols out of the two clusters. It should be noted that most of the arrows and bars corresponding to those faults are parallel to the great- and small-circles with the pole parallel to the mean fold axis.

In conclusion, most of the mesoscale faults plotted in Fig. 10 had tectonic transports more or less perpendicular to the mean orientation of the fold axes.

3.4 Dolerite sheets and dikes

In this study, doleritic sills and dikes in the Taishu Group were found to be affected by the folding. For example, the dolerite sheets shown in Fig. 12a were folded with the host strata. The hinterland-dipping duplex shown in Fig. 12b involved a dolerite sheet, the fault slices of which were bounded by thrust faults with tectonic transport directions roughly perpendicular to the general trend of folds (Fig. 12a). Accordingly, the fault-slip data from the duplex suggested the simultaneous formation of the duplex with the folding.

Dolerite dikes were also affected by the folding as well. Figure 13a shows a dolerite dike involved in a duplex with a NE–SW trending flexural-slip fault with NW–SE striae. Figure 13b shows an NW–SE trending dolerite dike involved in a strike-slip duplex. This deformation is consistent with the horizontal shortening in this trend by folding. This interpretation is supported by the fault-slip analysis of the faults involved in this duplex: We obtained NW–SE compressional stress from them (Fig. 14b) using the method of Sato (2006).

4 DISCUSSION

4.1 Deformation of the Taishu Group

The flexural-slips perpendicular to the general trend of fold axes were pervasive in the Taishu Group (Figs. 4, 8). The flexural slip folding resulted in the macroscale plane strain of the strata in the vertical plane parallel to the NW–SE trending tectonic transport by the flexural folding. The fold in the Unatsura area was an exception: The fold had bedding-parallel faults with striae not perpendicular to the fold axis (Fig. 4f). The striae leaning toward the southwestward plunging fold axis can be ascribed not to transpressional tectonics but to a tilting of strata before folding (Ramsay, 1967) or to a locally developed three-dimensional, flexural-slip folding (Tanner, 1989). Most of the tectonic transports by brittle faulting in the strata had roughly the same trend (Fig. 10). Both the reverse faults and NW–SE trending transfer faults among them are consistent with the plane strain in a map-scale. This is consistent also with the fact that a NW–SE trending joint system is dominant in the Taishu Group (Kitamura, 1962).

The folds in Tsushima have often been regarded as the en echelon folds (e.g., Silver, 1988) formed by the left-lateral movement of the Tsushima fault system (Figs. 1, 2) (Fabbri et al., 1996; Inoue, 1982; Ishikawa & Tagami, 1991; Kim et al., 2010). We are opposed to this hypothesis. The strike-slip faulting that forms such drag folds has various subsidiary faults oblique to the master fault. The trends of such faults have systematic relationship with the senses of faulting such as R and R′ shears (e.g., Silver, 1988). However, there was no such systematic relationship in the mesoscale faults that we observed in Tsushima (Fig. 10). Wilcox et al. (1973) found in their clay models that inter-layer sliding was needed to form en echelon folds in wrench tectonics. Slip vectors on bedding-parallel faults in a transpressional deformation zone are systematically rotated clockwise or counterclockwise (Holdsworth et al., 2002; Tanner, 1989), resulting in a triclinic strain of the zone (Tavarnelli et al., 2004). However, the orthogonality between fold axes and flexural-slip directions implies the absence or negligible amount of strike-slip component in the bulk strain of the Taishu Group during folding.

To investigate regional tectonics, previous researchers inverted fault-slip data obtained from mesoscale faults in the Taishu Group (Fabbri et al., 1996; Kim et al., 2008, 2010), but we did not. The reason why we did not study paleostresses was the difficulty to retrorotate fault-slip data to compensate tilting and paleomagnetic rotation. That is, the strata of the group had usually the dip angles of 30° or more. (The data set in Fig. 14b is an exception, because all the data were obtained around a dike where the host strata were approximately horizontal.) In addition, the strata were subjected to counterclockwise paleomagnetic rotations by 20–30° (Ishikawa et al., 1989). Kim and others report extensional stress during the accumulation of the Taishu Group from such mesoscale faults that were accompanied by soft-sediment deformations (Kim et al., 2008, 2010). They applied horizontal- and vertical-axis rotations to their fault-slip data for restoring fault attitudes. However, such finite rotations are affected by the order of rotations. The relative timing of the rotations is not clear. Fabbri et al. (1996) did not refer to the tilt correction of the fault-slip data. To investigate paleostress further from faults in the strata, stress tensor inversion combined with tilt correction (e.g., Tonai et al., 2011; Yamaji et al., 2005) must be applied to faults in the strata. Shimada (1977) and Golozubov et al. (2017) showed the dominant NW-SE trend of minearal veins in areas far from Taishu Mine. The veins indicate the σ_{Hmax}-axis perpendicular to the general trend of folds: Folding could have hardly influenced the dominant trend if the veining predated the folding. However, the formation age(s) of the veins are unknown.

4.2 Timing of folding

The timing of folding of the Taishu Group is controversial. Offshore seismic surveys indicate the formation of the Taiwan-Shinji fold belt mainly in the Late Miocene, but it is not obvious whether the folds in the group are the onshore parts of the fold belt or older structures. Matsumoto and Takahashi (1987) investigated the modes of occurrence of intrusive rocks in Tsushima, thereby argued the timing of folding. They found that constant thickness of plagiophyre sills in neighboring limbs of folds, and concluded that the intrusion predated the folding. Plagiophyre in Tsushima gave a fission-track age of 18–19 Ma (Takahashi & Hayashi, 1985). In addition, we found in this study that dolerites were involved in the folding. The mafic magmas under Tsushima were generated simultaneously with felsic ones including granitic magma in southern Tsushima by the same mantle upwelling event (Shin et al., 2009). Those observations suggest that all or most of the magmatism in Tsushima predated the folding. Okada (1969) reported a doleritic phacolith with a lateral dimension of ~1 km in northern Tsushima, thereby he suggested the intrusion being simultaneous with folding. However, thick vegetation makes it difficult to see whether the lateral variation in thickness of a map-scale intrusive body was affected by folding. Thick vegetation may hider a thrust duplex that apparently doubled a sill thickness.

Mining geologists considered that the veining in Taishu Mine was contemporaneous with and shortly after the folding (Matsuhashi, 1967, 1968; Uehara, 1959; Uehara & Matsushashi,1961). The ore veins were formed in the late cooling stage of the granitic pluton emplaced in the southern part of Tsushima: Muscovite from an ore vein gave the K-Ar age at 15.4 ± 0.8 Ma (Ikemi et al., 2001). The geologists of the mine classified ore veins into older 'bedding' and younger 'N-S trending' groups, which were formed on southeastward dipping faults. Matsuhashi (1967, Fig. 9; 1968, Fig. 7) described the precipitation of ore veins preferentially at dilational jogs in duplexes upon bedding-parallel faults, though he used the term 'drag folds' upon bedding-parallel faults instead of 'duplexes.' The latter term has become popular after Elliott and Johnson (1980) and Suppe (1983). Matsuhashi revealed the NW vergence of the deformation as well. The 'bedding' group was also formed as saddle and trough reefs (Fig. 15). Quartz porphyry sills were observed in the mine to be affected by the thrust faults that hosted the 'bedding' veins. Quartz porphyry intruded the Taishu Group in late Early to early Middle Miocene (Fig. 16). Those descriptions are consistent with the deformations that we observed at outcrops (Section 3). The observations of the 'bedding group' evidence the simultaneity of their deposition and folding, but do not disprove the beginning of the folding prior to the veining.

Although earlier studies suggested that the 'N-S trending group' were formed along easterly dipping normal faults, Imai (1973) observed slickenside striations to conclude that sinistral strike-slip components were dominant rather than dip-slip components on the faults. This is consistent with the fact that the N-S trending faults hosted ore veins preferentially at their jogs (Uehara, 1959). Their faulting is not explained by the reverse faulting stress regime consistent with the folding but by the strike-slip stress regime with an intermediate stress ratio and with the σ_3-axis subparllel to the general trend of folds in Tsushima. Kim et al. (2010) suggested the sinistral movements of N-S trending offshore faults by NNW-SSE compression, but such a stress should have resulted in not strike-slip but oblique normal faulting along the easterly dipping N-S trending faults in the mine. The strike-slip faults displaced the 'bedding group' (Imai, 1973), suggesting that the NW-SE compression responsible for the folding was followed by a strike-slip faulting stress regime which backgrounded the final phase of ore mineralization (Fig. 16). Fabbri et al. (1996) inferred the sinistral movements along the Tsushima Fault System and along N-S trending faults in Goto Islands (Fig. 1a) from 13 to 10 Ma. This movement may have begun at ~15 Ma.

The detailed geological mapping by mining geologists concluded that the folded Taishu Group was pierced by the granitic pluton to the southeast of the mine, suggesting that the folding did not postdate the granite emplacement (Matsuhashi et al., 1970). The intrusion of quartz porphyry magmas into the group was no later than the granite emplacement (Imai, 1973).

In conclusion, the Taishu Group was folded in the late Early to early Middle Miocene before the granite emplacement to bring about NW-SE trending crustal shortening (Fig. 2c). The folding involved the deformations of sills, dikes, and affected ore veining.

4.3 Implications for regional tectonics

The weakness of the arguments about the folding in Tsushima based on onshore geology comes from insufficient time control. Fortunately, since the turn of the century, some of offshore geological data obtained by Chinese and Korean geologists became easily accessible. They place constraints on the tectonic history of Japanese islands. Some researchers thought that the folds in Tsushima are the onshore part of the Taiwan-Shinji fold belt (e.g., Itoh & Nagasaki, 1996), which was formed mainly in the latest Miocene (Cukur et al., 2011; Gungor et al., 2012; Kong et al., 2000; Lee et al., 2006, 2011; Tanaka & Ogusa, 1981; Yoshioka et al., 2002). However, Korean geologists revealed that the folding began at ~12 Ma (Fig. 16) (Kim et al., 2019; Lee et al., 2001, 2011; Park et al., 2020; Yoon et al., 2002, 2003). It means that the folding in the belt was not simultaneous with the main phase of the folding in Tsushima (Fig. 16). This conclusion is based on the age of magmatism and ore veins in Tsushima, but a systematic work is necessary for their precise dating. However, the uncertainty of the ages does not affect this conclusion.

Japanese geologists suggested that the formation of the Taiwan-Shinji fold belt began at ~15 Ma since Tai's (1973) work, but their arguments were based on indirect evidence. That is, Middle Miocene isopach maps were used to argue the commencement (Tai, 1973; Kano & Yoshida, 1985; Nomura, 1986), where a roughly horizontal depositional surface was assumed to convert the lateral variation in stratal thickness to the subsidence of a syncline more rapidly than that of a neighboring anticline. However, this assumption is not always valid. On the other hand, the trends of parallel dike swarms were thought to suggest the transition from extensional to compressional at ~15 Ma (Tsunakawa, 1986; Yamamomo, 1991), but it was recently shown (Haji and Yamaji, submitted) that dikes in northern Hyogo prefecture where the tightest constraint for the transition was presented by Kobayashi (1979a, b) did not evidence the transition. Instead, Haji and Yamaji found extensional stress in the early Middle Miocene by means of the stress inversion technique of Yamaji and Sato (2011). The thrusting of the Tobe thrust—a part of the Median Tectonic Line in western Shikoku—at ~15 Ma was thought to mark the beginning of the compression that formed the fold belt (e.g., Takeshita, 1993). However, the Tobe thrust is exceptional: There is no other map-scale, contemporaneous thrust fault in SW Japan. Such an exceptional reverse fault can be locally activated in extensional tectonics (Gabrielsen et al., 1997; Dooley et al., 2003). A dike swam near the Tobe thrust indicates extensional stress at 14–15 Ma (Yamaji & Sato, 2011). However, the accretionary wedge off Shikoku was subjected to horizontal compression at that time (Haji & Sato, 2020). Thus, SW Japan was subjected largely to weak extension in the early Middle Miocene.

Folding in Tsushima was also argued in relation with the Japan Sea opening, which occurred in the Early to early Middle Miocene. They attributed the folding of the Taishu Group to the transpression (Fig. 2a, b) to accommodate the difference between the rapidly opening Tsushima Basin and the East China Sea which the researchers thought to be relatively stable at that time (Ishikawa & Tagami, 1991). Several researchers accepted this hypothesis (Golozubov et al., 2017; Kim et al., 2010). However, this hypothesis is inconsistent with the deformation styles in the Taishu Group found in this study.

The folding was regarded by Sakai (1993) and Kim et al. (2010) to be contemporaneous with the Japan Sea opening. Sakai assumed that the SW Japan arc and the entire Kyushu belonged to a coherent block that rotated clockwise, and he assumed the Euler pole of the drifting block to the east of Tsushima to explain the folding (Sakai, 1993, Fig. 11). This hypothesis is consistent with the orogen-perpendicular shortening found in this study. The Philippine Sea plate migrated northwestward along the Ryukyu trench in the Early Miocene (e.g., Hibbard & Karig, 1990). Kim et al. (2010) attributed the positioning of the Euler pole to the arrival of the plate off Kyushu to explain the folding in Tsushima.

The paleomagnetic rotation of SW Japan is expected to be simultaneous with the folding if the folding is explained by the rotation. However, this explanation is unlikely as follows. Paleomagnetic studies showed that the rotation occurred from ~18 to 16 Ma (Hoshi, 2018; Hoshi et al., 2015; Tamaki et al., 2006). So, the rotation was possibly accompanied by the early folding in Tsushima, but the folding simultaneous with the formation of the ore veins cannot be explained by the rotation (Fig. 16). The Taishu Group is thought to be a graben fill (Golozubov et al., 2017) or a result of extensional tectonics (Kim et al., 2010), whereas the deposition of the group was terminated at ~16 Ma (Ninomiya et al., 2014). So, the youngest part of the group may have been accumulated in the early folding stage. Changes in tectonic environment do not always make unconformities as exemplified by the Neogene-Quaternary succession in the Niigata basin, central Japan, where syn- and post-rift and inversion-stage stata are not separated by unconformities (e.g., Takano, 2002).

Recent Chinese and Korean data indicate that the basins in the East China Sea and Yellow Sea (Fig. 1a) were subjected to compression in the Early Miocene. It is improbable that compression in those regions had direct causal relationship with the Japan Sea opening (e.g., Cukur et al., 2011; Kong et al., 2000; Shin, 2015; Wang et al., 2019; Yoon et al., 2010). Accordingly, we suggest that the folding in Tsushima was the eastern most manifestation of the compressional tectonic regime around the Yellow Sea and East China Sea. We suggest also that the triple trench junction of the Eurasia, Pacific and Philippine Sea plate arrived off Kyushu at ~16 Ma. The plate model by Hall et al. (1995, Fig. 10) seems consistent with this interpretation, though they do not show the plate configuration at ~16 Ma. The buoyant subduction of the spreading Shikoku basin in the Philippine Sea plate may have been responsible to the compressional stress condition in and around Kyushu under which the Taishu Group was folded, while the SW Japan arc was largely subjected to extensional stress.

5 SUMMARY

Most of mesoscale faults that we observed at outcrops had NW and SE vergence, perpendicular to the axes of map-scale folds in in the Taishu Group. Bedding faults involved by flexural-slip folding had the vergence as well. Those structures indicated orogen-perpendicular shortening of the crust associated with the folding. Early to early Middle Miocene dikes and sills were also involved in such deformations. Our observations at the surface were consistent with the opinion given by the geologists of

Taishu Mine half a century ago based on their observations of ore veins in the mine. That is, the strata were folded shortly before and simultaneously with older ore veins that deposited at ca. 14.5–16.5 Ma. The compression at this timing was probably brought about by the arrival of the Philippine Sea plate to initiate buoyant subduction under Kyushu.

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REFERENCES

Chinzei, K. (1986). Opening of the Japan Sea and marine biogeography during the Miocene. *Journal of Geomagnetism and Geoelectricity*, *38*(5), 487–494.

Cukur, D., Horozal, S., Kim, D.C., & Han, H.C. (2011). Seismic stratigraphy and structural analysis of the northern East China Sea Shelf Basin interpreted from multi-channel seismic reflection data and cross-section restoration. *Marine and Petroleum Geology*, *28*(5), 1003–1022.

Dooley, T., McClay, K.R., & Pascoe, R. (2003). 3D analogue models of variable displacement extensional faults: applications to the Revfallet Fault system, offshore mid-Norway. In D.A. Nieuwland (Ed.), *New Insights into Structural Interpretation and Modelling*, (pp. 151–167), Geological Society of London.

Elliott, D., & Johnson, M.R.W. (1980). Structural evolution in the northern part of the Moine thrust belt. *Transactions of the Royal Society of Edinburgh*, *71*(2), 69–96.

Fabbri, O., Charvet, J., & Fournier, M. (1996). Alternate senses of displacement along the Tsushima fault system during the Neogene based on fracture analyses near the western margin of the Japan Sea. *Tectonophysics*, *257*(2-4), 275–295.

Fitches, W.R., Cave, R., Craig, J., & Maltman, A.J. (1986). Early veins as evidence of detachment in the Lower Paleozoic rocks of the Welsh Basin. *Journal of Structural Geology*, *8*(6), 607–620.

Florez-Nino, J.M., Aydin, A., Mavko, G., Antonellini, M., & Ayaviri, A. (2005). Fault and fracture systems in a fold and thrust belt: An example from Bolivia. *AAPG Bulletin*, *8*(4), 471–493.

Gabrielsen, R.H., Zalmstra, H., Sokoutis, D., Willingshofer, E., Faleide, J.I., & Braut, H.L. (2019). The influence of mechanically weak layers in controlling fault kinematics and graben configurations: Examples from analog experiments and the Norwegian continental margin. *AAPG Bulletin, 103*(5), 1097–1110

Golozubov, V.V., Kasatkin, S.A., Yokoyama, K., Tsutsumi, Y., & Kiyokawa. S. (2017) Miocene dislocations during the formation of the Sea of Japan basin: Case study of Tsushia Island. *Geotectonics, 51*(4), 412–427.

Gungor, A., Lee, G.H., Kim, H.-J., Han, H.-C., Kang, M.-H., Kimv J., & Sunwoo, D. 2012. Structural characteristics of the northern Okinawa Trough and adjacent areas from regional seismic reflection data: Geologic and tectonic implications. *Tectonophysics*, *522–523*, 198–207.

Haji, T., & Sato, K. (2020). Reverse-faulting regime of stress implied from middle Miocene basaltic 6 intrusions around the Cape Muroto, Southwest Japan. *Journal of the Geological Society of Japan, 126*(11), 621–630 (in Japanese with English abstract).

Haji, T., & Yamaji, A. (submitted) Post-rift stress history of SW Japan inferred from early to middle Miocene intrusions and meso-scale faults in the Tajima–Myokensan area. *Island Arc*

Hall, R., Fuller, M., Ali, J.R., & Anderson, C.D., (1995). The Philippine Sea Plate: Magnetism and reconstructions. In B. Taylor, & J. Natland (Eds.), *Active Margins and Marginal Basins of the Western Pacific* (pp. 371–403) Washington, D.C.,: American Geophysical Union.

Hibbard, J.P., & Karig, D.E. (1990). Alternative plate model for the early Miocene evolution of the southwest Japan margin. *Geology, 18*(2), 170–174.

Holdsworth, R.E., Tavarnelli, E., Clegg, P., Pinheiro, R.V. L., Jones, R.R., & McCaffrey, K.J. W. 2002. Domainal deformation patterns and strain partitioning during transpression: An example from the Southern Uplands terrane, Scotland. *Journal of the Geological Society, London, 159*(4), 401–415.

Hoshi, H. (2018). Miocene clockwise rotation of SW Japan. *Journal of the Geological Society of Japan, 124*(9), 675–691 (in Japanese with English abstract).

Hoshi, H., Kato, D., Ando, Y., & Nakashima, K. (2015). Timing of clockwise rotation of Southwest Japan: Constraints from new middle Miocene paleomagnetic results. Earth, Planets and Space, 67. https://doi.org/10.1186/s40623-015-0266-3.

Ibaraki, M. (1994). Ages and paleoenvironments of the Tertiary in northern Kyushu inferred from planktonic foraminifers. *Chikyu*, *16*, 150–153 (in Japanese).

Ikemi, H., Shimada, N., & Chiba, H. (2001). Thermochronology for the granitic pluton related to lead-zinc mineralization in Tsushima, Japan. *Resource Geology*, *51*(3), 229–238.

Imai, H. (1973). The geologic structure and mineralization at the Taishu Mine, Nagasaki Prefecture, Japan. *Journal of the Mining and Metallurgical Institute of Japan, 89*(1026), 509–514 (in Japanese English abstract).

Inoue, E. (1982). Geological problems on Cretaceous and Tertiary rocks in and around Tsushima-Korea straits. *U.N. ESCAP., CCOP Technical Bulletin*, *15*, 85–121.

Ishikawa, N., & Tagami, T. (1991). Paleomagnetism and fission-track geochronology on the Goto and Tsushima Islands in the Tsushima Strait area: Implications for the opening of the Japan Sea. *Journal of Geomagnetism and Geoelectricity*, *43*(3), 229–253.

Ishikawa, N., Torii, M., & Koga, K. (1989). Paleomagnetic study of the Tsushima Islands, southern margin of the Japan Sea. *Journal of Geomagnetism and Geoelectricity*, *41*(9), 787–811.

Isomi, H., & Nagahama, H. (1965). Unconformity between the Taishu Group and the Pliocene Ebishima Formation in the northernmost part of the Tsushima Islands, west Japan: A contribution to the age problem of the Taishu Group. *Journal of the Geological Society of Japan*, *71*(832), 32–35 (in Japanese with English abstract).

Itoh, Y., & Nagasaki, Y. (1996). Crustal shortening of Southwest Japan in the Late Miocene. *Island Arc*, *5*(3), 337–353.

Jolivet, L., Huchon, P., Brun, J.P., Le Pichon, X., Chamot-Rooke, N., & Thomas, J.C. (1991). Arc deformation and marginal basin opening: Japan Sea as a case study. *Journal of Geophysical Research*, *96*(B3), 4367–4384.

Jones, R.R., Holdsworth, R.E., Clegg, P., McCaffrey, K., & Tavarnelli, E. (2004). Inclined transpression. *Journal of Structural Geology*, *26*(8), 1531–1548.

Kano, K., & Yoshida, S. (1985). *Geology of the Sakaiminato District*. Quadrangle Series, 1:50,000. Geological Survey of Japan, AIST (in Japanese with English abstract).

Karakida, Y. (1987). K-Ar ages of the igneous rocks in Tsushima Shimojima, Nagasaki

Prefecture. *Journal of Nikkan Tunnel Study Group*, *7*, 32–42 (in Japanese).

Kim, H.G., Song, C.W., Kim, J.S., Son, M., & Kim, I.S. (2008). Tertiary Geological Structures and Deformation History of the Southern Tsushima Island, Japan. *Journal of the Geological Society of Korea*, *44*, 175–198 (in Korean).

Kim, H., Song, C.W., Son, M., Koo, H., & Bautista, F.E. (2010). Crustal deformation history of the Tsushima Island and its vicinity, Japan, during the Cenozoic Tertiary. *44th US Rock Mechanics Symposium and 5th US/Canada Rock Mechanics Symposium*, ARMA10-371.

Kim, K.-J., Yoo, D.-G., Kang, N.-K., & Yi, B.-Y. (2019). Tectonostratigraphic framework and depositional history of the deepwater Ulleung Basin, East Sea/Sea of Japan. *Basin Research, 32*(4)*,* 613–635.

Kimura, S., Shikazono, N. Kashiwagi, H., & Nohara, M. (2004). Middle Miocene–early Pliocene paleo-oceanic environment of Japan Sea deduced from geochemical features of sedimentary rocks. *Sedimentary Geology*, *164*(1-2), 105–129.

Kitamura, A., & Kimoto, K. (2006). History of the inflow of the warm Tsushima Current into the Sea of Japan between 3.5 and 0.8 Ma. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *236*(3-4), 355–356.

Kitamura, N. (1962). Preliminary report on systematic jointing in the Taishu Group developed in Mitsushima-cho, Tsushima Islands, Japan. Science Reports of Tohoku University, 2nd Ser., Geology, 5, 303–319.

Kiyosu, Y. (1977). Sulfur isotope ratios of ores and chemical environment of ore deposition in the Taishu Pb-Zn sulfide deposits, Japan. *Chemical Geology, 11*(2), 91–99.

Kobayashi, Y. (1979a). Late Neogene dike swarms and regional tectonic stress field in the inner belt of Southwest Japan. *Bulletin of the Volcanological Society of Japan, 2nd Ser., 24*(3), 153–168 (in Japanese with English abstract).

Kobayashi, Y. (1979b). Early and Middle Miocene dike swarms and regional tectonic stress field in the Southwest Japan. *Bulletin of the Volcanological Society of Japan, 2nd Ser., 24*(4), 203–212 (in Japanese with English abstract).

Koga, H., Taira, A., Ashi, J., Kuramoto, S., & Fujioka, K. (1988). A big collapsing in delta front: an example of the Taishu Group, Tsushima. Earth Monthly *(Gekkan Chikyu), 10*, 516–522 (in Japanese).

Kong, F., Lawver, L.A., & Lee, T.-Y. (2000). Evolution of the southern Taiwan-Shinzi folded zone and opening of the southern Okinawa trough. *Journal of Asian Earth Sciences*, *18*(3), 325–341.

Lee, G.H., Kim, H.J., Han, S.J., & Kim, D.C. (2001). Seismic stratigraphy of the deep

Ulleung Basin in the East Sea (Japan Sea) back-arc basin. *Marine and Petroleum Geology*, *18*(5), 615–634.

Lee, G. H., Yoon, Y. H., Nam, B. H., Lim, H. H., Kim, Y. S., Kim, H. J., & Lee, K. S. (2011). Structural evolution of the southwestern margin of the Ulleung Basin, East Sea (Japan Sea) and tectonic implications. *Tectonophysics, 502*(3-4), 293–307.

Lee, G.H., Kim, B., Shin, K.S., & Sunwoo D. (2006). Geologic evolution and aspects of the petroleum geology of the northern East China Sea shelf basin. *AAPG Bulletin*, *90*(2), 237–260.

Lee, S.A., & Son, B.-K. (2016). Petroleum system modeling of the Sora basin, offshore southern Korea. *Journal of the Geological Society of Korea, 52*(3)*,* 333–353 (in Korean with English abstract).

Matsuhashi, S. (1967). Structural control and prospecting of the bedding plane veins in the Taishu Mine. *Mining Geology*, *17*(82-83), 151–161 (in Japanese with English abstract).

Matsuhashi, S. (1968). Analysis of structural control and results of prospecting for bedding-plane veins in the Taishu Mine. *Mining Geology*, *18*(90), 161–172 (in Japanese with English abstract).

Matsuhashi, S., Kiriu, K., Nakashima, Y., Fukumoto, K., Nemoto, T., & Kuronuma, C. (1970). Geology of the Taishu Mine area in Shimo-shima, Tsushima Islands. *Memoirs of the National Science Museum, 3*, 1–8 (in Japanese with English abstract).

Matsumoto, Y., & Takahashi, K. (1987). Igneous activities in the Tsushima islands, Nagasaki Prefecture, Japan. *Association for Geological Collaboration in Japan Monograph*, *33*, 1–20 (in Japanese with English abstract).

Matsumoto, T. (1969). Geology of Tsushima and relevant problems. *Memoirs of the National Science Museum, Tokyo*, *2*, 5–14 (in Japanese with English abstract).

McClay, K.R. (1992). Glossary of thrust tectonics terms. In K.R. McClay (Ed.) *Thurst Tectonics* (pp. 419–433), London, UK: Chapman & Hall.

Millien-Parra, V., & Jaeger, J.J. (1999). Island biogeography of the Japanese terrestrial mammal assemblages: An example of a relict fauna. *Journal of Biogeography*, *26*(5)*,* 959–972.

Minami, A. (1979). Distribution and characteristics of the sedimentary basin offshore San-in to Tsushima Island. *Journal of Japanese Association of Petroleum Technologists*, *44*(5)*,* 321–328 (in Japanese with English abstract).

Miyata, Y. (2010). Tertiary Systems of Tsushima, Goto and Iki. In H. Sano *et al.* (Eds.) *Regional Geology of Japan*, vol. 8, Kyushu (pp. 85–87), Tokyo: Asakura Publishing

Co.

Nakajo, T., & Funakawa, T. (1996). Eocene radiolarians from the Lower Formation of the Taishu Group, Tsushima Islands, Nagasaki Prefecture, Japan. *Journal of the Geological Society of Japan*, *102*(8), 751–754 (in Japanese).

Nakajo, T., & Maejima, W. (1998). Morpho-dynamic development and facies organization of the Tertiary delta system in the Taishu Group, Tsushima Islands, southwestern Japan. *Journal of the Geological Society of Japan, 104*(11), 749–763.

Nakajo, T., Yamaguchi, Y., Komatsubara, J., & Ohtake, S. (2006). Sedimentation and tectonics of the Tertiary delta to basin successions in the Tsushima Islands, off northwestern Kyushu, Japan. *Field Excursion Guidebook, 17th International Sedimentological Congress, Fukuoka, Japan*, FE-B11, 1–12.

Ninomiya, T., Taniguchi, S., Shimoyama, S., Miyata, Y., Dunkley, D.J., Matsuda, H., Yamanaka, T., Aoki, T., Nishida, T., & Ichihara, T. (2009). Formative age and sedimentary environment of the Taishu Group, Nagasaki Prefecture, Southwest Japan. *Abstracts, the Annual Meeting of the Geological Society of Japan* 67 (in Japanese).

Ninomiya, T., Taniguchi, S., Shimoyama, S., Miyata, Y., Dunkley, D.J., Matsuda, H., Yamanaka, T., Aoki, T., Nishida, T., & Ichihara, T. (2010). Sedimentary enviroment of the Neogene Taishu Group, Nagasaki Prefecture, southwest Japan. *Abstracts, the Annual Meeting of the Geological Society of Japan*, 131 (in Japanese).

Ninomiya, T., Shimoyama, S., Watanabe, K., Horie, K., Dunkley, D.J., & Shiraishi, K. (2014). Age of the Taishu Group, southwestern Japan, and implications for the origin and evolution of the Japan Sea. *Island Arc*, *23*(3), 206–220.

Ninomiya, T., Shimoyama, S., Taniguchi, S., Takahashi, T., Danhara, T. & Iwano, H. (2019). Age of the Tsushima Lapilli Tuff and implication for Japan Sea opening. *Abstracts, the Annual Meeting of the Geological Society of Japan*, 14 (in Japanese).

Ninomiya, T., Shimoyama, S., Miyata, Y., Yamanaka, T., Shimazu, T., Taniguchi, S., Aoki, T., Nishida, T. & Takahashi, T. (2020). Origin and water depth of a newly identified seep carbonate and paleoecology of *Bathymodiolus* in the Miocene Taishu Group, southwestern Japan. *Palaeogeography, Palaeoclimatology, Palaeoecology, 546*, 109655.

Nomura, R. (1986). Geology of the central part in the Shimane Peninsula: Part 1 Miocene stratigraphy. *Journal of the Geological Society of Japan, 92*(6), 405–420 (in Japanese with English abstract).

Oho, Y., Yamaguchi, Y., & Hirayama, Y. (2007). Incipient slaty cleavage in the Taishu Group of north Tsushima Islands, southwest Japan. *Journal of the Geological*

Society of Japan, *113*(4), 146–157 (in Japanese with English abstract).

Okada, H. (1969). A preliminary study of the geological section across the northern area of the Tsushima Islands, Kyushu. *Memoirs of the National Science Museum, Tokyo*, *2*, 19–28 (in Japanese with English abstract).

Okada, H., & Fujiyama, I. (1970). Sedimentary cycles and sedimentation of the Taishu Group in the Shiohama area, central Tsushima, Kyushu. *Memoirs of the National Science Museum, 3*, 9–17 (in Japanese with English abstract).

Park, Y., Yoo, D., Kang, N., Yi, B., & Kim B. (2020). Tectonic control on mass-transport deposit and canyon-fed fan system in the Ulleun Basin, East Sea (Sea of Japan). *Basin Research, 32*(4), 613–635.

Petit, J.-P. (1987). Criteria for the sense of movement on fault surfaces in brittle rocks. *Journal of Structural Geology*, *9*(5-6), 597–608.

Ramsay, J. (1967). *Folding and Fracturing of Rocks*. New York: McGraw-Hill.

Sakai, H. (1993). Tectonics and sedimentation of the Tertiary sedimentary basins in the northem Kyushu. *Geological Society of Japan Memoir*, *42*, 183–201 (in Japanese with English abstract).

Sakai, H., & Nishi, H. (1990). Geologic ages of the Taishu Group and the Katsumoto Formation in the Tsushima and Iki Islands, off Kyushu on the basis of planktonic foraminifers. *Journal of Geological Society of Japan*, *96*(5), 389–392.

Sakai, H., & Yuasa, T. (1998). K-Ar ages of the Mogi and Ugetsuiwa subaqueous pyroclastic flow deposits in the Taishu Group, Tsushima Islands. *Memoir of National Science Museum, Tokyo*, *31*, 23–28 (in Japanese with English abstract).

Sato, K. (2006). Incorporation of incomplete fault-slip data into stress tensor inversion. *Tectonophysics*, *421*(3-4), 319–330.

Scheidegger, A.E. (1965). On the statistics of the orientation of bedding planes, grain axes, and similar sedimentological data. *USGS Professional Paper*, *525-C*, 164–167.

Shimada, N. (1977). Lead-zinc ore deposits of the Tsushima Islands, Nagasaki Prefecture, with special reference to Shigekuma-type mineralization. *Memoirs of the Faculty of Science, Kyushu University. D23*, 417–480 (in Japanese with English abstract).

Shin, K.-C., Kurosawa, M., Anma, R. & Nakano, T. (2009). Genesis and mixing/mingling of mafic and felsic magmas of back-arc granite: Miocene Tsushima Pluton, Southwest Japan. *Resource Geology*, *59*(1), 25–50.

Shin, Y.-J. (2015) Geological structures and controls on half-graben inversion in the western Gunsan Basin, Yellow Sea. *Marine and Petroleum Geology, 68*, 480–491.

Silver, A.G. (1988). Strike-slip faults. *GSA Bulletin*, *100*(11), 1666–1703.

Society of Mining Geologists of Japan (1968). Pictorial: Taishu Mine, Toho Zinc Company. *Mining Geology*, *18*(92), Plates 1–2 (in Japanese).

Suppe, J. (1983). Geometry and kinematics of fault-bending folding. *American Journal of Science*, *283*(7), 684–721.

Tai, Y. (1973). On the "Shinji Folded Zone." Memoir of Geological Society of Japan, 9, 137–146 (in Japanese with English abstract).

Takahashi, K., & Hayashi, M. (1985). Fission-track ages of igneous rocks from Tsushima Islands (I). *Bulletin of Faculty of Liberal Arts, Nagasaki University. Natural science*, *25*, 9–19.

Takahashi, K., & Hayashi, M. (1987). Fission-track ages of igneous rocks from Tsushima Islands (II). *Bulletin of Faculty of Liberal Arts, Nagasaki University. Natural Science*, *27*, 19–31.

Takeshita, T. (1993). Deformation of the forearc region and along the Median Tectonic Line in Southwest Japan during the opening of the Japan Sea: A preliminary report. *Memoirs of the Geological Society of Japan, 42*, 215–244 (in Japanese with English abstract).

Takano, O. (2002) Changes in depositional systems and sequences in response to basin evolution in a rifted and inverted basin: an example from the Neogene Niigata-Shin'etsu basin, Northern Fossa Magna, central Japan. *Sedimentary Geology, 152*, 79–97.

Tamaki, M., Itoh, Y., & Watanabe, M. (2006). Paleomagnetism of the Lower to Middle Miocene Series in the Yatsuo area, eastern part of southwest Japan: Clockwise rotation and marine transgression during a short period. *Bulletin of the Geological Survey of Japan, 57*, 73–88 (in Japanese with English abstract).

Tanaka, T., & Ogusa, K. (1981). Structural movement since middle Miocene in the offshore San-in sedimentary basin, the Sea of Japan. *Journal of the Geological Society of Japan*, *87*(11), 725–736.

Tanner, P.W.G. (1989). The flexural-slip mechanism. *Journal of Structural Geology*, *11*(6), 635–655.

Tavarnelli, E., Holdsworth, R.E., Clegg, P., Jones, R.R., & McCaffrey, K.J.W. (2004). The anatomy and evolution of a transpresional imbricate zone, Southern Uplands, Scotland. *Journal of Structural Geology*, *26*(8), 1341–1360.

Tokuyama, H., Honza, E., Kimura, M., Kuramoto, S., Ashi, J., Okamura, Y., Arato, H., Itoh, Y., Soh, W., Hino, R., Nohara, T., Abe, H., Sakai, S., & Mukaiyama, K. (2001). Tectonic development in the regions around Japan since latest Miocene. *Journal of* *the Japan Society for Marine Surveys and Technology*, *13*(1), 27–53 (in Japanese with English abstract).

Tomita, S., Yamashita, A., Ishibashi, K., Miki, T., Takahashi, R., Shuto, T., Urata, H., Hashimoto, I., Honza, E., & Igarashi, C. (1975). Submarine geology west of the Tsushima Islands. *Science Report, Department of Geology, Kyushu University*, 12, 77–90.

Tonai, S., Sato, K., & Ashi, J. (2011). Incremental fold test for paleostress analysis using the Hough transform inverse method. *Journal of Structural Geology*, *33*(7), 1158–1168.

Tsunakawa, H. (1986). Neocene stress field of the Japanese arcs and its relation to igneous activity. *Tectonophysics, 124*(1-2), 1–22.

Twiss, R.J., & Gefell, M.J. (1990). Curved slickenfibers—a new brittle shear sense indicator with application to a sheared serpentinite. *Journal of Structural Geology*, *12*(4), 471–481.

Twiss, R.J., & Moores, E.M. (2007). *Structural Geology, 2nd Edition.* New York: W.H. Freeman.

Uehara, Y. (1959). On the ore deposit and prospecting in the Taisyu Mine, Nagasaki Prefecture. *Mining Geology*, *9*, 265–275 (in Japanese with English abstract).

Uehara, Y., & Matsuhashi, S. (1961). Structural localization of ore shoot at the Taishu Mine, Nagasaki Prefecture, Japan. *Mining Geology*, *11*(45-46), 99–103 (in Japanese with English abstract).

Wang, B., Doust, H., & Liu, J. (2019). Geology and petroleum systems of the East China Sea Basin. *Energies*, *12*(21), 4088, doi:10.3390/en12214088.

Watanabe, M., & Ikeda, Y. (1989). Sasuna, Mine, Nii and Izuhara. In The Research Group for Active Tectonics in Kyushu (Ed.) *Active Tectonics in Kyushu* (pp. 72–79), Tokyo: Tokyo University Press.

Wilcox, R.E., Harding, T.P., & Seely, R.D. (1973). Basic wrench tectonics. *AAPG Bulletin*, *57*(1), 74–96.

Yamaji, A., & Sato, K. (2011). Clustering of fracture orientations using a mixed Bingham distribution and its application to paleostress analysis from dike or vein orientations. *Journal of Structural Geology, 33*(7), 1148–1157.

Yamaji, A., Tomita, S. & Otsubo, M. (2005). Bedding tilt test for paleostress analysis. *Journal of Structural Geology*, *27*(1), 161–170.

Yamamoto, T. (1991). Late Cenozoic dike swarms and tectonic stress field in Japan. *Bulletin of Geological Survey of Japan*, *42*(3), 131–148 (in Japanese with English abstract).

Yoon, S., Chough, S., & Park, S. (2003). Sequence model and its application to a Miocene shelf-slope system in the tectonically active Ulleung Basin margin, East Sea (Sea of Japan). *Marine and Petroleum Geology, 20*(10), 1089–1103.

Yoon, S.H., Park, S.J., & Chough, S.K. (2002). Evolution of sedimentary basin in the southwestern Ulleung Basin margin: Sequence stratigraphy and geologic structures. *Geosciences Journal*, *6*(2), 149–159.

Yoon, Y., Lee, G.H., Han, S., Yoo, D.G., Han, H.C., Choi, K., & Lee, K. (2010). Cross-section restoration and one-dimensional basin modeling of the Central Subbasin in the southern Kunsan Basin, Yellow Sea. *Marine and Petroleum Geology*, *27*(7), 1325–1339.

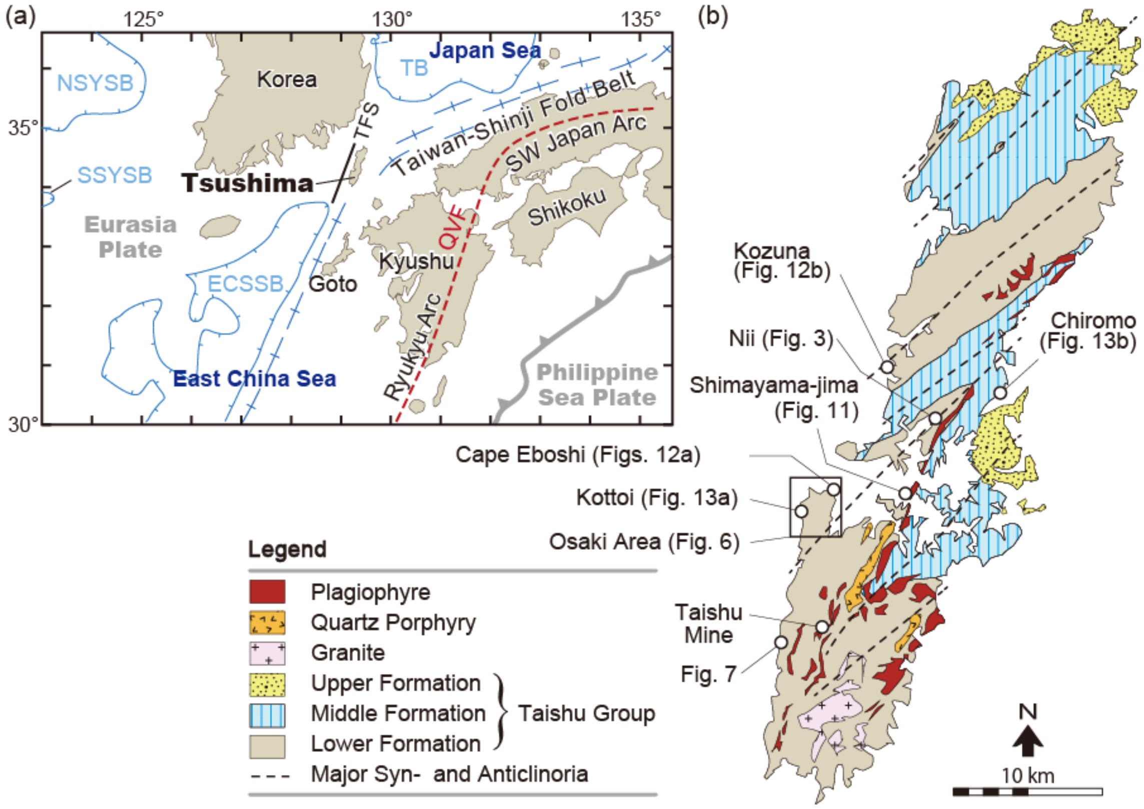

FIGURE 1 (a) Tectonic map around Tsushima. Dashed line indicates the Quaternary volcanic front. The outline of the East China Sea Basin is after Lee et al. (2006), and those of the Northern and Southern South Yellow Sea Basins (NSYSB and SSYSB) are after Yoon et al. (2010). QVF, Quaternary volcanic front; TB, Tsushima Basin; TFS, Tsushima Fault System. (b) Geologic map of Tsushima Islands simplified from the compile map of Miyata (2010).

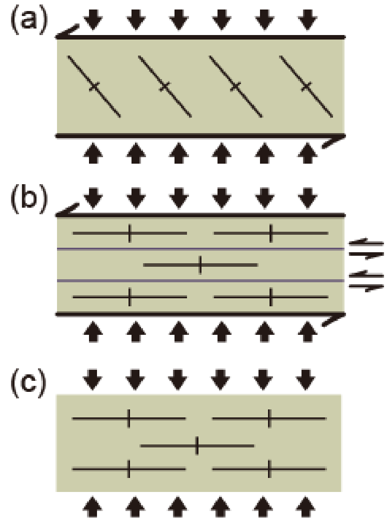

FIGURE 2 Schematic plan views of folds in orogens with (a, b) and without (c) significant orogen-parallel shear. Bold arrows represent the shortening of the orogenic belts, and crosses indicate folds. (a) Echelon folds in a transpressional zone, one or both sides of which are bounded by strike-slip fault(s). (b) Folds and strike-slip faults accommodating the deformations perpendicular to and parallel to the orogen, respectively. (c) Folds with similar trends accommodating the shortening perpendicular to the orogen.

FIGURE 3 An outcrop at near the port of Nii (Fig. 1b) showing mudstone with bedding and slaty cleavage.

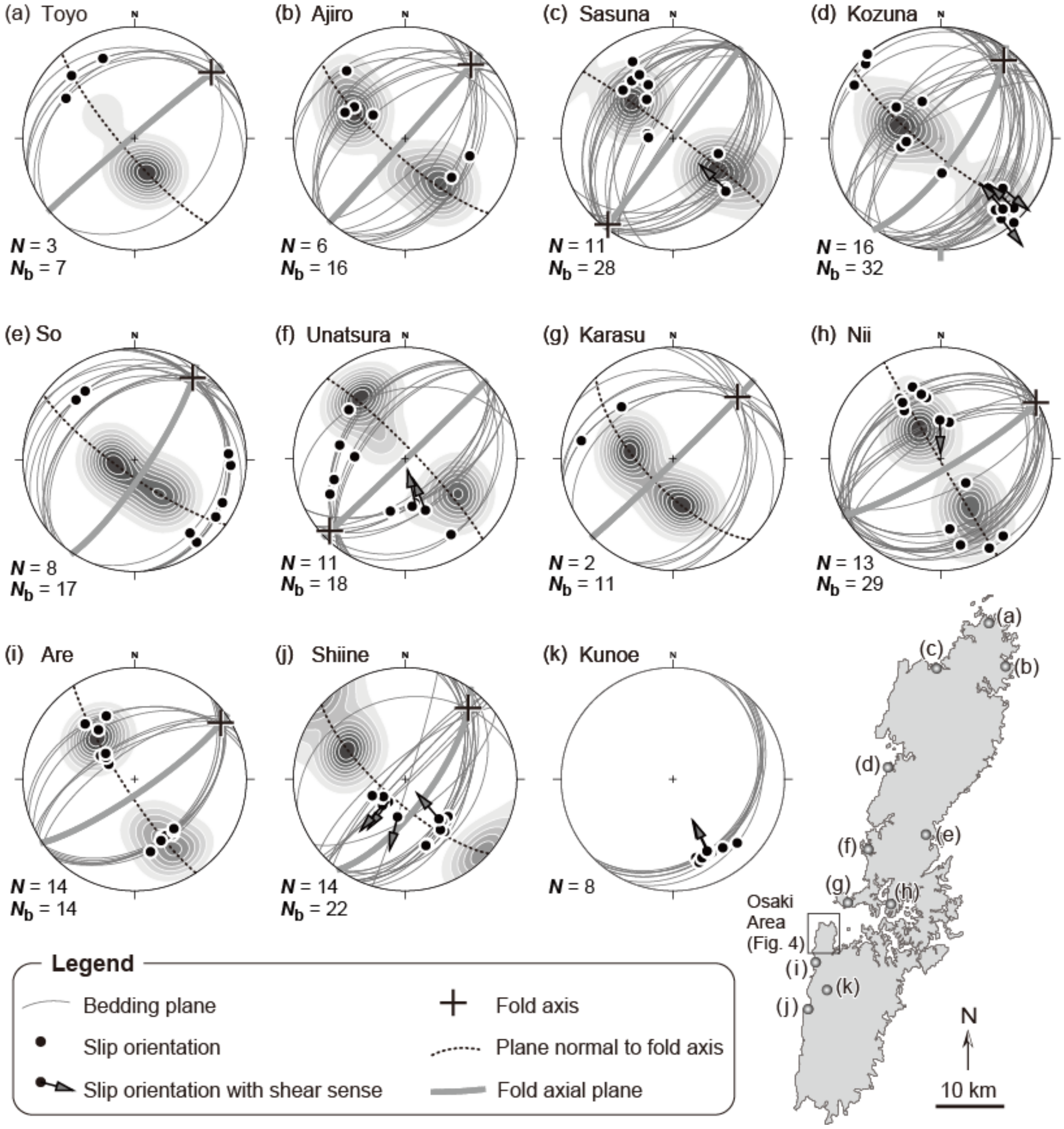

FIGURE 4 Lower-hemisphere, equal-area projections showing the attitudes of structural elements in neighboring fold limbs. Thin lines and arrows attached to the lines in the diagrams indicate the attitudes of bedding-parallel faults and the slip directions of hanging-wall blocks, respectively. Great circles without arrows represent the bedding-parallel faults whose senses of faulting were not determined. Contours in each diagram show the number density of bedding poles. Axial planes were determined by eyes as the central plane of the two clusters made by the poles in neighboring limbs.

FIGURE 5 The hinge zone of an open fold in the hinge zone of the map-scale anticline at Cape Eboshizaki (Figs. 1b, 6b). Faulting along bedding planes (white lines) is evidenced by quartz veins truncated at the planes. These brittle deformations evidence the tectonic origin of the open fold. Variation of their apparent displacements along one of the faults is due to the variation of vein orientations.

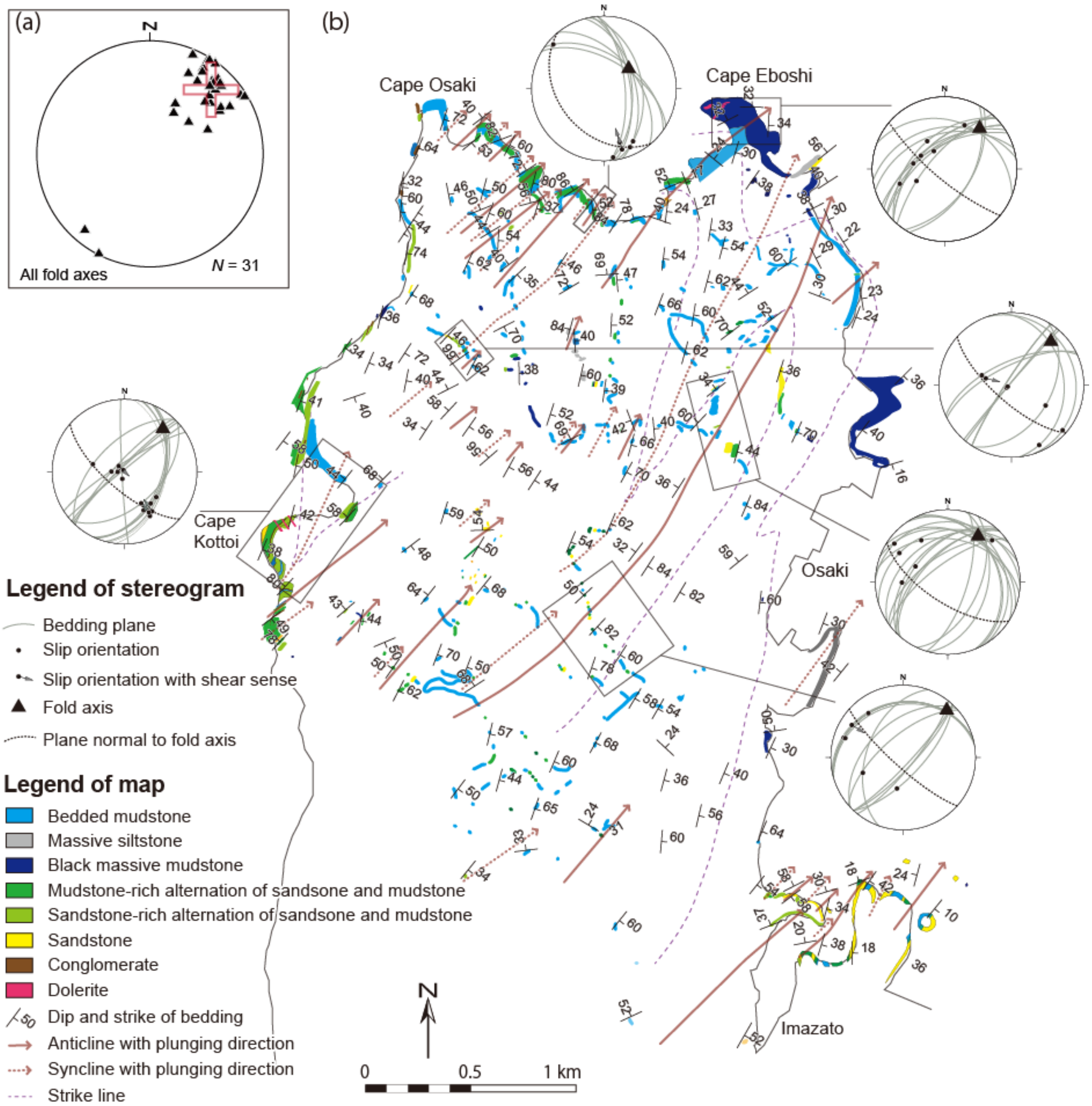

FIGURE 6 Field map of the Osaki area. Location is shown in Fig. 1b. Stereograms show the geometry of folds with bedding-parallel faults. The inset shows all fold axes around Osaki area. The stereograms use lower-hemisphere and equal-area projection.

FIGURE 7 (a) Overturned strata (shale and platy fine sandstone) to the south of Mt. Tohminodan (Fig. 1b). (b) Bedding parallel faults (arrows) indicated by quartz veins offset along bedding planes. The variation of their apparent displacements along a fault is due to the variation of vein attitudes.

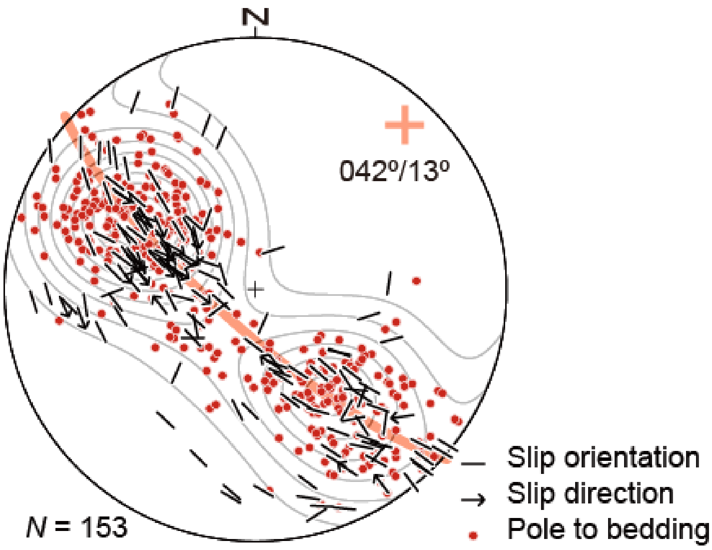

FIGURE 8 Lower-hemisphere, equal-area projection of slip directions (arrows) and slip orientations (bars) of bedding-parallel faults in Tsushima. A total of 153 bars and arrows

are plotted. The positions of the symbols in the projection indicate the poles to the fault plane. Arrows indicate the slip direction of footwall blocks. Poles to bedding planes are denoted by dots, the density of which is shown by contours. Blue cross indicates the representative orientation of fold axes that was obtained as the eigenvector corresponding to the minimum eigenvalue of the orientation distribution tensor made from the poles. Blue line indicates the great-circle perpendicular to the representative orientation.

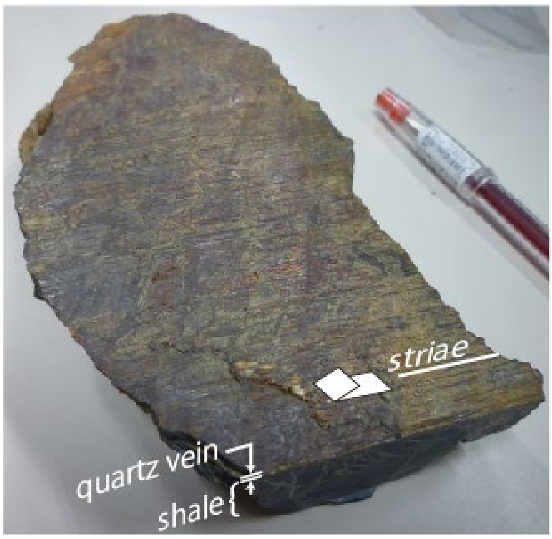

FIGURE 9 Slickenside striations on a bedding-parallel fault, the surface of which is coated by the ore vein including Zn- and Fe-rich minerals. Bold arrow depicts the sense of faulting. This sample was obtained near the Kunoe pit, Taishu Mine (Fig. 1b).

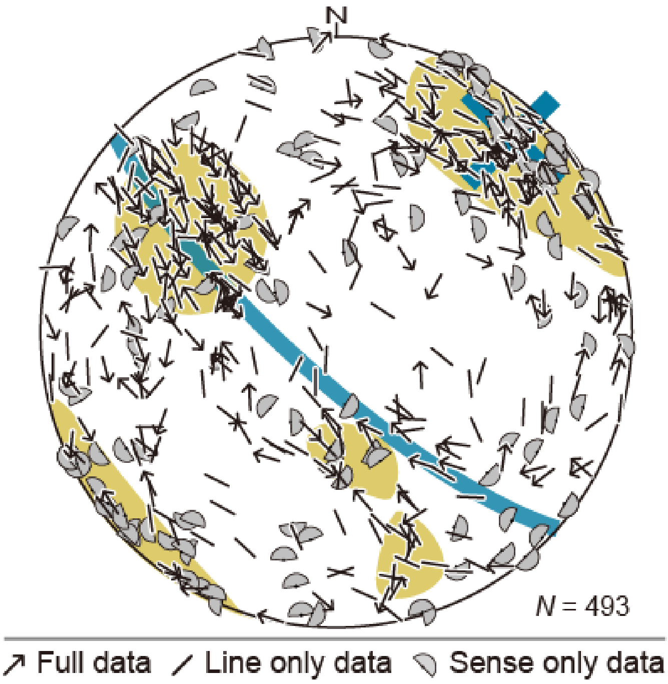

FIGURE 10 Fault-slip data obtained from mesoscale faults excluding bedding-parallel faults in the Taishu Group. The data are denoted by the tangent-lineation diagram (Twiss & Gefell, 1990) improved by Sato (2006) to plot data with deficiency. Lower-hemisphere, equal-area projection. An arrow represents a datum without deficiency: The position and direction of the arrow indicate the pole to a fault plane and the slip direction of the footwall, respectively. Line only and sense only data are incomplete fault-slip data. That is, the former type of data was obtained from such faults that their senses were not determined but striations were observed, and the latter type of data were obtained from such faults that striations were not observed by their senses were determined using the offset of reference planes such as bedding. In this case, the slip direction of a footwall block was constrained with the uncertainty of 180°. Fan-shaped symbols are plotted for this reason. Yellowish areas indicate clusters. Bold blue cross and thick blue line show the mean orientation of fold axes and the great-circle perpendicular to the orientation.

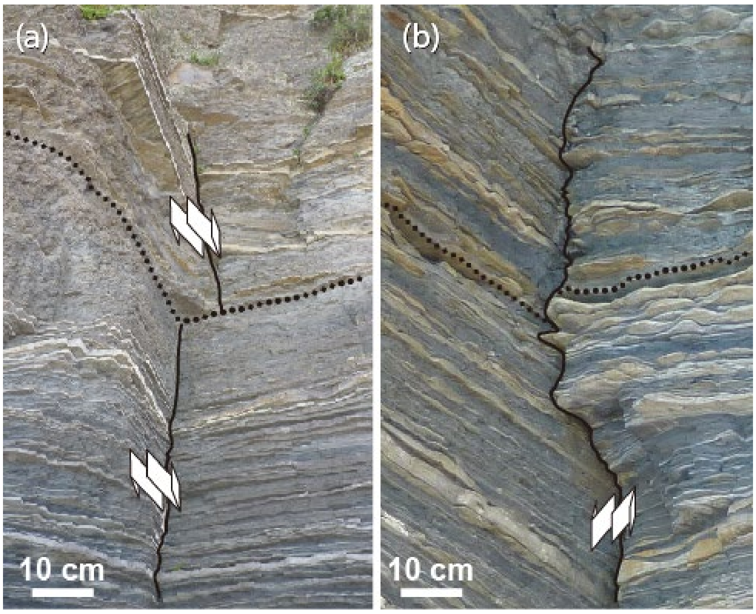

FIGURE 11 Cross-cutting relationship of bedding-parallel faults (dotted line) and NW-trending, mesoscale, strike-slip faults (solid line) at Shimayama-jima (Fig. 1b).

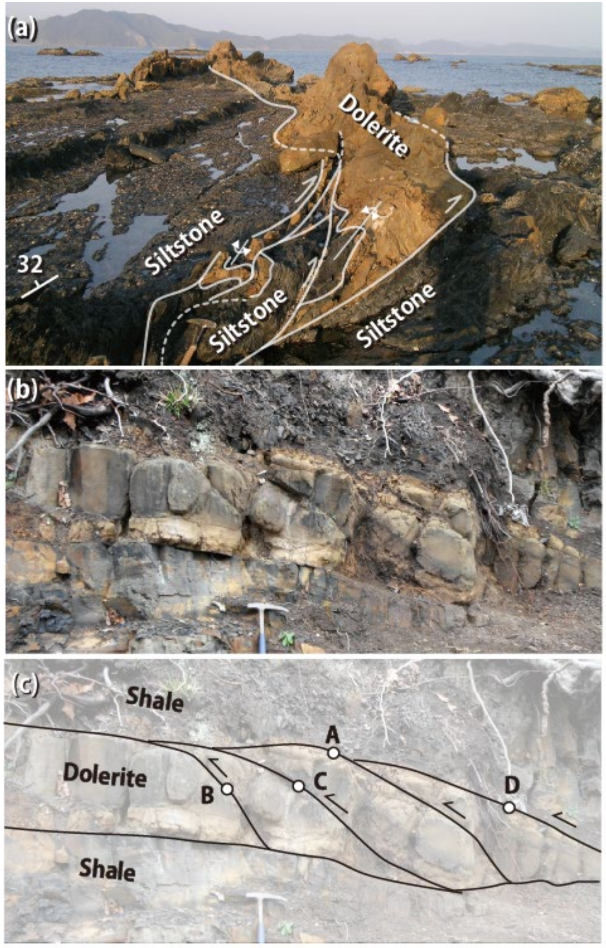

FIGURE 12 Duplexes involving dolerite sills. (a) A duplex made of originally a single sill with changing thickness in northward dipping strata at the cape Eboshi. (b, c) An NW-vergent, hinterland-dipping duplex near Kozuna (Fig. 1b). The locations are shown in Fig. 1b. Fault-slip data obtained from the points A, B, C and D are shown in Fig. 13a.

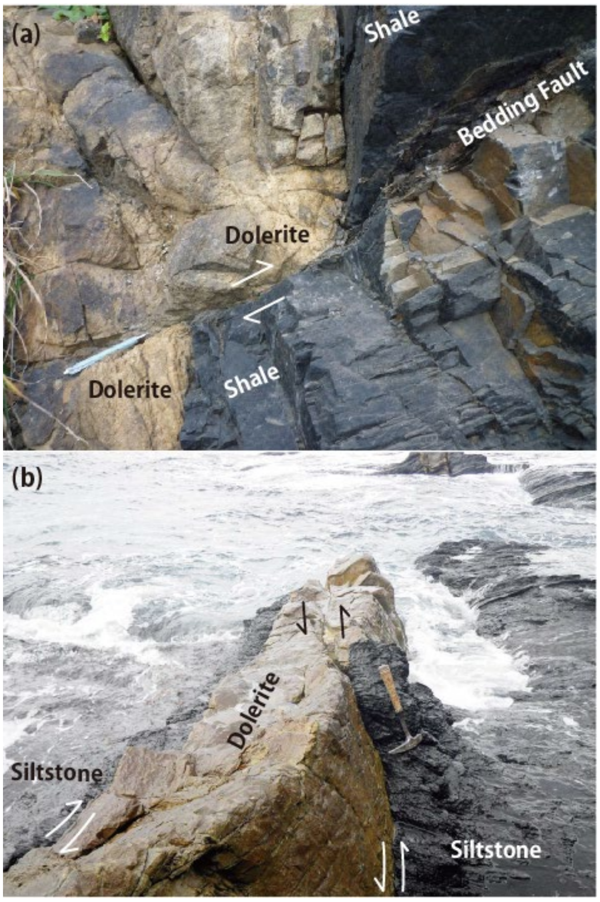

FIGURE 13 (a) A dolerite dike at Kottoi cut by a bedding-parallel fault, the hanging-wall of which moved northwestward. (b) Strike-slip duplex involving a NW–SE trending dolerite dike at Chiromo. The movements of the horses were subparallel to the trend of the dike (Fig. 14b). See Fig. 1b for the localities.

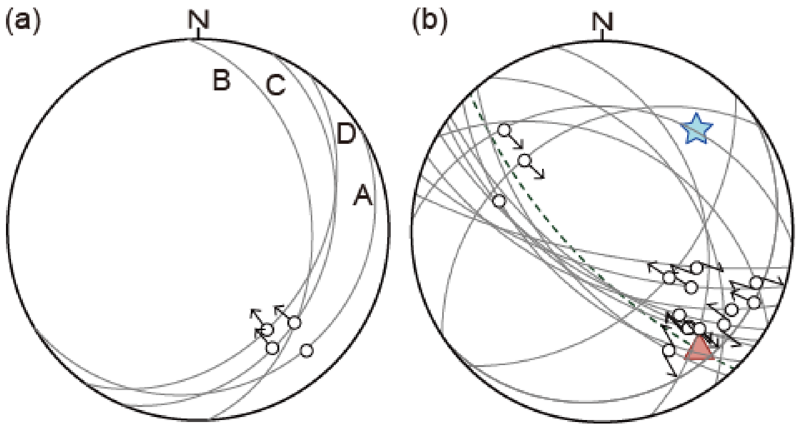

FIGURE 14 (a) Lower-hemisphere, equal-angle projection showing the fault-slip data

from the planes, A through D, between the horses of the duplex affecting the dolerite sill in Fig. 12c. The sense of movement on the plane A was not determined. (b) The data from the strike-slip duplex in Fig. 13b, and the σ_1- and σ_3-axes determined from them (triangle and star). Dotted line denotes the attitude of the dolerite dike.

FIGURE 15 A sketch showing ore veins formed preferentially at the dilational jogs of folds in the Taishu mine (The Society of Mining Geologists of Japan, 1968).

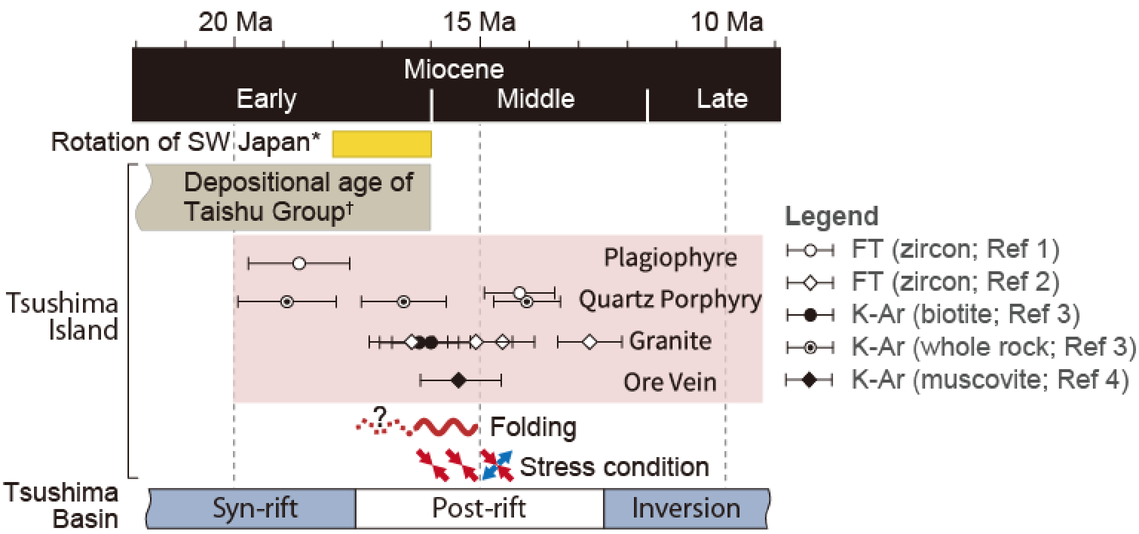

FIGURE 16 Radiometric ages of intrusive rocks in Tsushima with their $\pm 1\sigma$ error bars. Deposition of the Taishu Group ceased at ~20 or possibly at ~16 Ma. References: *Tamaki et al. (2006), Hoshi et al. (2015), Hoshi (2018); †Nakajo and Funakawa (1996), Ninomiya et al. (2014, 2019), Sakai and Nishi (1990), Sakai and Yuasa (1998); 1, Takahashi and Hayashi (1985); 2, Ishikawa and Tagami (1991); 3, Karakida (1987); 4,

Ikemi *et al.* (2001). Tectonic history in the Tsushima Basin after Kim *et al*. (2019).