

EXPRESS LETTER

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Trench and drilling investigation of the Median Tectonic Line in Shikoku, southwest Japan: implications for fault geometry

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Abstract

The Median Tectonic Line (MTL) is a thousand-kilometer-long fault that extends across southwest Japan. Near the Nyugawa region of Shikoku, the MTL comprises (i) a low-angle inactive *terrane boundary* fault (the MTLTB) that divides the Jurassic and Cretaceous geological terranes, and (ii) a subparallel high-angle *active fault zone* (the MTLAFZ; Kawakami Fault). To better understand the relationship between the MTLTB and MTLAFZ fault traces, we exposed a ten-meter-long trench of approximately 2-m depth across the Kawakami Fault. We also drilled and cored five boreholes with lengths 80–330 m along a 100 m transect to understand the cross-cutting relationship between the MTL faults and to determine the fault plane geometries and their dipping values. The Kawakami Fault was found to be a high-angle (> 70°) active fault exposed at the surface; however, it represents a non-vertical or listric fault that converges to the low-angle MTLTB fault dipping to the north at 30°. The Kawakami Fault was originally formed as a reverse fault, and subsequent dextral strike-slip displacement occurred along the same fault plane. Although the MTLTB is poorly oriented with respect to the regional stress field, it is capable of rupturing owing to its significantly weak interface; the properties of local faulted rock material are expected to play an important role in determining slip behavior.

Keywords: Median Tectonic Line, Active fault, Paleoseismology, Trench, Drilling, Seismic hazard

Introduction

In the continental crust, strike-slip faults such as the San Andreas Fault (Lawson 1895; Atwater 1970), North Anatolian Fault (Stein et al. 1997), Alpine Fault (Wellman and Willett 1942; Walcott 1998), and Wairarapa Fault (Rodgers and Little 2006; Little et al. 2009) represent the major loci of large and destructive earthquakes (> Mw 8.2) with long recurrence rates of 0.5 to 2 kiloyears, or even higher.

The seismic potential of such faults is often inferred from indirect observations and theoretical considerations.

The Median Tectonic Line (MTL; Naumann 1886; Tsutsumi and Okada 1996; Goto 2018; Kubota et al. 2020) is a trench 1000 km in length parallel to a dextral strike-slip fault, dividing southwest Japan into outer and inner zones (Fig. 1a). The active fault of the MTL is characterized by clear lineaments, that are visible on satellite images and are known to slip dextrally at a maximum rate of 5–10 mm/year in Shikoku Island, thereby making it one of Japan's most active onshore faults with recurrence intervals of 0.6 to > 1.0 kiloyears (Okada 1973; Tsutsumi and Okada 1996; Goto and Nakata 2000; Goto 2018). Trench surveys of active fault segments conducted at a few dozen sites along the MTL indicate strike-slip

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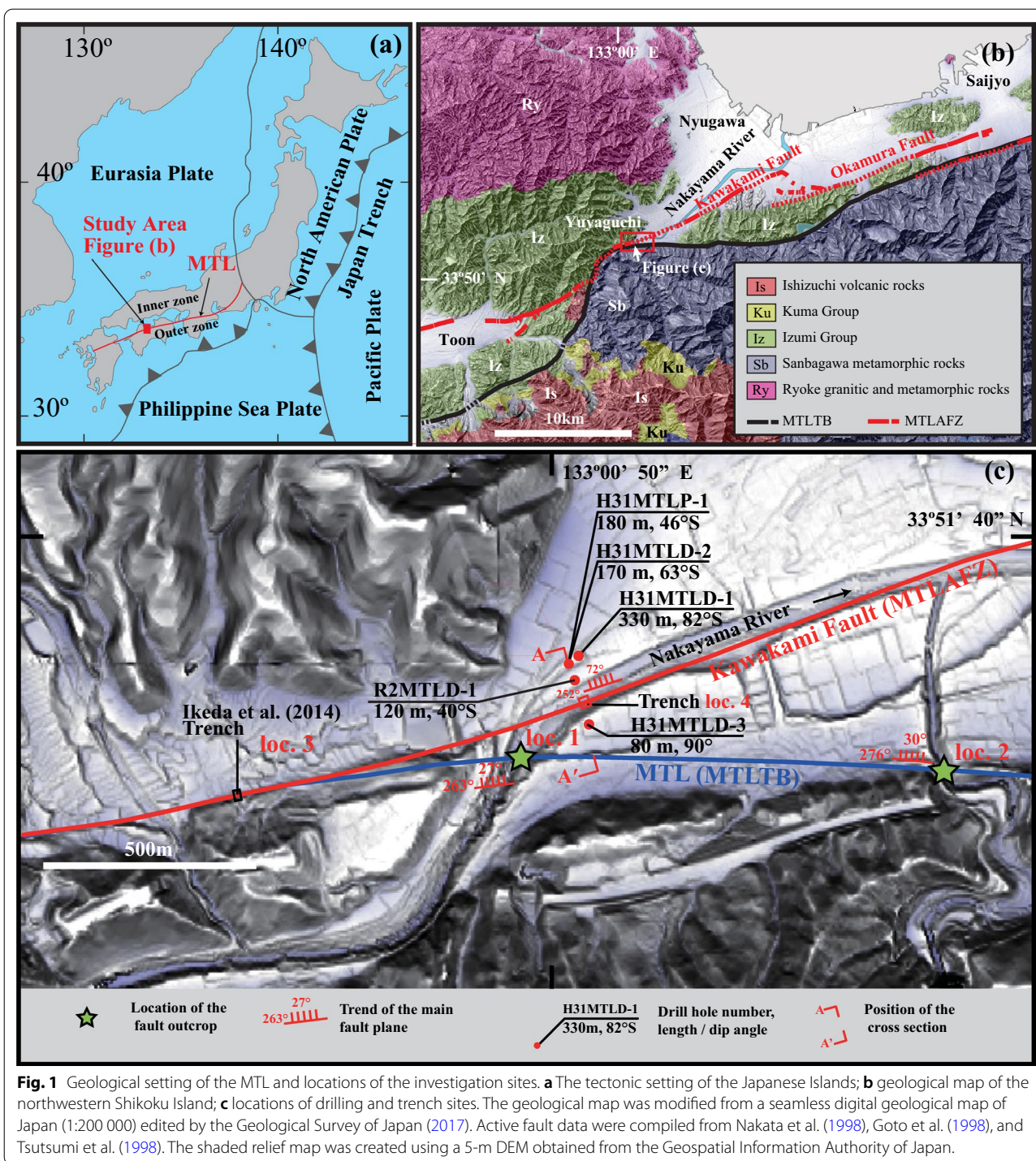


Fig. 1 Geological setting of the MTL and locations of the investigation sites. **a** The tectonic setting of the Japanese Islands; **b** geological map of the northwestern Shikoku Island; **c** locations of drilling and trench sites. The geological map was modified from a seamless digital geological map of Japan (1:200 000) edited by the Geological Survey of Japan (2017). Active fault data were compiled from Nakata et al. (1998), Goto et al. (1998), and Tsutsumi et al. (1998). The shaded relief map was created using a 5-m DEM obtained from the Geospatial Information Authority of Japan.

displacements, with a dip angle of more than 70°, predominantly in the Shikoku region (Tsutsumi et al. 1992; Okada and Tsutsumi 1997; Goto et al. 2001; Ikeda et al. 2012). Seismic reflection surveys image low-angle reflectors; these have been interpreted as fault planes by inferring that high-angle active faults, outcropping at the

surface, root to low-angle older terrane boundary faults at depth (Yoshikawa et al. 1992; Ito et al. 1996; Sato et al. 2015; Iwata et al. 2020).

However, the results of seismic reflection surveys are unclear in terms of the relationship between high-angle faults at the surface and deeper low-angle

terrane boundary faults. Since the frequency of seismicity along the MTL has remained low in recent times, it was not possible to accurately estimate the attitude of the fault plane based on information from aftershock distributions.

Therefore, it is difficult to infer the attitude of the subsurface fault from the attitude of the apparent fault on the surface. More than three million people live in Shikoku, and millions live in densely populated cities close to the MTL in Honshu. Knowledge of the seismic hazard posed by the MTL to people and infrastructure will help in making informed decisions to mitigate earthquake risks. In particular, evaluating the geometry of the MTL fault plane can influence seismic-hazard assessments of disaster distribution and earthquake magnitude. In this study, we describe the structure of the central segment of the MTL near Nyugawa resolved by shallow drilling and surface trenching.

Geological settings

The MTL has a long tectonic history since the Cretaceous, and has experienced several slip senses of dextral, sinistral, normal, and reverse faulting with changes in regional stress (e.g., Kobayashi 1941; Ichikawa 1980; Takagi and Shibata 1992; Aoya et al. 2013; Kubota et al. 2020). The current MTL displacement shows dextral movements in response to the oblique subduction of the Philippine Sea Plate (Nishimura et al. 2018). Active dextral MTL fault structures are typically observed on Shikoku (Okada 1970; Tsutsumi and Okada 1996; Goto and Nakata 2000). Detailed geological mapping (e.g., Takahashi 1992; Kubota and Takeshita 2007; Shigematsu et al. 2012; Aoya et al. 2013) and seismic reflection surveys (e.g., Ito et al. 1996; Tsutsumi et al. 2007; Shigei et al. 2014) have distinguished the high-angle MTL active fault zone (MTLAFZ) from the low-angle inherited MTL geological terrane boundary fault (MTLTB). The MTLTB and the MTLAFZ run subparallel to each other in central Shikoku (Fig. 1b).

In the Shikoku region, the MTLTB juxtaposes the Cretaceous sediments of the Izumi Group in the north against the Cretaceous Sanbagawa metamorphic rocks in the south (Fig. 1b). The Miocene Ishizuchi volcanic rocks unconformably cover the Sanbagawa metamorphic rocks. Typical MTLTB outcrops, exposed at the Yuyaguchi site, are preserved as a national natural monument (location 1 in Fig. 1c). The trend of the fault is along the east–west direction with a dip angle of 27° to the north. Andesite with a thickness of approximately 20 m intrudes along the fault and is generally brecciated by faulting (locations 1 and 2 in Fig. 1c). The K–Ar age of andesite is 21.1 ± 1.2 Ma, which is consistent with the age of Ishizuchi volcanic rocks. The andesites are possibly related

to volcanic activity in the Miocene (Tazaki et al. 1990). The MTLTB is assumed to be inactive because it does not offset Quaternary sediments and terrace surfaces (Nagai and Kondo 1972).

The MTLAFZ section in the study area is referred to as the Kawakami Fault (Okada 1973; Research Group for Active Faults of Japan 1991), which has developed at the hanging wall of the MTLTB. The Kawakami Fault, which strikes east–northeast, is subparallel to the MTLTB at a distance of 100 m and dips steeply (60–72°) northward (Fig. 1b and c) at the trench site. The Kawakami Fault bounds the Pliocene–Pleistocene half-graben Okamura Group and the Cretaceous Izumi Group. The presence of slickensides and the asymmetric structure of the fault zone indicate predominant strike–slip movement at the latest slip surface (Kubota et al. 2020). Based on ^{14}C dating at the Kawakami Fault, the most recent seismic event was traced to the Keicho earthquake of 1596 (Ikeda et al. 2014, 2019).

Trench and drilling investigations

The Secretariat of the Nuclear Regulation Authority, Japan, has been conducting trenching and scientific drilling near Nyugawa Shikoku since 2017. The specifications of the trench excavation and the boreholes are listed in Table 1. In this study, one trench was exposed and five boreholes drilled along a 100-m transect across the Kawakami Fault and the MTLTB (Fig. 1c). The trench was 10 m long and extended to a depth of approximately 2 m across the Kawakami Fault. Trenching was carried out to clarify only the attitude of the Kawakami Fault, and ^{14}C dating of exposed fluvial deposits was not undertaken as part of this study. The total length of the northernmost borehole (H31MTLD-1) was 330 m with an inclination of 82° to the south; it was the longest of the five boreholes. H31MTLD-1 and the other boreholes H31MTLD-2 (170 m), H31MTLP-1 (180 m), and R2MTLD-1 (120 m) penetrated both the Kawakami Fault and the MTLTB. The southernmost borehole (H31MTLD-3) was drilled vertically to a total length of 80 m to specifically target the MTLTB. Wireline logging was conducted in the longest borehole (H31MTLD-1), including measuring natural gamma rays, P-wave velocity, spontaneous potential, electric resistivity, and gamma-ray density. Observations using calipers and an acoustic borehole televiewer were also conducted. These wireline loggings and observations were made at all sections except those shallower than 50 m because of the casing. An optical borehole televiewer was also used in H31MTLD-2, H31MTLD-3, and R2MTLD-1 at each fault zone. All drill cores were recovered from sections below the casing. The fault rocks have been described in this study in accordance with

Table 1 Specifications of the trench and the boreholes

(a) Specification of the trench						
Location of bench mark		North latitude	33°51'27.16653"			
		East longitude	133°00'52.52249"			
Elevation of bench mark			61.99 m			
Size of trench			Length: 10 m, width: 5 m, depth: 1.5 m ~ 2 m			
(b) Specification of boreholes						
Borehole name		H31MTLD-1	H31MTLP-1	H31MTLD-2	R2MTLD-1	H31MTLD-3
Location	North latitude	33°51'30.481"	33°51'29.831"	33°51'29.855"	33°51'28.379"	33°51'25.443"
	East longitude	133°00'51.957"	133°00'51.079"	133°00'51.076"	133°00'51.433"	133°00'52.743"
Elevation of borehole top		71.11 m	71.13 m	71.16 m	66.93 m	74.97 m
Total length of borehole		330.00 m	180.00 m	170.00 m	120.00 m	80.00 m
Dip angle of borehole		82°	46°	63°	40°	90°
Direction of borehole		187°	167°	170°	172°	–
Cores recovered section		55.59-330.00 m	0.00-180.00 m	10.00-170.00 m	20.00-170.00 m	0.00-80.00 m
Drilling method		Rotary, wireline	Rotary, conventional			
Drill bit type		HQ, diamond bit	JIS Ø86mm, Ø66mm, diamond bit			

Sibson (1977). The orientation of the fault attitude has been determined using borehole televiewer analysis.

Structural features of the MTLTB and MTLAFZ fault zones

In the trench exposure, there were mudstones of the Cretaceous Izumi Group, fault gouges originating from the Izumi Group, and sand gravels of the Holocene fluvial deposit (Fig. 2 and Additional file 1: Fig. S1). The Kawakami Fault juxtaposed the Izumi Group to the south against fluvial deposits to the north. The fault damage zone, composed of mudstones, was developed at approximately 2 m or more at the footwall of the Kawakami Fault, and was characterized by a fractured damage zone and partial brecciation. In the fluvial deposits of the hanging wall (Fig. 2, Fd2), some gravels along the main fault exhibited a preferred orientation owing to rotation with the fault movement. The present fluvial deposit (Fd1) unconformably covered the most recent main fault (Fig. 2b), represented by the boundary between the fault gouge (Fig. 2, g1–g3) derived from the Izumi Group and the mixture of gouge and gravel of fluvial deposits (Fig. 2, g4) dipping at 72° to the north. The trace of the most recent main fault intersected the older fault gouge (Fig. 2, g1–g3) with a thickness of 2–3 m. The most recent main fault had a smooth surface with slightly eastward plunging striations (Fig. 2a). It is suggested that the shear sense indicates the dextral displacement at the outcrop near the trench site (Kubota et al. 2020). The old fault gouge dipped at more than 80° to the south and was composed

of more consolidated material compared to that of the g4 fault gouge. Foliation of the old gouge was partially rounded and discontinuous.

The geological column and composite well logging profiles of H31MTLD-1 and the geological columns of H31MTLD-2, H31MTLP-1, R2MTLD-1, and H31MTLD-3 are shown in Fig. 3. The columnar borehole sections in Fig. 3 were aligned with the MTLTB of each borehole at the same level. The drill core was composed of Sanbagawa metamorphic rocks, two sets of the main fault zone, sandstones and mudstones of the Izumi Group, conglomerates of the Okamura Group, and fluvial deposits, in ascending order. The main fault zone was composed of andesite-dominant breccia, serpentinite-dominant breccia, and mixed breccia. The MTLTB juxtaposed the Sanbagawa metamorphic rocks against the andesite-dominant breccia and had a sharp principal slip zone (PSZ), which was composed of a fault gouge less than a few-centimeters-thick along the geological boundary. The Sanbagawa metamorphic rocks were largely intact except for the rocks surrounding the MTLTB, which had few thin cohesive cataclasites of less than 1.8 m width within the intact section. The Kawakami Fault juxtaposed the Izumi Group against the andesite-dominant breccia or the Okamura Group and had a sharp PSZ composed of a fault gouge of less than a few-centimeters-thick along the geological boundary. Detailed descriptions of each site are provided below.

Borehole H31MTLD-1 penetrated a total length of 330 m with a plunge of 82° to the south. The drill core

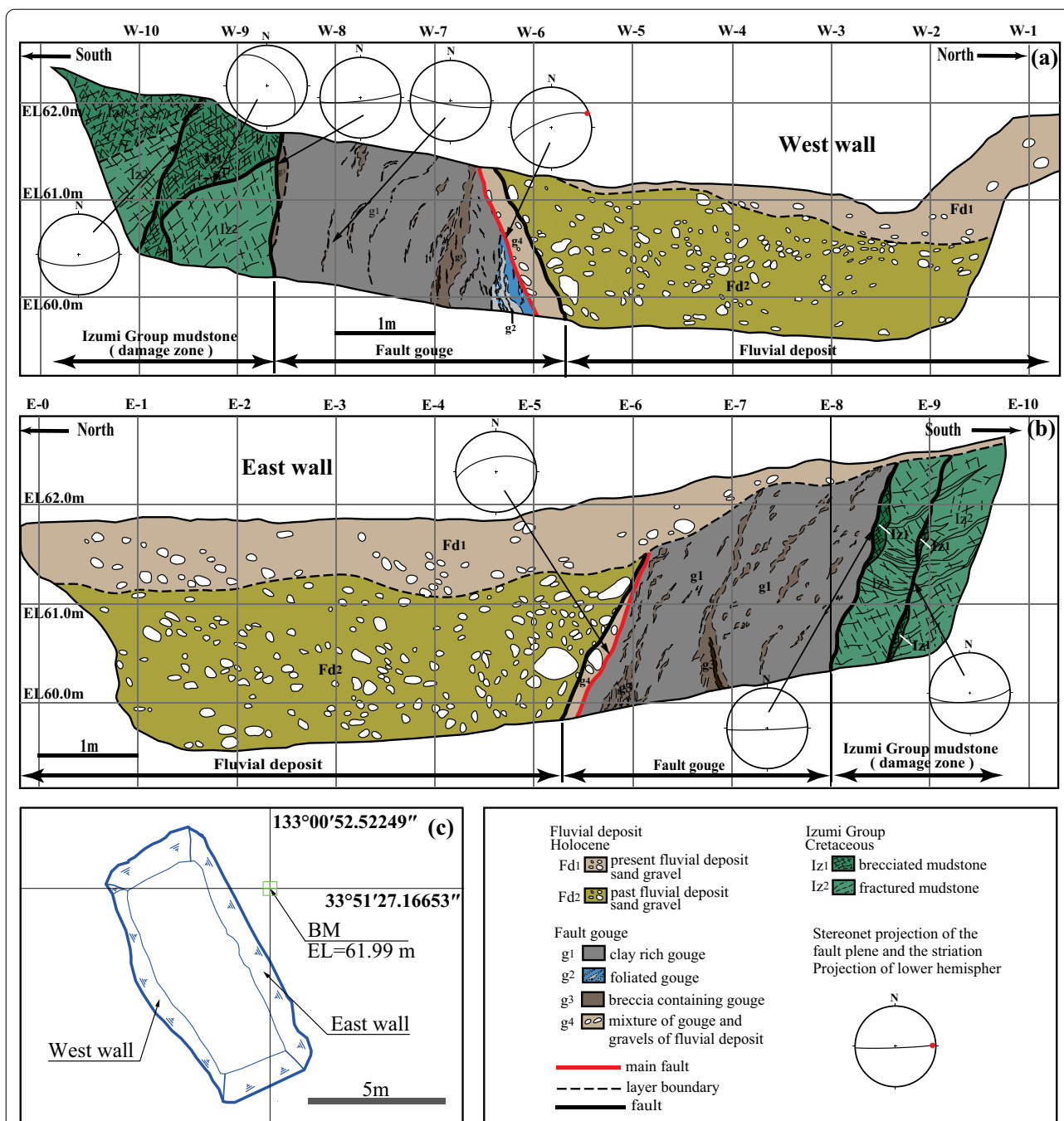
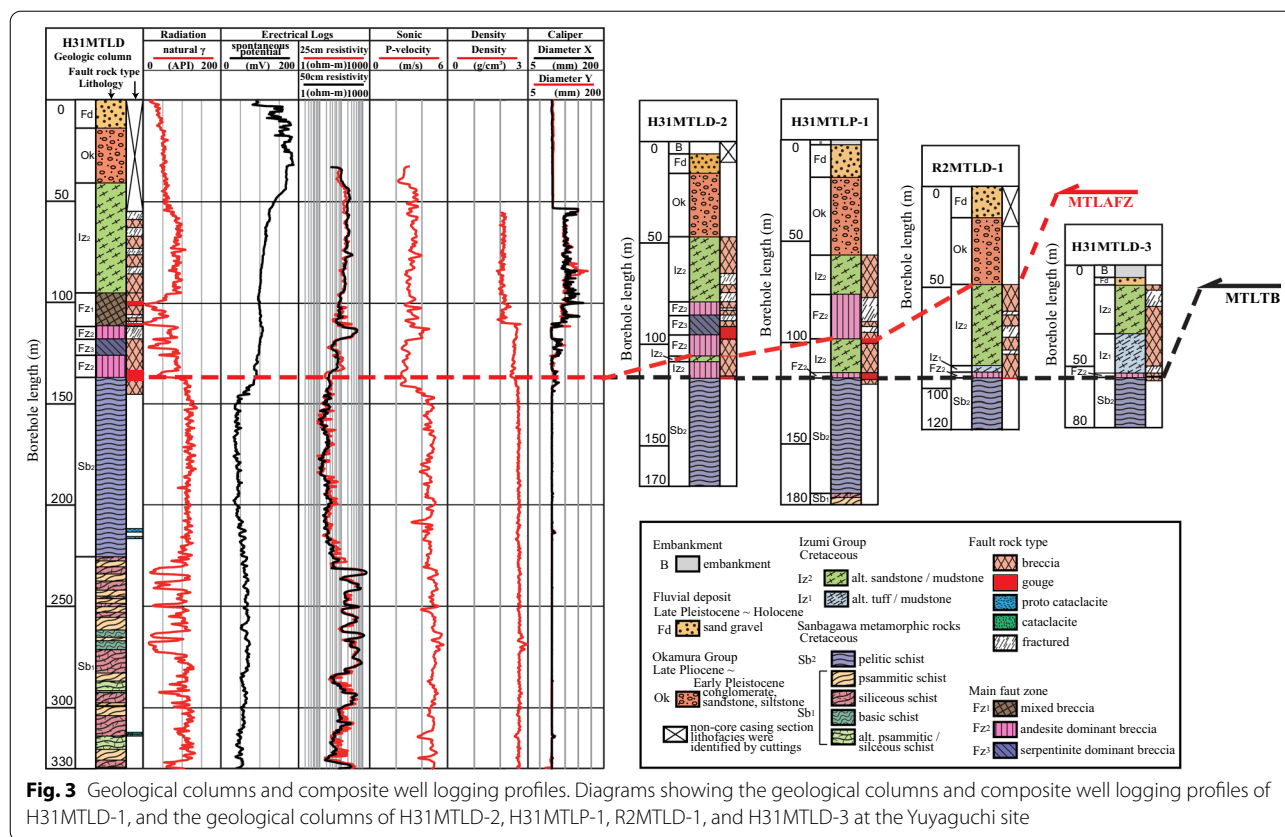


Fig. 2 Logs of the Kawakami Fault on the trench wall (Fig. 1 c, loc. 5). **a** Logs of the west wall, and **b** log of the east wall. **c** The survey map shows a trench site and a benchmark (BM) at the Yuyaguchi site

was composed of Sanbagawa metamorphic rocks, the main fault zone, mudstones and sandstones of the Izumi Group, conglomerates of the Okamura Group and sand gravels of the fluvial deposit, in ascending order. The Sanbagawa metamorphic rocks were divided into upper and lower parts. The upper Sanbagawa metamorphic rocks

consisted of pelitic schists and the lower Sanbagawa metamorphic rocks consisted of psammitic schists, siliceous schists, basic schists, and alternating psammitic and siliceous schists. The main identified fault zone in the core samples comprised andesite- and serpentinite-dominant breccias, and mixed breccias composed of fragments



of sandstones, basic rocks, schists, and andesites in a sheared mudstone matrix. The MTLTB juxtaposed the Sanbagawa metamorphic rocks against the andesite-dominant breccia of the main fault zone at 137.03 m; it had a sharp PSZ which was composed of a 4-cm-thick fault gouge along the geological boundary (Additional file 1: Fig. S2a). The dip angle of the PSZ was 30° to the north, as detected by the acoustic borehole televiwer (Additional file 1: Fig. S3a). The upper boundary of the main fault zone was recognized at 95.25 m; it had an irregular fault surface. The Izumi Group was characterized by a fractured damage zone and partial brecciation. Most parts of the Sanbagawa metamorphic rocks were intact, except for the breccia zone, which was approximately 1.5 m thick along the MTLTB. Cohesive cataclastic zones less than 1.8 m thick were found at 211.5 m, 215.57 m, and 312.15 m; they partially had a remnant original schistose structure (Additional file 1: Fig. S4). The borehole-logging analysis was completed in this section. The P-wave velocity was less than 4 km/s in the sedimentary rocks of the hanging wall of the MTLTB and was up to 5 km/s at the footwall. The observed step changes in the velocities occurred across the MTLTB within a few meters of the core. This contrast in P-wave velocity might be related to differences in lithology and the magnitude

of fault damage. The value of the spontaneous potential was higher than 100 mV at the hanging wall and less than 75 mV at the footwall. These high P-wave values and low spontaneous potentials at the footwall were consistent with the results obtained for soft sedimentary and hard metamorphic rocks, respectively. The values of the natural gamma rays and electrical resistivity were relatively stable along the entire borehole, except for the section of the breccia and the alternation zone of the psammitic, silicious, and basic schists. Around the fault zone, the natural gamma ray value was below approximately 100 API, and the electrical resistivity was lower than approximately 150 Ω·m. This might be related to differences in lithology and clay content within the fault damage zone.

Borehole H31MTLD-2 penetrated to a total length of 170 m with a plunge of 63° to the south. The drill core was composed of the Sanbagawa metamorphic rocks, two sets of the main fault zone, mudstones and sandstones of the Izumi Group, conglomerates of the Okamura Group, and sand gravels of the fluvial deposit, in ascending order. The Sanbagawa metamorphic rocks were composed of pelitic schists. The Izumi Group was characterized by a fractured damage zone and partial brecciation. The main fault zone was composed of andesite- and serpentinite-dominant breccias. The Kawakami Fault juxtaposed the

mudstones and sandstones of the Izumi Group against the andesite-dominant breccia of the main fault zone at 105.68 m; it had a sharp PSZ consisting of a 3–5 mm-thick fault gouge along the geological boundary (Additional file 1: Fig. S2b). The dip angle of the PSZ was 46° to the north, as detected by the optical borehole televiewer (Additional file 1: Fig. S3b). The upper boundary of the main fault zone was recognized at 79.95 m; it had an irregular fault surface. The MTLTB juxtaposed the Sanbagawa metamorphic rocks against the andesite-dominant breccia of the main fault zone at 116.75 m; it had a sharp PSZ consisting of an 8-mm-thick fault gouge along the geological boundary (Additional file 1: Fig. S2c). The dip angle of the PSZ was 38° to the north, as detected by the optical borehole televiewer (Additional file 1: Fig. S3c). Most parts of the Sanbagawa metamorphic rocks were intact except for the breccia zone, which was approximately 0.3 m thick along the MTLTB.

Borehole H31MTLP-1 penetrated to a total length of 180 m with a plunge of 46° to the south. The drill core was composed of the Sanbagawa metamorphic rocks, two sets of the main fault zone, mudstones and sandstones of the Izumi Group, conglomerates of the Okamura Group, and sand gravels of the fluvial deposit, in ascending order. The Sanbagawa metamorphic rocks in this borehole can be divided into upper and lower parts. The upper part consisted of pelitic schists, and the lower part consisted of psammitic schists and siliceous schists. The Izumi Group was characterized by a fractured damage zone and partial brecciation. The main fault zone was composed of andesite- and serpentinite-dominant breccias. The Kawakami Fault juxtaposed the mudstones and sandstones of the Izumi Group against the andesite-dominant breccias of the main fault zone at 100.46 m; it had a sharp PSZ which consisted of a 3-cm-thick fault gouge along the geological boundary. The upper boundary of the main fault zone was recognized at 74.35 m; it had an irregular fault surface. The MTLTB juxtaposed the Sanbagawa metamorphic rocks against the andesite-dominant breccias at 117.46 m; it had a sharp PSZ which consisted of a 5-mm-thick fault gouge along the geological boundary. Most parts of the Sanbagawa metamorphic rocks were intact, except for the breccia zone, which was approximately 3 m thick along the MTLTB.

Borehole R2MTLD-1 penetrated to a total length of 120 m with a plunge of 40° to the south. The drill core was composed of the Sanbagawa metamorphic rocks, the main fault zone, mudstones and sandstones of the Izumi Group, conglomerates of the Okamura Group, and sand gravels of the fluvial deposit, in ascending order. The Sanbagawa metamorphic rocks were composed of pelitic schists. The Izumi Group was characterized by a fractured damage zone and partial brecciation. The main

fault zone was composed of andesite-dominant breccias. The Kawakami Fault juxtaposed the mudstones and sandstones of the Izumi Group against the conglomerates of the Okamura Group at 48.45 m; it had a sharp PSZ consisting of a few-millimeter-thick fault gouge along the geological boundary (Additional file 1: Fig. S2d). The dip angle of the PSZ was 71° to the north, as detected by the optical borehole televiewer (Additional file 1: Fig. S3d). The upper boundary of the main fault zone was recognized at 74.35 m; it had an irregular fault surface. Most parts of the Okamura Group were not deformed except for the shear zone, which was approximately 10-cm thick along the Kawakami Fault. The MTLTB juxtaposed the Sanbagawa metamorphic rocks against the andesite-dominant breccia of the main fault zone at 94.65 m; it had a sharp PSZ consisting of a 1- to 3-cm-thick fault gouge along the geological boundary (Additional file 1: Fig. S2e). The dip angle of the PSZ was 26° to the north, as detected by the optical borehole televiewer (Additional file 1: Fig. S3e). Most parts of the Sanbagawa metamorphic rocks were intact except for the breccia zone, which was approximately 0.3 m thick along the MTLTB.

Borehole H31MTLD-3 penetrated vertically to a total length of 80 m. The drill core was composed of the pelitic schists of the Sanbagawa metamorphic rocks, the main fault zone, the Izumi Group, and sand gravels of the fluvial deposit, in ascending order. The Sanbagawa metamorphic rocks were composed of pelitic schists. The Izumi Group was composed of sandstone, mudstone, and tuff, and was characterized by a fractured damage zone and partial brecciation. The MTLTB juxtaposed the Sanbagawa metamorphic rocks against the andesite-dominant breccias of the main fault zone at 55.28 m; it had a sharp PSZ consisting of a 5-mm-thick fault gouge along the geological boundary (Additional file 1: Fig. S2f). The dip angle of the PSZ was 31° to the north, as detected the optical borehole televiewer (Additional file 1: Fig. S3f). Most parts of the Sanbagawa metamorphic rocks were intact except for the breccia zone, which was approximately 0.4 m thick along the MTLTB.

Discussion

Figure 4 shows the composite geological profile of the MTLTB and the MTLAFZ (Kawakami Fault) constructed using the data obtained from trenching and drilling. The attitudes of the faults were determined from borehole televiewer analyses and trench investigations. The Kawakami Fault was identified as a geological boundary between the fluvial deposit and Izumi Group at the exposed trench. Fault boundaries were also observed between the Okamura Group and the Izumi Group at R2MTLD-1, and between the andesite-dominant breccias and the Izumi Group at H31MTLP-1 and

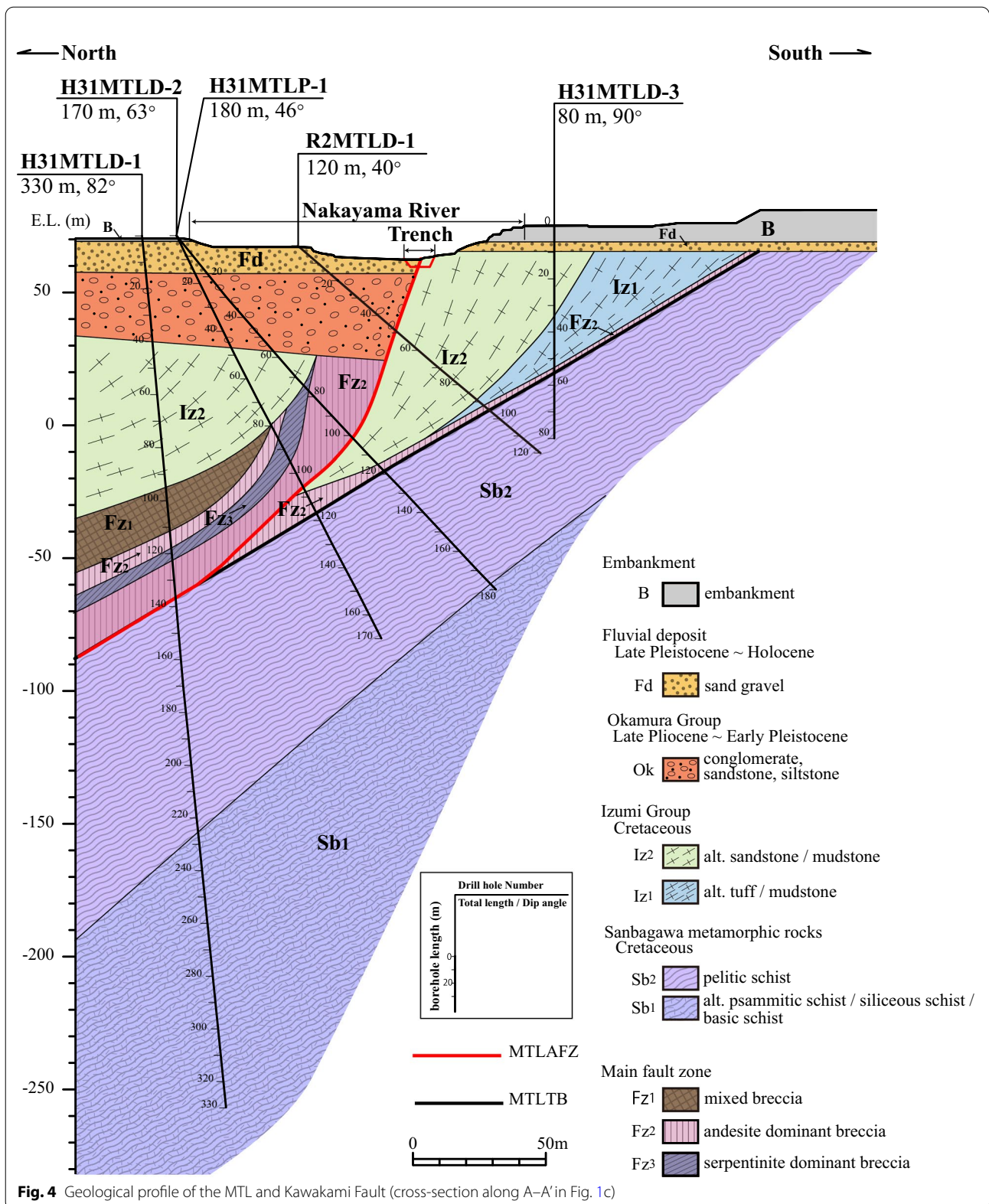


Fig. 4 Geological profile of the MTL and Kawakami Fault (cross-section along A–A' in Fig. 1c)

H31MTLD-2. The MTL was identified as the geological boundary between the andesite-dominant breccias and the Sanbagawa metamorphic rocks at all boreholes. The Kawakami Fault and the MTLTB had a sharp PSZ consisting of a fault gouge less than a few-centimeters-thick along the geological boundary. These PSZs can be traced along the lower boundary of the main fault zone. The dip angle of the PSZ with the Kawakami Fault was 72° to the north in the trench exposure, 71° to the north along R2MTLD-1, and 46° to the north along H31MTLD-2. In H31MTLD-1, the Kawakami Fault converged to the MTLTB, which dips to the north at 30° . The average dip angle of the MTLTB in the study area was estimated to be approximately 30° to the north (Additional file 1: Fig. S5). As another possible trace of the Kawakami Fault, the fault passed from the trench exposure to the upper boundary of the main fault zone and rooted to the MTLTB. However, there were no faults in the Okamura Group in the section of the predicted Kawakami Fault in R2MTLD-1. Therefore, it appears that the upper boundary fault of the main fault zone was eroded by deposition of the Okamura Group. The Kawakami Fault displaced the Izumi Group and andesite-dominant breccias upward toward the south. In addition, the Okamura Group half-graben deposits covered the hanging wall of the Kawakami Fault. This structure might reflect changes in the motion of the reverse fault displacement caused by compression and the subsequent normal displacement associated with an extension. The shear sense of the Kawakami Fault reflected that the latest shear sense was dextral and that of the cataclasite was sinistral-reverse (Kubota et al. 2020). At the trench, the latest fault plane of the ENE–WSW trending Kawakami Fault dipped at approximately 72° to the north, and the striations on the fault plane dipped slightly eastward (Fig. 2a). Therefore, the latest displacement was considered to accommodate a normal displacement, which is consistent with the deposition of the Okamura Group. It is suggested that the Kawakami fault was originally formed as a non-vertical reverse fault, and subsequent dextral strike–slip displacement occurred along the same fault plane. In this study area, previous seismic reflection surveys indicated a clear reflector dipping 30° to the north (Shigei et al. 2014). This is consistent with the north-dipping MTLTB, which juxtaposed the Izumi Group against the Sanbagawa metamorphic rocks. It was observed that most MTLAFZ segments run subparallel to each other for a few kilometers north of the MTLTB. Our finding that the high-angle MTLAFZ converges to the low-angle MTLTB at shallow depths, is consistent with the features observed in western Shikoku.

In this study, a combination of paleoseismic trenching and scientific drilling surveys confirmed that the high-angle MTLAFZ has a listric non-vertical fault geometry. The MTLAFZ can be traced at the surface, from where it converges to the low-angle (approximately 30°) northward-dipping MTLTB at approximately 140 m depth and approximately 100 m north of the trace of the Kawakami Fault. The listric non-vertical geometry of the active strike–slip MTLAFZ and its continuation in depth along the MTLTB indicate that the fault is poorly orientated with respect to the direction of the maximum horizontal stress (Sato et al. 2015), thereby implying that the fault must be weak at depth (Sibson 1990, 2020). Seismic reflection data have revealed reflectors associated with the MTLTB fault zone at larger depths (Ito et al. 1996, 2009; Tsutsumi et al. 2007; Sato et al. 2015). In a regional seismic study (Ito et al. 2009), the MTLTB was imaged as a band of high-amplitude reflector segments cutting through the entire upper crust and dipping northward at 35° . Crustal tomography beneath Shikoku and the Kii Peninsula (Gupta et al. 2009) indicates that the MTLTB is characterized by anomalous delay times coinciding with a low-seismic-wave speed zone in the upper crust. A localized reduction in velocity of 2–6% is broadly consistent with a moderately northward-dipping fault zone over a length of 300–350 km that penetrates to a depth of approximately 20 km (Gupta et al. 2009). Faulted rocks might have a low seismic velocity because of the clay-rich gouge, high crack density, and high pore fluid pressure. The combination of low seismic velocity and low resistivity ($< 50 \Omega\text{-m}$) at a depth of 15 km (Ikeda et al. 2013) suggests interconnected pore fluids at pressures approaching lithostatic and imply relatively low effective stress. Based on geodetic data along with the best-fitting fault plane model, the current configuration of the MTLTB appears to be locked with a dip of 35° – 45° in the northward direction. The boundary appears to be 100% locked at a depth of 15 km with a steady slip of 5 mm/yr at larger depths (Tabei et al. 2002).

The Wairarapa Fault, New Zealand, is a similar poorly oriented strike–slip fault exhibiting a listric geometry (Darby and Beanland 1992; Darby and Beavan 2001; Henrys et al. 2013). The association of high fluid pressures and long-term fault weakness with geodetic locking at the Wairarapa Fault implies that the properties of local materials might have played a significant role in determining the behavior of the localized fault slips (Kurashimo et al. 2015). For example, slip on a non-optimally oriented fault plan may occur if the work

required to generate a new fault is greater than the work against friction on a pre-existing surface. Given the contrasting physical properties and localized shear zones observed from the logs of the borehole televiewer across the MTLTB and MTLAFZ faults, we speculate that local frictional forces and other material properties might also be important parameters for promoting locking and failure in future large earthquake ruptures along the Shikoku segment of the MTLAFZ.

The Keicho earthquake in 1596 (Ikeda et al. 2014, 2019) is thought to have ruptured multiple segments of the MTLAFZ, indicating that weak fault segments and low shear stress patches did not impede the dynamic rupture of the Keicho earthquake. Thus, high-magnitude earthquakes with rupture dimensions of several hundred kilometers remain a realistic future scenario along the MTLTB and MTLAFZ.

Conclusions

Based on the shallow trench and borehole data collected at the Yuyaguchi site across the MTL, situated 10 km southwest of Nyugawa in western Shikoku, we were able to confirm that the Kawakami Fault (MTLAFZ) roots to the MTLTB at approximately 140 m beneath the surface. We infer that the MTLTB at this locality dips at approximately 30° to the north. The trace of the high-angle (>70°) active MTLAFZ fault observed at the trench site was considered to be limited to depths of less than 140 m below the surface. This suggests that the main MTLTB fault, which divides the island-arc crust, forms a low-angle (approximately 30°) northward-dipping structure extending to the base of the crust. These results are consistent with those of other studies conducted on this segment of the MTLTB (Ito et al. 1996). Moreover, the MTLTB extends further east along the Kii Peninsula (Sato et al. 2015). The Kawakami fault was originally formed as a non-vertical reverse fault, and subsequent dextral strike-slip displacement has occurred along the same fault plane. Our results support previous studies that indicate that the MTLTB, although poorly oriented with respect to the regional stress field, is capable of rupturing given its sufficiently weak interface, and the properties of local materials might play a significant role in determining slip behavior. Knowledge of the dip angle of the MTL fault plane is expected to help in evaluating earthquake rupture scenarios for hazard modeling and assessment. In a future study, we will clarify the deformation conditions of fault rocks by conducting petrological and chemical analyses. We will also clarify the evolution of the MTL from microstructural analysis.

Abbreviations

MTL: Median Tectonic Line; MTLAFZ: Median Tectonic Line active fault zone; MTLTB: Median Tectonic Line terrane boundary; PSZ: Principal slip zone.

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s40623-021-01526-w>.

Additional file 1: A file containing three supplemental figures: **Figures S1, S2, S3, S4, and S5.**

Acknowledgements

We thank S. Shibutani, T. Takahashi, Y. Fujimoto, and A. Tanase of Chi-ken Sogo Consultants Co., Ltd. for operating the drilling and trench investigations over the last three years. The manuscript has been greatly improved from the comments of Editor Dr. Stuart Henrys and the reviewer Dr. Norio Shigematsu. We thank Dr. M. Komatsu, former president of Ehime University, for insightful discussions.

Authors' contributions

MM conducted trench and drilling surveys. AS conducted the drilling survey. Both authors contributed to the data analysis, interpretation, and preparation of the manuscript. Both authors read and approved the final manuscript.

Funding

Not applicable to this study.

Availability of data and materials

Project reports including trench photos, trench logs, drill core photos, drill core descriptions, and geophysical logs will be available at the National Diet Library, Japan, after all related manuscripts are published.

Declarations

Ethics approval and consent to participate

Not applicable to this study.

Consent for publication

Not applicable to this study.

Competing interests

The authors declare that they have no competing interests.

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Received: 29 April 2021 Accepted: 5 October 2021

Published online: 21 October 2021

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