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Doctoral Thesis

Kinematic analyses and radiometric dating of the Paleogene two-phase and large-scale faulting
along the Median Tectonic Line, south-west Japan

(西南日本中央構造線に沿う古第三紀の2回の大規模断層活動の運動像と放射年代の解析)

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Abstract

The Median Tectonic Line (MTL) in southwest Japan, a major east–west-trending arc-parallel fault, has been defined as the boundary fault between the Cretaceous Sambagawa metamorphic rocks and Ryoke granitic and metamorphic rocks, which are unconformably covered by the Upper Cretaceous Izumi Group. For the long time span of the Paleogene period (66–23 Ma), the fault movement along the MTL has not been fully clarified. Based on detailed fieldwork and previous studies, the authors reconstruct the kinematic history along the MTL during the Paleogene period. The authors proposed in the previous studies that the Paleogene kinematic history of the MTL is divided into the Ichinokawa phase and Pre-Tobe phase: the Ichinokawa phase is large scale normal faulting accompanied by a wide fracture zone along the MTL, while the Pre-Tobe phase is defined as the activation of of the parallel faults to the MTL in the Upper Cretaceous Izumi Group, which are perhaps connected to the MTL at depth. In this study, the author has analyzed the kinematic movement along the MTL at the Pre-Tobe phase, based on the field survey and microstructural analyses in fault rocks. We found that *en échelon* folds oriented clockwise for the fault of map-scale were developed along the parallel faults, which are accompanied by a cataclasite zone of 60 to 25 m wide consisting of foliated cataclasite, cataclasite, and fault gouge zone. The map-scale south-vergent folds in the disturbed zone and microstructures (e.g. composite planar structures) in the cataclasite zone which accompanies the parallel faults strongly suggest that they formed due to sinistral and reverse faulting with a top-to-the-SW sense along the MTL. Moreover, based on previous studies and the K-Ar age measurements of authigenic illite from fault gouge along the parallel faults and MTL in this study, it has been found that the MTL was activated at two discrete stages of 60–57 Ma and 41 Ma. A combination of kinematic analyses with K-Ar age dating of authigenic clay minerals from the cataclasite zones allows us to reconstruct the kinematic history of the MTL: normal faulting during 60–57 Ma (Ichinokawa phase) and sinistral and reverse faulting during 41 Ma (Pre-Tobe phase). The MTL as a large-scale, arc-parallel fault records the movements of subducting oceanic plate relative to continental plate. According to previous studies, the movement direction of the subducting Pacific oceanic plate relative to proto-southwest Japan arc

had changed from almost that normal to the arc at the Ichinokawa phase to that oblique to the one to generate sinistral slip along the MTL at Pre-Tobe phase. Therefore, the change in kinematic movement along the MTL and large-scale arc-parallel faults in fact reflects the movements of subducting oceanic plate relative to continental plate.

Key words: kinematic history, Median Tectonic Line, normal faulting, sinistral-reverse faulting, K-Ar geochronology, Paleogene.

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1. Introduction

The Median Tectonic Line (MTL) is the largest scale arc-parallel tectonic line in southwest Japan, which divides the southwest Japan arc into the Inner zone (mostly consisting of Permian–Jurassic accretionary complexes and granitoids) and Outer zone (mostly consisting of Jurassic–Paleogene accretionary complexes; Figure 1). Because large-scale, arc-parallel faults record the movements of subducting oceanic plate relative to continental plate [Fitch, 1972; Jarrard, 1986; Chemenda *et al.*, 2000], kinematic studies on these faults are important to elucidate plate tectonic framework in geological ages. The studies on the movement history of the MTL are numerous. It has been demonstrated that left-lateral strike-slip dominated along the MTL in the Late Cretaceous [Hara *et al.*, 1980; Ichikawa, 1980; Takagi and Shibata, 1996], while a large amount of right-lateral strike-slip occurred along it during the Quaternary period [e.g. Okada, 1972]. However, for the long time span of the Tertiary period, the kinematic movement along the MTL has not been fully clarified, in particular, that after the Paleocene period when large-scale normal faulting occurred along the MTL [Kubota and Takeshita, 2008].

The purpose of this study is to reconstruct the kinematic history of the MTL during the Paleogene. It has been found that in the Paleogene, two large-scale movements occurred along the MTL. One is the normal faulting which is associated with the final exhumation of the Sambagawa metamorphic rocks in the Outer zone, and its juxtaposition against the Cretaceous Izumi Group which unconformably overlays the Cretaceous granitoids in the Inner Zone at depth [Kubota and Takeshita, 2008]. The other one is defined as the activation of the parallel faults in the Upper Cretaceous Izumi Group to the MTL, which are perhaps connected to the MTL at depth. Since the kinematics and ages of the second movement have not been clarified, we analyze these in the present paper. The central and western Shikoku has been chosen as the study area, because the MTL was not much disturbed by the Quaternary faulting [e.g. Okada, 1973a,b]. Furthermore, since the geological units, which were deposited before and after the Paleogene, the Upper Cretaceous Izumi and Lower Miocene Kuma Groups, respectively, are distributed along the MTL, the deformation, which occurred during the Paleogene period, can be constrained. The degree and style of deformation of these strata are keys

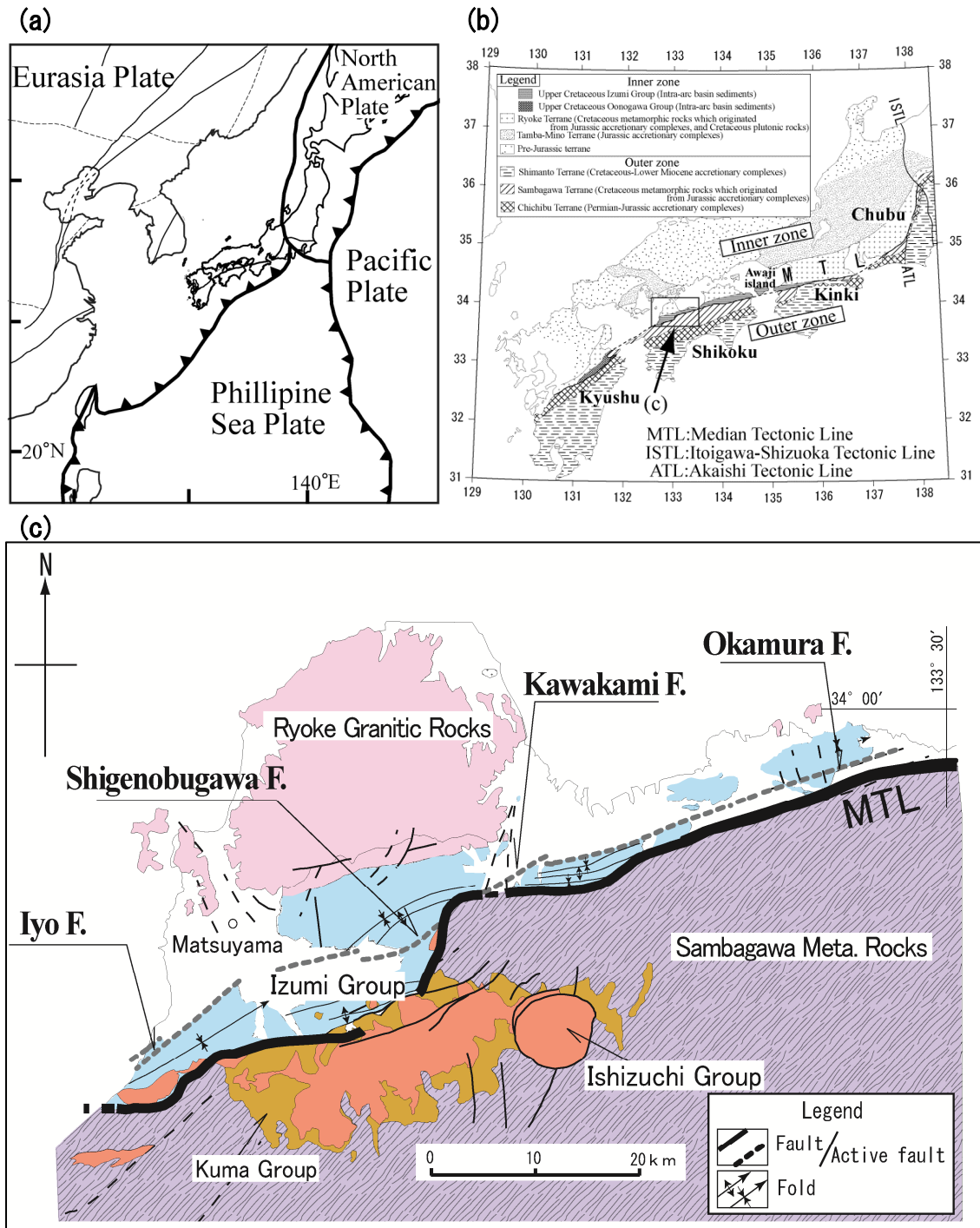


Figure 1. (a) Distribution of tectonic units and boundaries in eastern Asia. (b) Tectonic units of southwest Japan and location of study area (Fig. 2). Modified after [Kubota and Takeshita, \[2008\]](#). ATL, Akaishi Tectonic Line; ISTL, Itoigawa–Shizuoka Tectonic Line; MTL, Median Tectonic Line. (c) A simplified geological map of the study area. The distributions of the Ryoke metamorphic and plutonic rocks, Sambagawa metamorphic rocks, Izumi, Kuma and Ishizuchi Groups are modified after [Momoi et al. \[1991\]](#).

to reconstruct the kinematic history of the MTL. Based on detailed geological survey in a wide area, the present study first documents previously unrecognized map-scale fold structures of the Izumi Group along the parallel faults. Second, we document cataclasite and gouge zones accompanying the parallel faults in the Izumi Group, for which detailed structural and microstructural analyses are conducted. In particular, we document for the first time the evidence for normal faulting overprinted by sinistral and reverse faulting in the cataclasite along the north-dipping MTL. Furthermore, based on the K-Ar age measurements of authigenic illite from fault gouge along the parallel faults and MTL, the geologic ages of the two stages of movement along the MTL have been determined. A combination of kinematic observations with K-Ar age dating of authigenic clay minerals from the cataclasite zones along the MTL allows us to reconstruct the kinematic history of the MTL from the latest Cretaceous to Paleogene. Further, the possible relation of these two-stage movements along the MTL to tectonics in the east Asia is discussed in the present paper.

2. Geological setting

The geological setting and review on the movement history along the MTL in the following section are summarized in Figure 2, and the geological map and cross-sections of the study area are shown in Figure 3. The study area extends ~80 km along the MTL in western Shikoku (Figure 1). The Cretaceous Sambagawa metamorphic rocks are distributed in the Outer zone, while in the Inner zone the Cretaceous Ryoke metamorphic and granitic rocks, unconformably covered by the Upper Cretaceous Izumi Group, are distributed, which are juxtaposed against the Sambagawa metamorphic rocks, bounded by the MTL. The Lower Eocene Hiwada-toge Formation [Narita *et al.*, 1999] unconformably overlies the Sambagawa metamorphic rocks. The Lower Miocene Kuma Group unconformably overlies both the Sambagawa metamorphic rocks and the Izumi Group in central-western Shikoku [Kashima and Takechi, 1996; Narita *et al.*, 1999; Takeshita *et al.*, 2000]. Moreover, the Middle Miocene Ishizuchi Group widely covers all of these strata unconformably [Tazaki *et al.*, 1990; Takeshita *et al.*, 2000]. While most of the Kuma and Ishizuchi Groups are distributed in the Outer zone, part of these is distributed in the Inner zone across the MTL (Figure 2a).

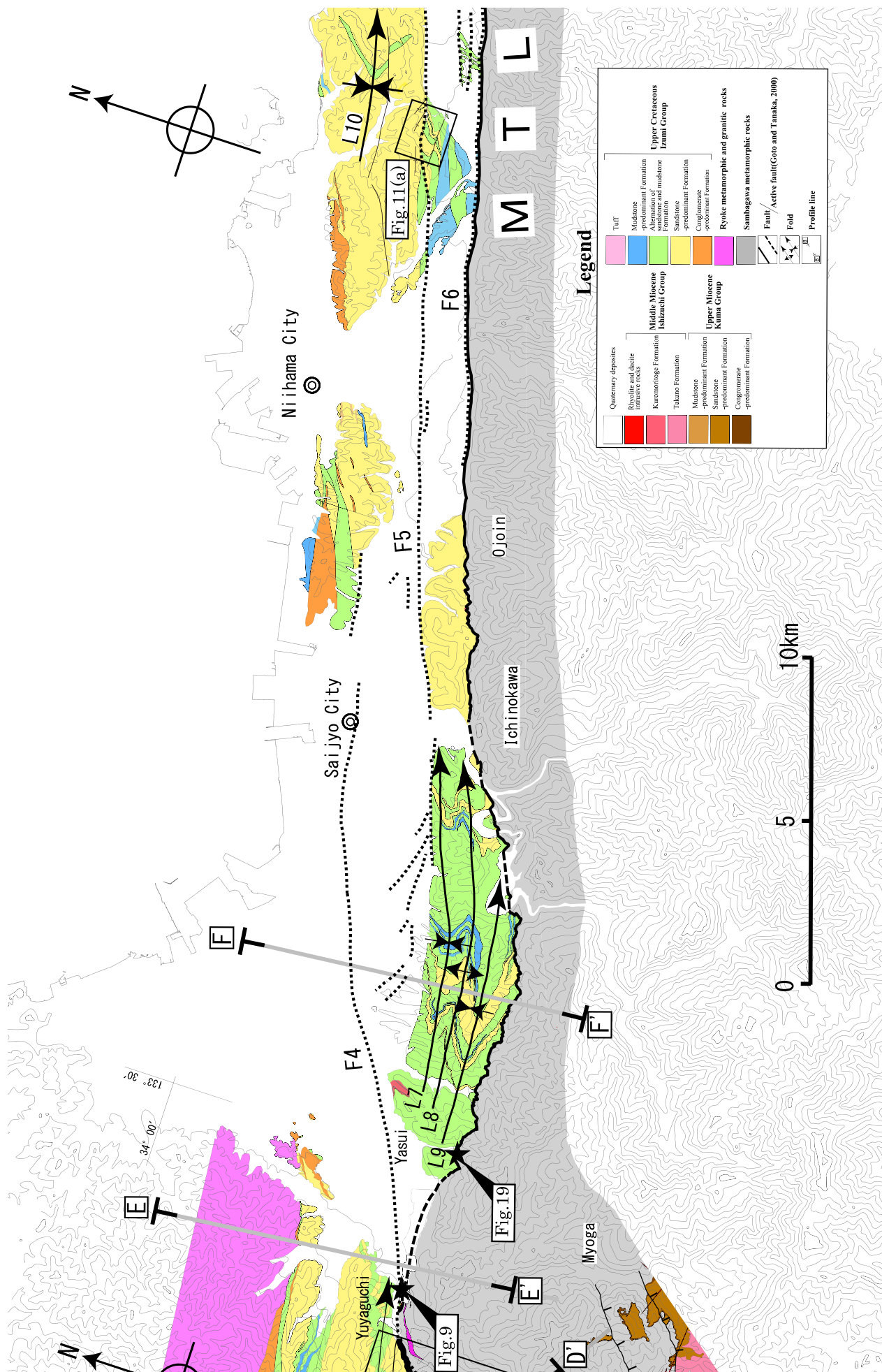


Figure 2(a)

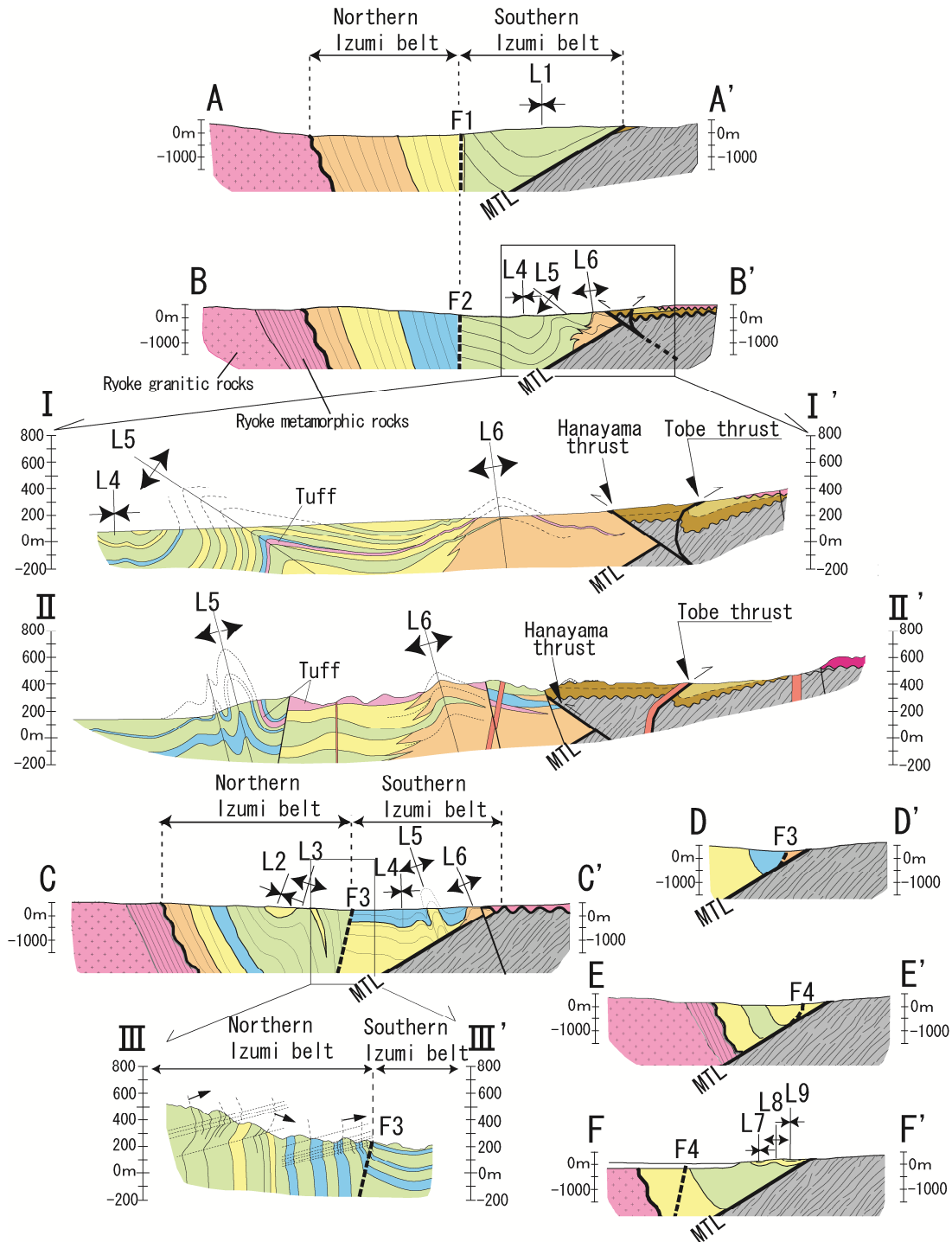


Figure 2. (b) (a) Geological map and (b) cross-sections of western Shikoku. The traverse lines of the cross-sections are shown in the geological map. See Figure 2 (a) for the mapped area. The distributions of the Ryoke metamorphic and plutonic rocks, Sambagawa metamorphic rocks, Kuma and Ishizuchi Groups are mapped by this study and modified after [Momoi et al. \[1991\]](#), [Kubota and Takeshita, \[2008\]](#), [Aoya et al. \[2013\]](#) and [Miyazaki et al. \[2016\]](#). This map is based on the Digital Map 200000 (Map Image) published by Geospatial Information Authority of Japan. The contour interval is 100 m. In Figure 2b, cross-sections of I-I' to III-III' show more detailed structures of those of B-B' to C-C' on larger scale. Thin solid lines in the same symbols (i.e. lithology) indicate bedding plane, and modified after [Kubota and Takeshita, \[2008\]](#)

2.1. Sambagawa belt

The Sambagawa metamorphic rocks are of high-P/T type, mainly consisting of basic schist, pelitic schist and quartz schist [e.g. [Banno and Sakai, 1989](#)]. The deposition age of the Sambagawa metamorphic rocks has been inferred from microfossils such as radiolarians and conodonts, which occur only in the lowest grade part [[Matsuda, 1978](#); [Faure et al., 1991](#)]. Their fossil ages range from the Late Triassic to Late Jurassic [[Isozaki and Itaya, 1990](#)]. The age of peak metamorphism has been recently determined as 120–110 Ma, based on zircon U-Pb ages with the sensitive high mass-resolution ion microprobe [[Okamoto et al., 2004](#)], while the ages for cooling and exhumation were dated at 90–70 Ma, based on phengite K-Ar ages and zircon fission track ages [e.g. [Itaya and Takasugi, 1988](#)].

The deformation phases have been divided into three phases D₁, D₂ and D₃ [[Hara et al., 1977](#); [Faure, 1983](#); [Wallis, 1990](#)]. D₁ is characterized by a penetrative subhorizontal schistosity and east–west-trending lineation formed by ductile flow [e.g. [Takeshita and Yagi, 2004](#)]. D₂ is recognized by south-vergent overturned folds with crenulation cleavages. D₃ resulted in the formation of open and upright folds with horizontal east–west-trending axes. The D₃ folds are considered to have formed after substantial exhumation [[Banno and Sakai, 1989](#)], in relation to left-lateral displacement along the MTL [[Hara et al., 1977](#); [Shiota et al., 1993](#)].

2.2. Ryoke belt

The Upper Cretaceous Izumi Group mainly consists of alternating beds of sandstone and mudstone, and rare conglomerate, which unconformably overlies the Ryoke metamorphic rocks, and is unconformably covered by, or contacted by faults with the Kuma and Ishizuchi Groups (Figure 2a). Note that there has been no detritus ever reported in the Izumi Group from the Sambagawa metamorphic rocks, indicating that the latter were never exposed at the surface during the sedimentation of the former. Although the width perpendicular to its extension is ~13 km around Matsuyama city, it becomes very narrow ~4 km in the north of the Sakuraki Bend (described below), and 6–8 km in the further eastern part [e.g. [Momoi et al., 1991](#)].

The strata always dip eastward at moderate angles and also become young in this direction, which was perhaps caused by the migration of deposition center toward the east with time [e.g. Miyata, 1990]. The Izumi Group in western Shikoku, the maximum thickness is 10,800 m, consists of alternation of sandstone and mudstone (divided into sandstone-predominant, equal ratio and mudstone-predominant subfacies), and conglomerate, sandstone and mudstone (Figure 2) [Takahashi and Yamazaki, 1991]. The former and latter lithofacies are distributed in the central area and along the northern margin, which are considered to be turbidite sediments deposited at deep-sea fan and continental shelf sediments, respectively. The continental shelf sediments interfinger with the turbidite sediments in the central area.

For the deposition age of Izumi Group in the study area, Noda and Tashiro [1973] inferred it to be the Campanian–Maastrichtian stage, while Tashiro [1985] inferred that it is the Middle Campanian, based on the macrofossils (e.g. *Gaudryceras striatum* and *Inoceramus schmidtii*). Based on radiolarian fossils Yamazaki [1987] inferred that it is the Early–Middle Campanian, while Kashima et al. [1988] inferred it to be the Campanian. Furthermore, based on paleomagnetic stratigraphy, Kodama [1990] inferred it to be Chron 33 of Early Campanian [after Cande and Kent, 1995] in the east of Matsuyama city, and also Chron 33 in the central to eastern Shikoku. Fission track ages of 76.8 ± 4.8 Ma in central Shikoku and 77.3 ± 4.4 Ma at western Shikoku, have been reported for acidic tuff of the Izumi Group. Whole rock K-Ar ages of 81.2 ± 1.8 , 82.7 ± 1.8 and 82.9 ± 1.9 Ma have been reported for acidic dykes of the Ryoke granitic rocks, which are covered unconformably by the Izumi Group of the northern Matsuyama city [Tazaki et al., 1990]. From these studies it can be inferred that the deposition age of the Izumi Group in the study area ranges between 78 and 76 Ma of the Late Cretaceous.

2.3. Paleogene-Neogene sedimentary rocks

In study area, the Paleogene-Neogene sedimentary rocks consist of the Kuma and Ishizuchi Group. The Kuma Group is distributed in a southeastern part of Matsuyama city. This formation renamed as the Hiwada-toge Formation, has been further dated as the Early Eocene based on dinoflagellate fossils, and separated from the Kuma Group [Narita et al., 1999]. The Hiwada-toge Formation is distributed 10 km south

of the MTL and constitutes only <1 area percentage of the Kuma Group defined earlier (Figure 2a), which mostly consists of non-marine conglomerate, sandstone, and mudstone. Although Matsuo [1981] originally inferred the age of the Kuma Group to be the Early Miocene, based on plant fossils, it has been only recently dated as the latest Early Miocene (18–16 Ma), based on zircon fission track ages [Kashima and Takechi, 1996; Narita *et al.*, 1999], and biotite K-Ar ages [Takeshita *et al.*, 2000] of the acidic tuff. From these studies it can be inferred that the deposition age of the Kuma Group is the latest Early Miocene.

The Middle Miocene Ishizuchi Group unconformably covers the Kuma Group [Nagai, 1957]. It consists of intermediate–felsic lava, volcanoclastic rocks and intrusive rocks (dyke and sill). Dyke rocks are also commonly observed along the MTL. The Ishizuchi cauldron [e.g. Yoshida, 1984], which is centered at Mount Ishizuchi, is one of the largest ancient cauldrons in the world (Figure 2a). The deposition age of the Ishizuchi Group can be inferred to be 15–14 Ma of the Middle Miocene, based on the following radiometric ages. Whole rock and biotite K-Ar ages of 15.4 ± 0.4 Ma, 15.3 ± 0.4 Ma and 15.1 ± 0.4 Ma [Tazaki *et al.*, 1990] have been determined for the dyke rocks. Takeshita *et al.* [2000] have also dated the Takano Formation (ash-flow acidic tuff), which is the lowest formation of the Ishizuchi Group. The biotite from the acidic tuff yielded the K-Ar ages of 15.1 ± 0.6 Ma and 14.9 ± 0.4 Ma, comparable with the ages of the dyke rocks.

2.4. Review on the movement history along the MTL

The movement history of the MTL had been extensively studied before 1980 [e.g. Ichikawa, 1980], which had been divided into five stages: the Kashio phase (Early–Middle Cretaceous, before 83 Ma), the Ichinokawa phase (divided into two substages: Late Cretaceous, 80–65 Ma and early Paleogene, 65–49 Ma), the Tobe phase (Middle Eocene–earliest Miocene, 49–20 Ma), the Ishizuchi phase (Middle Miocene–Pliocene, 15–2 Ma) and the Shoubutani phase (middle Pleistocene and later, 1–0 Ma) (original nomenclature after Kobayashi [1941] except for the Ishizuchi phase after Suyari and Akojima [1980]; geological ages after Ichikawa [1980]). The study by Ichikawa [1980] is summarized in Kubota and Takeshita [2008], where the ages of the movement phases of the MTL have been renewed by recent studies. The Kashio phase is the birth stage of the MTL, which formed as granite mylonite zones [e.g. Hara and

[Yokoyama, 1974](#)] centered in the southern marginal part of the Ryoke Belt. [Hara et al. \[1977, 1980\]](#) showed that a left-lateral strike-slip (or a top-to-the-west) movement occurred along the MTL from structural analysis of these granite mylonite zones in the east of central Kinki.

The Ichinokawa phase is the movement stage of the MTL, during which the formation of sedimentary basin of the Upper Cretaceous Izumi Group, and its subsequent juxtaposition against the Sambagawa metamorphic rocks occurred. Hence, the MTL that bounds the Sambagawa metamorphic rocks and the Izumi Group at outcrops originally formed at the Ichinokawa phase, not at the Kashio phase. It has been shown that the Izumi sedimentary basin formed as a pull-apart basin, which resulted from a left-lateral strike-slip along the MTL [e.g. [Miyata, 1990](#)]. [Miyata et al. \[1980\]](#) showed that a left-lateral strike-slip fault movement also occurred after the deposition of the Izumi Group at the Ichinokawa phase. Later, [Kubota and Takeshita \[2008\]](#) showed that large scale normal fault movement occurred along the MTL in the Paleocene (63-58 Ma) from structural analysis of disturbed zone along the MTL, and redefined that the Ichinokawa phase is the phase of juxtaposition of the Izumi Group against Sambagawa metamorphic rocks.

The Pre-Tobe phase has been defined as the movement stage of the MTL, when the northern part of the Izumi Group thrust over the southern part of the Izumi Group due to a north-south-directed shortening in the Middle Eocene to late Oligocene (25-45 Ma) [[Kubota and Takeshita, 2008](#)], although the detailed kinematics has not been investigated by the study.

The Tobe phase was originally defined as the movement stage of the MTL, when the Izumi Group thrust over the Lower Miocene Kuma Group [e.g. [Takahashi, 1992](#)], which unconformably overlies the Sambagawa metamorphic rocks. The Middle Miocene Ishizuchi Group, which unconformably overlies the Kuma Group, was not folded by the Tobe thrusting [[Takeshita, 1993](#)]. It has been therefore concluded that the Tobe thrusting occurred in a short time interval during the Middle Miocene (*ca* 15 Ma), although the Tobe phase had long been believed to be in the Eocene. In contrast, detailed structural work on the Tobe thrusting has recently shown that it represents the inversion tectonics of the Early Miocene Kuma basin, not thrusting of the Izumi Group over the Kuma Group [[Takeshita, 1993](#); [Takeda, 1996](#)]. The Tobe thrust itself is not the reactivated MTL, which bounds the Izumi Group against the Sambagawa metamorphic rocks formed at the

Ichinokawa phase, but rather it formed as a fault in the Sambagawa metamorphic belt (see cross-sections B-B' and I-I' in Figure 2b, [Takeshita \[1993\]](#)). This fault originally worked as a detachment and normal fault to form the Kuma basin, and later reactivated as a thrust. During this inversion both north- and south-vergent thrusts called the Hanayama [[Takahashi, 1986; 1992](#)] and Tobe thrusts, respectively, are generated, forming a pop-up structure in the Sambagawa belt near the MTL (Figure 2b). [Takeshita \[1993\]](#) also argued that although the folding of the Kuma Group occurred during the Tobe phase in a strict sense dated at the Middle Miocene (*ca* 15 Ma), only minor folding of the Upper Cretaceous Izumi Group occurred during this phase. However, the shortening of the Izumi Group is much greater than the amount of shortening in the Kuma Group. [Takeshita \[1993\]](#) refers to this phase of folding in the Izumi Group as the pre-Tobe phase; this could have resulted from thrusting along the MTL as mentioned in the present paper.

The Ishizuchi phase can be defined as the intrusion of so-called 'Seto Inland Sea igneous rocks' of the Middle Miocene (15–14 Ma) along the MTL and the subsequent faulting that cut these [e.g. [Suyari and Akojima, 1974](#)]. Although there has been no strong tectonic movement along the MTL reported at this stage, a group of K-Ar ages (14–10 Ma) of clay minerals from the gouge along the MTL has been reported, which could indicate the age of the Ishizuchi phase [[Takagi and Shibata, 1992](#)]. [Takagi et al. \[1992\]](#) dated clay minerals of the gouge derived from the sheared Sambagawa metamorphic rocks along the MTL, which yielded a K-Ar age of 14.7 Ma. They also determined the sense of shear to be normal in the gouge, based on composite planar fabric, and attributed this normal faulting along the MTL to the north–south extension at the Ishizuchi phase.

The Shoubutani phase can be defined as the phase when the MTL has been reactivated as a major active fault in southwest Japan. Due to a strong compression in the WNW–ESE direction, which results from the subduction of both Pacific and Philippine Sea plates underneath the southwest Japan arc in similar directions, the MTL has been reactivated as a right-lateral strike-slip fault since 2 Ma [e.g. [Okada, 1973a,b](#)].

3. Kinematics of the MTL

3.1. Method

In order to constrain the kinematics of the MTL, I conducted geological mapping, and structural analysis along the MTL and parallel faults. For structural analysis of fault, it described about detail investigated outcrop and shear planes were measured at mesostructures, and thin section and slab of oriented fault samples at microstructures. Based on the macro-meso-microstructure, paying attention to deformation sequence, the kinematics of the MTL was constrained.

3.2. Outline of parallel fault system along the MTL

Major faults and folds develop in the Izumi Group along the MTL in the study area, which will be described here. Although the major faults have been already reported in the previous studies (refs), there has been little study of fault movement based on structural analyses. Therefore, the kinematics of the major faults is not clear, which is analyzed in the present study for the first time.

It is first of all very important to note that the Izumi Group in this study area can be divided into the Northern and Southern Izumi belts, bounded by F1 to F6 faults, which are more or less continuous (Figure 2). The structure in the Izumi Group from central Shikoku to Kinki is essentially characterized by a large-scale syncline with the axis plunging moderately toward the east. However, this structure is not simply continuous to that in western Shikoku. In the Izumi Group in western Shikoku, [Nishimura \[1984\]](#) originally inferred that a northern part is elevated by ~1–2 km relative to a southern part, based on the study of zeolitization in the Izumi Group. Furthermore, significant differences are observed in the structures of the northern and southern parts, and a broad disturbed zone of ~100 m occurs parallel to the boundary, as mentioned in the present paper. Considering the importance of this structural discontinuity, [Takeshita \[1993\]](#) named the northern and southern parts as the Northern and Southern Izumi belts, respectively. In fact, in the Southern Izumi belt, conglomerate, sandstone and mudstone (i.e. southern marginal facies of the Izumi basin) develop along the MTL [Figure 2, [Takeshita, 1993](#)]. Similar lithology is sporadically distributed (or the Southern Izumi belt occurs) along the MTL in the Awaji island and Kinki district [e.g. [Hashizume et al., 1993](#)]. However, in most of the Izumi belt from Shikoku to Kinki, the southern marginal facies do not occur and no structural discontinuity is documented, indicating that the Northern Izumi belt is in a direct fault

contact with the Sambagawa metamorphic rocks along the MTL.

3.3. The deformation structure of parallel fault system along the MTL

The parallel fault system along the MTL is described in detail for selected outcrops, thin sections and slab of fault rock samples. In this study, F1, F3, F4, and F5 faults from west to east are investigated in details, which are not covered by an alluvial bed (Figure 2a).

F1 (Iyo fault): The fault extends for 15 km in the Izumi Group in the NE–SW direction. Along the fault zone, andesitic or dacitic dyke rocks of several to ten several meters wide locally intruded. A fault zone, which consists of cataclasite and fault gouge, is disturbed sandstone, mudstone, and dyke rocks. At locality IY-1 (Figure 2a, 3), the fault zone consists of cataclasite with ~30 m wide and fault gouge with one meter width. The fault strikes N66°E and dips 90° (Figure 3; locality IY-1). The composite planar fabrics (P-Y-R1 fabrics; [Rutter et al. \[1986\]](#)) of the cataclasite zone shows sinistral and reverse slip. In the fault gouge, dextral and normal slip can be inferred from the composite planar fabrics. The fault gouge is located on the active fault trace, therefore it seems that the fault gouge formed due to the recent movement along the MTL during the Quaternary period. At locality IY-2 (Figure 2a), the fault zone is consists of cataclasite with ~30 m wide and fault gouge with one meter width. The fault strikes N62°E and dips south at 75 to 90° (Figure 5). The composite planar fabrics of the cataclasite zone shows sinistral and revers slip. In the fault gouge, dextral and normal slip can be inferred from the composite planar fabrics. The fault gouge is located on the active fault trace, therefore it seems that the fault gouge formed due to the recent movement along the MTL during the Quaternary period.

F3 (Shigenobugawa fault): The fault extends for 8 km in the Izumi Group in the NE–SW to ENE–WSW direction (Figures 2a, 6a). The fault zone consists of cataclasite and fault gouge, which is derived from sandstone and mudstone (Figure 6c). At locality SG-2,3 (Figure 6c), the fault strikes N40°E and dips north at 54°, the fault zone of which consists of cataclasite with 60 m wide and fault gouge with 0.3 meter wide. The composite planar fabrics of the cataclasite and fault gouge (Figure 7b) and the drag folds of sandstone beds in direct proximity to the fault gouge (Figure 7c) could indicate sinistral and reverse sense of slip along

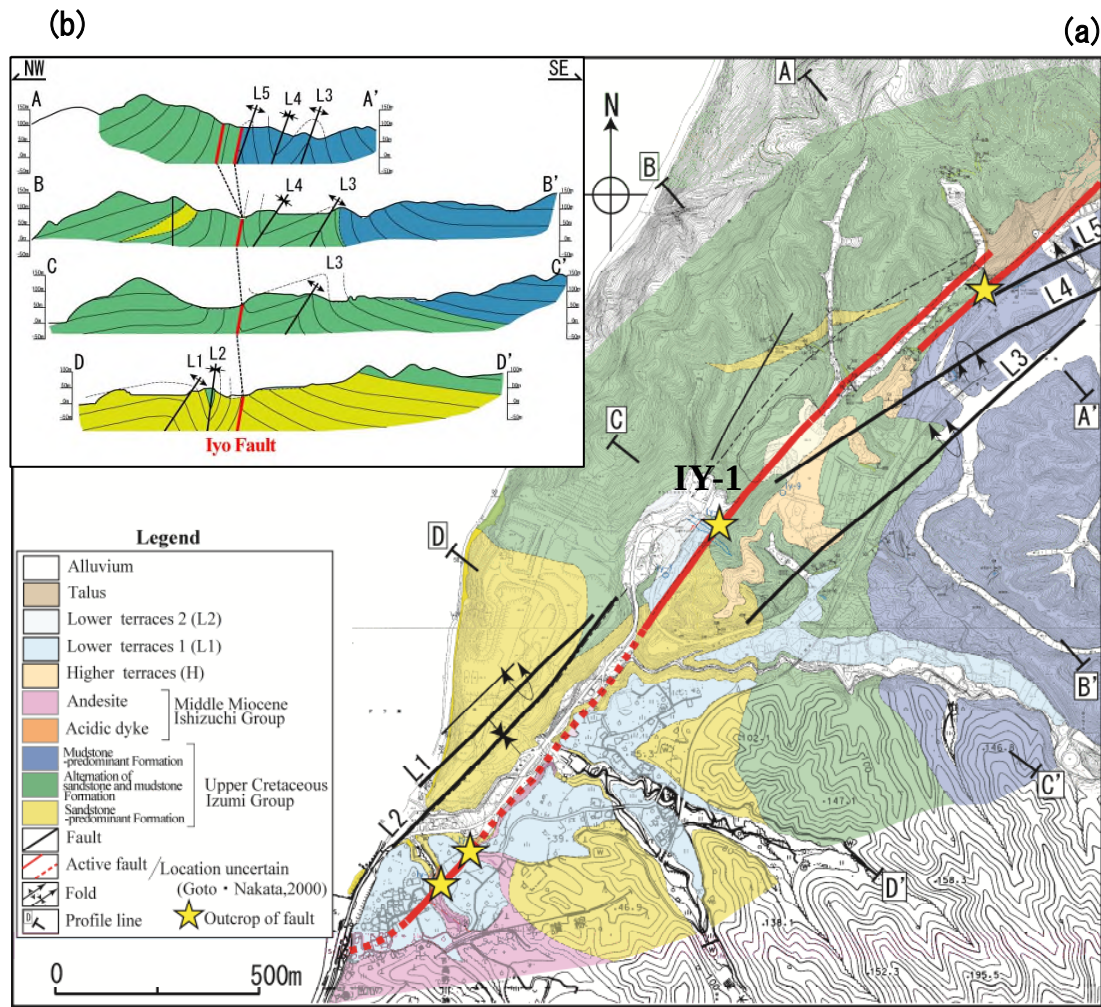


Figure 3. (a) Geological map and (b) cross section of the Iyo fault. See Figure 2 (a) for location of the map. (c) Geological route map to show lithofacies and geological structure of fault zone. See Figure 3 (a) for location of the route map. At Figure3 (a) and 3 (b), active fault trace is modified after [Goto and Nakata \[2000\]](#).

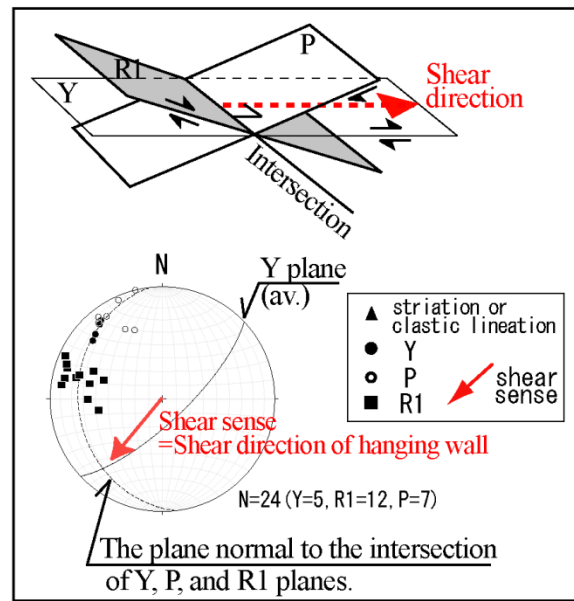
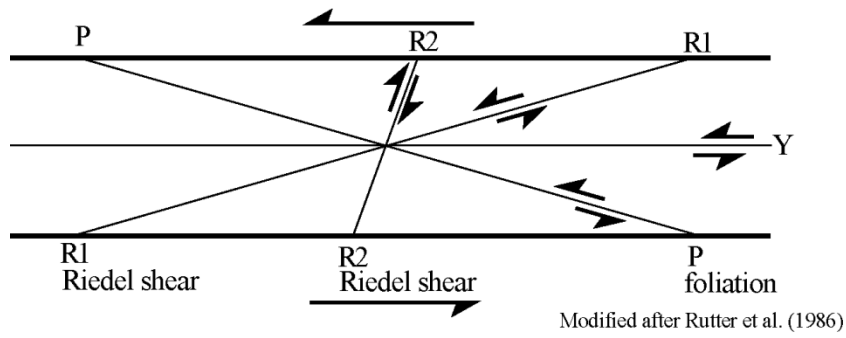


Figure 4. Stereographic projections (lower hemisphere) of foliation and lineation of the cataclasite and fault gouge. Small dots indicate measured poles of the composite planar fabrics (P-Y-R1 fabrics; [Rutter et al. \[1986\]](#), Y-shear plane (●), P-foliation (○), R1-shear plane (■)), orientations of striation or clastic lineation (▲), and N indicates the number of measurements. The fault planes and best fit great circle of P-Y-R1 fabrics attitude are indicated by solid and dashed great circles. Red arrows indicate shear sense of hanging wall based on aforementioned structure.

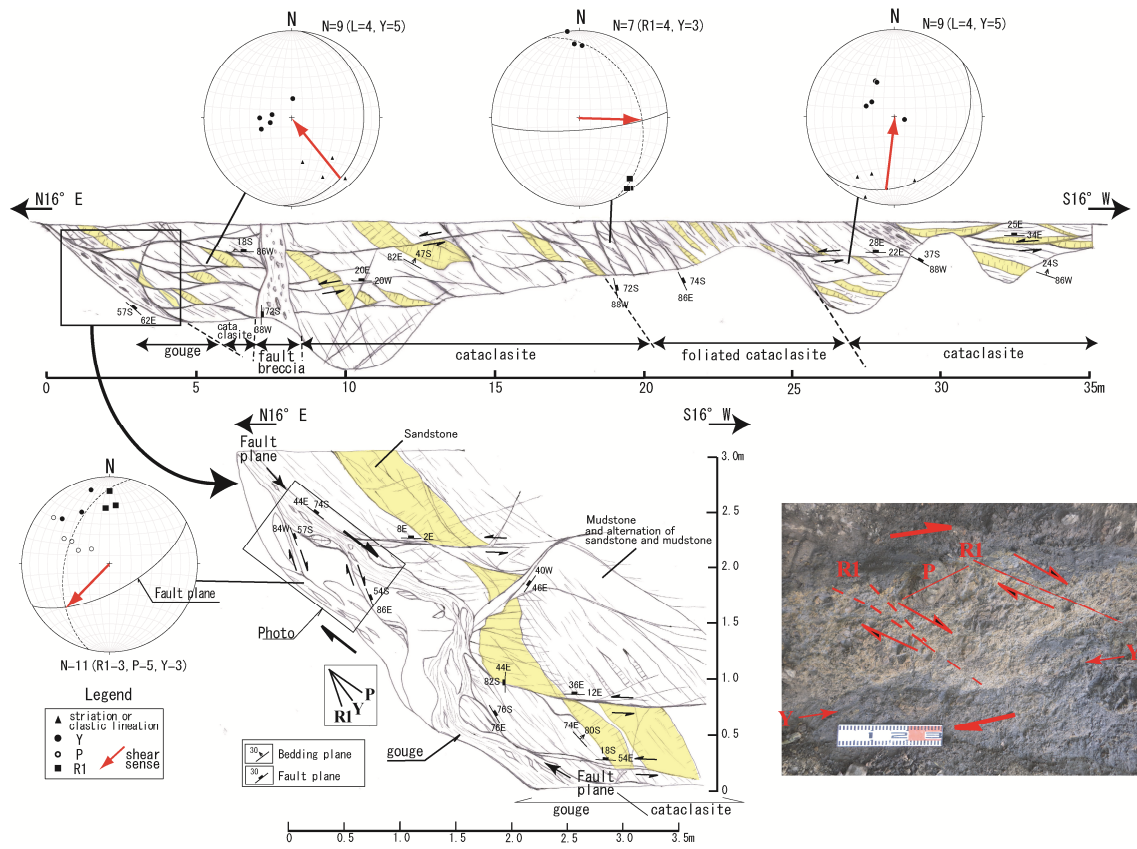


Figure 5. Pictures and sketch of outcrop of the Iyo fault at locality IY-2. See Figure 2 (a) for location of the Outcrop. Sketch of outcrop of cataclasite. Stereographic projection (lower hemisphere) of foliation and lineation of the cataclasite and fault gouge. See captions of Figure 4 for definition of the composite planar fabrics. The composite planar fabrics of the cataclasite zone shows sinistral and revers slip. In the fault gouge, dextral and normal slip can be inferred from the composite planar fabrics. The fault gouge is located on the active fault trace.

the fault (Figures 7a, 8).

F4 (Kawakami fault): The fault extends for 12 km in the Izumi Group in the NE–SW direction (Figure 2a). Fault zone consists of cataclasite and fault gouge, which is derived from sandstone and mudstone, where the width of fault zone is uncertain, because of it is for the most part covered by an alluvial bed. At the locality YY-1 (Figure 2a), the fault strikes N60 to 70°E and dips south at 80 to 90°, the fault zone of which consists of cataclasite with ~70 m wide and fault gouge with ~10 meter wide. The composite planar fabrics of the cataclasite and fault gouge could indicate sinistral and reverse sense of slip (Figures 9, 10). The fault gouge at the northern boundary of fault zone displaced a Quaternary conglomerate bed, and dextral and normal slip can be inferred from the composite planar fabrics in the fault gouge of a few meter wide (Figures 9, 10). The shear sense in fault gouge at the northern boundary accords with the recent movement of the MTL during the Quaternary period.

F5 (Okamoto fault): The fault extends for 35 km in the Izumi Group in the ENE–WSW direction. A fault zone consists of cataclasite and fault gouge, which is derived from sandstone and mudstone. At locality OK-1 (Figure 11a), the fault strikes N76°E and dips north at 80°, the fault zone of which consists of cataclasite with 30 m wide and fault gouge with one meter width (Figure 11c). The composite planar fabrics of the cataclasite zone and fault gouge show sinistral and reverse sense of slip (Figure 11c), while the fault gouge distributed at the southern boundary of fault zone shows dextral and normal slip (Figures 11c, 12). Since the fault gouge is located on the active fault trace (Figures 11a, 11c), it seems that the shear sense of fault gouge shows the recent movement of the MTL during the Quaternary period.

3.4. The overprinting deformation structure in fault zones along the MTL

The MTL is described about detail investigated outcrop, thin section and slab of fault samples, showing in the following. Oriented thin sections, cut perpendicular to the foliation (Z axis) and parallel to the lineation (X axis), corresponding to the XZ plane of finite strain, have been used for textural and microstructural studies of cataclasite and fault gouge.

At Locality MTL-1 (Figures 2a, 9), the MTL strikes N80°W and dips north at 35°, and is intruded by an

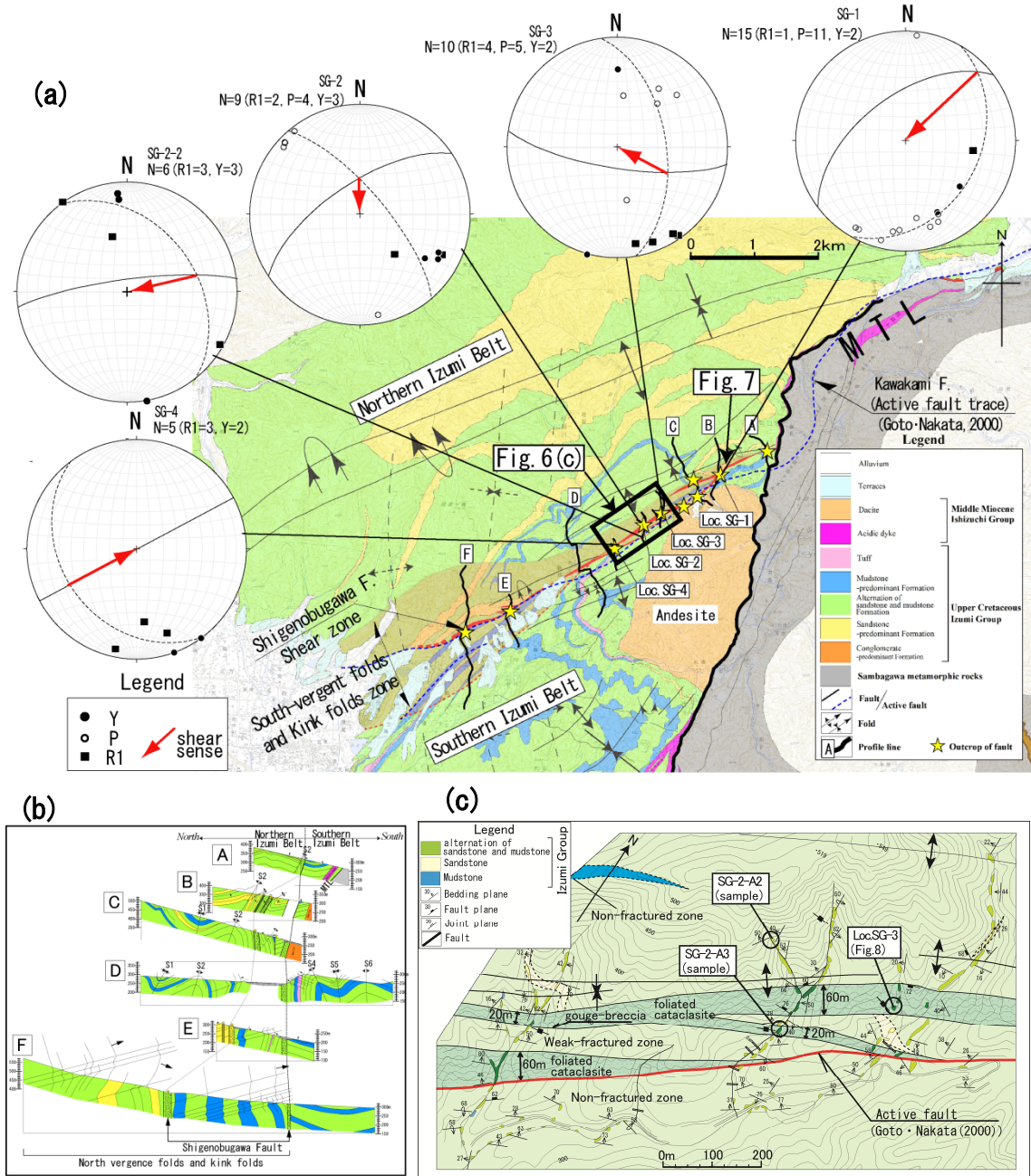


Figure 6. (a) Geological map and (b) cross section of the Shigenobugawa fault. See Figure 2 (a) for location of the map. Stereographic projection (lower hemisphere) of foliation and lineation of the cataclasite and fault gouge. See captions of Figure 4 for definition of the composite planar fabrics. (c) Geological route map to show lithofacies and geological structure of fault zone. See Figure 6 (a) for location of the route map. At Figure 6(a) and 6(c), active fault trace is modified after [Goto and Nakata \[2000\]](#).

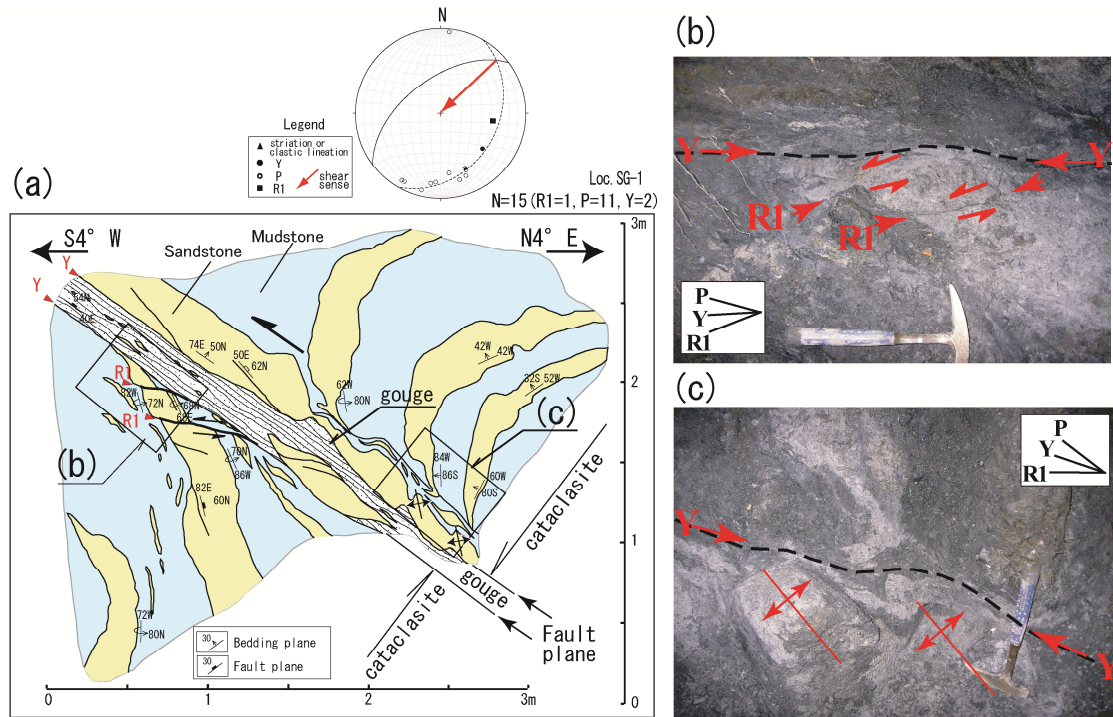


Figure 7. Pictures and sketch of outcrop of the Shigenobugawa fault at locality SG-1. See Figure 7 (a) for location of the Outcrop. (a) Picture and sketch of outcrop of cataclasite. Stereographic projection (lower hemisphere) of foliation and lineation of the cataclasite and fault gouge. See captions of Figure 4 for definition of the composite planar fabrics. Based on the composite planar fabrics, fault displacement sense indicate sinistral-reverse slip sense of top-to-the SW. (b) shear plane structure and (c) drag folds show sinistral-reverse slip sense.

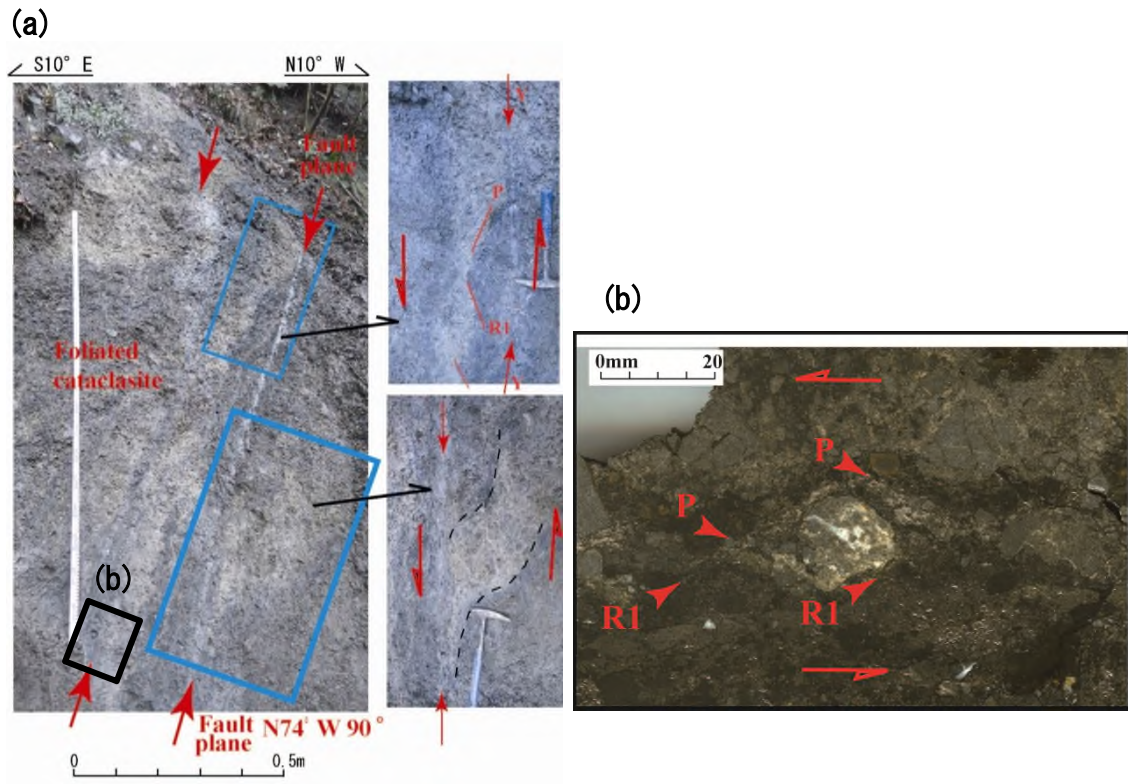


Figure 8. Pictures of outcrop and slab of the Shigenobugawa fault at locality SG-3. See Figure 7 (a) for location of the Outcrop. (a) Pictures of outcrop of cataclasite. Based on the composite planar fabrics, fault displacement sense indicate sinistral-reverse slip sense of top-to-the SW. (b) Picture of slab of cataclasite shows sinistral-reverse slip sense.

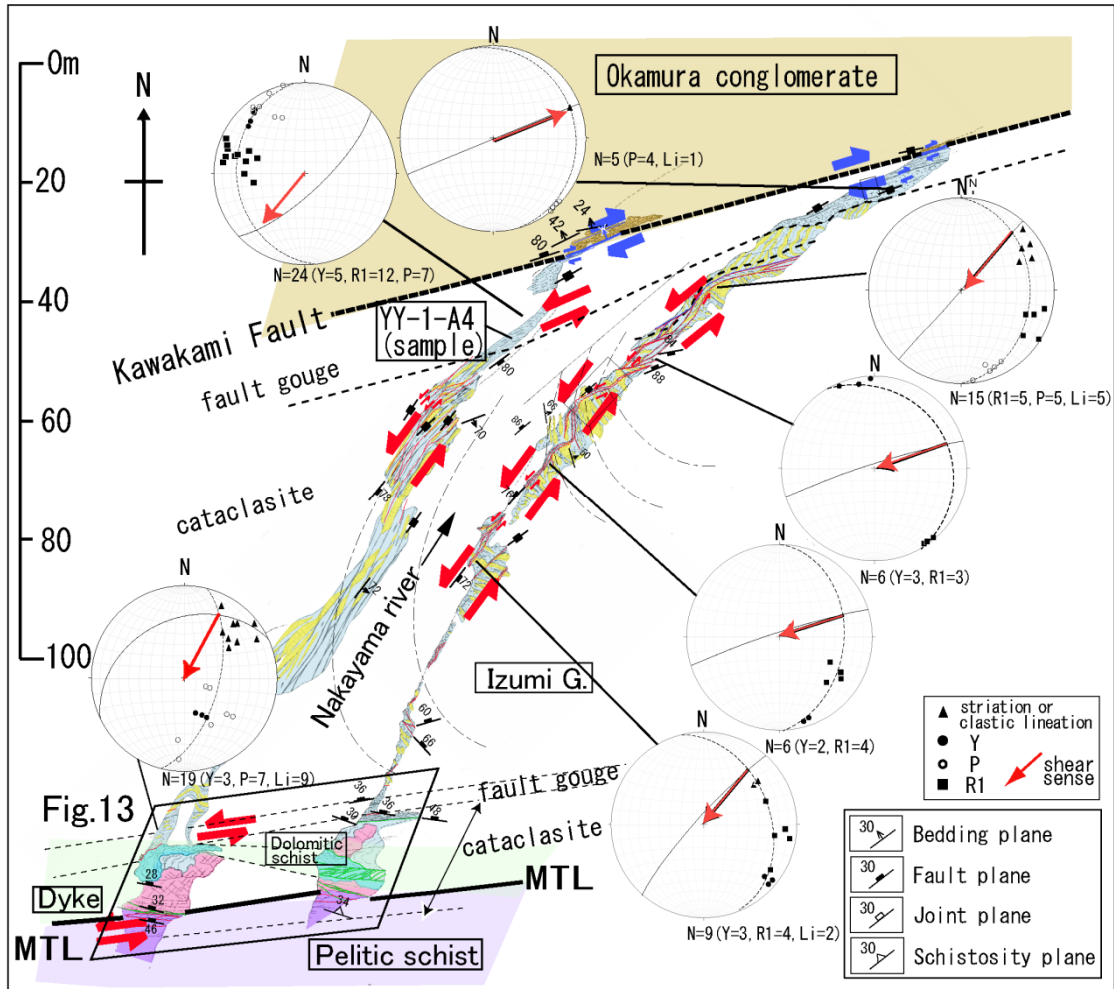


Figure 9. Sketch of outcrop of the Kawakami fault and MTL at locality YY-1. See Figure 2 (a) for location of the outcrop. Stereographic projections (lower hemisphere) of foliation and lineation of the cataclasite and fault gouge. See captions of Figure 4 for definition of the composite planar fabrics. Based on the composite planar fabrics, fault displacement sense indicate sinistral-reverse slip sense of top-to-the SW. The fault gouge in northern boundary of fault zone displaced Quaternary conglomerate bed and the composite planar fabrics of fault gouge with a few meter width from the fault boundary shows dextral normal slip.

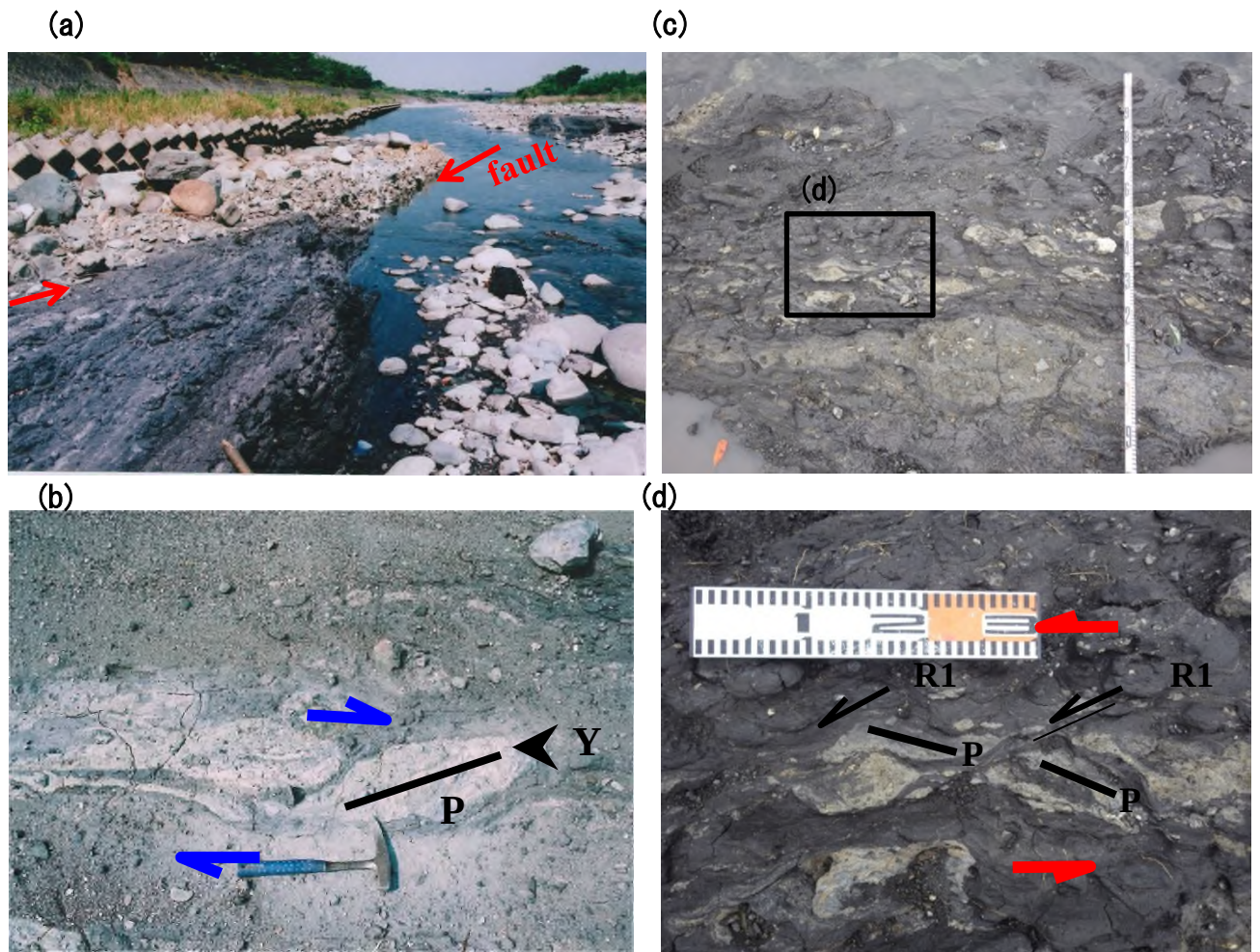


Figure 10. Pictures of outcrop of the Kawakami fault at locality YY-1. See Figure 9 for location of the Outcrop. (a) Picture of outcrop of Kawakami fault, which the cataclasite of sandstone and mudstone Izumi Group contacts the Quaternary conglomerate by fault. (b) Fault gouge with 3m from fault boundary shows dextral slip sense based on the composite planar fabrics. (c) and (d) fault gouge with 5m from fault boundary fault indicate sinistral-reverse slip sense of top-to-the SW.

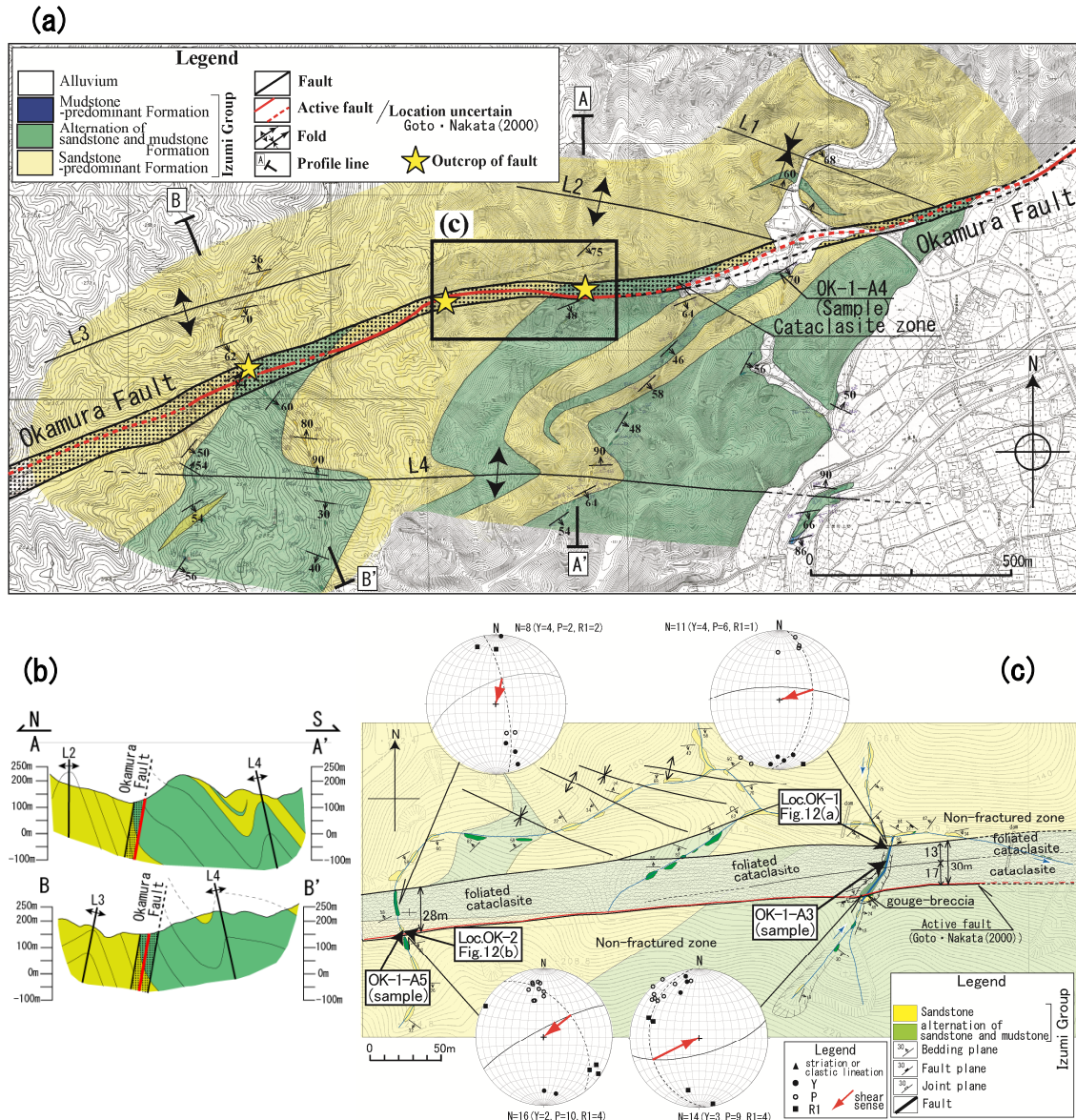


Figure 11. (a) Geological map and (b) cross section of the Okamura fault. See Figure 2 (a) for location of the map. (c) Geological route map to show lithofacies and geological structure of fault zone. See Figure 6 (a) for location of the route map. Active fault trace is modified after [Goto and Nakata \[2000\]](#). Stereographic projections (lower hemisphere) of foliation and lineation of the cataclasite and fault gouge. See captions of Figure 4 for definition of the composite planar fabrics. Based on the composite planar fabrics, fault displacement sense indicate sinistral-reverse slip sense of top-to-the SW.

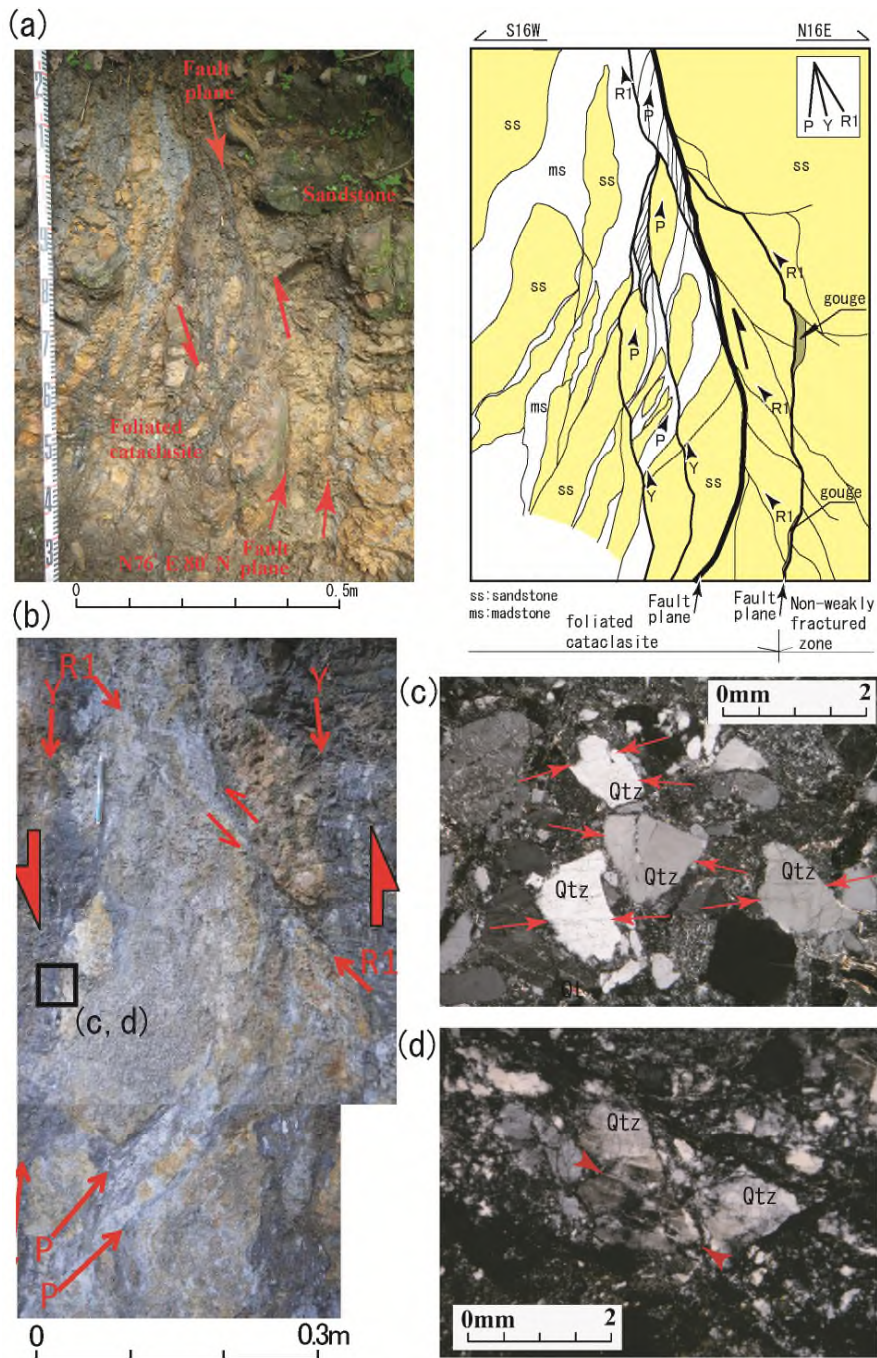


Figure 12. Picture and sketch of outcrop and thin section micrographs of the Okamura fault at locality OK-1 and OK-2. See Figure 11 (a) for location of the Outcrop. (a) Picture and sketch of outcrop of cataclasite at locality OK-1, (b) locality OK-2. Thin section micrograph under crossed nichols of cataclasite of (b) shows quartz distributed micro fractures (c), undulose extinction in quartz (d). Abbreviations: Qtz = Quartz

acidic dyke of 6 m wide. Here, the attitude of the MTL is obtained as average strike and dip of the boundary planes between the Sambagawa metamorphic rocks and the acidic dyke, and between the later and the Izumi Group. The fault zone consists of cataclasite with 70 m wide from the MTL in the Izumi Group, and cataclasite with 70 m wide from the MTL in the Sambagawa metamorphic rocks. It should be noted that the dolomitic schist, which originated from the Sambagawa pelitic and basic schist, occurs along the MTL (Figures 13, 14). A top-to-the-north sense of normal slip is inferred from the composite planar fabrics in the cataclasite zone consisting of dolomitic schist. Further, the cataclasite zone was folded with NW-SE axes (Figure 15). This superposed deformation structure could indicate that normal faulting was overprinted by sinistral and reverse faulting (Figure 15). Microstructures of slabs and thin sections from the cataclasite of dolomitic schist also show that shear planes formed by normal slip with a sense of top-to-the-north was overprinted by sinistral and reverse slip with a sense of top-to-the-SW (Figures 16 - 18). This structure is intruded by weakly fractured acidic dyke of Middle Miocene, therefore it formed before the Early Miocene. At Locality MTL-2 (Figures 2a, 19), The MTL strikes N88°W and dips north at 25°, and is intruded by an acidic dyke 5 m wide. Here the attitude of the MTL is obtained as average strike and dip of the boundary planes between the Sambagawa metamorphic rocks and the acidic dyke, and between the later and the Izumi Group. Microstructure of slabs and thin sections of the cataclasite of dolomitic schist show shear planes of normal slip sense of top to the north and sinistral-reverse slip sense of top to the SW, and latter formed after the former (Figure 21). The former structure is intruded by acidic dyke weakly fractured of Middle Miocene, therefore it has formed before Early Miocene. Based on the observation of thin sections of the cataclastic dolomitic schist, fine actinolite grains densely recrystallized aligned along the shear bands with a normal slip sense, and later these shear bands are deformed to form kink bands and fractures showing sinistral-reverse slip sense (Figure 22). At Locality MTL-3 (Figures 2a, 23), The MTL strikes N69°E and dips north at 32°, a 6-m-thick sheared zone of the Izumi Group, consisting of fault breccia and gouge occurs. The Early Miocene Kuma Group unconformably overlies the Sambagawa metamorphic rocks, and is apparently thrust by the Izumi Group bounded by the MTL. However, the fault probably indicates the thrusting of a sliver (only 50 cm thick at MTL-3) of the dolomitic schist from the Sambagawa metamorphic rocks over the Kuma

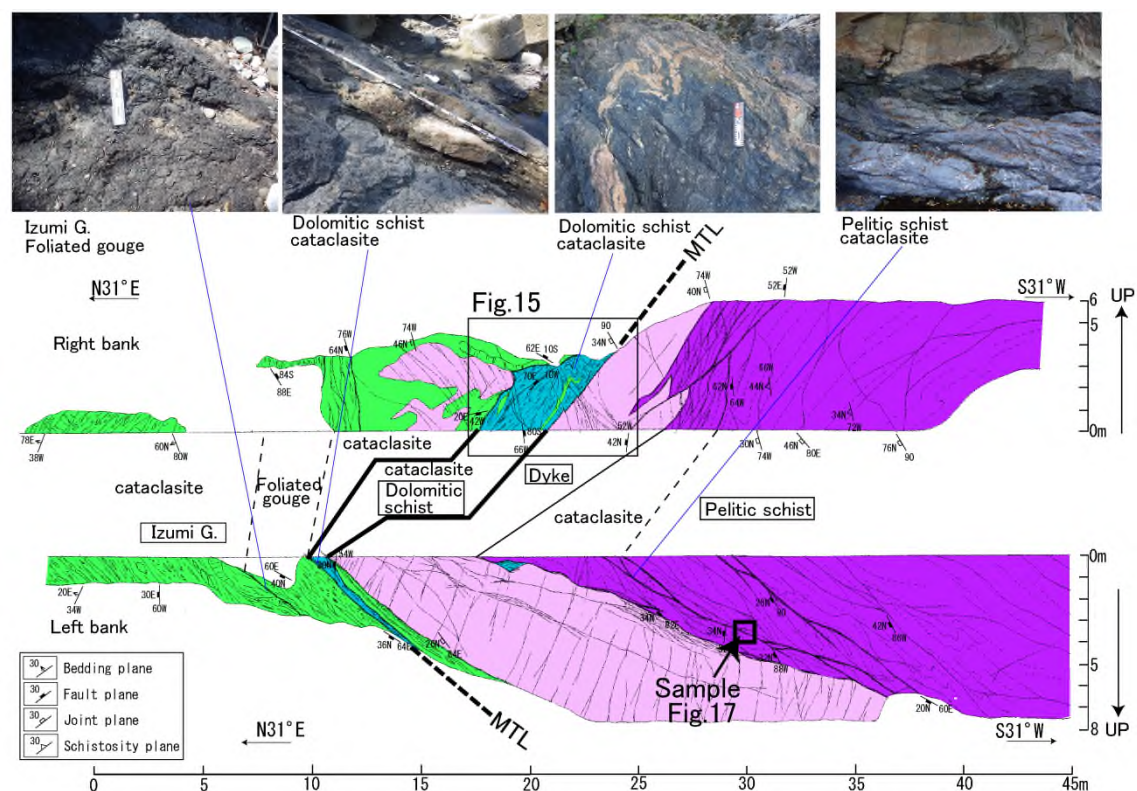


Figure 13. Pictures and sketch of outcrop of the MTL at locality MTL-1. See Figure 2 (a) for location of the Outcrop. The MTL strikes N88°W and dips north at 25°, and is intruded by an acidic dyke 5 m wide. Here the attitude of the MTL is obtained as average strike and dip of the boundary planes between the Sambagawa metamorphic rocks and the acidic dyke, and between the later and the Izumi Group. The cataclasited dolomitic schist distributes between the Izumi Group and Sambagawa metamorphic rocks, and intruded by an acidic dyke.

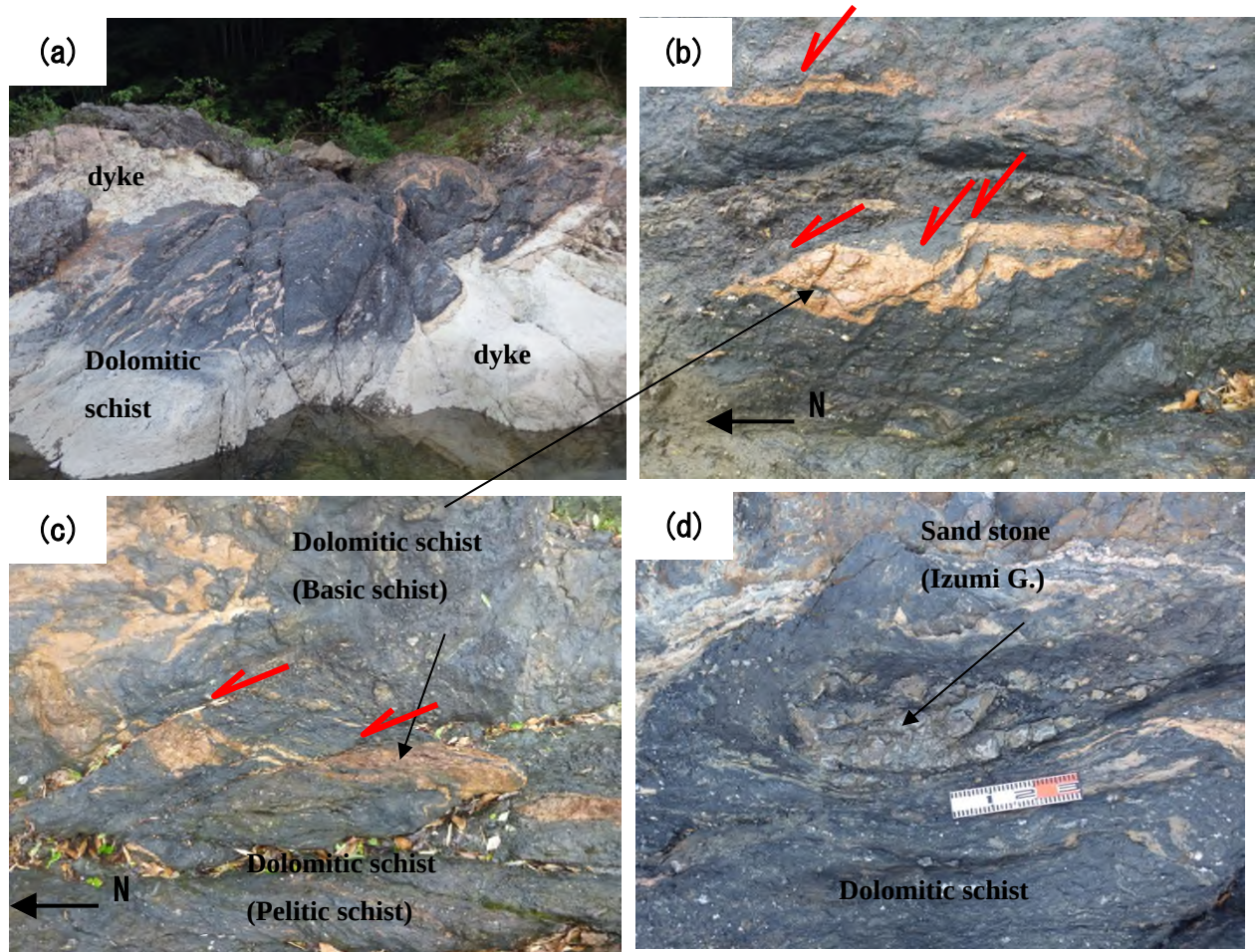


Figure 14. Pictures of outcrop of the MTL at locality MTL-1. (a) The dolomitic schist is distributed between the Izumi Group and Sambagawa metamorphic rocks, and intruded by an acidic dyke. It had deformed and altered from pelitic and basic schist of the Sambagawa metamorphic rocks. (b) and (c) The cataclasite zone of dolomitic schist based on the composite planar fabrics shows normal slip sense of top to the north. (d) The cataclasite of the dolomitic schist contains of the sandstone clast of the Izumi Group. It shows that the cataclasite zone had formed during contacting the Izumi group.

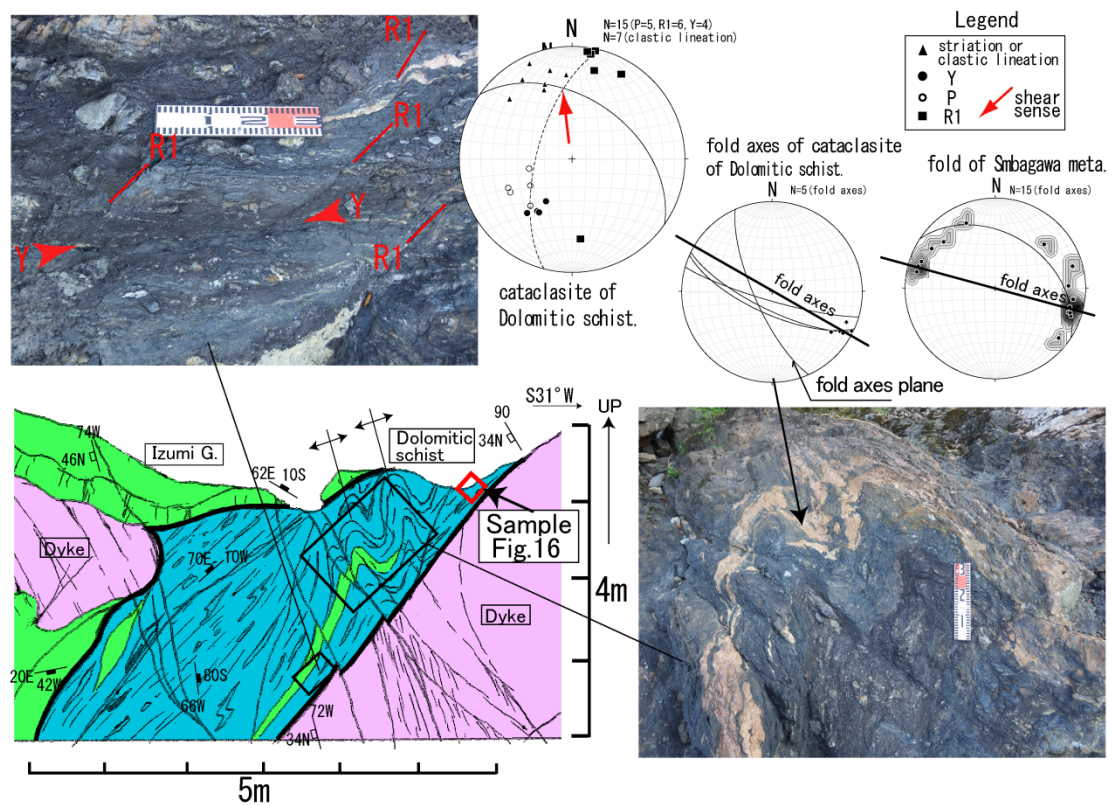


Figure 15. Pictures and sketch of outcrop of the MTL at locality MTL-1. See Figure 8 for location of the Outcrop. Stereographic projection (lower hemisphere) of foliation and lineation of the cataclasite. See captions of Figure 4 for definition of the composite planar fabrics. The cataclasite zone of dolomitic schist shows shear planes of normal slip sense of top to the north, and which has been folded with NW-SE axes. This overlapped deformation structure show sinistral-reverse faulting after normal faulting.

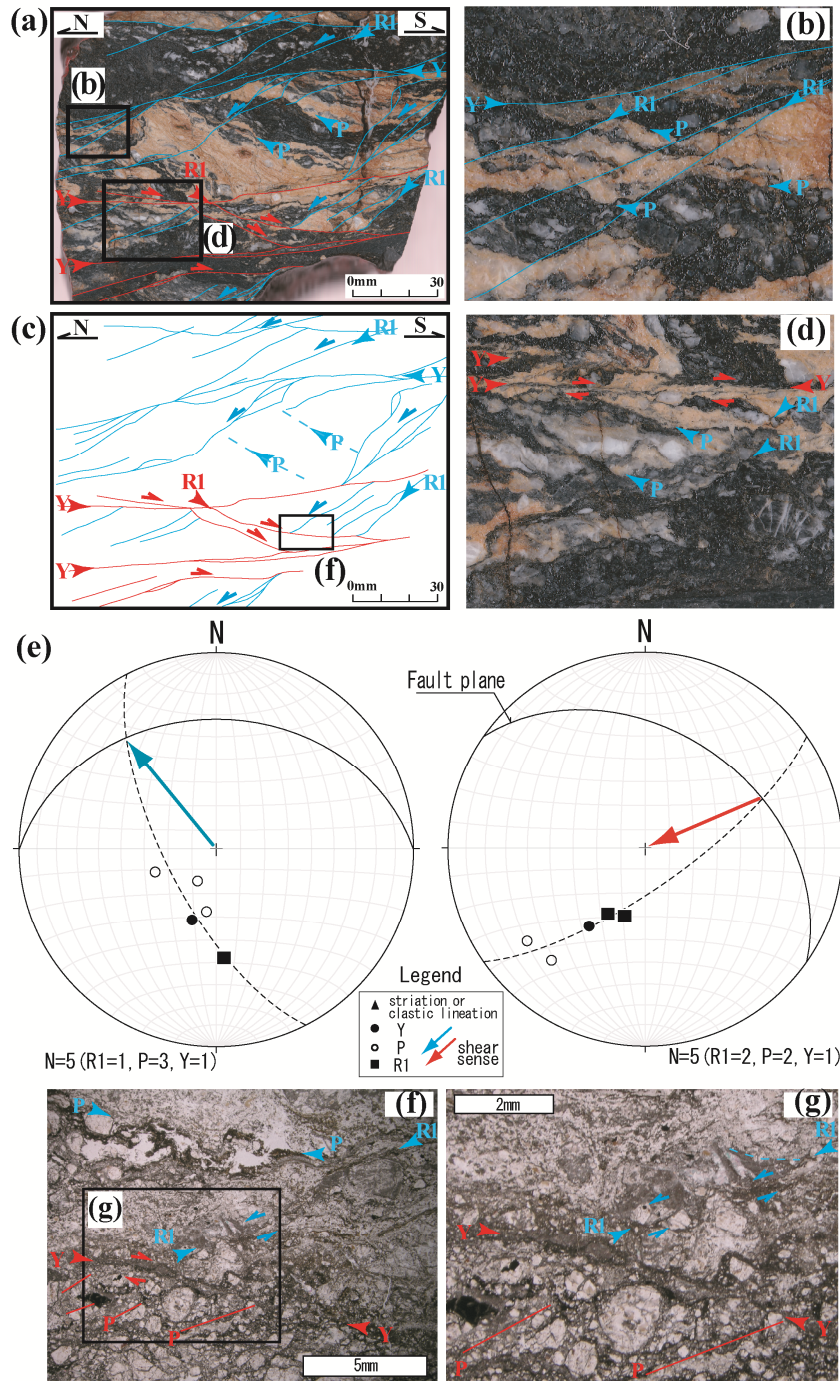


Figure 16. Pictures of slabs and thin section micrographs of the cataclasite of dolomitic schist at locality MTL-1. See Figure 15 for location of the samples. (a) to (d) Picture of slabs show shear planes of normal slip sense of top to the north (blue lines, allows and letters) and sinistral-reverse slip sense of top to the SW (red lines, allows and letters), and latter formed after the former. (e) Stereographic projection (lower hemisphere) of foliation and lineation measured for the slabs. See captions of Figure 4 for definition of the composite planar fabrics. (f) to (g) Pictures of thin section micrographs under crossed nichols show shear planes of normal slip sense displaced by shear planes of sinistral-reverse slip sense.

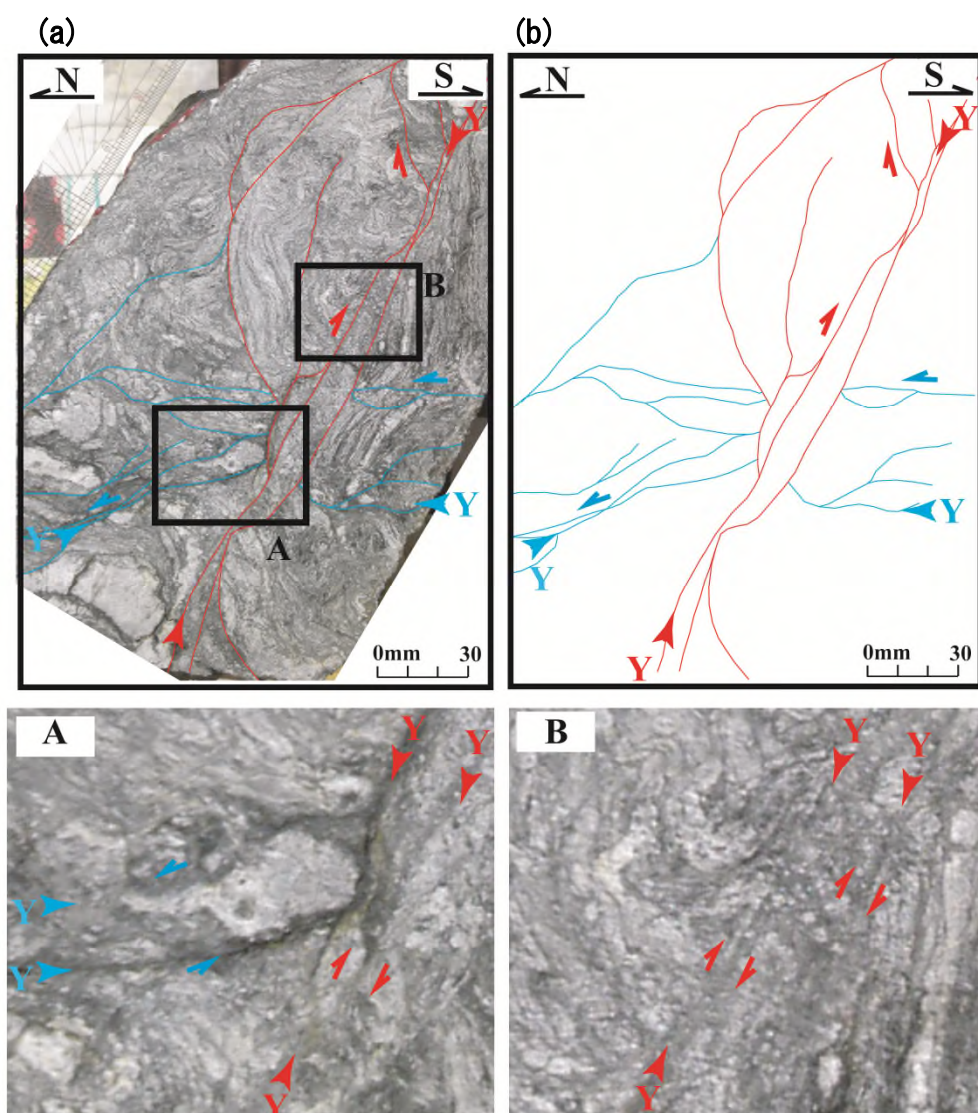


Figure 17. Pictures of slabs of the cataclasite of pelitic schist at locality MTL-1. See Figure 13 for location of the samples. (a), A, and B Picture and (b) sketch of slab shows shear planes of normal slip sense of top to the north (blue lines, allows and letters) and sinistral-reverse slip sense of top to the SW (red lines, allows and letters), and latter formed after the former. See captions of Figure 6 for definition of the composite planar fabrics.

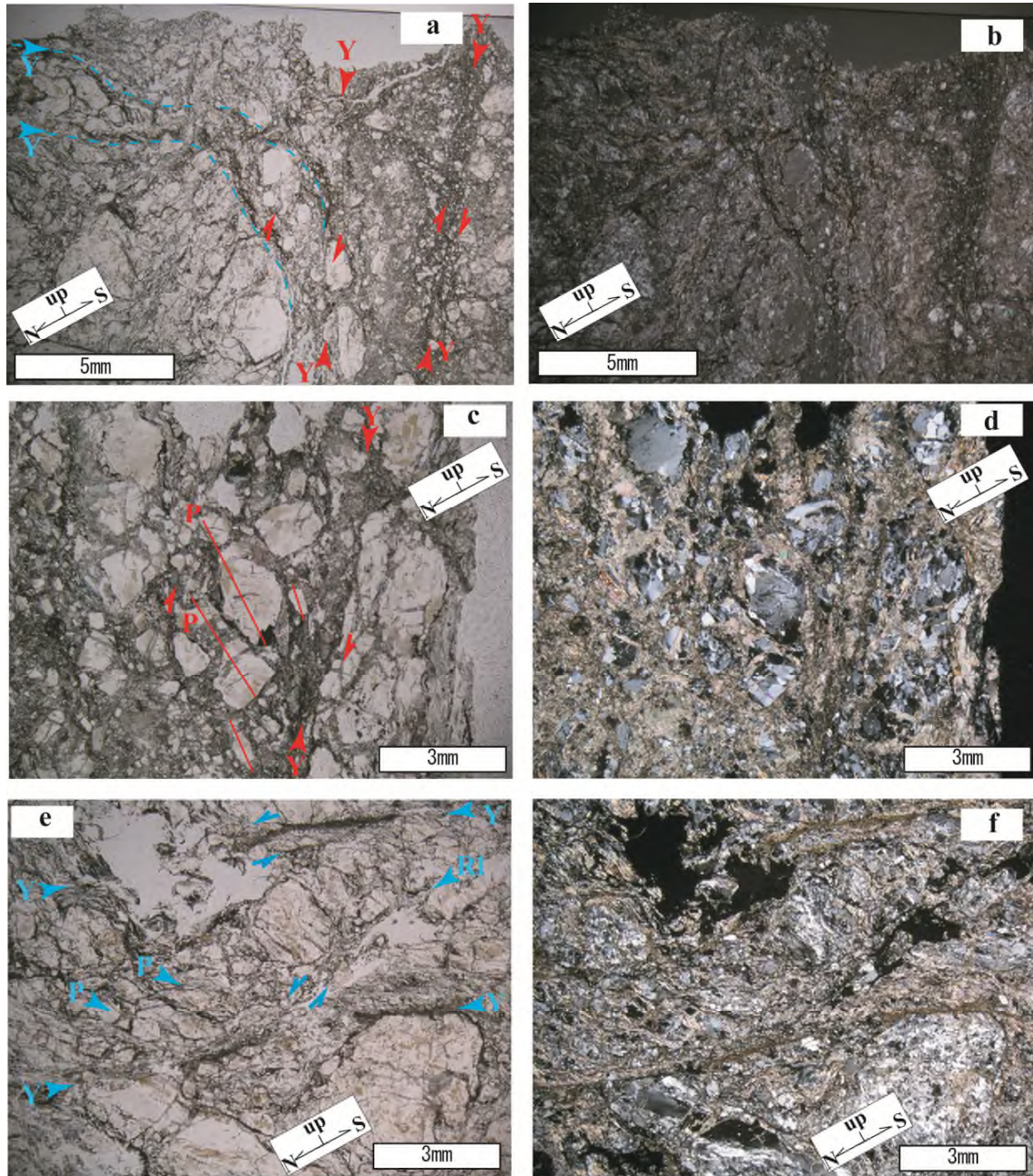


Figure 18. Thin section micrographs of the cataclasite samples of Fig. 17. (a) to (d) Picture of slabs show shear planes of normal slip sense of top to the north (blue lines, allows and letters) and sinistral-reverse slip sense of top to the SW (red lines, allows and letters), and latter formed after the former. See captions of Figure 6 for definition of the composite planar fabrics. (a), (b), and (c) Pictures of thin section micrographs under opened nichols, (b), (d), and (f) under crossed nichols, show shear planes of normal slip sense displaced by shear planes of sinistral-reverse slip sense.

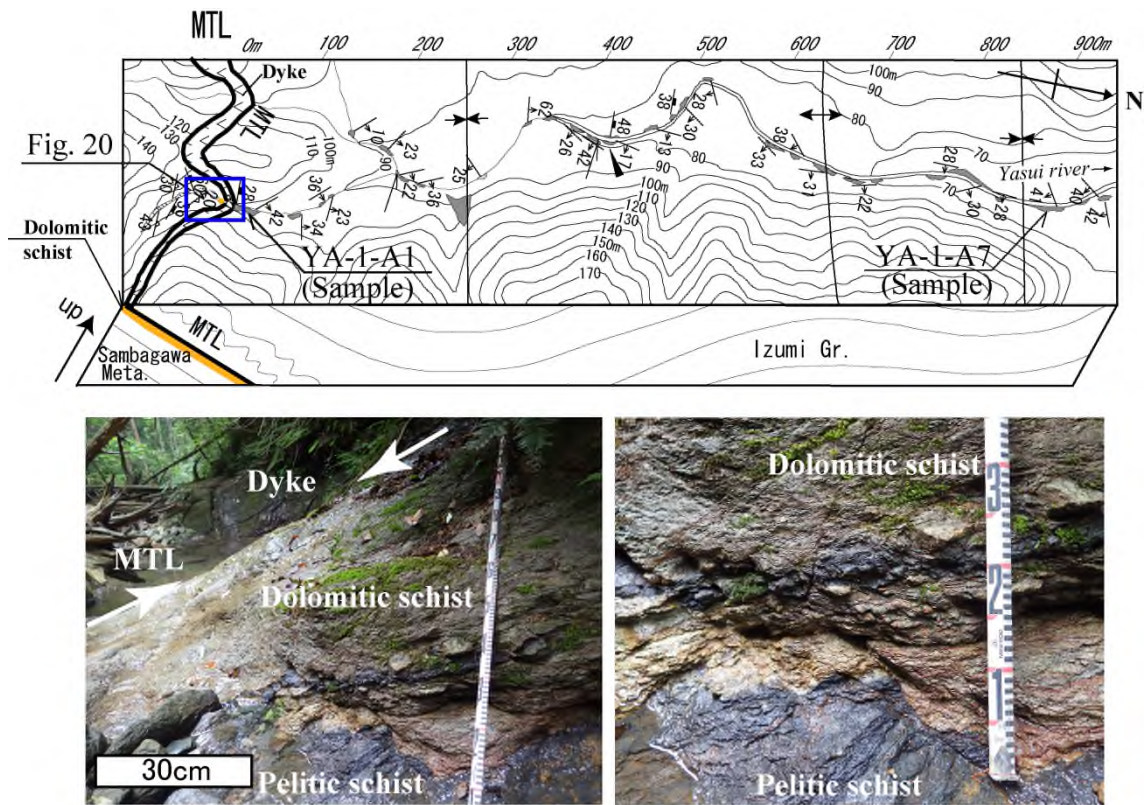


Figure 19. Route map and Pictures of outcrop of the MTL at locality MTL-2. Route map is modified after [Kubota and Takeshita \[2008\]](#). See Figure 2 (a) for location of the Outcrop. The MTL strikes $N88^{\circ}W$ and dips north at 25° , and is intruded by an acidic dyke 5 m wide. Here the attitude of the MTL is obtained as average strike and dip of the boundary planes between the Sambagawa metamorphic rocks and the acidic dyke, and between the later and the Izumi Group. The cataclasited dolomitic schist distributes between the acidic dyke and the pelitic schist of Sambagawa metamorphic rocks, and intruded by an acidic dyke.

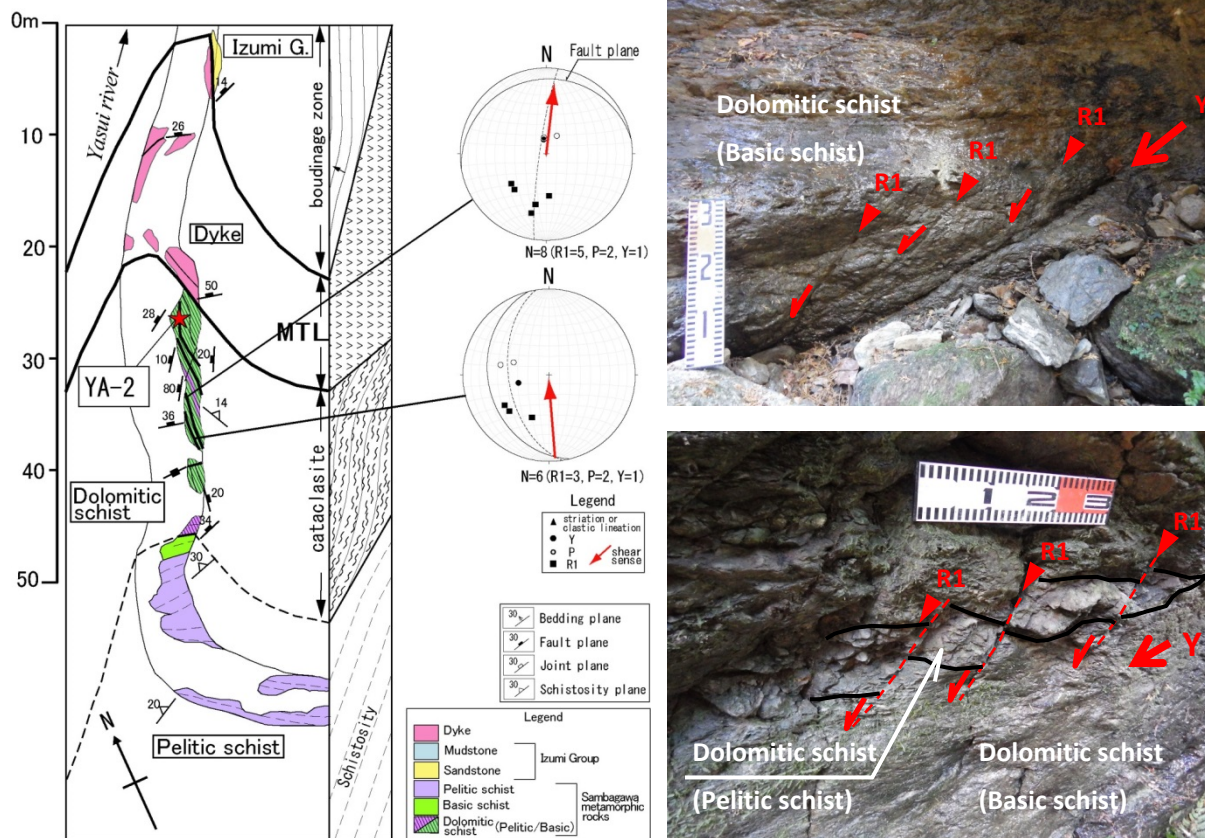


Figure 20. Route map and Pictures of outcrop of the MTL at locality MTL-2. See Figure 19 for location of the Outcrop. The cataclasited dolomitic schist had deformed and altered from pelitic and basic schist of the Sambagawa metamorphic rocks, and shear bands distribute densely. Stereographic projections (lower hemisphere) of foliation and lineation of the cataclasite and fault gouge. See captions of Figure 4 for definition of the composite planar fabrics. Based on the composite planar fabrics, fault displacement sense indicate normal slip sense of top-to-the North.

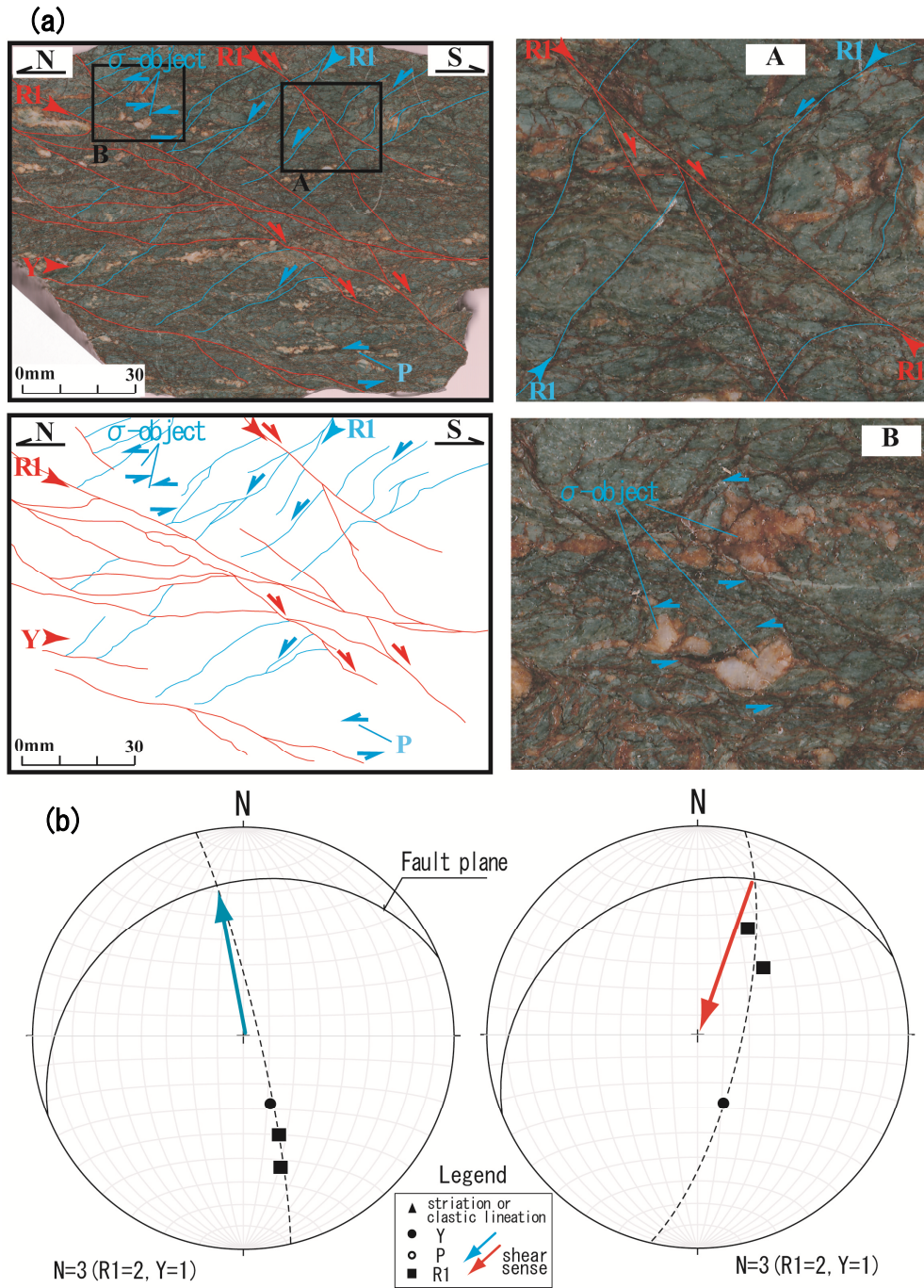


Figure 21. Pictures of slabs of the cataclasite of dolomitic schist at locality MTL-2. See Figure 20 for location of the samples at YA-2. (a) Picture of slabs show shear planes of normal slip sense of top to the north (blue lines, allows and letters) and sinistral-reverse slip sense of top to the SW (red lines, allows and letters), and latter formed after the former. (b) Stereographic projection (lower hemisphere) of foliation and lineation measured for the slabs. See captions of Figure 4 for definition of the composite planar fabrics. Pictures of slabs show shear planes of normal slip sense displaced by shear planes of sinistral-reverse slip sense.

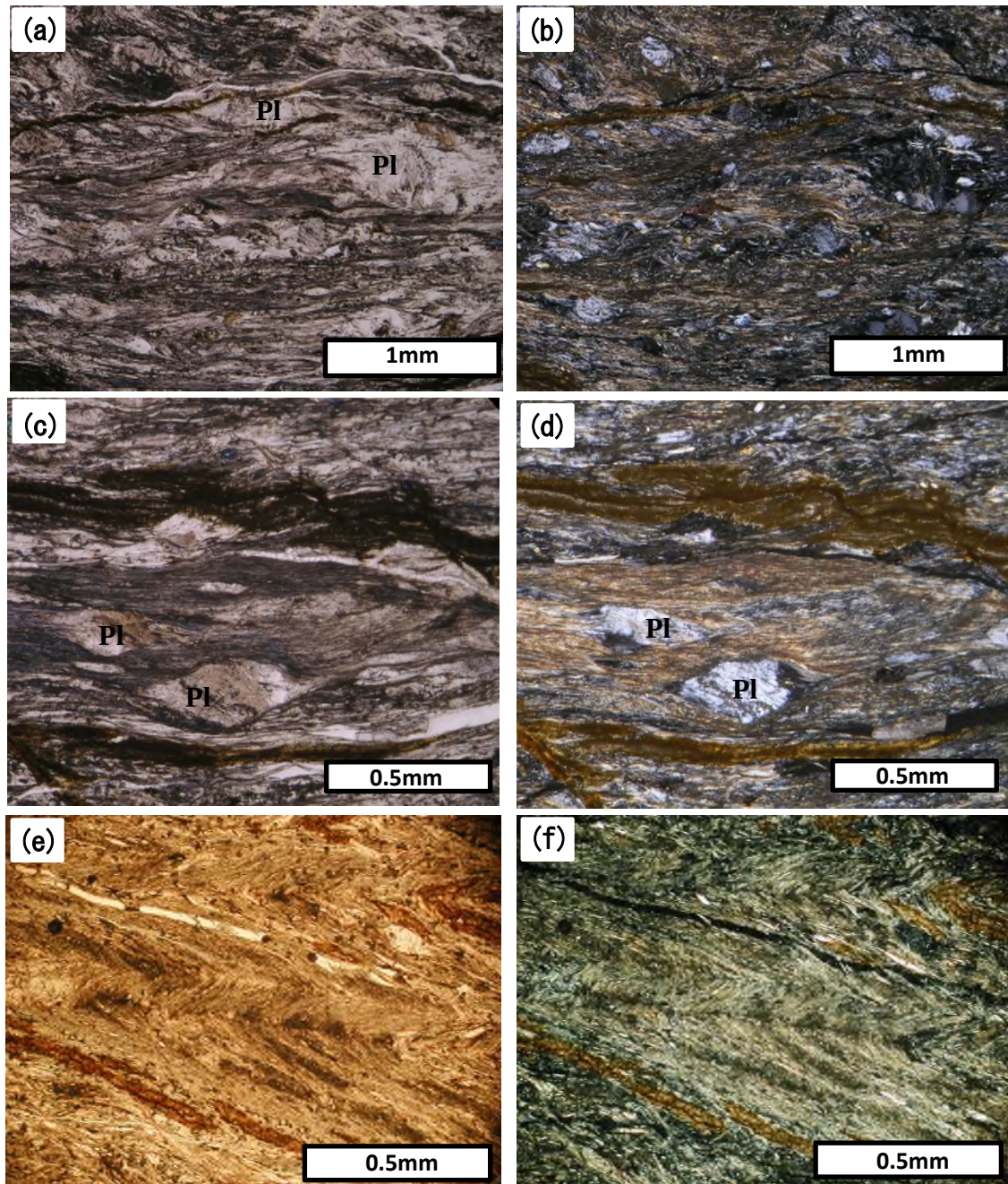


Figure 22. Thin section micrographs of the cataclasite samples of Fig. 21. (a) to (d) The dolomitic schist distributes intense shear bands, and consists of fine actinolite abundantly. (e) and (f) kink band. (a), (c), and (e) Pictures of thin section micrographs under opened nichols, (b), (d), and (f) under crossed Nichols. Abbreviations: Qtz = Quartz; Pl = Plagioclase; Ac = Actinolite

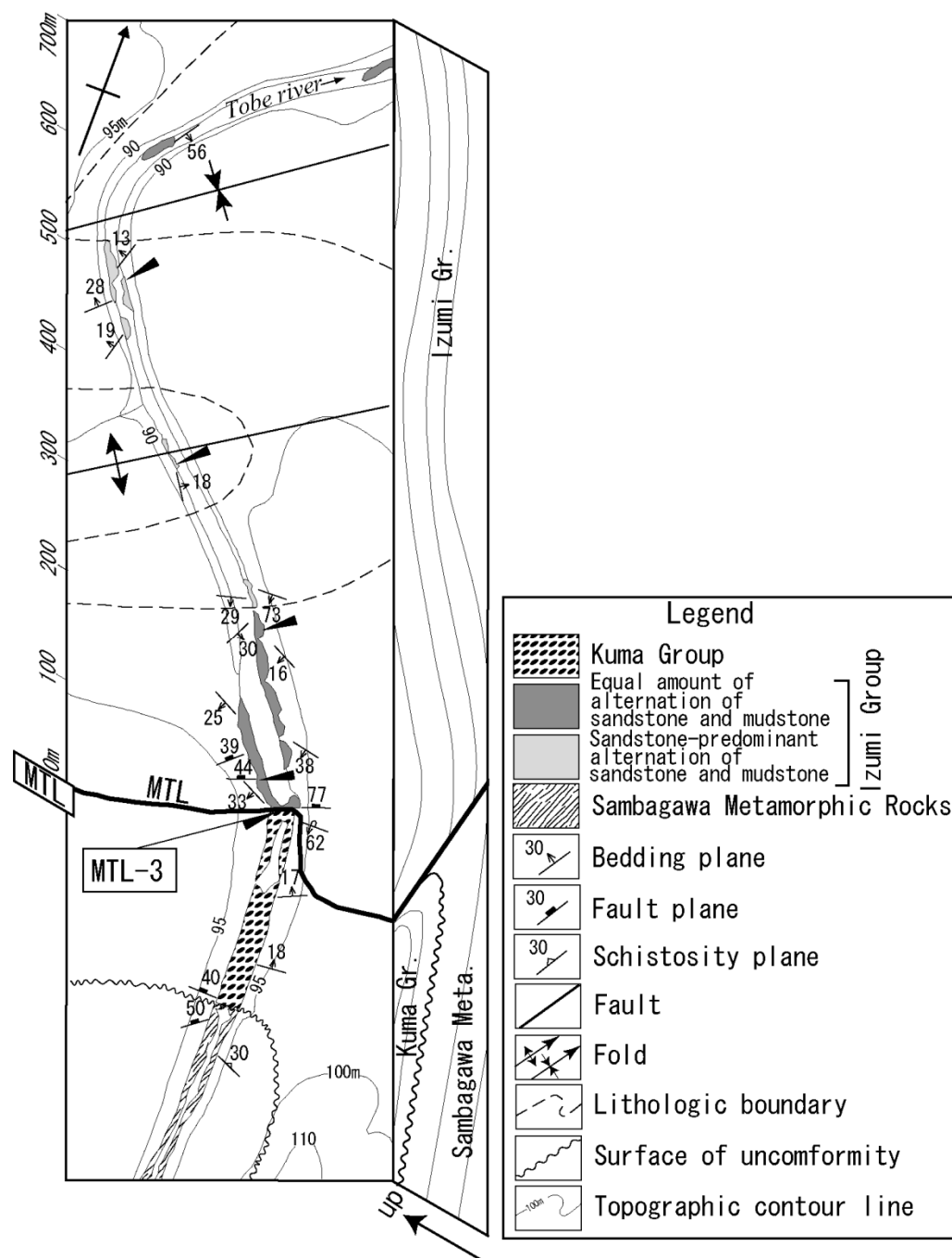


Fig. 23 Route map of the MTL at locality MTL-3. See Figure 2 (a) for location of the Outcrop. It shows lithofacies, geological structures around the MTL, modified after [Kubota and Takeshita \[2008\]](#). The cross-section is also shown in the right column.

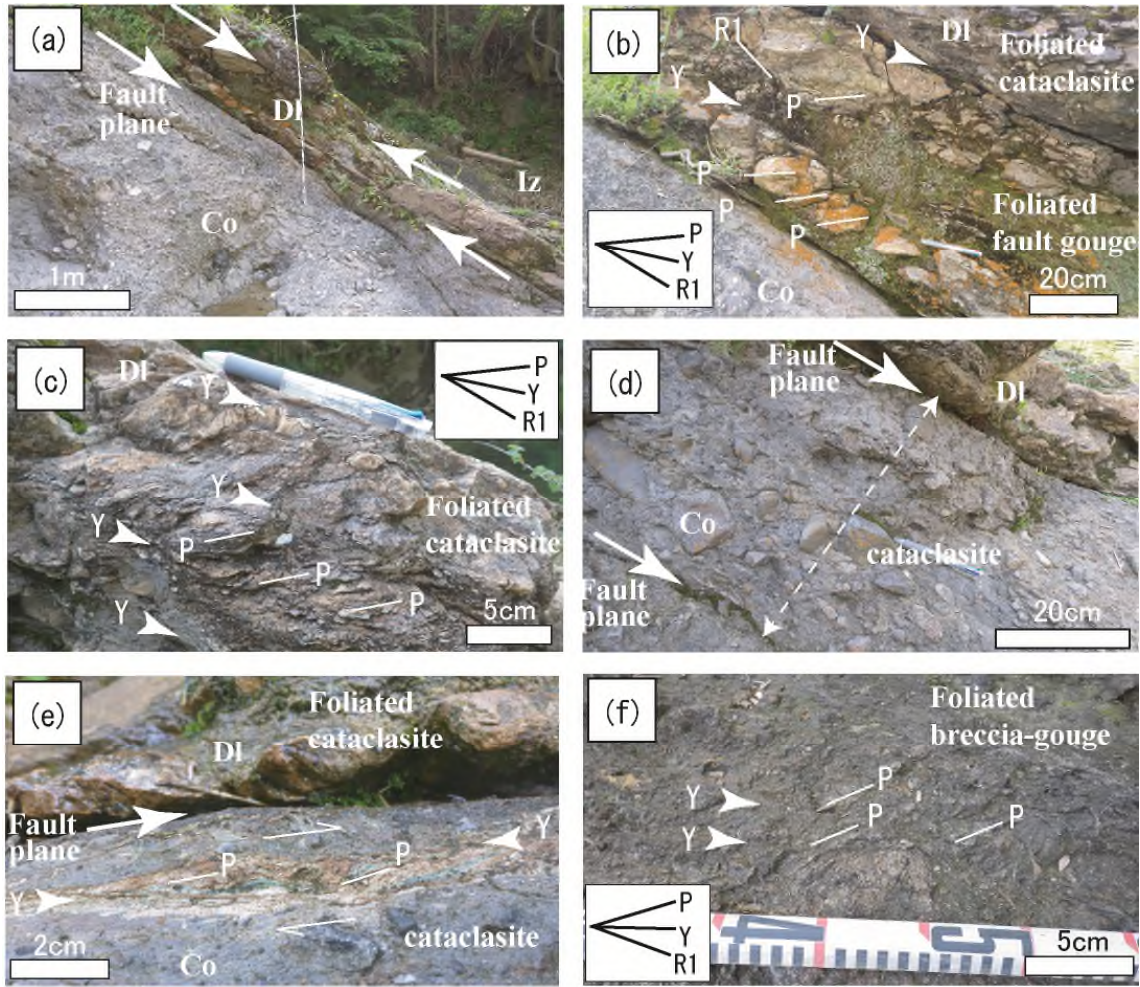


Fig. 24 Pictures of outcrop of the MTL at locality MTL-3. (a) (b) Fault zone composed dolomitic schist with foliated cataclasite and foliated gouge layers. Note that the striations developed on the fault plane plunge dip-slip. (c) Foliated cataclasite layers (d) Cataclasite of conglomerate of the Kuma Group. (e) Shear lens of dolomitic schist at cataclasite layer of conglomerate of the Kuma Group at the outcrop of right bank. (f) Foliated fault gouge-breccia of dolomitic schist at boundary of the Izumi Group. See captions of Figure 6 for definition of the composite planar fabrics.

Abbreviations: Dl = dolomitic schist, Co = conglomerate of the Kuma Group, Iz = Izumi Group

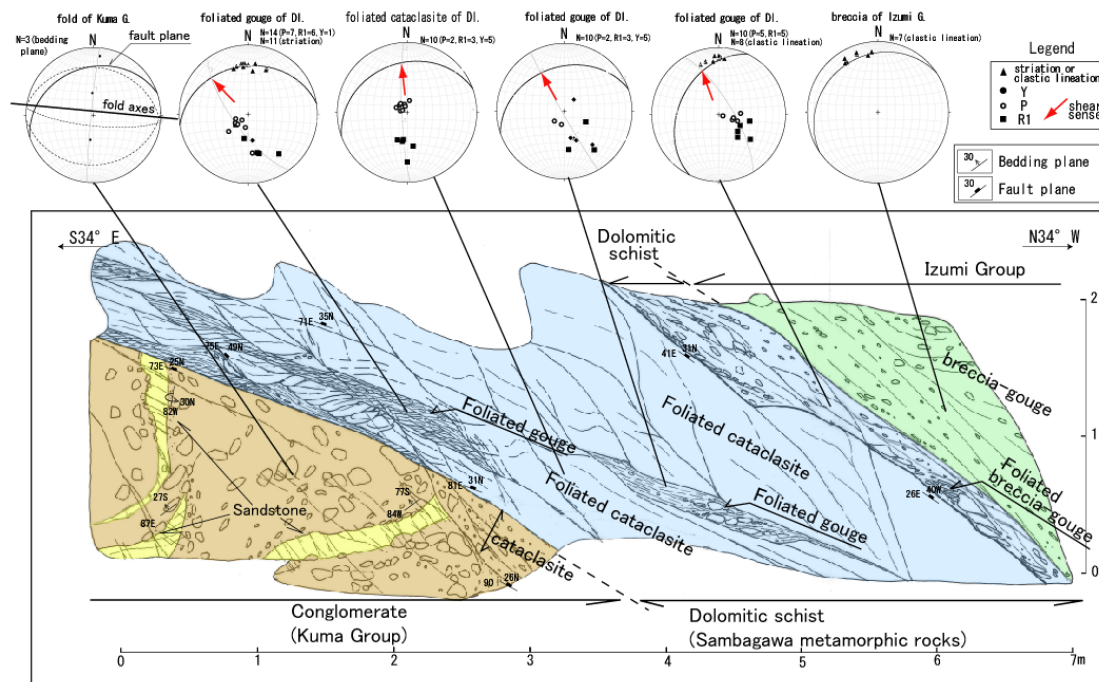


Fig. 25 The sketched outcrop of the MTL-3 at left bank. Note that the deformation of the dolomitic schist, is complex, which consist of foliated cataclasite and foliated gouge. In contrast, conglomerate of Kuma Group is distributed the drag fold of south-vergent with east–west-trending axis and cataclasite along the fault plane. Stereographic projection (lower hemisphere) of foliation and lineation of the cataclasite. See captions of Figure 4 for definition of the composite planar fabrics. Based on the composite planar fabrics, fault displacement sense indicate normal slip sense of top-to-the North.

Group as mentioned earlier, which is sandwiched between the Izumi Group and the Kuma Group [Kubota and Takeshita, 2008]. The cataclasite zone of dolomitic schist based on the composite planar fabrics shows normal slip sense of top to the north (Figures 24, 25).

4. K-Ar geochronology

4.1. Analytical method

4.1.1. Sample Preparation

Eight samples have been analyzed for K-Ar geochronology. Five samples were taken from foliated fault gouge layers in the fault core (Figures 3, 5, 6), which are named as SG-2-A3 from Shigenobugawa fault (Figure 6c), YY-1-A4 from Kawakami fault (Figure 9), OK-1-A3 and OK-1-A5 from F5 Okamura fault (Figure 11c), YA-1-A1 from the MTL (Figure 19). Other three samples were taken from non-fractured host rocks at about 100 to 500 m apart from the fault zones (Figures 3, 6), which are named as SG-2-A2 from Shigenobugawa fault (Figure 6c), OK-1-A4 from Okamura fault (Figure 11a), and YA-1-A7 from the MTL (Figure 19). Approximately 500 to 700 g of each sample of fresh gouges and host rocks was taken from the outcrops. Samples were taken from the part below the surface to avoid potential contamination from the surface materials. Then, they are washed in deionized water with an ultrasonic washing machine several times in order to remove organic materials. After drying at low temperature (40°C), samples from the host rocks were crushed by hammer, and fractions finer than 48 mesh were collected. The <2µm grain size fraction was separated by means of elutriation in deionized water, which were further divided into the grain size fractions of 0.2-0.4µm, 0.4-1.0µm, 1.0-2.0µm using a high-speed centrifuge machine. These samples were then characterized by X-ray Diffraction (XRD) (air dried, ethylene glycolated), Scanning Electron Microscopy (SEM), and dated by conventional K-Ar dating.

4.1.2. Petrography

Description of textural and chemical characteristic of fault gouge and foliated cataclasites was conducted by scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS). The SEM-EDS

analysis was carried out using a SEM (JSM-5310) and EDS system (Oxford-7068) operating at a 10 Pascal vacuum condition in the backscattered electron (BSE) mode with 20 kV installed at Hokkaido university. Polished thin sections of fault gouge and foliated cataclasite samples were prepared by placing one drop of clay solution on a micro carbon grid film and drying under air. The chemical composition of individual particles was investigated by an attached EDS system.

4.1.3. XRD and polytype quantification

The mineralogy of the different size fractions was determined by X-ray Diffraction (XRD) analysis of air dried and ethylene glycolated (EG) samples. XRD analysis of each fraction was carried out using a Mac science MX-Labo at Hokkaido University under conditions of CuK α radiation and 40 KV/20 mA. Step mode is 1 s for 0.02° (2 θ) step and 2 θ range (2-45°). Data processing (profile smoothing and background subtraction) was performed using Jade-06 software. The half-height width (2 θ) of the first-order basal reflection of the illites at 10 Å was measured from the XRD patterns as representing the illite crystallinity index or kubler index [Kubler, 1984].

The method of illite-polytype quantification compares experimental XRD patterns with calculated patterns modeled using WILDFIRE© [Reynolds, 1994]. The experimental XRD patterns of the randomly oriented samples for all size fractions were used to determine the relative abundance of the illite polytype in each size fraction, which is simulated with the proper XRD pattern of the illite polytype using WILDFIRE©. Illite is a major component of authigenic and detrital minerals in sedimentary rocks. The 2M₁-illite is detrital in origin and the 1M_d and 1M polytypes are commonly authigenic in shales [Bailey, 1966], moreover Grathoff and Moore [1996] show that these are mainly polytypes. The 1M_d and 1M polytypes neocrystallize at low temperature less than 180°C, which forms during brittle faulting in the shallow crust [Grathoff et al., 2001; Vrolijk and van der Pluijm, 1999]. On the other hand, Zwingmann et. al. [2010] shows possible presence of authigenic 2M₁-illite in fault gouge, thus discuss the necessity to compare it with the one in host rocks. Therefore, in this study we determined authigenic and detrital illite polytypes by comparing fault gouge with host rocks for the illite polytypes, moreover determine the relative abundance of the illite polytype in each

size fraction.

4.1.4. K-Ar dating

K-Ar dating was conducted by measuring the total potassium and radiogenic argon at the Okayama University of Science. The total potassium content was determined in duplicate by flame photometry using a 2000 ppm Cs buffer within an error of $\pm 2\%$ at 95% (2σ) confidence level [Nagao *et al.*, 1984]. The radiogenic argon was determined on a 15 cm radius sector type mass spectrometer with a single collector system, using an isotopic dilution method and ^{38}Ar spike [Itaya *et al.*, 1991]. Multiple runs of the standard (JG-1 biotite, 91Ma) indicate the error of argon analysis is about 1% at a 2σ confidence level [Itaya *et al.*, 1991; Yagi *et al.*, 2015]. The samples of known weight (300-600 mg) were wrapped in thin aluminum foil approximately and heated at 180-200°C preliminarily for 72 hours under a vacuum exhausted it, and after extracted sample gas at 1500°C. The active gas was eliminated using Ti-Zr getter. Calculations of ages and error followed the method described by Nagao and Itaya [1988] using the decay constants of Steiger and Jäger [1977], ^{40}Ar to ^{40}Ar , ^{40}K to ^{40}Ca and ^{40}Ar content potassium are $0.581 \times 10^{-10}/\text{yr}$, $4.962 \times 10^{-10}/\text{yr}$, and 0.0001167, respectively. Further details of the experimental technique employed are described in Itaya and Takasugi [1988].

4.2. Results

4.2.1. Petrography results

Optical microscopic observation reveals that the fault gouge is clay rich and a foliations developed in it. Both BSE image and EDS investigations of clay minerals reveal that the illite in the fault gouge is authigenic. The BSE image represents that the fault gouge has the massive matrix having extremely fine grain size ($<1\mu\text{m}$) (Figure 26b) and the EDS measured 1.6 to 1.9 for Si/Al ratio (Figure 26c). This rate indicates the existence of the illite-1M_d [Meunier and Velde, 1989; Song *et al.*, 2014], therefore the fault gouge consists of illite-1M_d of an authigenic illite.

4.2.2. XRD results and polytype quantification

The XRD analytical data and illite polytype quantifications are listed in Table 1, and the XRD patterns are shown in Figure 27 (1) – (8). And typical XRD patterns are shown in Figure 26a. The XRD patterns and illite polytype quantifications of the different size fractions of fault gouge indicate illite-2M₁, illite-1M, illite-1M_d and smectite-illite as the main clay minerals, and kaolinite and chlorite as minor ones. The host rocks are mainly composed of illite-2M₁, illite-1M and illite-smectite (I/S) as the main clay minerals, and kaolinite and chlorite as minor ones. The experimental and simulated XRD patterns for the size fractions of fault gouge sample are showed in Figure 28 (1) – (6), and typical pattern (YA-1-A1, 0.2-0.4µm) are shown in Figure 26b. The illite-polytype quantification using WILDFIRE© indicates that the amount of illite-2M₁ and illite-1M tends to decrease in the finer size fraction of fault gouge. Alternatively, one of illite-1M_d increases steeply in the finer fractions. In the fault gouge samples YY-1-A4 and SG-2-A3 the amount quantity of illite-2M₁ and illite-1M tended to decrease in the finer size fraction of fault gouge, while one of illite-1M_d increases steeply in the finer fractions. The other fault gouge samples OK-1-A3 and OK-1-A5 contain few or no illite-2M₁, and the amount of illite-1M and illite-1M_d changed little for the different size fractions. Moreover, the host rock samples OK-1-A4, YA-1-A7, and SG-2-A2 contain illite-2M₁ and illite-1M.

4.2.3. K-Ar dating results

Analytical data for twenty K-Ar age determinations are listed in Table 1. For the fault gouge samples, the size fractions 0.2-0.4 through 0.4-1.0 to 1.0-2.0 µm yield the age values ranging from 40.9 ± 1.0 to 74.3 ± 1.6 Ma (n = 15). The host rock samples of which the grain size is less than 2 µm (SG-2-A2 > 2.0µm, YA-1-A7 > 2.0µm) yield the age values ranging from 71.6 ± 1.6 to 78.1 ± 1.7 Ma (n = 2), and for a host rock sample (OK-1-A4), the grain size fractions 0.2-0.4 through 0.4-1.0 to 1.0-2.0 µm yield the age values ranging from 74.4 ± 1.7 to 78.1 ± 1.8 Ma (n = 3). Illite is dominant in each size fraction of the fault gouge samples, as shown by the potassium content ranging from 4.8 to 6.4 wt.% (K₂O 5.8-7.7 wt.%), while quartz and illite are dominant the fine-grained fractions of host rock samples, as shown by the potassium content of 3.8 to 5.7 wt% (K₂O 5.5-6.9 wt%). The K-Ar ages of the fault gouge samples are younger than the host rock ones, and

Table 1. K-Ar dates from each fraction obtained from samples in fault gouge. And results of XRD Polytype Analyses.

Sample No.	Classification	Grain size (μm)	Mineral composition	Relative proportion (%)			Illite crystallinity	K content (wt.%)	Rad. ⁴⁰ Ar (10 ⁻⁸ cc STP/g)	K-Ar age (Ma)	Non-rad. ⁴⁰ Ar (%)
Okamura Fault				1M _d	1M	2M ₁					
OK-1-A3	Fault gouge	0.2-0.4	Ill, Q, (Ka, I/S)	63.0	37.0	0.0	0.738	5.886 ± 0.118	1054.6 ± 11.3	45.6 ± 1.0	9.0
		0.4-1.0	Ill, Q, (Ka, I/S)	61.0	39.0	0.0	0.711	5.822 ± 0.116	1069.7 ± 11.5	46.7 ± 1.0	8.1
		1.0-2.0	Ill, Q, (Ka, I/S)	61.0	39.0	0.0	0.767	5.562 ± 0.111	1046.2 ± 11.0	47.8 ± 1.1	7.6
OK-1-A5	Fault gouge	0.2-0.4	Ill, Q, I/S, (Ka)	59.9	30.5	9.6	0.681	4.927 ± 0.099	791.7 ± 10.0	40.9 ± 1.0	19.5
		0.4-1.0	Ill, Q, I/S, (Ka)	62.8	31.8	5.4	0.621	4.900 ± 0.098	794.0 ± 9.8	41.3 ± 1.0	18.9
		1.0-2.0	Ill, Q, Ka, I/S	58.8	37.5	3.8	0.632	4.871 ± 0.097	802.0 ± 9.8	41.9 ± 1.0	18.5
OK-1-A4	Host rock	0.2-0.4	Ill, Q, (Ka, Chl, I/S)	-	-	-	0.496	5.753 ± 0.115	1696.5 ± 18.9	74.4 ± 1.7	11.1
		0.4-1.0	Ill, Q, (Ka, Chl, I/S)	-	-	-	0.457	5.424 ± 0.108	1679.0 ± 19.1	78.1 ± 1.8	12.5
		1.0-2.0	Q, Ill, (Chl, Ka, I/S)	0.0	37.0	63.0	0.489	5.251 ± 0.105	1601.1 ± 18.0	76.9 ± 1.7	11.5
Shigenobugawa Fault											
SG-2-A3	Fault gouge	0.2-0.4	Ill, Q, (I/S)	46.4	30.9	22.7	0.674	5.990 ± 0.120	1410.0 ± 15.3	59.7 ± 1.3	9.5
		0.4-1.0	Ill, Q, (I/S)	31.6	27.6	40.8	0.495	5.620 ± 0.112	1453.6 ± 15.4	65.5 ± 1.5	8.0
		1.0-2.0	Ill, Q, (I/S)	29.7	22.8	47.5	0.545	5.149 ± 0.103	1403.9 ± 14.9	68.9 ± 1.5	7.4
SG-2-A2	Host rock	< 2.0	Q, Ill, I/S, (Ka, Chl)	0.0	45.7	54.3	0.753	3.840 ± 0.077	1088.3 ± 11.5	71.6 ± 1.6	7.4
Kawakami Fault											
YY-1-A4	Fault gouge	0.2-0.4	Ill, Q, (Ka, I/S)	39.6	32.7	27.7	0.493	5.917 ± 0.118	1589.7 ± 16.3	67.9 ± 1.5	4.6
		0.4-1.0	Ill, Q, (Ka, I/S)	27.5	33.9	38.5	0.462	5.415 ± 0.108	1592.4 ± 16.3	74.2 ± 1.6	4.8
		1.0-2.0	Ill, Q, (Ka, I/S)	13.3	38.1	48.7	0.460	5.046 ± 0.101	1485.5 ± 15.3	74.3 ± 1.6	5.5
Median Tectonic Line											
YA-1-A1	Fault gouge	0.2-0.4	Ill, Q, (Ka, I/S)	69.5	13.7	16.8	0.553	6.495 ± 0.130	1288.0 ± 13.4	50.4 ± 1.1	6.3
		0.4-1.0	Ill, Q, (Ka, I/S)	67.4	14.0	18.6	0.517	6.229 ± 0.125	1336.5 ± 13.9	54.5 ± 1.2	6.2
		1.0-2.0	Ill, Q, (Ka, I/S)	61.5	15.4	23.1	0.541	6.080 ± 0.122	1327.5 ± 13.7	55.4 ± 1.2	5.9
YA-1-A7	Host rock	< 2.0	Q, Ill, (Chl, Ka)	0.0	28.6	71.4	0.643	5.040 ± 0.101	1560.2 ± 15.8	78.1 ± 1.7	4.0

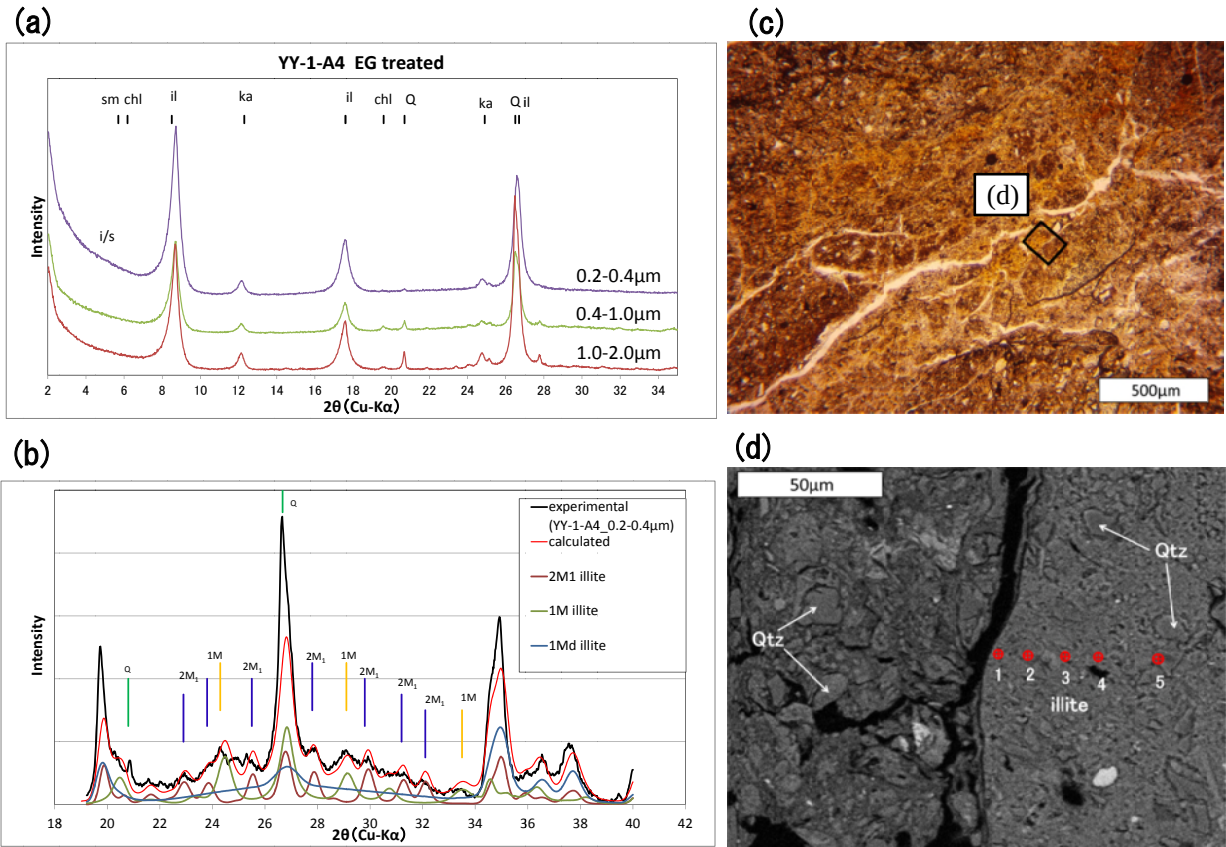


Figure 26. (a) Oriented micro focused XRD on ethylene glycolated (EG) samples result for all size fractions of the YY-1-A4 fault gouge samples. (b) XRD experimental pattern (black solid) and best matching calculated pattern (red solid) for each size fraction of the fault gouge (sample YY-1-A4 ; 0.20-0.4 μm) using the full-pattern-fitting method. (c) Cross-polarized microscope image of gouge sample (sample OK-1-A3) (d) BSE image of gouge sample (sample OK-1-A3) shows that it mainly consists of 1Md polytype as authigenic illite. See Figure 26 (c) for location of the Image. Abbreviations: Qtz = Quartz; il = illite; sm = smectite; ka = kaolin; chl = chlorite; i/s = illite/smectite

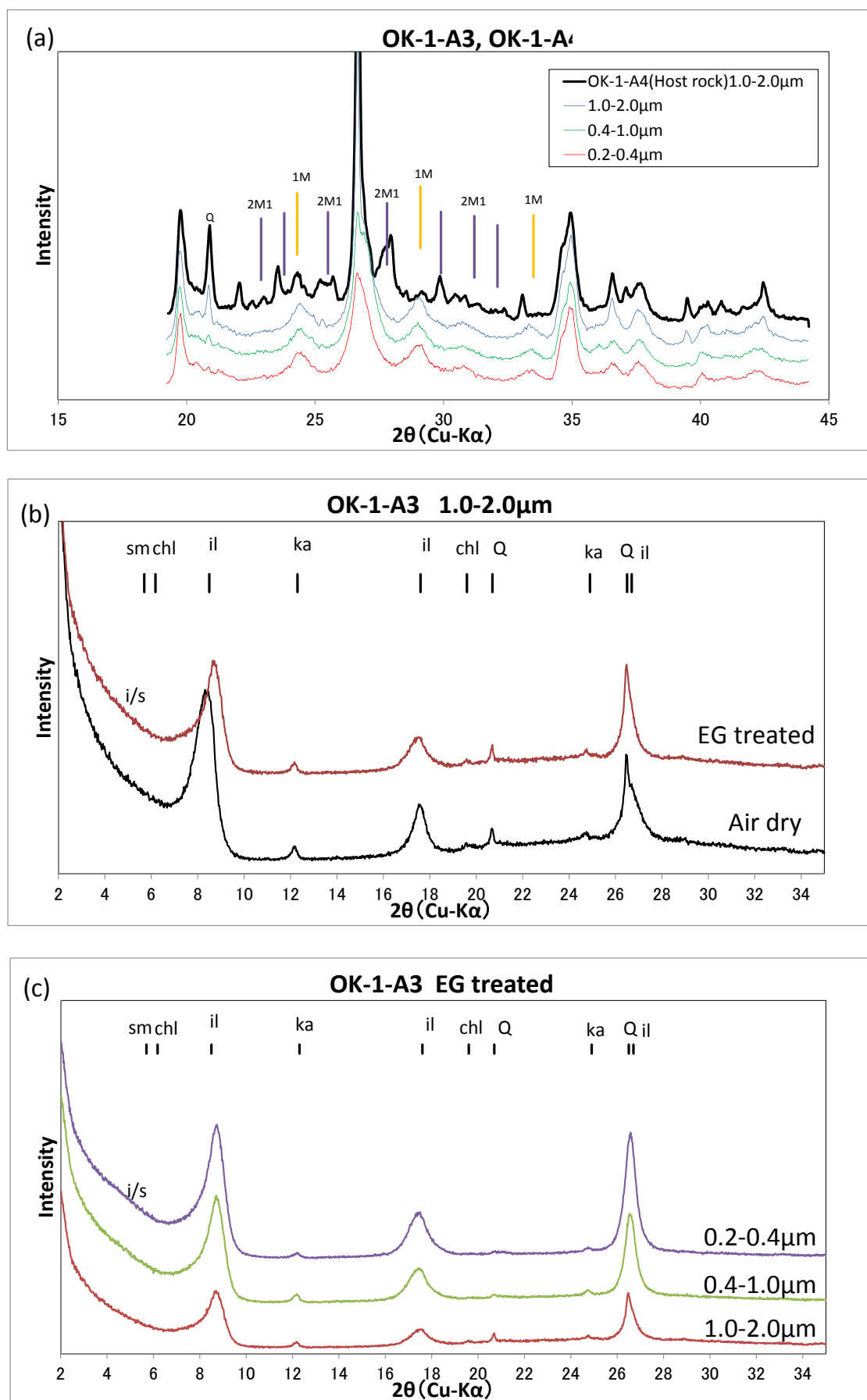


Figure 27(1). XRD experimental pattern of OK-1-A3 fault gouge samples. (a) Randomly oriented micro focused XRD on samples result for all size fractions. (b) Oriented micro focused XRD on ethylene glycolated (EG) and air dried (fraction 1.0-2.0μm) (c) Oriented micro focused XRD on EG samples result for all size fractions. Abbreviations: Qtz = Quartz; il = illite; sm = smectite; ka = kaolin; chl = chlorite; i/s = illite/smectite

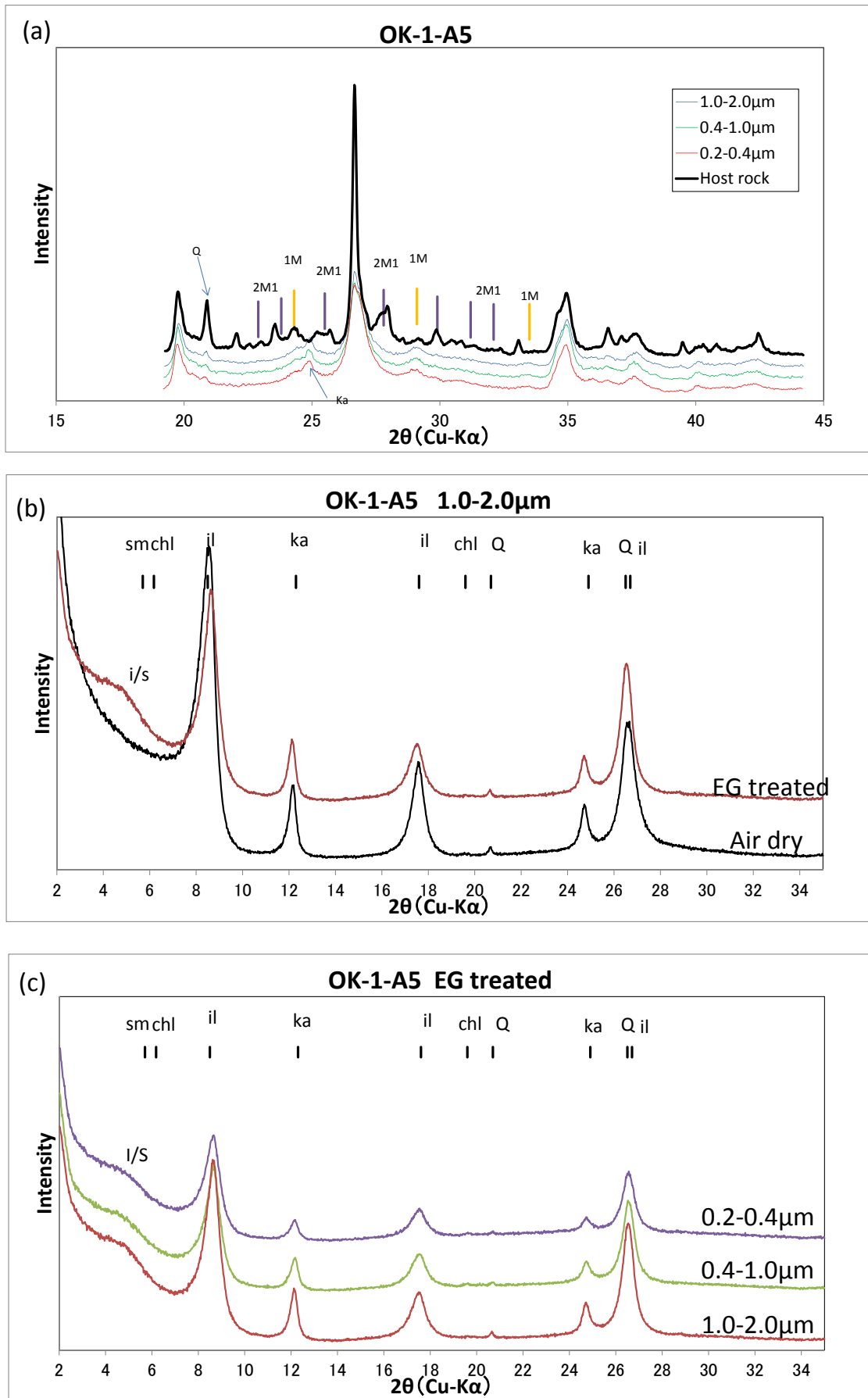


Figure 27(2). XRD experimental pattern of OK-1-A5 fault gouge samples. (a) Randomly oriented micro focused XRD on samples result for all size fractions. (b) Oriented micro focused XRD on ethylene glycolated (EG) and air dried (fraction 1.0-2.0μm) (c) Oriented micro focused XRD on EG samples result for all size fractions. Abbreviations: Qtz = Quartz; il = illite; sm = smectite; ka = kaolinite; chl = chlorite; i/s = illite/smectite

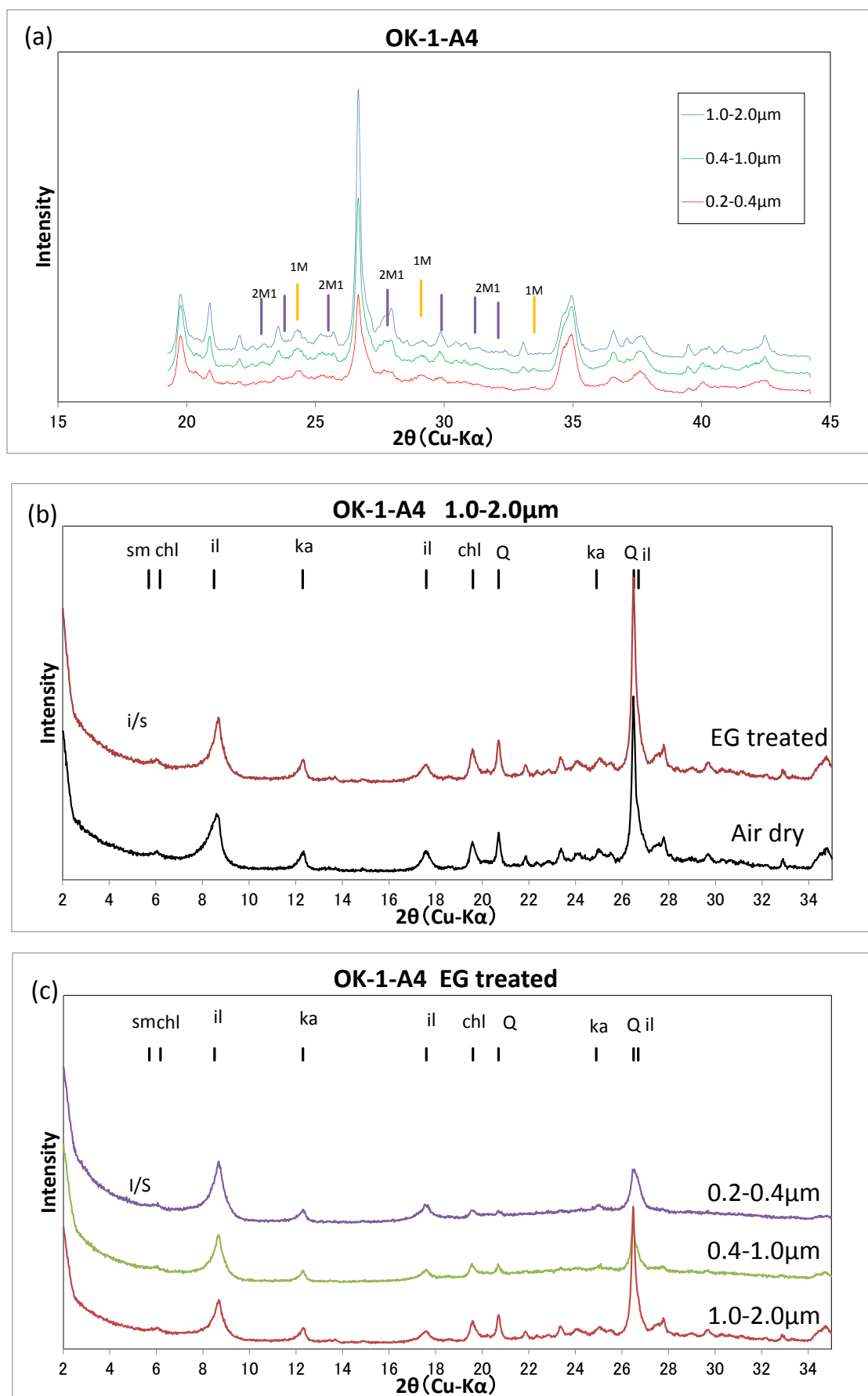


Figure 27(3). XRD experimental pattern of OK-1-A4 host rock samples. (a) Randomly oriented micro focused XRD on samples result for all size fractions. (b) Oriented micro focused XRD on ethylene glycolated (EG) and air dried (fraction 1.0-2.0µm) (c) Oriented micro focused XRD on EG samples result for all size fractions. Abbreviations: Qtz = Quartz; il = illite; sm = smectite; ka = kaolin; chl = chlorite; i/s = illite/smectite

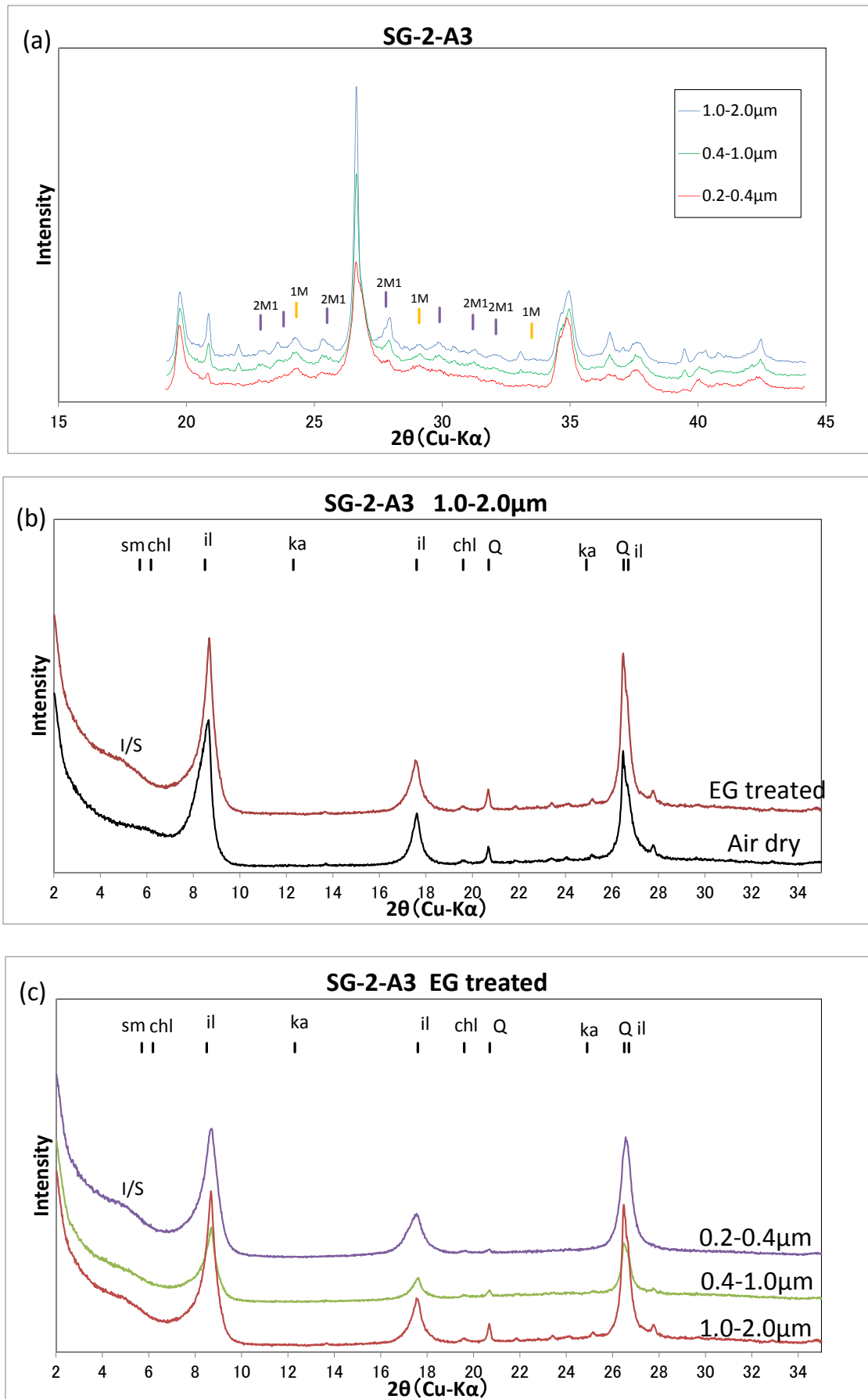


Figure 27(4). XRD experimental pattern of SG-2-A3 fault gouge samples. (a) Randomly oriented micro focused XRD on samples result for all size fractions. (b) Oriented micro focused XRD on ethylene glycolated (EG) and air dried (fraction 1.0-2.0 μ m) (c) Oriented micro focused XRD on EG samples result for all size fractions. Abbreviations: Qtz = Quartz; il = illite; sm = smectite; ka = kaolin; chl = chlorite; i/s = illite/smectite

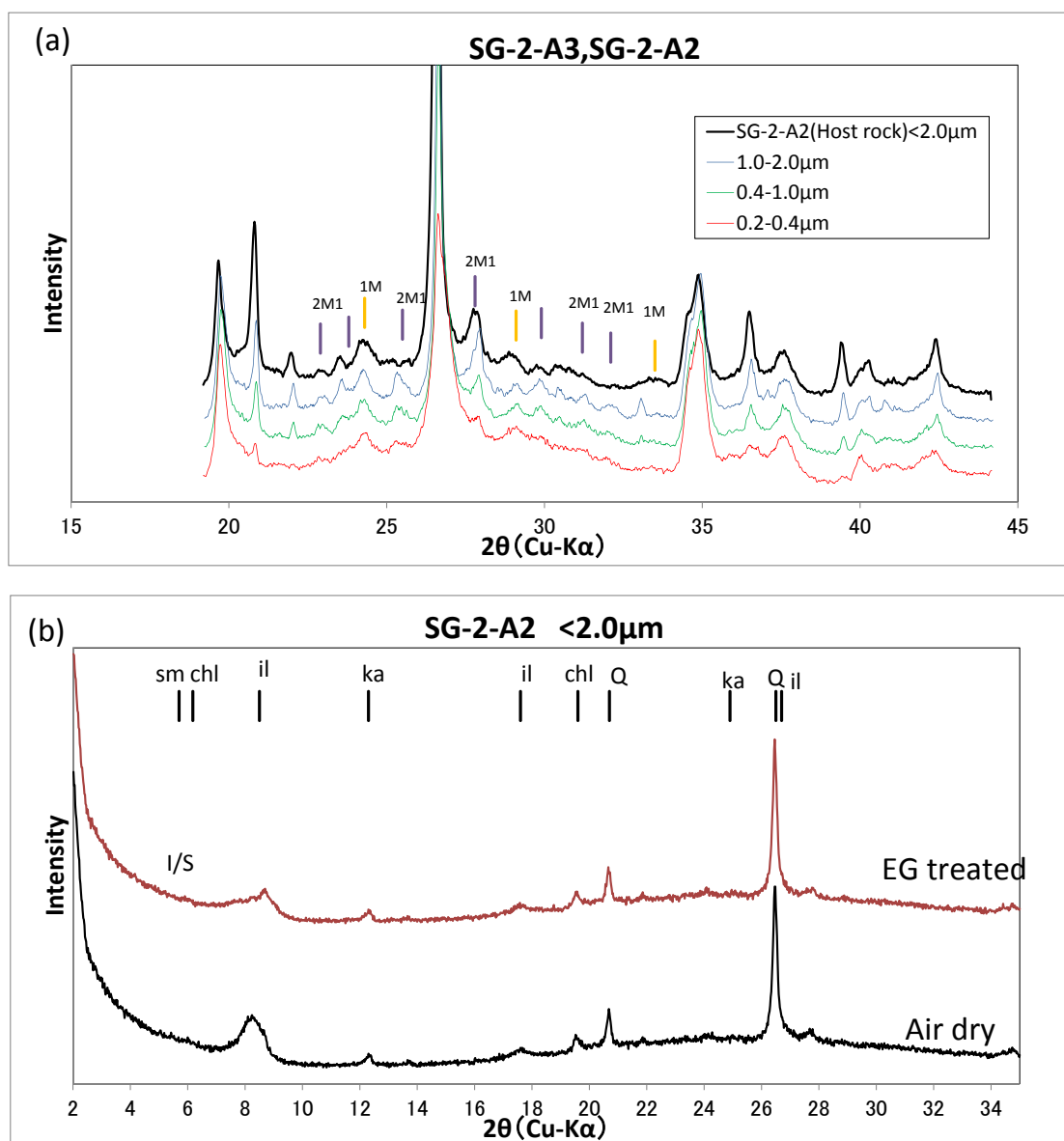


Figure 27(5). XRD experimental pattern of SG-2-A2 host rock samples. (a) Randomly oriented micro focused XRD on samples result for all size fractions of SG-2-A2 host rock and SG-2-A3 fault gouge samples. (b) Oriented micro focused XRD on ethylene glycolated (EG) and air dried (fraction <2.0μm) Abbreviations: Qtz = Quartz; il = illite; sm = smectite; ka = kaolin; chl = chlorite; i/s = illite/smectite

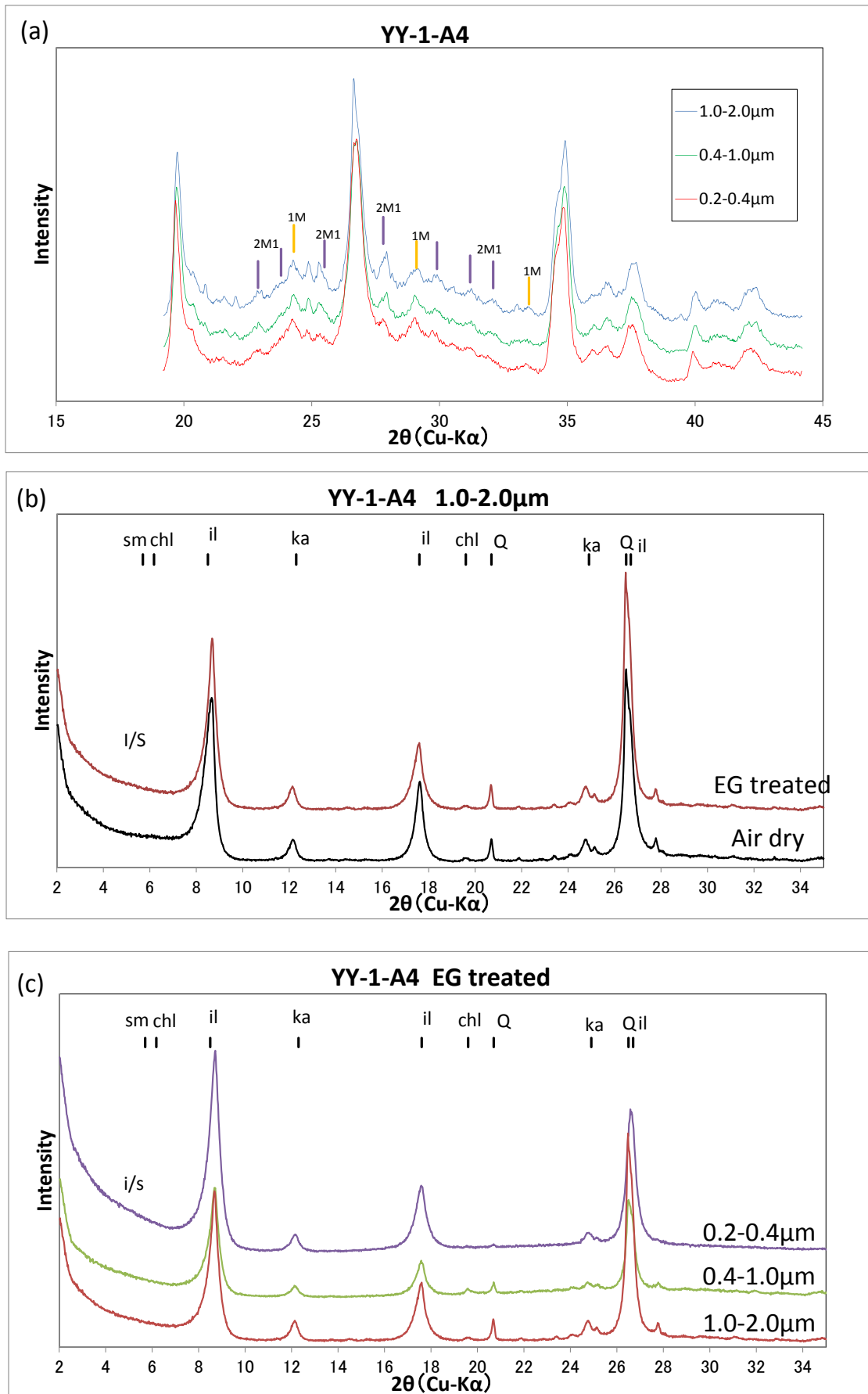


Figure 27(6). XRD experimental pattern of YY-1-A4 fault gouge samples. (a) Randomly oriented micro focused XRD on samples result for all size fractions. (b) Oriented micro focused XRD on ethylene glycolated (EG) and air dried (fraction 1.0-2.0 μ m) (c) Oriented micro focused XRD on EG samples result for all size fractions. Abbreviations: Qtz = Quartz; il = illite; sm = smectite; ka = kaolin; chl = chlorite; i/s = illite/smectite

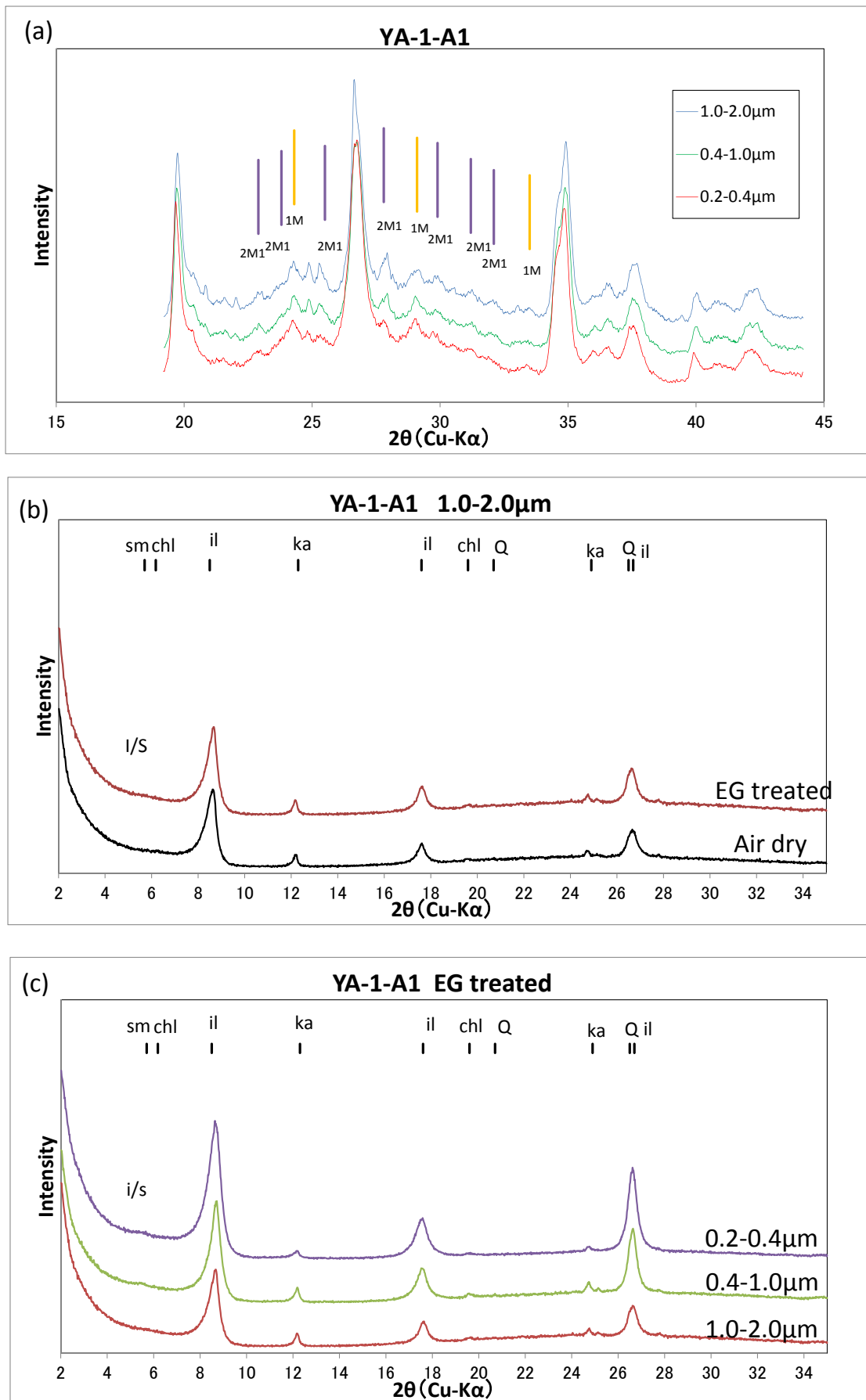


Figure 27(7). XRD experimental pattern of YA-1-A1 fault gouge samples. (a) Randomly oriented micro focused XRD on samples result for all size fractions. (b) Oriented micro focused XRD on ethylene glycolated (EG) and air dried (fraction 1.0-2.0µm) (c) Oriented micro focused XRD on EG samples result for all size fractions. Abbreviations: Qtz = Quartz; il = illite; sm = smectite; ka = kaolin; chl = chlorite; i/s = illite/smectite

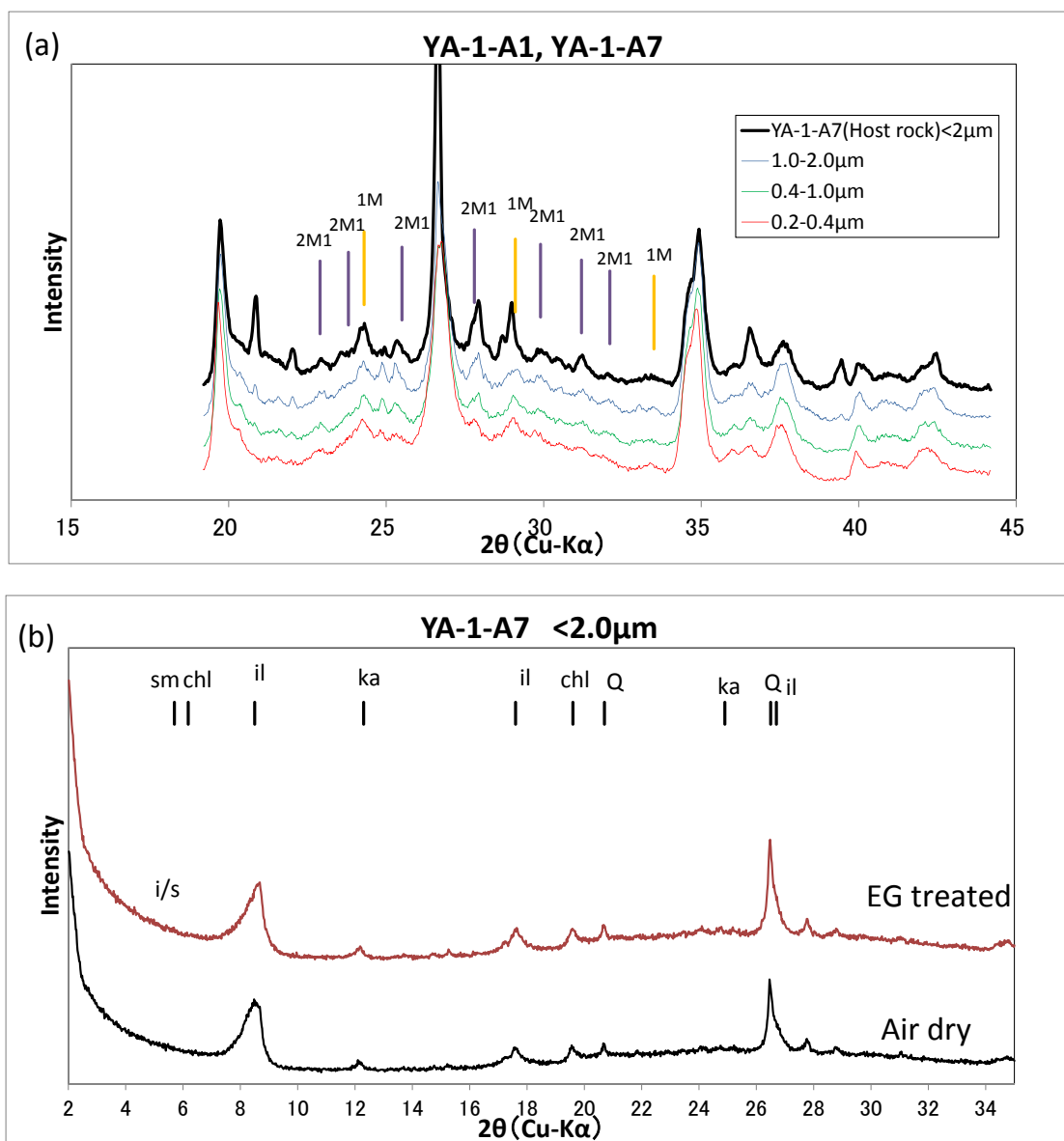


Figure 27(8). XRD experimental pattern of YA-1-A7 host rock samples. (a) Randomly oriented micro focused XRD on samples result for all size fractions of YA-1-A7 host rock and YA-1-A1 fault gouge samples (b) Oriented micro focused XRD on ethylene glycolated (EG) and air dried (fraction <2.0 μ m) Abbreviations: Qtz = Quartz; il = illite; sm = smectite; ka = kaolin; chl = chlorite; i/s = illite/smectite

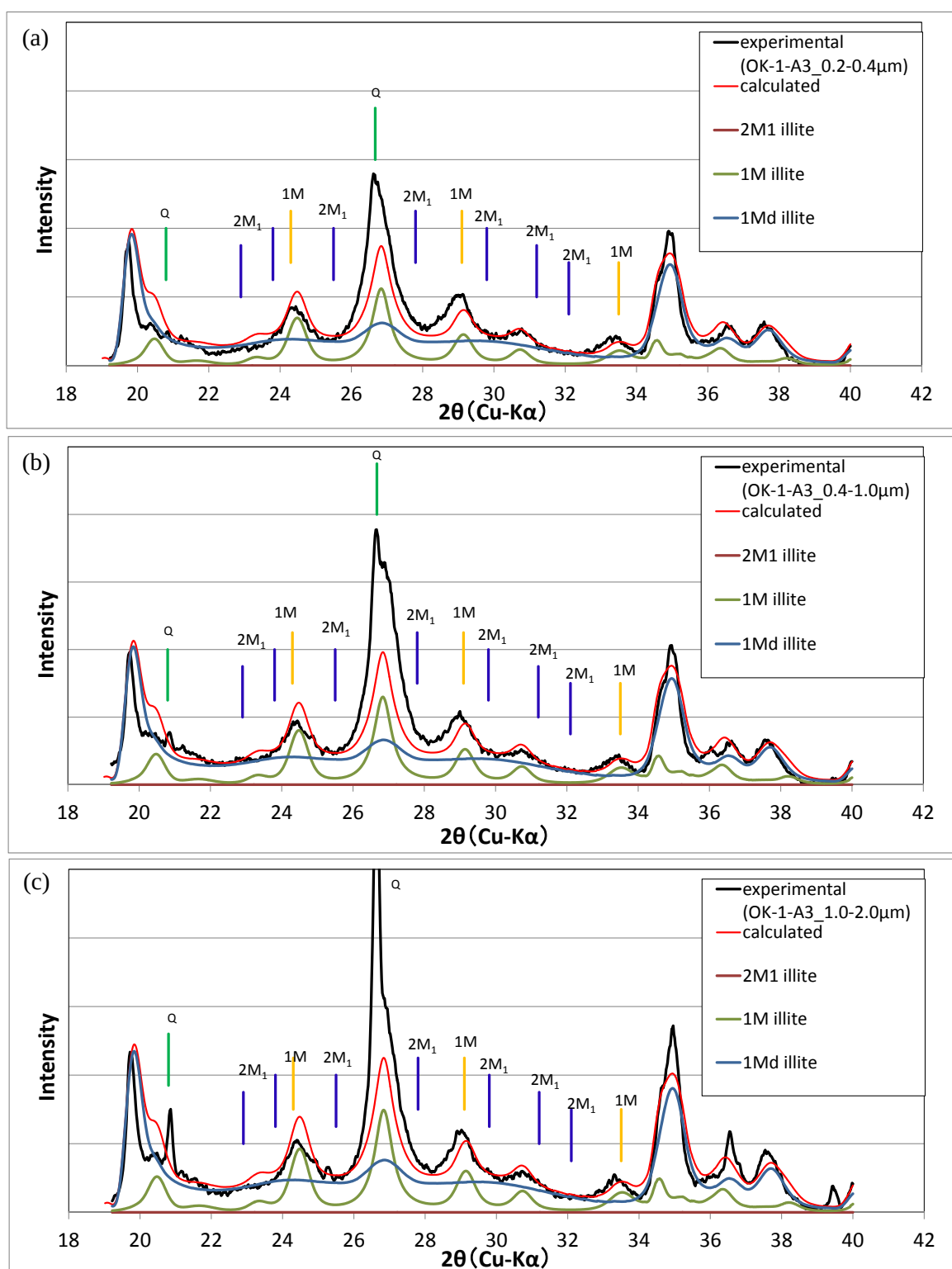


Figure 28(1). XRD experimental pattern (black solid) and best matching calculated pattern (red solid) for each size fraction of the fault gouge (sample OK-1-A3) using the full-pattern-fitting method.(a)0.20-0.4 μ m, (b)0.40-1.0 μ m, (c)1.0-2.0 μ m
Abbreviations: Q = Quartz

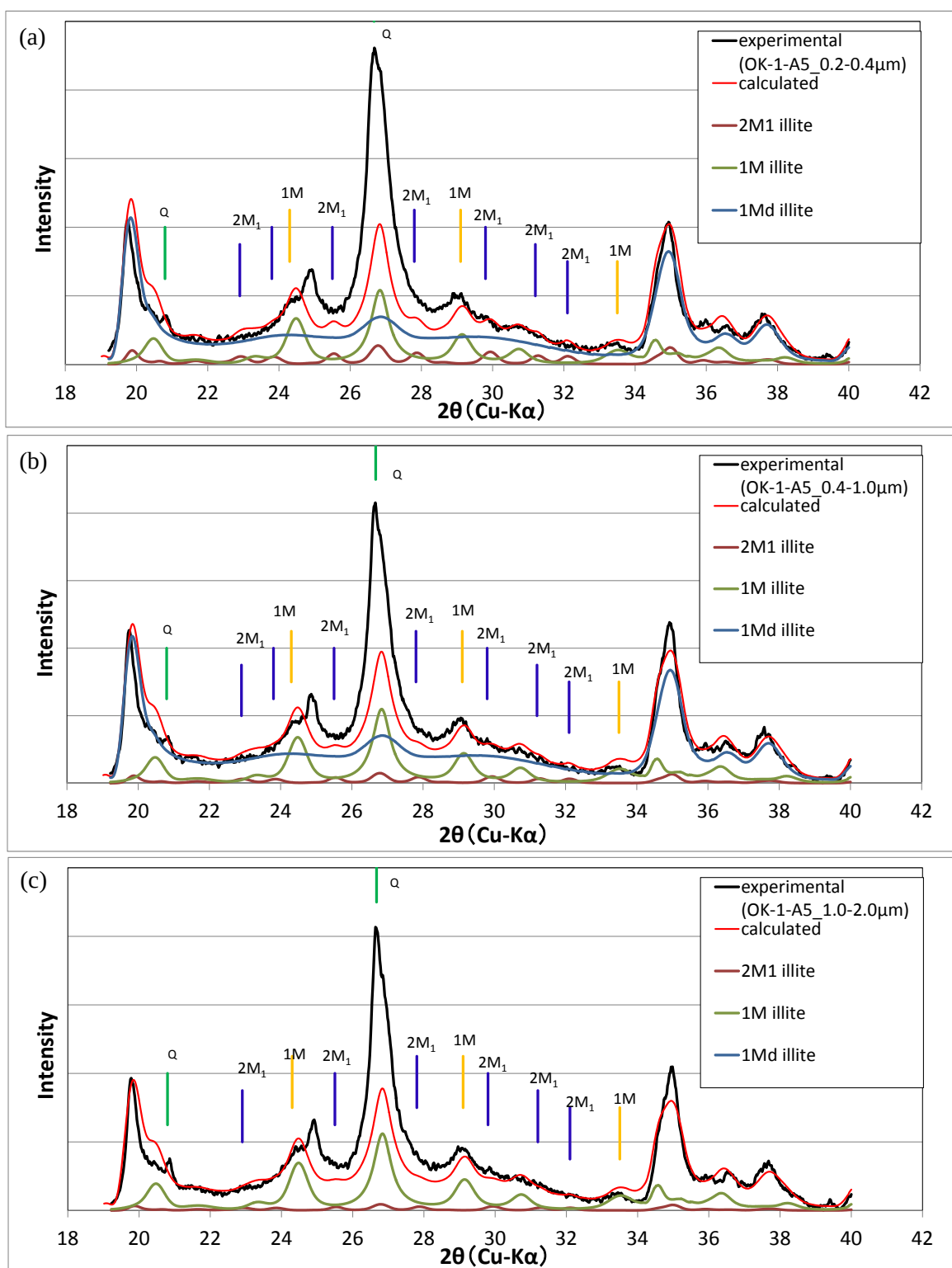


Figure 28(2). XRD experimental pattern (black solid) and best matching calculated pattern (red solid) for each size fraction of the fault gouge (sample OK-1-A5) using the full-pattern-fitting method.(a)0.20-0.4 μ m, (b)0.40-1.0 μ m, (c)1.0-2.0 μ m
Abbreviations: Q = Quartz

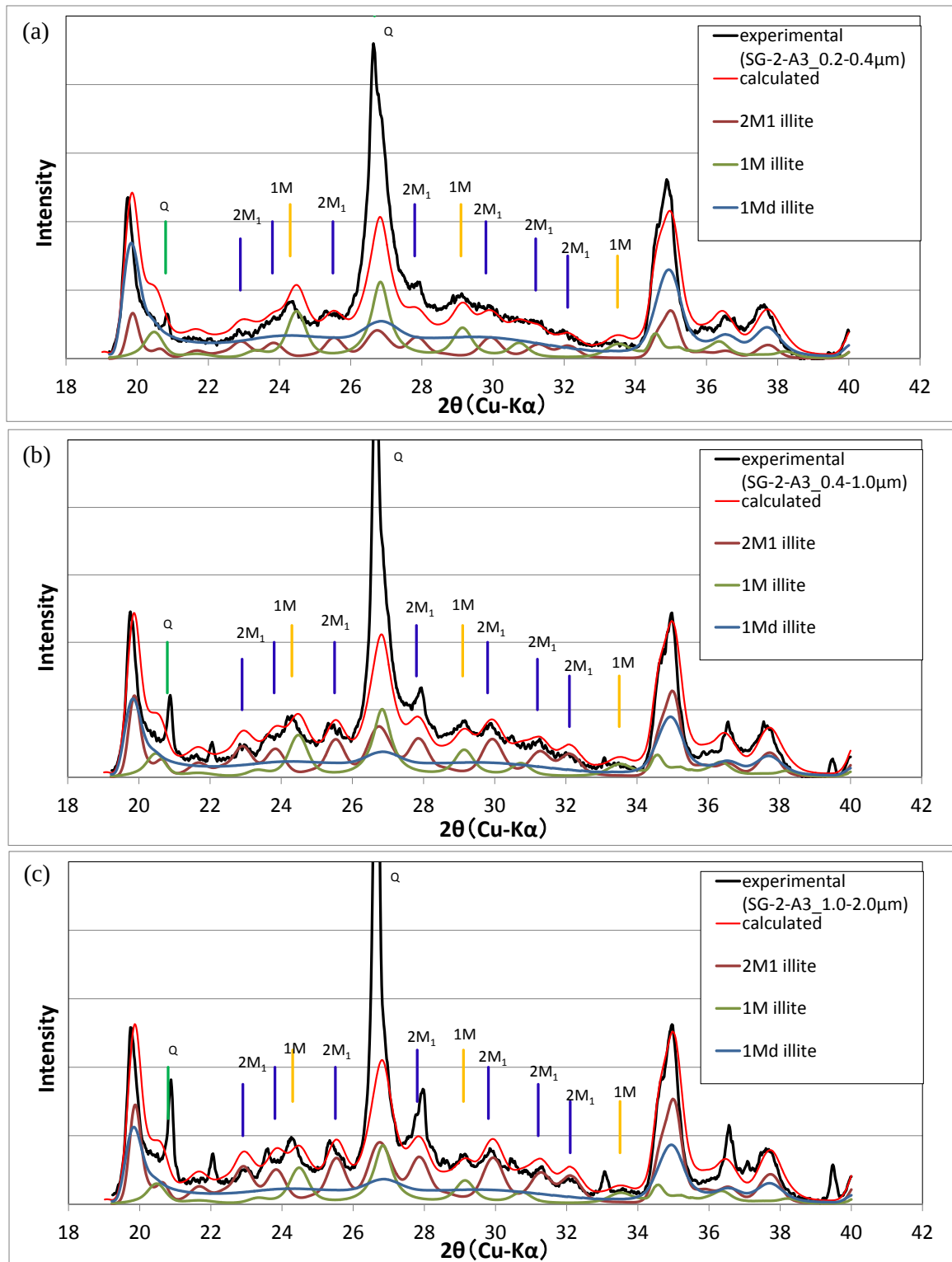


Figure 28(3). XRD experimental pattern (black solid) and best matching calculated pattern (red solid) for each size fraction of the fault gouge (sample SG-2-A3) using the full-pattern-fitting method.(a)0.20-0.4 μ m, (b)0.40-1.0 μ m, (c)1.0-2.0 μ m
Abbreviations: Q = Quartz

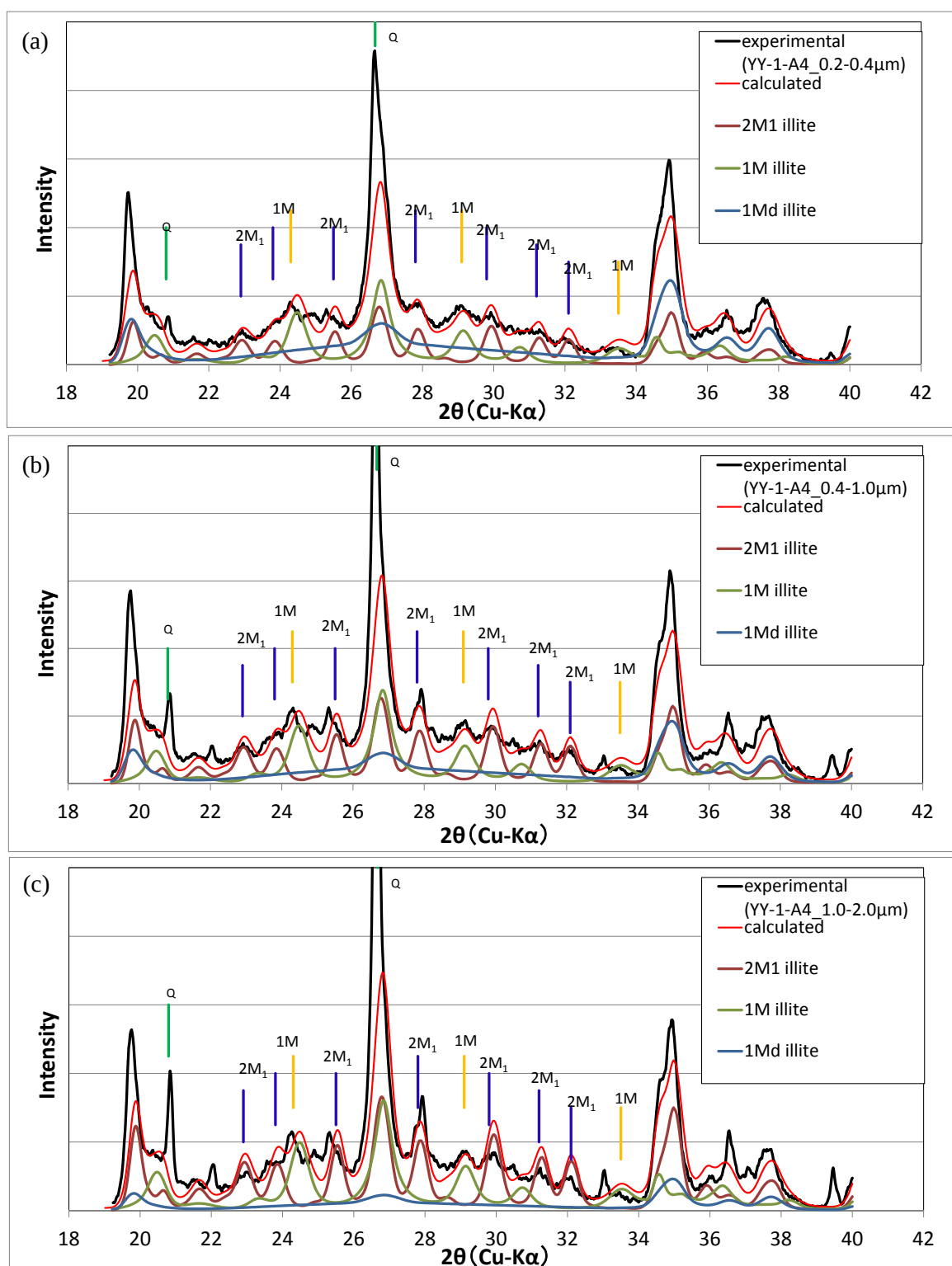


Figure 28(4). XRD experimental pattern (black solid) and best matching calculated pattern (red solid) for each size fraction of the fault gouge (sample YY-1-A4) using the full-pattern-fitting method.(a)0.20-0.4 μ m, (b)0.40-1.0 μ m, (c)1.0-2.0 μ m
Abbreviations: Q = Quartz

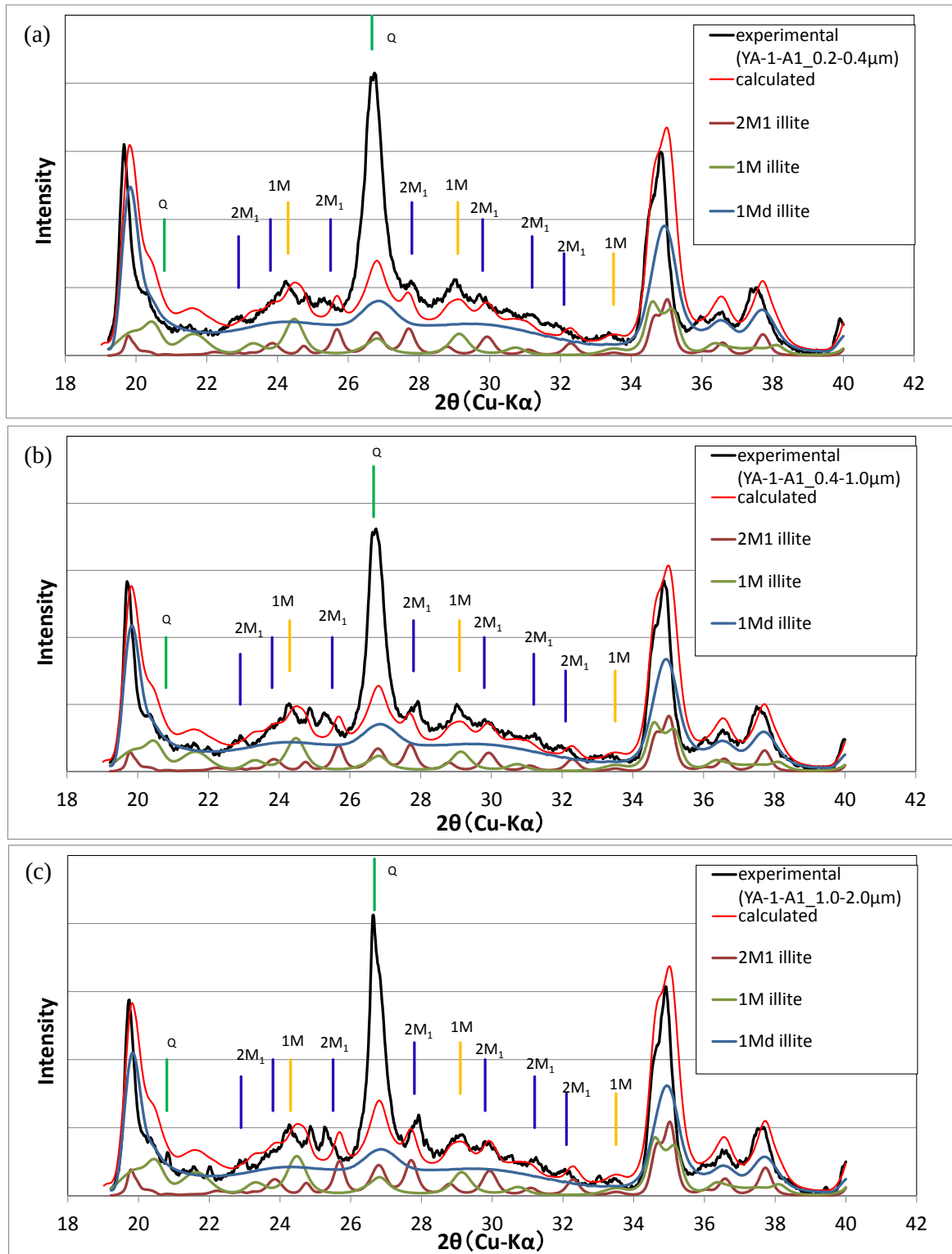


Figure 28(5). XRD experimental pattern (black solid) and best matching calculated pattern (red solid) for each size fraction of the fault gouge (sample YA-1-A1) using the full-pattern-fitting method.(a)0.20-0.4 μm , (b)0.40-1.0 μm , (c)1.0-2.0 μm
Abbreviations: Q = Quartz

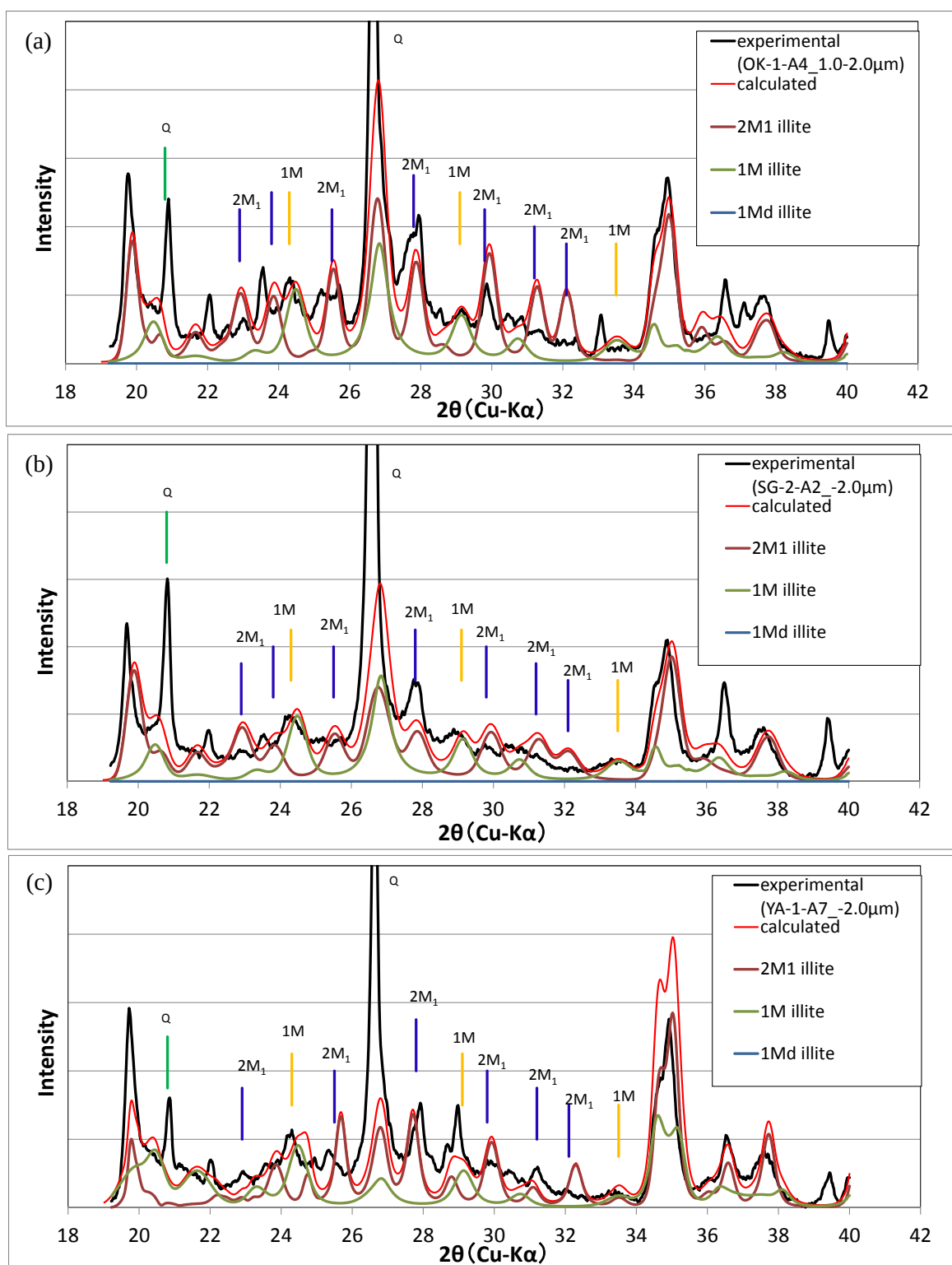


Figure 28(6). XRD experimental pattern (black solid) and best matching calculated pattern (red solid) for each size fraction of the host rock using the full-pattern-fitting method. (a) OK-1-A4, (b) SG-2-A2, (c) YA-1-A7 Abbreviations: Q = Quartz

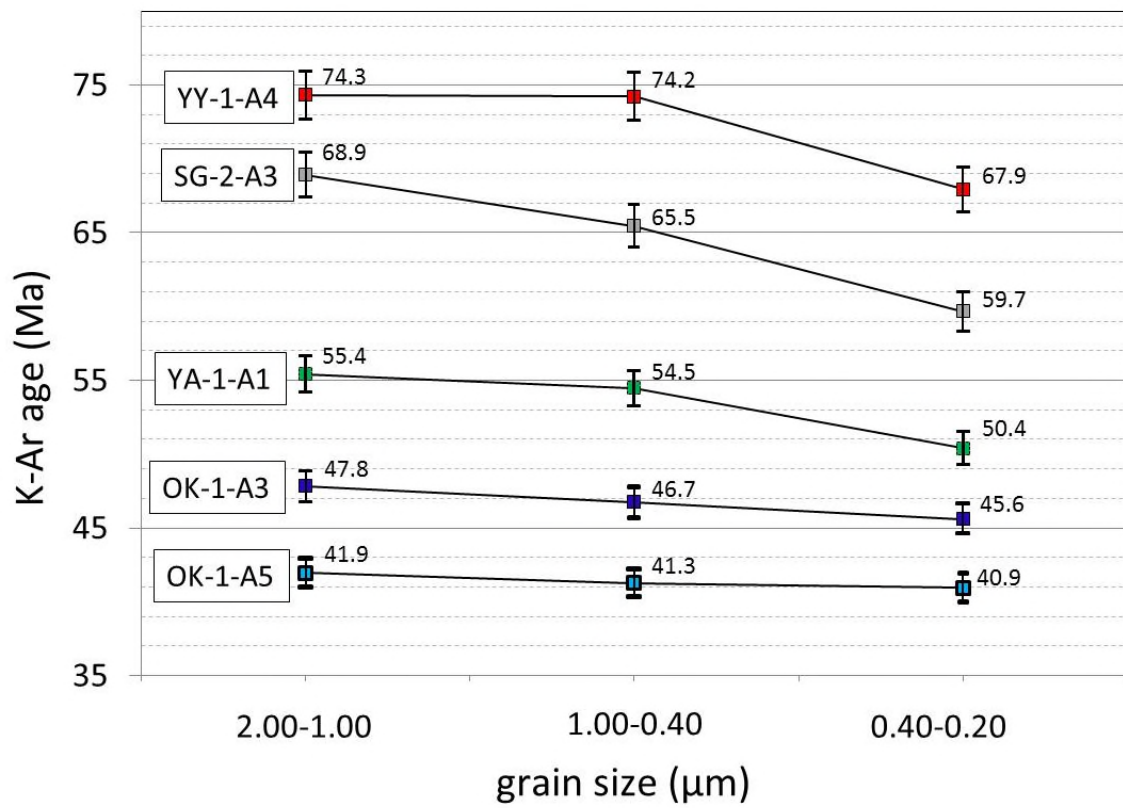


Figure 29. K-Ar ages with respect to the grain size of fault gouge samples.

become younger in the order of 1.0-2.0 μm , 0.4-1.0 μm , and 0.2-0.4 μm size fractions of the fault gouge samples (Figure 29).

5. Discussion

5.1. Sinistral and reverse faulting along the MTL

In the study area the parallel fault system along the MTL develops in the Izumi Group, defining a fault zone up to 100 m thick along the faults (F3; Figure 6, F4; Figure 9, F5; Figure 11). The faults distribute *en échelon* arrangement, oriented counterclockwise for the MTL at the northern side of it. In this, the faults of F5 and F6 are oblique at relatively low angles to the strike of the MTL, which extends straightly. On the other hand, the faults F1 to F4 are oblique at relatively high angle to the strike of the MTL forming a left bend. Furthermore, the south-vergent to upright folds with *en échelon* arrangement, oriented clockwise for the strike of faults, which could have been formed as drag folds due to sinistral and reverse slip fault movement along the faults (F1; Figure 3, F3; Figure 6, F5; Figure 11). These macroscopic geological structures show that the parallel faults were formed as *en échelon* faults by left-lateral faulting of the MTL. Further, based on the observation of the outcrops, slabs and thin sections of the oriented samples from fault zone, the fault zone of parallel faults consist of cataclasite and fault gouge, where structures indicating a sinistral and reverse slip sense with a top-to-the-southwest (F1; Figure 5, F3; Figures 6-8, F4; Figures 9-10, F5; Figures 11-12). The microstructural observation (Figure 12) of deformed quartz grains in thin sections of the cataclasite provides evidence that quartz grains are both micro cracked and plastically deformed, and show patchy (or inhomogeneous) and wavy extinction, indicating deformation in quartz at the brittle–ductile transition, while these microstructures are not recognized in host rocks apart from the faults. This indicates that the temperatures in the fault zones in the study area reached those less than but close to the conditions for the brittle–ductile transition for quartz (ca. 300 °C, [Takeshita \[1995\]](#); [Stöckhert et al. \[1999\]](#)).

5.2. The deformation sequence during the Paleogene along the MTL

As mentioned above, based on the observation of the outcrop of MTL at locality MTL-1 (Figures 13-18)

and MTL-2 (Figures 19-22), the superposed deformation structure in the fault zone showing sinistral and reverse faulting overprinting normal faulting in the MTL has been documented. Based on the mineral assemblages in the dolomitic schist, in particular, densely recrystallized fine-grained actinolite which perhaps formed simultaneously during the normal faulting, the normal faulting is inferred to have occurred at subgreenschist conditions (ca. 250 °C, e.g. [Robinson et al. \[1981\]](#)). Further, the actinolite aggregates formed along shear bands and kink bands formed in them and fractures formed by sinistral and reverse slip sense show that the latter microstructures occurred at lower temperature than ca. 250 °C. Moreover, it has been reported that illite K–Ar ages of fault zones are reset at the temperatures where detrital illite-2M₁ and illite-1M polytype are stable, which form at ~250-350 °C and ~200-300 °C, while authigenic illite-1M_d forms at ~100-200 °C [[Srondon and Eberl, 1984](#); [Walker, 1993](#); [Yates and Rosenberg, 1996](#); [Rosenberg, 2002](#)]. Hence, it is inferred that the temperatures of fault zone had been ~100-200 °C during faulting.

And, anywhere, the parallel fault system develops at the northern side of the MTL, dipping north at high angles. It is inferred that these faults branch from the MTL dipping north at a low angle (ca. 30°) at depth. The other, study by seismic survey has shown that the active faults of parallel faults branch away from the MTL at a depth of about 5 km [[Ito et al., 1996](#)]. Hence, it could be inferred that the MTL has faulting with the sinistral and reverse slip, when the parallel faults were formed. Further, the macro and microstructures based on observation of fault gouge, for example F1 (Figures 4-5) and F4 (Figures 9-10), with dextral slip sense develops locally in the fault zone of the parallel faults, which indicate the reactivation of these fault zones at late from faulting with sinistral and reverse slip. This movement can be correlated with the phase when the MTL has been reactivated as a major active fault in southwest Japan. Due to a strong compression in the WNW–ESE direction, which results from the subduction of both Pacific and Philippine Sea plates underneath the southwest Japan arc in similar directions, the MTL has been reactivated as a right-lateral strike-slip fault since 2 Ma [e.g. [Okada, 1973a,b](#)].

5.3. Interpretation of K–Ar dates from the gouge along the MTL and parallel faults

[Pevear \[1999\]](#) discussed that the influence of detrital mineral phases on authigenic illite formation in detail

for sedimentary rock, and the size fractions, the polytype contents, and the K-Ar ages have a distinct relationship. To resolve the influence of contamination of detrital ages for the K-Ar dates from the fault gouge, the percentage detrital illite of each of the size fractions by XRD is plotted against their apparent K-Ar ages as a function of $\exp(\lambda t) - 1$, and linearly extrapolated to 0% and 100% detrital component to evaluate authigenic and detrital end member ages. [Pevear \[1999\]](#) calls the method for illite age analysis (IAA). [Pevear \[1999\]](#) proposed that the extrapolated authigenic age should represent the mean age of the time interval over which illite grew. In this study, previously described method was used to determine ages of authigenic illite. The methods in the IAA approach and previous studies applied to dating fault gouge (e.g., [Solum et al. \[2005\]](#); [Haines and van der Pluijm \[2008\]](#)).

In this study, the relative proportions of the detrital $2M_1 + 1M$ -illite for all fractions were plotted against their K-Ar ages as a function of $\exp(\lambda t) - 1$, which was linearly related to the radiogenic $^{40}\text{Ar}/\text{K}$ ratio [[Pevear, 1999](#); [Grathoff and Moore, 1996](#)]. The interceptions at 0% and 100% $2M_1 + 1M$ -illite were converted to $1M_d$ and $2M_1 + 1M$ -illite ages, respectively. The IAA plots for all size fractions of the fault gouge samples were characterized by two liner regression lines in Figure 30. The age of the authigenic $1M_d$ -illite in the fault gouge is well defined at 41.3 ± 1.2 (YA-1-A1), 41.2 ± 1.4 Ma (SG-2-A3), 57.4 ± 1.6 Ma (YY-1-A4) with an error range of ca. ± 1.2 - 1.6 Ma. The other, the fault gouge samples (OK-1-A3 and OK-1-A5) contain few or no quantity of illite- $2M_1$, and the quantity of illite- $1M$ and illite- $1M_d$ changed little for the different size fractions. These samples consists more I/S, in such a case, [Solum et al. \[2005\]](#) shows to quantify the amount of discrete illite considering that discrete illite can be considered to be detrital and I/S to be authigenic [[Pevear, 1999](#)]. The study of these samples would show to other article.

The ages of host rock are 74.4 ± 1.7 to 78.1 ± 1.8 Ma (OK-1-A4), 71.6 ± 1.6 Ma (SG-2-A2), and 78.1 ± 1.7 Ma (YA-1-A7). The host rock sample SG-2-A2 contains lower K content of 3.840 ± 0.077 wt% (K_2O 4.9 wt%). On the other hand, this sample contains I/S and small amount of kaolin and chlorite based on XRD. Therefore, this sample could have become slightly younger than the formation age perhaps by the influence of weathering. The average value of K-Ar age of host rocks is 76.8 ± 1.7 Ma ($n = 4$) excluding 71.6 ± 1.6 Ma (SG-2-A2), and matches approximately with the age of detrital illite- $2M_1$ and illite- $1M$ by the IAA plots for

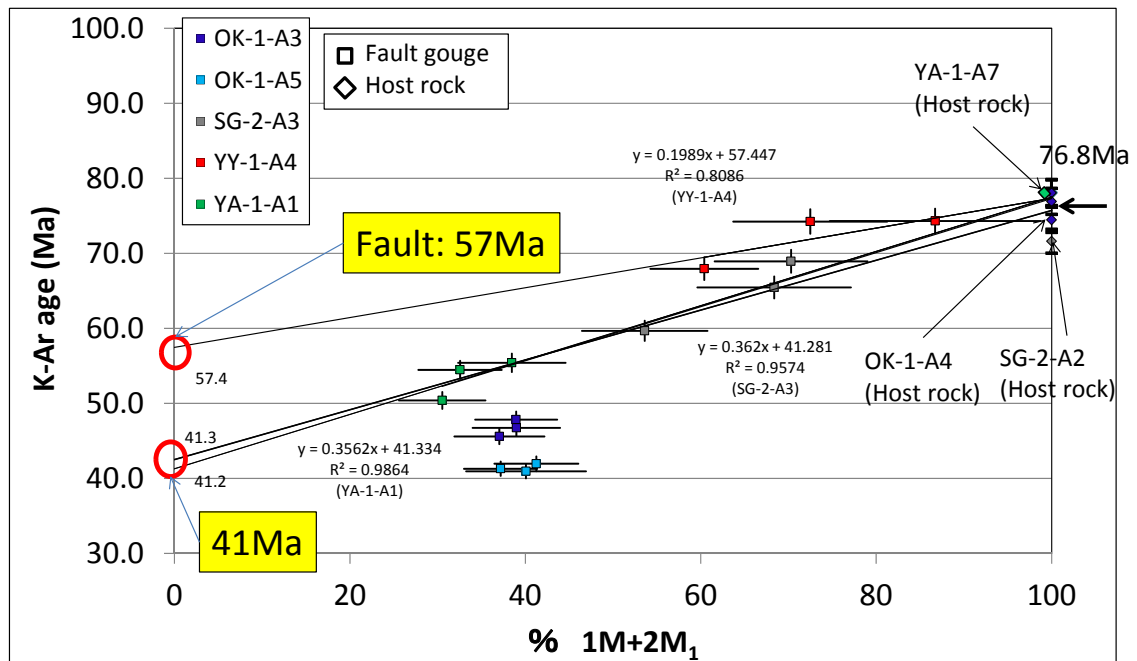


Figure 30. Illite age analysis for all size fractions of all the fault gouge samples, based to evaluate authigenic and detrital end member ages (IAA; illite age analysis) (e.g. [Zwingman et al. \[2011\]](#)). See table 1. for values of illite-polytype quantification and K-Ar ages.

the fault gouge samples, indicating that these ages can be reliable ages. Further, in previous study, fission-track dating of zircon from host rocks of felsic tuff beds in Izumi Group in study area yielded 79.1 ± 2.2 Ma [Noda *et al.*, 2010] and 77.3 ± 4.4 Ma [Sato *et al.*, 2005]. Hence, the K-Ar ages of host rocks obtained in this study is the age of the sedimentation of the Izumi Group.

The other, it examined the interpretation of K-Ar dates by other methods in this study. First, the relative polytype proportions based on peak areas of experimental XRD patterns [Grathoff and Moore, 1996] result the K-Ar age of fault gouge could be divide two ages of 44.2 to 49.1 ± 1.4 Ma and 66.8 ± 1.6 Ma (Figure 31, table 2). Second, the K-Ar age of fault gouge based on illite crystallinity index [Tanaka *et al.*, 1996] could be inferred ages of ca. 40 to 46 Ma (Figure 32). The first method has a large error [Grathoff and Moore, 1996], and second one could obtain only most younger age, hence be insufficient in the case of multiple ages. Therefore, this study adopts the method of IAA approach.

Based on the above discussion, the K-Ar age of Ichinokawa phase is 57.4 ± 1.6 Ma which is constrained into amore narrow range in this study. Pseudotachylyte vein associated with the MTL fault gouge in Kinki district yield a zircon fission-track age of 60.0 ± 3.5 Ma [Takagi *et al.*, 2010]. The pseudotachylyte vein is formed by seismic faulting and record one fault event unless the texture breaks, and the closure temperature of zircon fission-track system is about 300 °C [Hurford, 1986; Tagami *et al.*, 1995]. Therefore, it is inferred that the Ichinokawa phase is 57.4-60.0 Ma. It is probable that when the Izumi Group and the Sambagawa metamorphic rocks were juxtaposed by normal faulting at depth during the Ichinokawa phase, the latter was not exposed at the surface. Therefore, the normal faulting probably occurred before the deposition of the Lower Eocene Hiwada-toge Formation [Narita *et al.*, 1999], when the Sambagawa metamorphic rocks were finally exposed to the surface, and eroded, providing detritus to the Hiwada-toge Formation. The estimated age for 57.4-60.0 Ma is just before the period of sedimentation of the Hiwada-toge Formation and consistent with the inferred age of Hiwada-toge Formation. Moreover, the K-Ar age of pre-Tobe phase is 41.2 to 41.3 Ma which is also constrained into the more narrow range in this study (Figure 34).

In previous study of K-Ar age dating along the MTL [Shibata *et al.*, 1989; Takagi and Shibata, 1992; Takagi *et al.*, 1992; Yamakita *et al.*, 1995], the sample separation for fine-grained fraction only conducted for

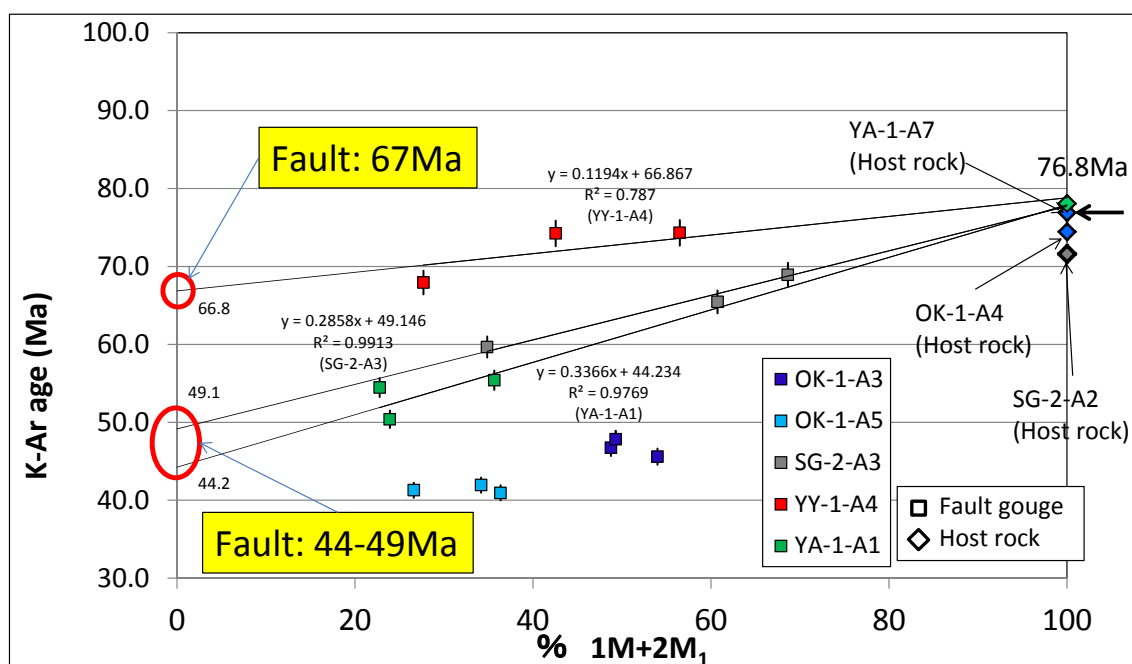


Figure 31. Illite age analysis for all size fractions of all the fault gouge samples, based on peak areas of experimental XRD patterns ([Grathoff and Moore \[1996\]](#)). See table 2. for values of illite-polytype quantification and K-Ar ages.

Table 2. Illite polytype quantifications based on peak areas of experimental XRD patterns (*Grathoff and Moore [1996]*).

sample	Equations	(1)	(2)	(3)	(4)	(5)	(6)	(7)	1M (Area)	1Md (Area)	%2M ₁ (Area)
	$2\theta(\text{Cu-K}\alpha)$	23.8	25.5	27.8	29.8	32.1	24.3	29.1			
	Å	3.74	3.50	3.21	3.00	2.80	3.66	3.07			
	grain size	%2M ₁ (Area)					%1M(Area)				
SG-2-A3	1.0-2.0 μm	39.0129402	43.84865	105.843	24.36844	44.00043	26.34104	8.12124	17.2	31.4	51.4
	0.4-1.0 μm	44.9940461	74.8633	77.64538	21.15749	19.70092	15.64774	10.48774	13.1	39.3	47.7
	0.2-0.4 μm	14.4902453	17.42089	31.71693	11.67952	13.50673	22.99277	11.19465	17.1	65.1	17.8
YA-1-A1	1.0-2.0 μm	5.95616887	24.31575	44.7354	10.86134	24.40131	14.93779	12.27197	13.6	64.3	22.1
	0.4-1.0 μm	5.75713106	18.11972	33.56954	6.909102	15.5298	13.70305	10.85809	12.3	71.7	16.0
	0.2-0.4 μm	4.2531972	11.39132	24.69606	7.839325	4.293825	15.21977	11.64597	13.4	76.1	10.5
YY-1-A4	1.0-2.0 μm	24.8574098	39.38955	72.74177	21.56121	34.79249	21.78876	13.85103	17.8	43.5	38.7
	0.4-1.0 μm	17.6754601	33.70574	43.16191	22.21775	26.00625	15.93697	12.06223	14.0	57.4	28.6
	0.2-0.4 μm	3.55690466	14.96613	22.57836	15.30027	14.08974	12.43295	14.76622	13.6	72.3	14.1
OK-1-A3	1.0-2.0 μm	2.78707991	10.95534	2.05	3.25	1.88	46.54085	43.69404	45.1	50.7	4.2
	0.4-1.0 μm	1.4	7.498092	2.05	3.25	1.88	47.31213	43.79285	45.6	51.2	3.2
	0.2-0.4 μm	1.4	3.19	2.05	3.25	1.88	49.47379	53.81875	51.6	46.0	2.4
OK-1-A5	1.0-2.0 μm	1.4	3.19	2.05	5.712542	1.88	37.12228	25.54307	31.3	65.8	2.8
	0.4-1.0 μm	1.4	3.19	2.05	6.371556	1.88	26.97928	20.30674	23.6	73.4	3.0
	0.2-0.4 μm	1.4	3.19	2.05	3.25	1.88	43.37935	24.64185	34.0	63.6	2.4

Grathoff and Moore(1996)

(1) %2M₁(Area)=1.40+543×area of 3.74 $\text{\AA}$ band /area of the 2.58 $\text{\AA}$

(2) %2M₁(Area)=3.19+386×area of 3.50 $\text{\AA}$ band /area of the 2.58 $\text{\AA}$

(3) %2M₁(Area)=2.05+360×area of 3.21 $\text{\AA}$ band /area of the 2.58 $\text{\AA}$

(4) %2M₁(Area)=3.25+335×area of 3.00 $\text{\AA}$ band / area of the 2.58 $\text{\AA}$

(5) %2M₁(Area)=1.88+702×area of 2.80 $\text{\AA}$ band /area of the 2.58 $\text{\AA}$

(6) %1M(Area)=4.98+136×area of 3.66 $\text{\AA}$ band /area of the 2.58 $\text{\AA}$

(7) %1M(Area)=3.40+132×area of 3.07 $\text{\AA}$ band /area of the 2.58 $\text{\AA}$

(8) %2M₁(Area)=((1)+(2)+(3)+(4)+(5))/5

(9) %1M(Area)=((6)+(7))/2

(10) %1Md=100-(%1M+%2M₁)

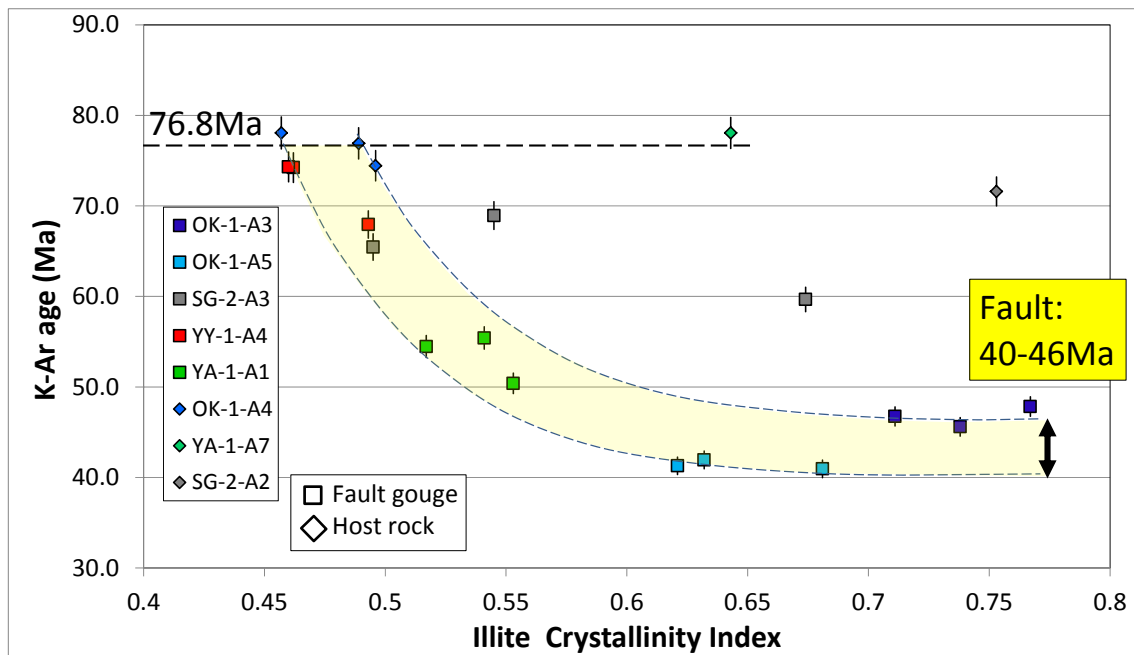


Figure 32. Illite age analysis for all size fractions of all the fault gouge samples, based on illite crystallinity index ([Tanaka et al. \[1996\]](#)). See table 1. for values of illite crystallinity index and K-Ar ages.

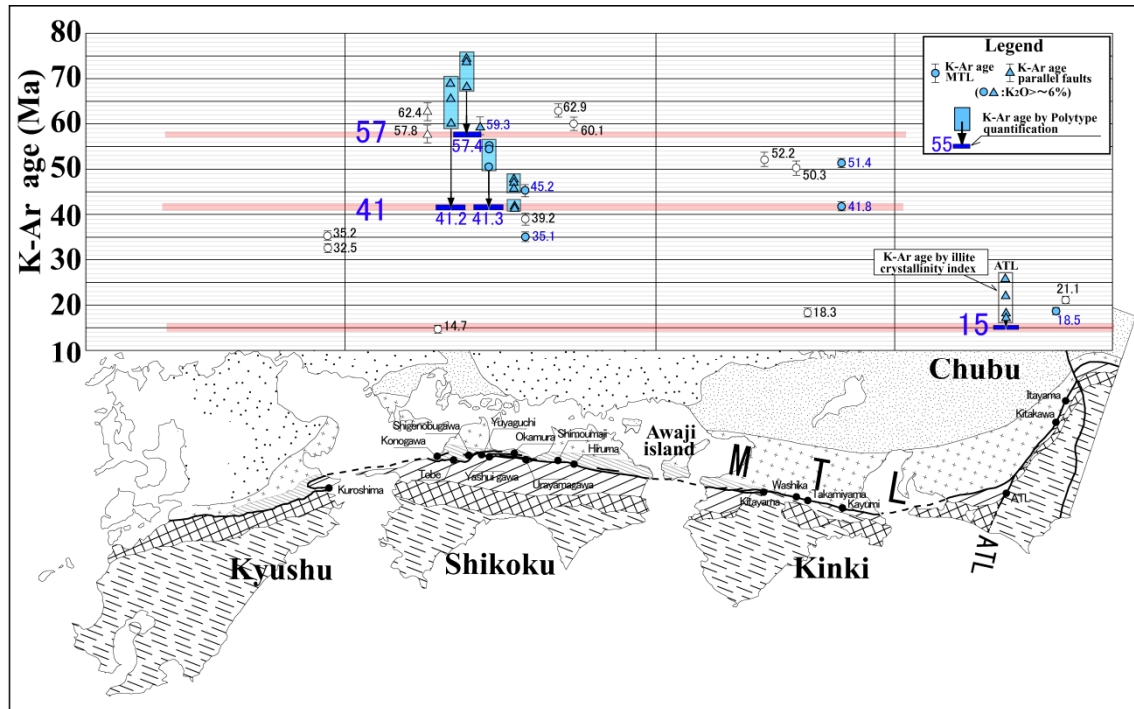


Figure 33. K-Ar dates of fine fractions (< 2 μm) of fault gouge from the MTL, parallel faults of MTL and the ATL (Akaishi Tectonic Line). K-Ar dates mark of blue lines, points and letters indicate measured K_2O are higher than 6% and reliable measurements as K-Ar dates of illite. This study and references cited are: 1:Kuroshima [Yamakita et al., 1995], 2:Konokawa, 4:Yuyaguchi, 5:Urayamakawa, 6:Shimoumaji, 7:Hiruma [Shibata et al., 1989], 3:Tobe [Takagi et al., 1992], 8:Kitayama [Shibata and Uchiuni, 1992], 9:Washiya, 10:Takamiyama [Shibata et al., 1988], 11:Kayumi [Takagi et. al., 1989], 12:ATL [Tanaka et. al., 1995], 13:Kitakawa [Shibata and Takagi, 1988], 14:Itayama [Takagi et al., 1991]

[*Takeshita, 1993*], *4 [*Yamakita et al., 1995*], *5 [*Takagi and Shibata [1992]* modified after *Shibata et al. [1989]*], *6 [*Miyata et al., 1980*], *7 [*Miyata, 1990*], *8 [*Takagi and Shibata [1992]* modified after *Shibata and Takagi [1988]*; *Takagi et al. [1991]*; *Tanaka et al. [1992]*], *9 [*Tanaka and Hara, 1990*], *10 [*Tanaka et al., 1992*], *11 [e.g. *Takeshita et al., 2000*], *12 [*Narita et al., 1999*], *13 [e.g. *Tashiro, 1985*], *14 [*Teraoka, 1977*], *15 [*Ichikawa, 1980*], *16 [e.g. *Otofuji and Matsuda, 1984*], *17 [e.g. *Itaya and Takasugi, 1987*], *18 [*Tanaka et. al., 1995*], *19 [*Takagi et. al., 2010*], *20 [*Maruyama and Seno, 1986*].

<2 μ m grain size fraction of fault gouge, and the ratio of different polytypes of illite has not been analyzed. It is then inferred that the precision of ages by the previous K-Ar dating is not enough to compare with those from the IAA plots. Therefore, these ages are only considered as reference values in this study.

In this study, the ages of first and second phase fault movements obtained for the K-Ar dating of MTL at locality MTL-2 (Figure 19) fault gouge showing normal slip and sinistral and reverse slip sense, yields 41.3 ± 1.2 Ma (YA-1-A1) (Figure 30). The other, the ages of second phase fault movements obtained for the K-Ar dating of F4 fault gouge showing sinistral and reverse slip sense yields 57.4 ± 1.6 Ma (YY-1-A4) (Figure 30). The amount of illite-1M_d of sample YY-1-A4 is relatively lower than other samples, especially sample YA-1-A1. It is inferred that the amount of illite-1M_d of the fault zone increase caused by repeatedly receiving a heat more higher temperature than stable one of illite-1M_d. Therefore, it is interpreted in the following way. At locality MTL-2, authigenic illite-1M_d formed by rising temperature in the fault zone along the MTL by normal faulting at the first stage, followed by sinistral and reverse slip faulting at second. The latter faulting occurred under relatively lower temperatures than ~ 100 - 200 °C that is stable temperature of illite-1M_d, where the age of one was reset and increased amount of illite-1M_d. The other, at locality of sample YA-1-A1 of F4 authigenic illite-1M_d formed by rising temperature in the fault zone along the MTL by normal faulting at the first stage, followed by the formation of F4 formed by sinistral and reverse slip faulting at second. However, the latter faulting occurred under relatively lower temperatures than ~ 100 - 200 °C, where the age of one was not reset. Therefore, the age of latter movement could have been acquired and preserved in the sample YA-1-A1, and one of former movement could have been acquired and preserved in the sample YY-1-A4 only ca. 100 m apart from the MTL.

5.4. Tectonics in the southwest Japan in the late Cretaceous-Paleogene and its relation to plate tectonic framework

The MTL of pre-Neogene age was located in the arc crust inside of the subduction zone, and had behaved as a major arc-parallel fault oriented in the NNE–SSW direction, before the clockwise rotation of southwest Japan arc due to opening of the Japan Sea at ca 15 Ma [*Otofuji and Matsuda, 1984, 1987*]. At the birth stage

of the MTL (Kashio phase), the MTL was activated as a large-scale left-lateral strike-slip fault or low-angle fault with a top-to-the-west sense of shear, as aforementioned. The faulting occurred immediately after or during the intrusion of plutonic rocks in the Ryoke belt, the K-Ar and Rb-Sr mineral ages [Yamana *et al.*, 1983] and CHIME ages [Suzuki *et al.*, 1994] of which vary between 90 Ma and 80 Ma and 95–87 Ma, respectively, in its western part. According to Engebretson *et al.* [1985], which are summarized by Maruyama and Seno [1986], the Izanagi oceanic plate had subducted in the direction of NNW beneath NNE–SSW-trending proto-southwest Japan arc between 100 Ma and 85 Ma in the Cretaceous. Therefore, the strongly left-lateral oblique subduction of the Izanagi oceanic plate is perhaps responsible for the left-lateral strike-slip movement along the MTL during the Kashio phase, and also a top-to-the-west sense of shear in the Sambagawa metamorphic rocks during their exhumation [Otsuki, 1992; Takeshita and Yagi, 2004]. After, between 85 Ma and 70 Ma, the sedimentary basin of the Upper Cretaceous Onogawa (93–82 Ma) and Izumi Group (77–70 Ma) had formed along the MTL [e.g. Seike *et al.*, 2013]. It has been shown that the Izumi sedimentary basin formed as a pull-apart basin, which resulted from a left-lateral strike-slip along the MTL [e.g. Miyata, 1990].

At the Ichinokawa phase at 60–57 Ma, Kubota and Takeshita [2008] suggested that normal faulting could have occurred along the MTL, resulting in the juxtaposition of the Sambagawa metamorphic rocks against the Izumi Group. The change in tectonic movement along the MTL from the Kashio to Ichinokawa phase might have been caused by the change in plate tectonic framework. Again, according to Engebretson *et al.* [1985], the Pacific oceanic plate had subducted beneath proto-southwest Japan arc (i.e. Eurasian plate) in the northwest direction, almost normal to the arc between 74 Ma and 53 Ma. It should be noted that the relative convergent velocity between the oceanic plate and proto-southwest Japan arc was reduced from 23.5 cm/year at 100–85 Ma to 10.4 cm/year at 74–53 Ma (Figure 35). Further Müller *et al.* [2016] shows that the ocean ridge of Izanagi-Pacific and young oceanic plate subducted beneath proto-southwest Japan arc between about 60 Ma to 50 Ma. Extension and normal faulting along the MTL are not solely explained by the reduction of plate convergence rate, although they might be triggered by it. Kubota and Takeshita [2008] inferred that a most plausible explanation for the normal faulting and the resultant final exhumation of the Sambagawa

metamorphic rocks is dynamic equilibrium between crustal thickening at depth (underplating) and extension at shallow level [Platt, 1986]. In fact, the Upper Cretaceous Shimanto Group in eastern Shikoku (e.g. Tei melange) was underplated around 65 Ma [Hasebe *et al.*, 1993], nearly coeval with the timing of normal faulting. Also, the top-to-the-north normal faulting, the movement direction of which is normal to proto-southwest Japan (N75°E in the present orientation), suggests gravitational force is the sole driving force for the extension and normal faulting.

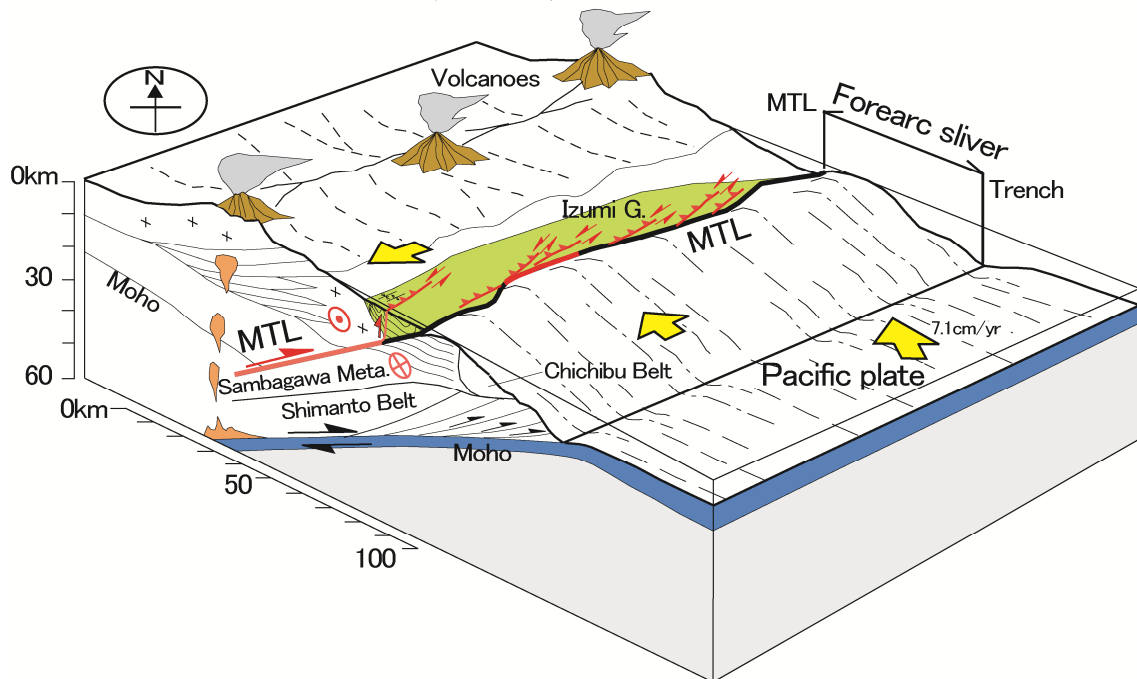
The pre-Tobe phase at 41 Ma, that sinistral-reverse faulting could have occurred along the MTL, resulting in formation of parallel fault system along the MTL, and a large-scale folding of the Izumi Group and thrusting of the Northern over the Southern Izumi belt. The change in tectonic movement along the MTL from the Ichinokawa to pre-Tobe phase might have been caused by the change in plate tectonic framework. According to Engebretson *et al.* [1985], which are summarized by Maruyama and Seno [1986], the Pacific oceanic plate had subducted in the direction of North to NNW beneath NNE–SSW-trending proto-southwest Japan arc, and the relative convergent velocity between the oceanic plate and proto-southwest Japan arc was from 8.9 to 7.1 cm/year between 53 Ma and 43 Ma (Figure 35). The pre-Tobe phase is equivalent at the almost end time of the period, the left-lateral oblique subduction of the Pacific oceanic plate is perhaps responsible for the sinistral and reverse slip movement along the MTL, and branch faults with *en échelon* arrangement oriented counterclockwise for the MTL formed in the Izumi Group in the northern side of one. On the other hand, Müller *et al.* [2016] shows that the Pacific oceanic plate subducted beneath proto-southwest Japan arc between 60 Ma and 40 Ma without remarkably changing the relative velocity and direction from those at the previous ages, and they inferred that it does not appear to be directly related to the Hawaiian-Emperor Bend formed during the same period.

In addition to the MTL, the fault ages during Paleocene-Middle Eocene have been also reported from widespread localities in Japan: the Atera fault [Yamada *et al.*, 1992], the Morozumi-Sukenobu fault [Takagi *et al.*, 2005], the Asuke shear zone [Kanai and Takagi, 2016], Nojima fault [Murakami and Tagami, 2004; Zwingmann *et al.*, 2010] known as major faults in Japan, and fault zone in the Toki granite [Yamasaki *et al.*, 2013]. Takagi *et al.* [2005] suggested that the major hydrothermal events associated with faulting in the

southwest Japan occurred at approximately 60-50 Ma. [Kanai and Takagi \[2016\]](#) inferred that the Asuke shear zone was activated under a stress state that caused sinistral and normal movements during the period 70-50Ma, and [Yamasaki et al. \[2013\]](#) inferred that the fault zone in the Toki granite was activated during the period 54-43Ma. [Famin et al. \[2014\]](#) inferred that based on analysis of rock deformation microstructures and mesostructures to reconstruct the long-term orientation of stresses around faults, the MTL and the Rokko-Awaji Segment (included Nojima fault) may have been activated as a sinistral lateral fault during the period 65-45 Ma. Moreover, [Takagi et al. \[2008\]](#) and [Kanai et al. \[2014\]](#) estimated the paleostress conditions of σ_3 axis which trended nearly normal to the MTL in 68-63Ma, and nearly parallel to the MTL in 63-60 Ma, based on analyzed the preferred orientation of healed microcracks in quartz of the Ryoke granite in central Japan. As stated above the previous studies, the paleostress conditions had changed extension to lateral stress field at the MTL in Paleocene, and sinistral faulting had been formed inside Japan arc during Paleocene-Middle Eocene. Moreover, during the Late Eocene to Early Oligocene (38-30 Ma) after the Middle Eocene tectonic stress around the MTL changed to extensional stressfield. [Mitamura et al. \[2016\]](#) inferred North-South extension during the late Eocene to Early Oligocene based on field observations and microstructural analyses of meso-scale faults in the Ikoma fault zone. In these period, sedimentary basins in the Japan arc formed under extensional paleostress condition, for example the Kobe Group in Kinki district during the Late Eocene to Early Oligocene [[Okazaki, 2009](#)], Chikuhō-type structure sedimentary basins in Kyūshū district during the Middle Eocene to Early Oligocene [[Sakai, 1993](#)].

Previous geophysical studies conducted along the MTL at locations from Kyushu to the Kinki district have indicated that the fault plane of MTL dips northward at low angles [e.g., [Goto et al., 1998](#); [Ito et al., 2009](#); [Ohno et al., 1989](#)]. [Ito et al. \[2009\]](#) reported on the basis of a seismic reflection survey results that the MTL cuts the whole upper crust down to 24km depth, dipping almost straight northward at about 30° to 40°. [Ikeda et al. \[2014\]](#) reported the resistivity structure by magnetotelluric survey across the MTL in Shikoku district, where the remarkable low-resistivity zone dipping northward at 40° and extending to 20 km depth in the resistivity image probably corresponds to the MTL. Further, [Shimamoto \[1989\]](#) estimated the strength in the horizontal compression stress field to form a reverse fault based on the friction strength and flow law, and

Pre-Tobe Phase (41Ma)



Ichinokawa Phase (57–60Ma)

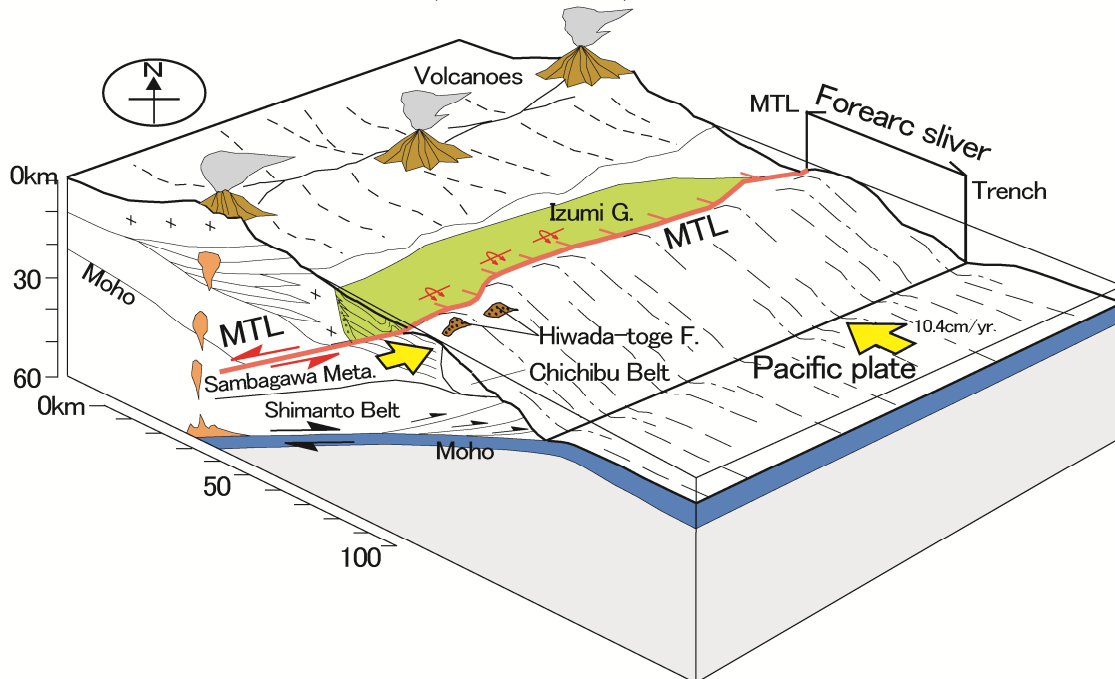


Figure 35. Schematic diagram (NW–SE cross-sections) to show tectonic development from subduction zone to Median Tectonic Line (MTL). Tectonics and geological ages during the Paleogene are refined by this study. The Ichinokawa phase at 57–60 Ma, normal faulting could have occurred along the MTL, resulting in the juxtaposition of the Sambagawa metamorphic rocks against the Izumi Group. According to [Engelbreton et al. \[1985\]](#), which are summarized by [Maruyama and](#)

showed the strength section of the Japan arc, and inferred the thickness of rigid crust is only 20 km depth. Further, he also suggests that at least in Shikoku area the MTL are a kind of strike slip fault of Fitch type [Fitch, 1972]. Fitch [1972] proposed that the relative movement vector of oblique plate convergence decouples into a component of convergence normal to the plate boundary and a shear component taken up by strike-slip faulting on a transcurrent fault in the interior of the overriding plate. Therefore, because large-scale arc-parallel faults record a shear component of the movement of subducting oceanic plate relative to continental plate [Fitch, 1972; Jarrard, 1986; Chemenda *et al.*, 2000], kinematic studies on these faults are important to elucidate plate tectonic framework in geological ages. Jarrard [1986] argued, strike-slip movement along a major arc-parallel fault hardly occurs in the case that the obliquity of plate subduction is $<20^\circ$. In this study, since the obliquity angle at 74-53 Ma is $\sim 15^\circ$ inferred from the relative plate movement by (Engebretson *et al.*, 1985) and the reconstructed direction of southwest Japan arc ($N30^\circ E$, e.g. Otofujii *et al.*, 1985), sinistral strike-slip movement could not have occurred along the MTL at the Ichinokawa phase (60-57 Ma), while sinistral slip movement could have occurred along the MTL at the pre-Tobe phase (41 Ma) because of the obliquity angle of $\sim 15^\circ$ at 55-40 Ma.

5.5. Tectonics in the East Asia in the late Cretaceous-Paleogene

Along the Pacific of the East Asia, the Meso-Cenozoic was a time of intense deformation. Large horizontal displacement occurred within the continent along some major fault zone with NNE–SSW-trend, these faults are important geological structure for tectonics and played an important role in reformation of the Mesozoic tectonic framework in east Asia [e.g., Xu *et al.*, 1989]. There are large horizontal faults of faults in East Asia during the Meso-Cenozoic, such as the Tancheng–Lujiang (also called Tan–Lu) fault zone (TLF) of eastern China, the MTL of Japan, and South Korean Tectonic Line (SKTL) of South Korea [e.g., Chough and Sohn, 2010]. The TLF is a large left-lateral transcurrent fault system, which longitudinally transected the East Asian continent, with a NNE–SSW trend, that may be followed for over 2000 km from the boundary between Russia and China in northern China, to the Yangtze River in southern China, and continues to Yilan-Yitong fault zone (YYFZ) and Fushan-Mishan fault (FMF) in northern China (Figure 36). The SKTL is a major fault

with a NNE–SSW trend in the Korean peninsula along which several small basins formed. These small basins are interpreted to have formed by sinistral strike slip faults and then terminated in the Late Cretaceous [Chough and Sohn, 2010].

Based on previous studies and this study, tectonics in the East Asia in the Cretaceous-Paleogene divided into four main phases (Figure 36). At the first phase during the Cretaceous to Paleocene, along some major fault zones with NNE–SSW-trend large-scale sinistral faulting occurred [e.g., Xu, 1993; Chough and Sohn, 2010]. The MTL was activated as a large-scale left-lateral strike-slip fault during this period (Kashio phase). The Izanagi oceanic plate had subducted Eurasian plate in the direction of NNW beneath NNE–SSW-trending continental margin of proto-southwest Japan arc and the relative convergent velocity between the oceanic plate and continental margin was 23.5 cm/year [Engelbreton et al., 1985; Maruyama and Seno, 1986]. Therefore, the strongly left-lateral oblique subduction of the Izanagi oceanic plate is perhaps responsible for the left-lateral strike-slip movement along some major fault zone with NNE–SSW trend. It is inferred that the movement had continued ca. 70Ma.

The second phase during from the Late Paleocene to the Early Eocene, some major fault zone with NNE–SSW trend in continent had been not displacement in this period. In this study, that normal faulting could have occurred along the MTL at 60-57 Ma. In this period, the Pacific oceanic plate had subducted Eurasian plate in the northwest direction, almost normal to continental margin, and the relative convergent velocity between the oceanic plate and continental margin was 10.4 cm/year [Engelbreton et al., 1985; Maruyama and Seno, 1986], moreover Izanagi-Pacific ridge subducted Eurasian plate during 60-55Ma [Whittaker et al., 2007]. It is inferred that some major fault zone with NNE–SSW trend in continent had been not displacement because of the compression axis which trended nearly normal to major fault zone with NNE–SSW trend, however the MTL close to subduction zone had occurred normal faulting because of dynamic equilibrium between crustal thickening at depth (underplating) and extension at shallow level is a plausible explanation for the normal faulting because the arc-normal extension suggests gravity as the driving force [Kubota and Takeshita, 2008]. Moreover, the MTL had been reconstructed to fault plane of lower slope by the juxtaposition of the Sambagawa metamorphic rocks against the Izumi Group.

For the third phase during the Middle Eocene, there are also few previous studies in this period. In this study, it has been shown that the sinistral-reverse faulting could have occurred along the MTL at 41 Ma. The Pacific oceanic plate had subducted in the direction of North to NNW beneath NNE–SSW-trending continental margin of proto-southwest Japan arc, and the relative convergent velocity between the oceanic plate and continental margin was from 8.9 to 7.1 cm/year [Engelbreton *et al.*, 1985; Maruyama and Seno, 1986]. In continental margin of proto-southwest Japan arc, branch faults along the MTL and other faults had formed because the MTL reconstructed to low slope fault is hard to eliminate lateral stress.

At the fourth phase during from the Late Eocene to the Oligocene, extensional faulting associated with differential vertical movements occurred [Xu, 1993]. Same sedimentary basins have a large area of deposition with significant subsidence, caused by a number of approximately E–W-trending normal faulting under an extensional stress condition in the N–S direction [e.g., Zhang *et al.*, 2015; Sakai, 1993]. The Pacific oceanic plate had subducted in the direction of NW to WNW beneath NNE–SSW-trending continental margin of proto-southwest Japan arc, and the relative convergent velocity between the oceanic plate and continental margin was from 10.6 to 5.8 cm/year [Engelbreton *et al.*, 1985; Maruyama and Seno, 1986].

6. Conclusions

The MTL in southwest Japan has been defined as the boundary fault between the Sambagawa metamorphic rocks belonging to the Outer zone and the Ryoke metamorphic and plutonic rocks belonging to the Inner zone, which are unconformably covered by the Upper Cretaceous Izumi Group. In Paleogene, two phases faulting occurred after the deposition of the Izumi Group (called the Ichinokawa and pre-Tobe phase, Kubota and Takeshita, 2008). Based on detailed geological mapping of the Izumi Group, western Shikoku, and structural analyses of a disturbed zone along the MTL, and K–Ar geochronology, we reach the following conclusions on the kinematics of the MTL during the period from the Paleocene to Eocene. Although Kubota and Takeshita [2008] inferred that the latter faulting at the Pre-Tobe phase occurred in the Paleogene, movement picture has been not clarified. In this study, based on detailed structural analyses, the movement pictures at Pre-Tobe phase has been analyzed in detail.

In the study area, the parallel fault system along the MTL develops in the Izumi Group, defining a deformation zone consisting of cataclasite and fault gouge up to 30 m thick along the faults. The faults are arranged in *en échelon* arrangement oriented counterclockwise for the MTL along the northern side of one. Furthermore, the south-vergent to upright folds with *en échelon* arrangement oriented clockwise for the faults nearly parallel to the strike of the faults could have formed as drag folds due to sinistral and reverse slip fault movement along the faults. These macroscopic geological structure shows that the parallel faults had been formed as *en échelon* faults by left-lateral faulting of the MTL. Further, based on the observation of the outcrops, slabs and thin sections of the oriented samples from fault zone with ca. 30 m wide it has been shown that sinistral and reverse slip with a sense of top-to the southwest occurred along these faults. The fault system develops along the northern side of the MTL, dipping to north at high angles. Therefore, it is inferred that these are faults branch from the MTL dipping at a low angle at depth. In fact, it has been shown that sinistral and reverse faulting overprints normal faulting in the MTL fault zone, indicating that the MTL was also affected by sinistral and reverse faulting at the Pre-Tobe phase.

K-Ar dating has been conducted for five samples from foliated fault gouge layers in the fault core of the parallel faults, and other three samples of non-fractured host rocks 100 to 500m apart from the fault zone. In this study, for the age determination of authigenic illite from fault gouge, the methods of the IAA approach and previous studies has been applied (e.g., [Solum et al. \[2005\]](#); [Haines and van der Pluijm \[2008\]](#)). Further, the method of illite-polytype quantification to compare experimental XRD patterns with calculated patterns modeled using WILDFIRE© [[Reynolds, 1994](#)] has been applied. The experimental XRD patterns of the randomly oriented samples for all size fractions were obtained to determine the relative abundance of the illite polytype in each size fraction, and they are compared with the simulated XRD patterns of the different illite polytypes using WILDFIRE©. As a result, the ratio of the different illite polytypes was obtained for each sample, and the age of the 100 % authigenic 1M_d-illite is extrapolated, yielding the ages of the fault gouge at 41.3±1.2 Ma (YA-1-A1), 41.2±1.4 Ma (SG-2-A3), 57.4±1.6 Ma (YY-1-A4) with an error range of ca. ± 1.2-1.6 Ma, respectively. These K-Ar ages of fault gouge are divided into two age groups of 41.2 to 41.3 ± 1.4 Ma and 57.4 ± 1.6 Ma, which could indicate the ages for the Pre-Tobe and Ichinokawa phases

respectively, because the latter older ages could be interpreted as the relict age of the Ichinokawa phase considering that the locality is close to the MTL, and also the ratio of $1M_d$ illite is low. Further, considering also the previous studies of a zircon fission-track age of the pseudotachylyte vein, the Ichinokawa phase is constrained into the narrower age range between 60.0 to 57.4 Ma. Also, the pre-Tobe phase is constrained into the narrower age range between 41.3 to 41.2 Ma in the present study.

In this study, the obliquity angle of plate subduction at 74–53 Ma is $\sim 10^\circ$, which can explain that sinistral strike-slip movement does not occur along the MTL during this period, the other the obliquity angle at 53–43 Ma is $\sim 55\text{--}35^\circ$, which can explain that sinistral slip movement occur along the MTL during the pre-Tobe phase. For the Ichinokawa phase, it is inferred that dynamic equilibrium between crustal thickening at depth (underplating) and extension at shallow level is a plausible explanation for the normal faulting because the arc-normal extension suggests gravity as the driving force. The normal faulting might have been triggered by the reduction of convergence rate between the Eurasian and oceanic plates.

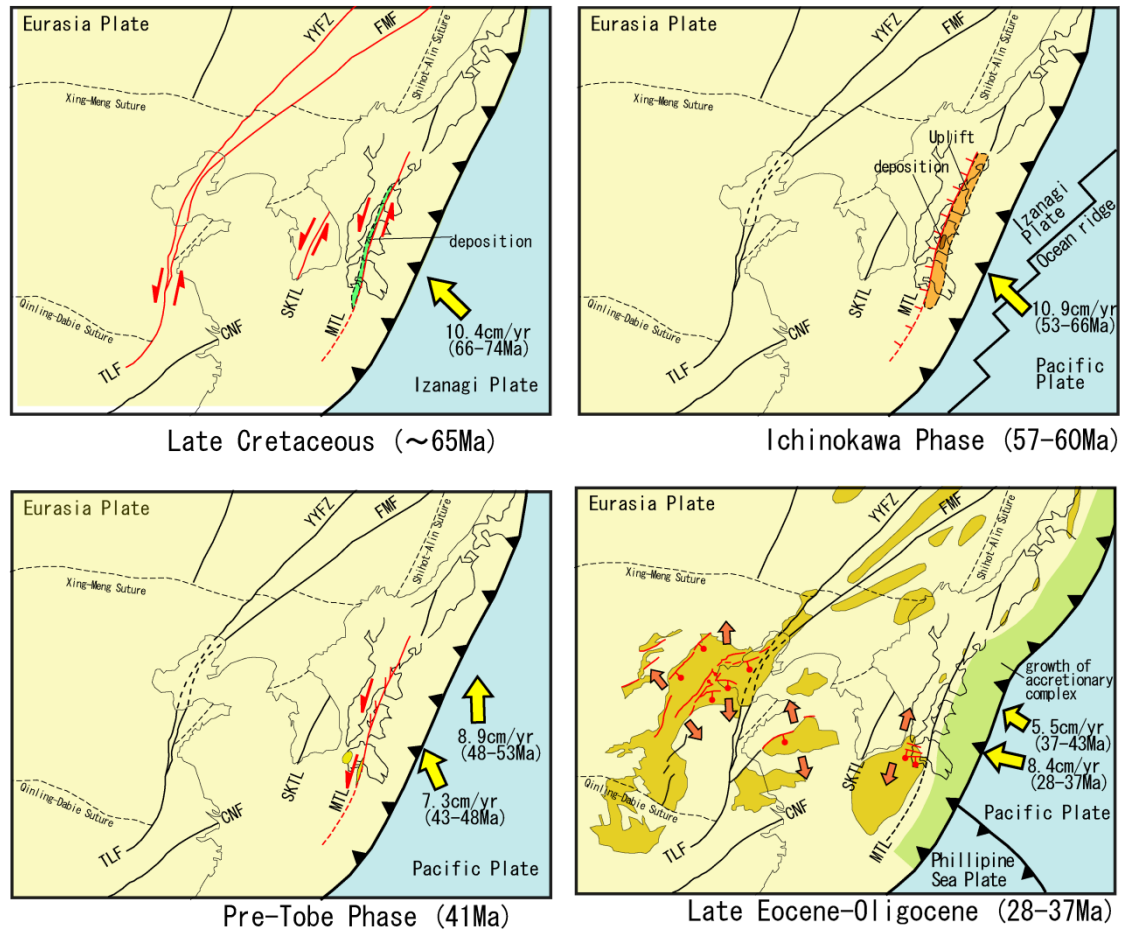


Figure 36. Based on previous studies, tectonics in the East Asia in the Cretaceous-Paleogene divided into four main phases. At the first phase during the Cretaceous to Paleocene, along some major fault zones with NNE-SSW-trending occurred large-scale sinistral faulting occurred with magnitude of displacement [e.g., [Xu, 1993](#); [Chough and Sohn, 2010](#)]. The MTL was activated as a large-scale left-lateral strike-slip fault during this period (Kashio phase). The Izanagi oceanic plate had subducted Eurasian plate in the direction of NNW beneath NNE-SSW-trending continental margin of proto-southwest Japan arc and the relative convergent velocity between the oceanic plate and continental margin was 23.5 cm/year [[Engelbreton et al., 1985](#); [Maruyama and Seno, 1986](#)]. The second phase during from end of the Paleocene to the Early Eocene. In this study, that normal faulting could have occurred along the MTL at 60-57 Ma. The Pacific oceanic plate had subducted Eurasian plate in the northwest direction, almost normal to continental margin, and the relative convergent velocity between the oceanic plate and continental margin was 10.4 cm/year, moreover Izanagi-Pacific ridge subducted Eurasian plate during 60-55Ma [[Whittaker et al., 2007](#)]. The third phase during from the Middle Eocene, there are few previous studies in this period. In this study at 41 Ma, that sinistral-reverse faulting could have occurred along the MTL. The Pacific oceanic plate

had subducted in the direction of North to NNW beneath NNE–SSW-trending continental margin of proto-southwest Japan arc, and the relative convergent velocity between the oceanic plate and continental margin was from 8.9 to 7.1 cm/year. The forth phase during from the Late Eocene to the Oligocene, extensional faulting associated with differential vertical movements. The Pacific oceanic plate had subducted in the direction of NW to WNW beneath NNE–SSW-trending continental margin of proto-southwest Japan arc, and the relative convergent velocity between the oceanic plate and continental margin was from 10.6 to 5.8 cm/year. Modified after [Maruyama et al.\[1997\]](#).

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