Evolutionary Models of Convergent Margins : Origin of Their Diversity

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Structural Features Along the Median Tectonic Line in Southwest Japan: An Example of Multiphase Deformation on an Arc-Bisecting Fault

Yasuto Itoh and Tomotaka Iwata

Additional information is available at the end of the chapter

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Abstract

A geological survey for the Late Cretaceous Izumi Group distributed on the Median Tectonic Line (MTL) active fault system in the central part of southwestern Japan has revealed varied deformation styles. Among the confined deformation zones found in the western and central parts of the study area, some are located far from the active trace of the MTL (Negoro Fault), at distances of up to 300–350 m. Such kink zones may have been generated during a contraction phase of the MTL from the end of the Pliocene to the early Pleistocene. We identified clear active foldings in a narrow zone sandwiched between a north dextral and a south reverse active fault. Western and eastern upheavals of the crustal sliver show ridge and domal active morphologies, respectively. Structural analysis was extended to the north of the MTL, where the Izumi Group has suffered multiphase deformation since the Cretaceous. The phase stripping method was introduced to extract the neotectonic trend, which successfully delineated complicated deformation zones related to the morphological divergence of the MTL active fault system.

Keywords: structural geology, active fault, active fold, Median Tectonic Line (MTL), southwest Japan

1. Introduction

The activity levels of neotectonic zones on convergent margins are usually assessed based on the geomorphological features or deformation of unconsolidated outcropping sedimentary layers by trench surveys. Such means achieve high resolution in describing superficial ruptures but provide little information on the mid-crustal architecture of faults, which is crucial for the evaluation of earthquake hazards. In contrast, geophysical researches exemplified by reflection seismic surveys can achieve great penetration into Earth's deep interiors but do not allow the deciphering of detailed time sequences of tectonic events. Geologic studies, in between, yield a reasonable definition, allowing the delineation of the upper crustal structure, which is useful in the understanding of the three-dimensional morphology of active faults. This has been, however, often misused for a one-sided interpretation, ignoring the cumulative processes of structures. In this chapter, the authors aim to extract a target deformation phase by stripping superimposed geologic features based on reliable tectonic models of structural build-up. The focus of the present field survey is the southwestern Japan arc, where the long-standing convergence of oceanic plates with variable obliqueness has provoked repeated slips upon an arc-bisecting fault and the complicated development of a damage zone.

2. Geological background

2.1. Median Tectonic Line (MTL)

The Median Tectonic Line (MTL) was formed during the Cretaceous, when a remarkably rapid northward movement of the Izanagi Plate resulted in the sinistral wrenching and eventual break-up of the eastern Eurasian margin [1]. Paleogeographic reconstruction suggested that the incipient MTL had been connected with the Central Sikhote Alin Fault to the north and constituted a regional transcurrent fault [2]. Propagating termination of the MTL was a site of pull-apart basin formation that was buried by an enormous amount of clastics, collectively called the Izumi Group [3].

After an essentially dormant period during the Paleogene, the MTL resumed activity under the strong influence of changes in the convergent mode of the Philippine Sea Plate. The Pliocene was marked by an intensive inversion related to the north-south compressive regime [4]. Although the inversion is most obviously observed on the backarc shelf, contemporaneous contraction features can also be identified on the forearc shelf [5]. Watershed mountain ranges emerged on the northern bank of the MTL, as was clarified by provenance studies of basin-filling clasts (e.g., [6]). The Philippine Sea Plate shifted its converging direction counterclockwise at ca. 2–1 Ma [7] and induced the production of vigorous dextral slips by the MTL.

2.2. Izumi Group

The present study area is located at the easternmost part of the basin, which was buried with the Maastrichtian marine sediments of the Izumi Group [8]. It is a series of marine sediments and is composed of the main facies (turbidite) and southern facies (non-turbidite). The main facies comprise voluminous turbidites associated with coarse clastics and intercalated by acidic tuff layers. It is divided into the Kada, Shindachi, Iwade and Kokawa Formations in ascending order. They form a large syncline with an east-plunging axis.

A previous sedimentological study [9] showed that the Izumi Group basically consists of stacks of mega-units. Facies associations indicate that the constituents of the units are classified into depositional systems, including main channels with overspilled deposits, distributary channels and sheet flows.

Zircon fission track ages obtained from acidic tuffs in the group range from 77 to 72 Ma, and molluscan fauna yielded from the unit is assigned to the latest Cretaceous [8].

3. Field observation

The results of our field survey are shown in **Figure 1** (upper) along with a previously developed geologic map of the same area [8] for comparison. In the following sections, we present a thorough description of structural features of the Izumi Group.

3.1. Confined deformation zones

The most remarkable fault damage zone was identified and described in the western part of the study area. **Figure 2** presents a plan view of a road construction site where deformed and brecciated sedimentary rocks of the Izumi Group are exposed. As shown in the figure, the azimuth of the damage zone inferred from the observation of surrounding exposures is coincident with the strike of the MTL, a fact which strongly indicates the development of the kink zone under the influence of shearing on the regional fault. It is noted, however, that the observatory is located far from the active trace of the MTL (Negoro Fault) with a distance of up to 300–350 m (see Figure 14 of Chapter 3). Hence, the kink zone may have been generated during a contraction phase of the MTL from the end of the Pliocene to the early Pleistocene. **Figure 3** shows typical photographs of the kink zone, with Photo 22 depicting mudstone and sandstone blocks in a chaotic matrix.

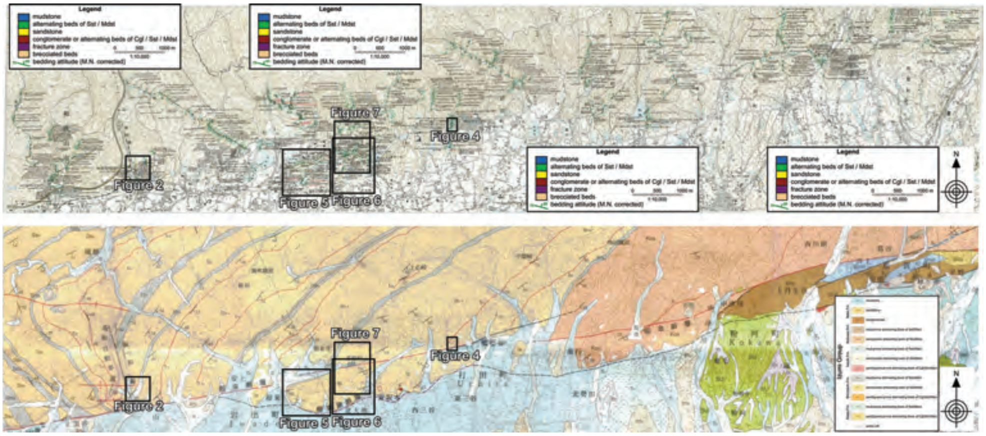

Figure 1. A field survey map of the present study (upper) together with a previous geologic map (lower; [8]). See prologue of this section for regional index.

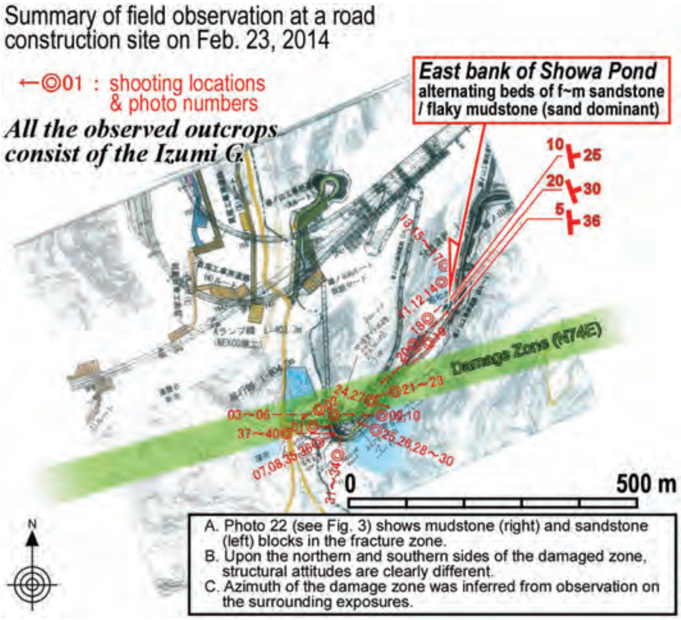

Figure 2. A summary of field observation on February 23, 2014, at a road construction site where a fault-related fracture zone was exposed. See **Figures 1** and **3** for the locality and example photographs, respectively.

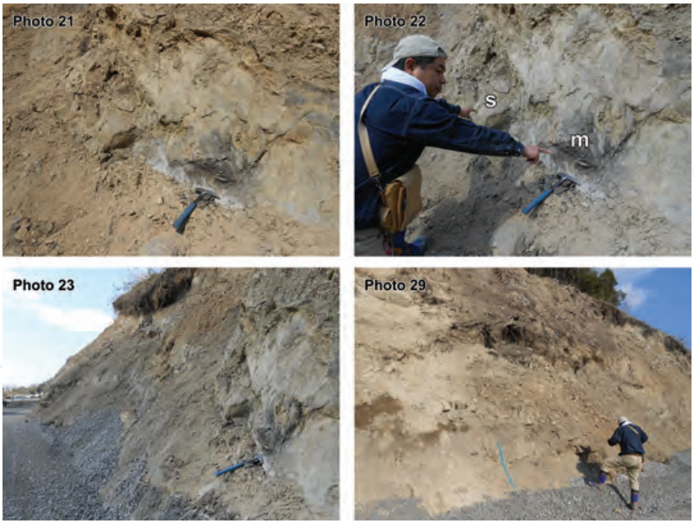

Figure 3. Example photographs of the fracture zone described in **Figure 2**. Photo 22 shows mudstone (right; m) and sandstone (left; s) chaotic blocks in the fracture zone.

Another notable deformation adjacent to the MTL active fault system in the central part of the study area was described in detail. In **Figure 4**, the ENE-WSW-trending active dextral fault runs along a carriageway in the southernmost part [10]. Along a rivulet crossing the fault, a broad damage zone with a width of nearly 200 m was confirmed; in this zone, the bedding attitudes of the Izumi Group show complicated undulation discordant with the general trend of the plunged syncline. From what can be observed, the level of damage shows no clear tendency to decrease in proportion to the distance from the fault trace. Brecciated sedimentary rocks in

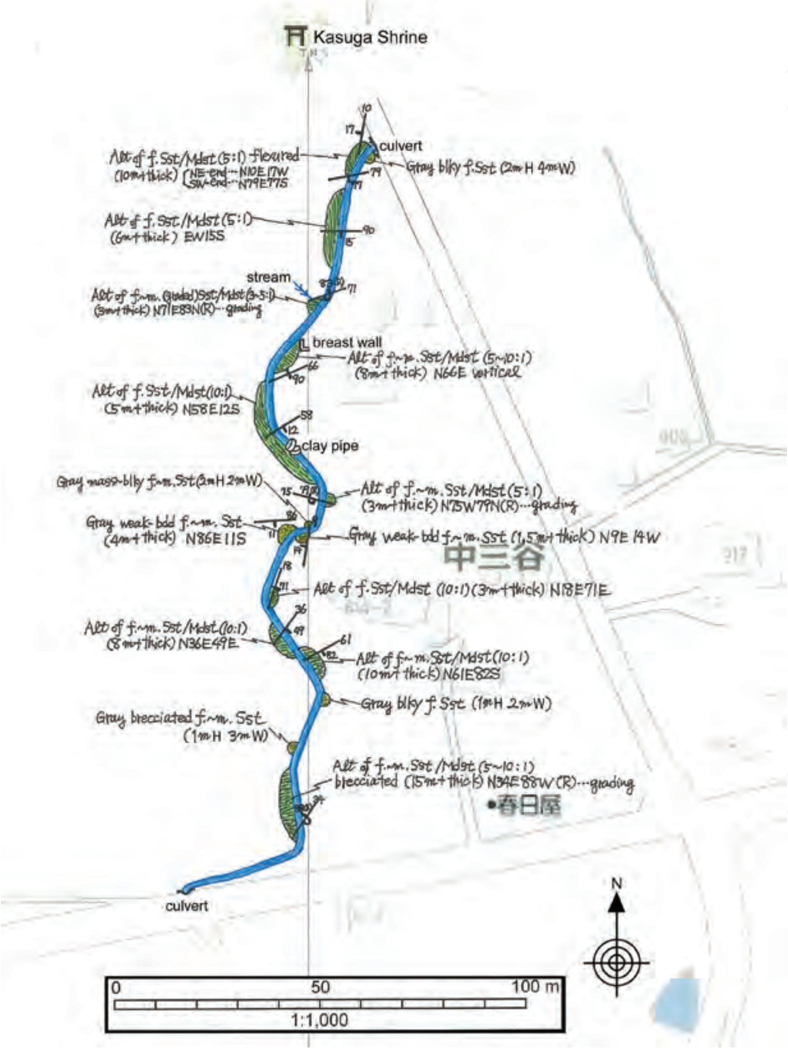

Figure 4. Field observation of a broad deformation zone adjacent to the Median Tectonic Line active fault system. See **Figure 1** for location.

the southern portion have steep structures parallel to the azimuth of the MTL, whereas the central and northern outcrops show often overturned bedding with flexure.

3.2. Active foldings

The MTL active fault system within the study area is specifically divided into two strands, the straightforward dextral Negoro Fault to the north and the sinuate reverse Negoro-Minami Fault to the south (see **Figure 1** (bottom)). An elongated sliver sandwiched between the faults, which mainly comprises sandy units of the Izumi Group, is expected to exhibit unique deformation acquired during recent periods. However, previous geologic [8] and geomorphological [10] studies have not remarked on its features. Hence, the authors attempted to describe the structural characteristics of the crust piece spooned up by the faults. In the following analysis, it was assumed that the initial structure of the Cretaceous system is horizontal since the block is situated outside of the pull-apart basin that experienced post-depositional contraction and harsh bending of the infill sediments.

Figure 5 shows the structural features of the Negoro-Maeyama Hill in the western part of the fault-bounded sliver. Although the previous geologic map (a; [8]) depicts tilting only on

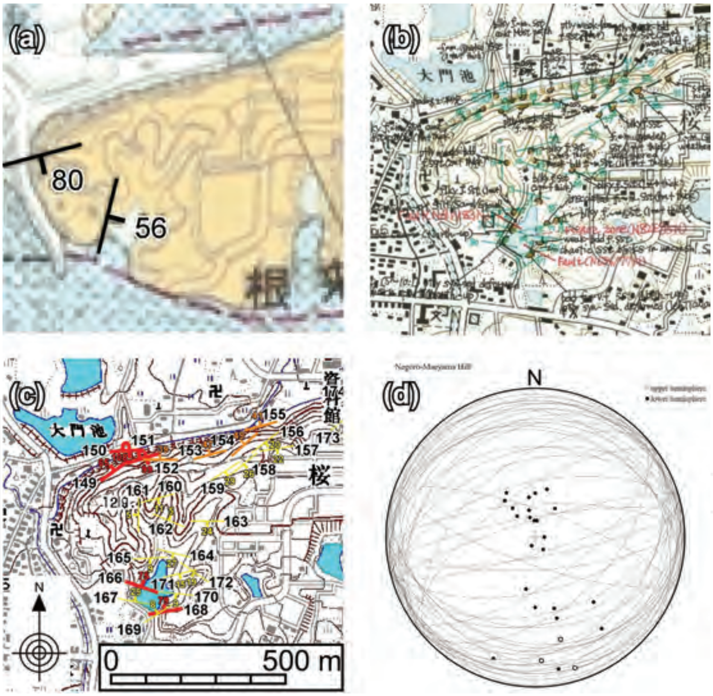

Figure 5. Structural analysis of the Negoro-Maeyama Hill (see **Figure 1** for the area of the maps a, b and c) between the Negoro and Negoro-Minami Faults. (a) Previous structural data based on a geologic map [8]. (b) A field survey map of the present study. (c) A compiled map showing the structural trends. Yellow, orange and red marks correspond to gentle (less than 30°), intermediate (between 30° and 60°) and steep (60° or more) dipping angles, respectively. (d) An equal-area projection of bedding girdles and their poles. Open dots represent overturned beds.

the hillside, the present detailed geologic investigation (b, c) clarified that the centre of the hill is characterized by gentle dipping, which is surrounded by steeply dipping (occasionally overturned) strata. A stereographic projection showing the poles and girdles of bedding planes (d) indicates that the initially flat-lying beds were folded around the ENE-WSW axis and formed a ridge parallel to the MTL.

Figure 6 shows the structural features of the Atago-yama Hill in the eastern part of the fault-bounded sliver. Similar to the analysis for the Negoro-Maeyama Hill, the present geologic investigation (b, c) clarified that the core of the hill is characterized by a gentle structure surrounded by steeply dipping (occasionally overturned) strata, although the previous geologic map (a; [8]) depicts tilting only on the hillside. A stereographic projection showing the

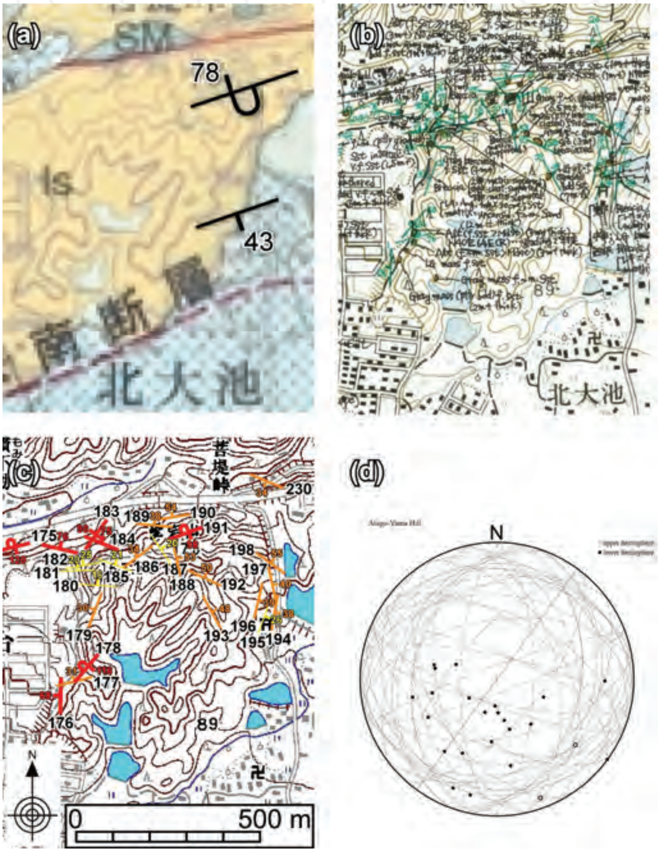

Figure 6. Structural analysis of the Atago-yama Hill (see **Figure 1** for the area of the maps a, b and c) between the Negoro and Negoro-Minami Faults. (a) Previous structural data based on a geologic map [8]. (b) A field survey map of the present study. (c) A compiled map showing the structural trends. Yellow, orange and red marks correspond to gentle (less than 30°), intermediate (between 30° and 60°) and steep (60° or more) dipping angles, respectively. (d) An equal-area projection of bedding girdles and their poles. Open dots represent overturned beds.

poles and girdles of bedding planes (d) indicates that the initially flat-lying beds were folded around the axes with varied azimuths and formed active domal morphologies.

As for the Atago-yama Hill, closer observation suggests the presence of monomictic unconsolidated gravel beds composed of angular sandstone pebbles and cobbles with finely ground matrices (see **Figure 7**). The conspicuous unit was interpreted as a reworked Quaternary sediment that originated from fault breccia.

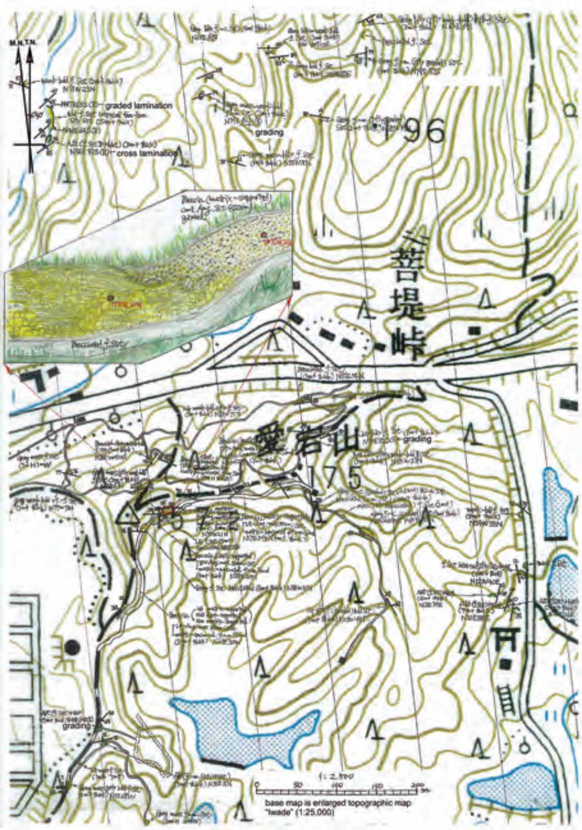

Figure 7. Detailed field observation of the Atago-yama Hill showing a sketch of the highly brecciated beds of the Izumi Group. See **Figure 1** for location.

4. Structural analysis

4.1. Recognition of the general trend

To extend our structural analysis north of the MTL, the general trend in the pull-apart basin buried by the Izumi Group had to be considered. As mentioned before, the primitive geologic framework was an east-plunging syncline. The previous geologic map [8] depicts the fold axis as being crosscut by the MTL, and only the north wing of the synclinal structure is preserved except in the westernmost part of the study area (**Figure 1** (bottom)). However, the present three-year geologic expedition obtained a considerably different structural model showing that the axis of syncline is traceable from the western to eastern ends of the study area as shown in **Figure 1** (top).

This discrepancy arises from different data densities. Although southeastward-dipping attitudes are common in the central and eastern parts of the map, as suggested in previous works, a careful inspection in the present study revealed kink zones with opposite tilting sense in many survey routes, which is conceived as overlapping neotectonic features developed through the waxing and waning of compressive stress linked with changes in the convergence modes of the Philippine Sea Plate since the Pliocene [11]. It is necessary, however, to separate multiphase deformation to comprehend tectonic episodes because the geologic structure described on the basis of the field survey is a product of intermittent structural developments. In the next section, a stripping method for deformation phases is introduced.

4.2. Phase stripping method

Figure 8 presents a map of the general structural trend of the Izumi Group. The initial plunged syncline appears to be well preserved throughout the study area, excluding the areas between the strike-slip and reverse fault strands of the MTL.

Based on the incipient tilting trend, A, the total deformation recorded during the field survey, C, is expressed as the following matrix product:

$$C = BA \tag{1}$$

where B is the desired tilting trend acquired since the Pliocene. In each field observation location, B can be estimated using a simple calculation as:

$$B = BA\,A^{-1} = C\,A^{-1} \tag{2}$$

In the present study, this phase stripping method was applied to structural data obtained from 472 sites.

Figure 8. A base map of the phase stripping analysis of the Izumi Group. Orange lines represent significant faults after a geologic map [8]. Peach lines with dipping angles define the initial structure (plunged syncline) of the Izumi Group, which buried the late Cretaceous pull-apart basin along the Median Tectonic Line.

4.3. Neotectonic structural trend

Figure 9 presents all the neotectonic structural attitudes plotted on an equal-area projection. It is obvious that the poles of bedding planes are aligned on a perpendicular plane with an ENE-WSW horizontal pole, which agrees with the azimuth of the MTL active fault system. Thus, the younger deformation likely developed during rising compressive episodes on the MTL since the Pliocene.

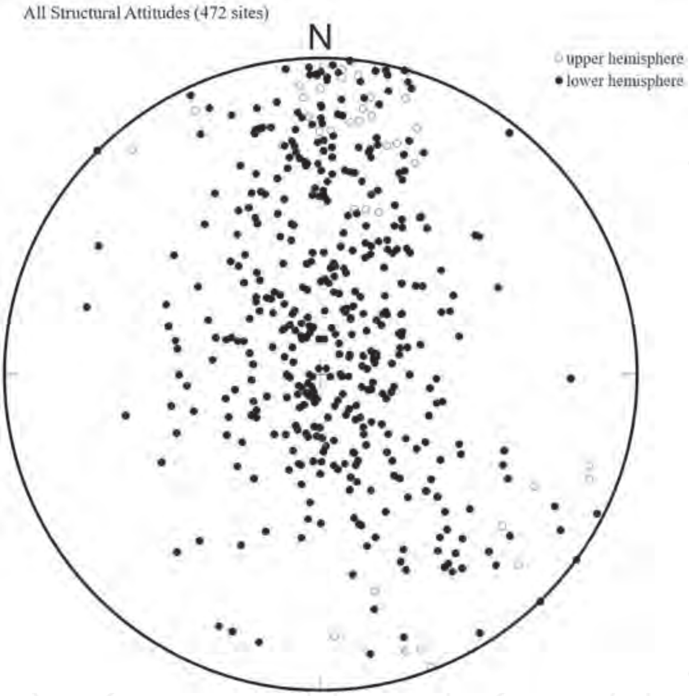

Figure 9. An equal-area projection of poles of bedding planes showing the extracted neotectonic deformation trend. Open dots represent overturned beds.

5. Discussion

The results of the structural analysis performed in the present study are summarized in **Figure 10**. The spatial variation in the extracted neotectonic feature clearly suggests the uneven deformation of the Izumi Group. Steeply dipping sites, which are highlighted by red symbols, are concentrated in the coexistent interval of the Negoro and Negoro-Minami Faults. It is noteworthy that the deformation is not confined between the two fault segments but extends north of the Negoro Fault, forming a broad damage zone. Another remarkable

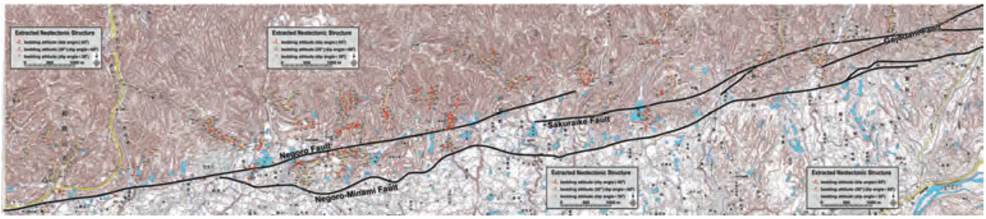

Figure 10. A map of bedding attitudes showing the extracted neotectonic deformation trend. Yellow, orange and red marks correspond to gentle (less than 30°), intermediate (between 30° and 60°) and steep (60° or more) dipping angles, respectively. The names of significant faults are as those given in the previous geologic map [8].

deformation is observed at the eastern termination of the Negoro Fault, where a complicated deformation is anticipated according to active dextral slips on the fault. In sharp contrast, the Cretaceous strata within the westernmost part of the study area, where the Negoro Fault has a straightforward morphology, are immune to serious deformation.

Multidisciplinary studies presented in several chapters of this publication are in close agreement with some of tectonic episodes around southwest Japan since the end of the Miocene. This section chronicles these episodes and outlines the empirical assessment of the sensitivities of the research methods used in these studies.

5.1. Regional contraction (ca. 6 Ma) and basin development related to lopsided convergence (5–3 Ma)

Around southwest Japan, one of the most noted tectonic events in the late Cenozoic era is remarkable north-south backarc contraction, which was originally described by Tai [12] based on the structural trend on the coastal area. Utilizing reflection seismic data, Itoh and Nagasaki [4] clarified that the deformation zone covers the whole of the backarc shelf. Although the activity level seems to diminish eastward, Itoh et al. [2, 13] demonstrated a coeval deformation on the eastern side of the southwestern Japan backarc. In the case that the regional event is linked with oceanic plate motion, the Philippine Sea Plate probably enforced northerly convergence at ca. 6 Ma. As reported in Chapter 5 of this publication, the fission track thermochronology of the Izumi Group has confirmed the impact of the regional exhumation event even on the forearc side.

In contrast to the preceding stage, the early Pliocene is characterized by emergence of an enormous area of extension and basin formation around the western part of the MTL [14]. North-south tensile stress was dominant around the western part of southwest Japan, whereas the eastern part of southwest Japan was a site of strong compression, which was accompanied by the collision of the Tanzawa landmass against the eastern forearc [15]. Between both disturbed ends of the island arc, the central part of southwest Japan was free from strong deformation, and basin formation was inactive throughout the period. It was assumed that such a tectonic trend is related to lopsided subsidence, namely the jump of the Euler pole of the Philippine Sea/Eurasian Plates.

5.2. Expansion of contractional domain (3–1 Ma)

The early Quaternary was an era of contractional deformation around southwest Japan. The eastern part of the arc was under a continuous compressive regime, which provoked the formation of regional unconformity in the eastern forearc at ca. 3.0–2.5 Ma (e.g., [16]). Watershed mountains simultaneously emerged along the MTL in the central part of southwest Japan (e.g., [6]); this was succeeded by the extensive deformation of the adjoining forearc basin [5]. A tension graben around the Beppu Bay in the western part of the island arc became inactive and changed the basin architecture. Such tectonic features may be related to the continued migration of the Euler pole of the Philippine Sea Plate. Within this publication, the reverse faulting and development of a half-graben along the MTL have been delineated in detail based on the reflection seismic survey results (Chapter 3).

5.3. Dominance of simple shear deformation (1 Ma–present)

The latest change in the convergence mode is thought to have occurred at ca. 1–2 Ma. Nakamura et al. [7] have described the submarine topography and shallow structure along the eastern forearc slope of southwest Japan and advocated a counterclockwise shift (NNW to WNW) in the convergent direction of the Philippine Sea Plate. The cessation of the uplift of the watershed mountain ranges [6] and the dominance of simple shear deformation [17] in the central part of southwest Japan is concordant with such a tectonic event.

The present chapter based on authentic geological survey has delineated the structural trend of the Izumi Group on the MTL active fault system that was provoked by uneven tectonic stress related to the morphological diversity of the active fault.

6. Conclusions

The present field survey for the Izumi Group distributed on the MTL active fault system in the central part of southwest Japan has revealed the following points.

(1) Confined deformation zones are present in the western and central parts of the study area. Some of them are located far from the active trace of the MTL (Negoro Fault), at distances of up to 300–350 m. Such kink zones may have been generated during a contraction phase of the MTL from the end of the Pliocene to the early Pleistocene.

(2) Active foldings were identified in the Negoro-Maeyama Hill and Atago-yama Hill, which are sandwiched between the Negoro and Negoro-Minami Faults. They show ridge and domal active morphologies, respectively.

(3) The phase stripping method was introduced to extract the neotectonic trend, which successfully delineated complicated deformation zones related to the morphological divergence of the MTL active fault system.

As for the detailed structural analysis of the study area, original large figures in this chapter are available at OPERA: Osaka Prefecture University Education and Research Archives (http://hdl.handle.net/10466/15058). References to color figures in this chapter are available in the public digital archive.

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Author details

Yasuto Itoh[1]* and Tomotaka Iwata[2]

*Address all correspondence to: yasutokov@yahoo.co.jp

1 Graduate School of Science, Osaka Prefecture University, Osaka, Japan

2 Disaster Prevention Research Institute, Kyoto University, Uji, Japan

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