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Time-Series Analysis of Crustal Deformation on Longstanding Transcurrent Fault: Structural Diversity along Median Tectonic Line, Southwest Japan, and Tectonic Implications

Yasuto Itoh

Abstract

The Median Tectonic Line (MTL) along the longstanding convergent margin of eastern Eurasia has been activated intermittently since ca. 100 Ma. In its incipient phase, propagating strike slips on the MTL generated an elongate pull-apart depression buried by voluminous clastics of the Late Cretaceous Izumi Group. In this study, the complicated deformation processes around this regional arc-bisecting fault are unraveled through a series of quantitative analyses. Our geological survey of the Izumi Group was exclusively conducted in an area of diverse fault morphology, such as jogs and steps. The phase stripping method was introduced to elucidate the time sequence of cumulative tectonic events. After stripping away the initial structure related to basin formation, neotectonic signatures were successfully categorized into discrete clusters originating from progressive wrenching near the active MTL fault system, which has been reactivated by the Quaternary oblique subduction of the Philippine Sea Plate. The method presented here is simple and effective for the detection and evaluation of active crustal failures in mobile belts where records of multiphase architectural buildup coexist.

Keywords: oblique subduction, transcurrent fault, pull-apart basin, neotectonics, Median Tectonic Line (MTL)

1. Introduction

Island arcs exhumed along convergent plate boundaries surrounding the globe are under intensive stress, and hence, they are sites where diverse tectonic forms can be found. Among such features, arc-bisecting faults activated under a regime of oblique subduction [1] have great importance with regard to regional deformation and terrane rearrangement within mobile belts.

The Japanese Islands exhibit the widest range of active landforms since their recent tectonic processes are under the control of four interacting plates around

the east Eurasian margin (see **Figure 1** inset). This study focuses on the south-western part of the arc-trench system, in which transient convergent modes of the Philippine Sea Plate along the Nankai Trough (**Figure 1**) have governed its architectural development.

Except for Kyushu Island in front of a chain of underthrusting bumps on the oceanic plate (Kyushu-Palau Ridge in **Figure 1**), ongoing neotectonic events within southwest Japan can simply be understood by evaluating the obliqueness of plate convergence and related activity levels on a regional arc-bisecting fault, the Median Tectonic Line (MTL).

Here, the research focus is placed on the northwestern part of Shikoku Island (**Figure 1**) because a previous study [3] identified deformation events along with the MTL based on a detailed geologic survey of a Quaternary unit. In the following sections, the tectonics of southwest Japan since the Cretaceous are reviewed, and original results are presented based on an extensive structural analysis making use of the phase stripping method to distinguish recursively overlaid tectonic events, and active crustal damage zones along the MTL are then extracted. This study provides a precedent for further quantitative geologic explorations of mobile belts, where superimposed records of the Earth's evolution remain untouched.

Figure 1. Index maps for the east Eurasian margin and southwest Japan. Offshore geomagnetic anomalies are after [2]. The open arrow shows the present relative motion of the Philippine Sea Plate.

2. Geological background

2.1 Longstanding activities on the MTL

Most active faults in the Japanese Islands have been vitalized under the complex and unstable regime of plate tectonics through the Quaternary (inset in **Figure 1**). The MTL, however, has an exceptionally long history of activity that dates back to the Cretaceous, when the vigorous northward motion of the Izanagi Plate [4] triggered a breakup of the continental rim and sinistral slips on the proto-MTL. Note that southwest Japan in that period still constituted a part of the east Eurasian margin because the Japan Sea (**Figure 1**) is a back-arc basin that began to open in the mid-Cenozoic [5], although its spreading center is not obviously identified (see the geomagnetic anomalies in **Figure 1** after [2]).

After a period of substantial dormancy during the Paleogene era, the MTL was reactivated under control of the intermittent convergence of the Philippine Sea Plate that had developed during the late Cenozoic around the northwestern Pacific [6]. Southwest Japan at the beginning of the Pliocene was a site of strong inversion. N-S compressive structures that simultaneously built up along the Japan Sea back-arc shelf are suggestive of resumed northward movement of the oceanic plate [7]. Reflecting such a tectonic context, the MTL in the Pliocene stage acted as a low-angle fault, on which watershed mountainous ranges successively emerged [8].

A close observation of the geologic characteristics along the subduction zone [9] found that the Philippine Sea Plate changed its converging azimuth to counterclockwise at approximately 2–1 Ma. This significant fact implies that the west-northwestward motion of the plate around southwest Japan (arrow in **Figure 1**) inevitably enhanced right-lateral activity on the regional fault. Cumulative lateral separation on the present MTL (e.g., [10]) matches well with this tectonic model. To make an explicit distinction between this and older MTL activity, the Quaternary fault driven by dominantly dextral shear is hereafter referred to as the MTL active fault system (MTLAFS).

2.2 Izumi Group filling a regional pull-apart basin

As stated above, the MTL was activated as a left-lateral fault along the Eurasian margin during the Late Cretaceous. Around a propagating termination of the regional rupture, enormous trench-parallel pull-apart basins developed and were promptly buried by voluminous marine siliciclastics that are collectively named the Izumi Group [11]. This group is exposed in an area 300 km long by 10–20 km wide along with the MTL, and it topographically coincides with the core of watershed ranges uplifted during the Pliocene.

Ruled by the general development processes of pull-apart basins [12] and contraction in the Pliocene event of N-S inversion, the stereotypical geologic architecture of this Cretaceous unit is an east-plunging syncline. Such a monotonous structural feature is crucial for isolating neotectonic deformation trends by means of a filtering method that is fully explained in Section 3.

2.3 Gunchu Formation: An indicator of active basin formation and exhumation

2.3.1 Geologic system in the coastal area on the Iyonada Sea

Figure 2 depicts the geologic system around the study area in the northwestern part of Shikoku Island [13, 14]. In a broad way, the Cretaceous basin fill of the Izumi Group is in contact with the high-pressure Sanbagawa metamorphic

Figure 2. Geological summary of the northwestern part of Shikoku Island. The geologic system is after [13]. (a) Base map and morphology of the Median Tectonic Line active fault system are after [14–16], respectively. See **Figure 1** for the mapped area. (b) Sense of active movements on the Iyo Fault is after [17].

rock to the south, which ascended rapidly in a subduction zone during the sinistral phase of the MTL (cf. Section 2.1). In contrast, the Izumi Group rests on Cretaceous granitic rock accompanied by low-pressure Ryoke metamorphic rock on its northern border. It is noted that a monoclinical nonmarine Pleistocene formation known as the Gunchu Formation is cropped out on the coast of the inland sea. Its steep structure is a result of Quaternary activity on the MTLAFS that runs through northwest Shikoku and the southern coastal zone of the Iyonada Sea [14–17].

2.3.2 Stratigraphy and structural trend

The fluvial sequence of the Gunchu Formation was originally divided into three members [18, 19] and redivided by Itoh [3] into two from the viewpoint of the provenance of pre-Neogene clasts. As delineated in **Figure 3**, the Gunchu Formation lies unconformably on an eroded surface of the Izumi Group and has a steep homoclinal structure. Offsets of its stratigraphic boundaries point to the presence of faults crosscutting the unconsolidated strata. Kitabayashi et al. [20] dated zircon grains separated from volcanic ash intercalated in the basal part of the lower member to be 2.2 ± 0.3 Ma (FT age) and 2.13 ± 0.05 Ma (U–Pb age), whereas an ash layer near

the top of the same member yielded zircon ages of 1.8 ± 0.2 Ma and 1.92 ± 0.05 Ma based on FT and U–Pb methods, respectively [3].

2.3.3 Sedimentology and basin-forming process

The Gunchu Formation is a stack of channel and bar deposits with minor facies fluctuation that reflects the migration of channels within an alluvial basin. Apart from such phenomena, Itoh [3] recognized drastic changes in gravel compositions probably linked to successive exhumations of hinterlands driven by tectonic uplift.

Figure 4 exemplifies the compositional variety observed in the fault-bounded Block 1 (**Figure 3**) of the Gunchu Formation. As depicted in the pie charts, the lower member contains a considerable amount of granitic pebbles, the U–Pb ages of which range from 106.5 to 93.8 Ma, as measured for five clusters in four sites [3]. Although these radiometric dates reflect the Cretaceous plutons extensively found in southwest Japan, igneous rocks in that period are enigmatically absent around the present study area. The base of the upper member is defined by an abrupt influx of high-pressure metamorphic clasts. The concentration of schist-originated material is so extreme that some outcrops possess a blue-greenish appearance. The content of metamorphosed

Figure 3. Geologic map of the Pleistocene Gunchu Formation after Itoh [3]. See **Figure 2b** for the mapped area. Background topography is a part of the “Kaminada” locality map at 1:25,000, published by the Geospatial Information Authority of Japan.

Figure 4. Spatiotemporal variation in gravel compositions for Block 1 of the Gunchu Formation after [3]. Relative abundance of rock facies was determined from 100 data points for each observation station.

gravels tends to decrease upward, and sandstones derived from the nearby Izumi Group become prevalent in the uppermost part of the sedimentary unit.

Itoh [3] attempted to reconstruct the Quaternary basin-forming process based on the above-stated spatiotemporal changes in gravel composition, and additionally, paleocurrent directions that were determined from the imbricated structure of clasts for the same 26 sites in the compositional analysis. **Figure 5** schematically shows the neotectonic evolution of the northwestern part of Shikoku Island. As described previously, granitic pebbles ubiquitously detected in the lower part of the Pleistocene sediments yielded numerical ages concordant with those of the Cretaceous intrusions within the inner zone (north of the MTL; see **Figure 1**). Significant scatter in the U–Pb ages implies that the granites were not derived from a local intrusive body having a uniform cooling history but from asynchronously emplaced plutons, which are widely exposed on the south side of Honshu Island (**Figure 1**). Thus, all the available data point to an assumption that the depocenter at an early stage was located around the area now occupied by the Gunchu Formation (**Figure 5a**).

Figure 5.
Paleoenvironments during depositional stages of the Gunchu Formation after [3]. Base geologic map is after [13].

As for the setting of later stages, the massive influx of the Sanbagawa metamorphic rock demonstrates regional uplift in the outer zone (south of the MTL; see **Figure 1**). It is, however, intriguing that the upper member contains a few of the Miocene volcanics that extensively cover the area between the Gunchu basin and the Sanbagawa terrane. Itoh [3] thereby assumed that the region of intensive uplift and erosion progressively expanded northward during the mid-Pleistocene. This resulted in a

sharp increase of upward sandstone clasts coming from the nearby Izumi Group and brought about seaward migration of the depocenter, in which clastics derived from the inner zone are trapped. This is the reason why granite pebbles disappeared from the upper member. This tectono-sedimentary model is summarized in **Figure 5b**. The regional and incremental contraction eventually urged the recent basin fills to build up a steep monoclinical structure along with the coastline.

Our review has thus shown a longstanding history of MTL activity and relevant processes of basin formation and deformation. In the following sections, more extensive and quantitative analyses of fault-related tectonics are discussed based on the results of this study.

3. Analysis

3.1 Application of phase stripping method

Previous studies have shown that the structural and sedimentological features of the Pleistocene Gunchu Formation have preserved neotectonic information linked to activity on the MTLAFS. As for advanced research on the fault-bound tectonics, however, confined exposure of the fluvial unit hinders more regional analysis. Therefore, this study focuses on the Cretaceous Izumi Group, which is distributed along the proto-MTL. Although the widespread sediments probably record recent episodes, they also reflect the initial architecture built up during the growth of pull-apart basins. In conventional geological mapping, neotectonic signatures related to active deformation are interpreted as secondary features of basin-forming processes or are excluded as noisy data near local faults. Thus, an overlapped event usually ends up as misread or dead information in a one-sided interpretation.

During the course of research on the easternmost part of the MTLAFS, Itoh and Iwata [21] developed a simple method to separate the multiphase deformation. Their “phase stripping method” regards the geologic architecture revealed through field surveys as an integration of an initial tilting and a younger event. The total structure directly measured on an outcrop, C , is expressed using a matrix product as follows:

$$C = BA \quad (1)$$

where A is the trend acquired during the initial tectonic phase, a pull-apart basin evolution in this case, and B is the pursued phase formed in a recent period. At each observation point, B can be determined using the known structural data as follows:

$$B = BAA^{-1} = CA^{-1} \quad (2)$$

In this study, the author applied this simple calculation to field data obtained from 720 outcrops of the Izumi Group.

Figure 6 represents the concrete procedure of phase stripping. In spite of later disturbance, a general structural trend can be identified based on 280 and 440 points of field data in the northeastern and southwestern blocks of the three-year geologic survey, respectively.

As mentioned before, the typical architecture of the Izumi Group, A in Eq. (1), is a monotonous east-plunging syncline developed through the progradational burial of a series of pull-apart basins and is delineated by red contours in the figure. For reference, the Pleistocene Gunchu Formation is located near the north corner of the southwestern block.

Figure 6.
 Base map for the phase stripping analysis of the Izumi Group. See magenta enclosure in **Figure 2a** for the mapped area. Detailed topographies of the two analyzed blocks are parts of the “Kaminada” and “Gunchu” localities at 1:25,000, published by the Geospatial Information Authority of Japan. There are 280 and 440 data points in the northeastern and southwestern blocks, respectively. Thin red lines and attached dip angles represent the initial east-plunging synclinal structure of the Cretaceous basin fill.

3.2 Detection of damage zones

The analytical results of this study are summarized in **Figure 7**. As shown by magenta lines, a previous geomorphological study [17] recognized two branches of the MTLAFS, namely, the minor Kominato Fault and the major Iyo Fault, for which right-lateral offsets were confirmed (**Figure 2b**).

Elaborate field observations led the author to realize that the density of visible fractures in the Izumi Group varies considerably under the possible influence of local deformation. To perform a quantitative evaluation, the fracture density was measured at 18 sites along with the coast. At every station, all the visible cracks residing within a massive sandstone bed were counted on a 10×10 grid of graticules ruled in 3-cm divisions, which were drawn on a transparent polyethylene film pasted on the outcrop surface. All the fracture counts at 18 stations are shown in **Figure 7**, and histograms in the figure present selected results of such measurements.

In the same figure, regions of severe deformation are highlighted by red symbols for steep and overturned bedding attitudes of phase *B* in Eq. (2). As for the northeastern part of the analyzed area, a major damage zone lies on or near the Iyo Fault, and minor trends extend along gorges subparallel to the main active fault. In contrast, more diverse structural disturbances characterize the southwestern area. Some data indicating intense motions in phase *B* are aligned near the straight scarp of the Iyo Fault, but others show elongated clusters with different orientations, implying the existence of unknown active failure zones. In both the analyzed areas of **Figure 7**, remarkable phase *B* deformations are found irrelevant to the initial synclinal structure of phase *A*. In the next section, the recent progressive deformation process is examined by integrating geological evidence, and a neotectonic model of the MTLAFS is derived that matches the structural framework.

Figure 7. Extracted neotectonic features based on the phase stripping method. The mapped area is the same as in **Figure 6**. Previously reported active faults (magenta lines) are after [17]. Refer to the main text for trends A to D (thick gray lines), fracture numbers at 18 stations pasted along the coast, and histograms of the fracture density. Bedding attitudes developed under recent stress are categorized as gentle (yellow, less than 30°), intermediate (orange, between 30° and 60°), and steep (red, 60° or more, including overturned structures).

4. Discussion

4.1 Subordinate active faults

The phase stripping method applied to the Izumi Group distributed around northwestern Shikoku Island successfully delineated recent damage zones in connection with activities on the MTLAFS. As for the wedge between the coastline and the Iyo Fault, four-fault traces were identified based on linear clusters of the strong phase *B* motions (shown by red symbols in **Figure 7**) and are depicted as gray zones A to D in the figure. Trends A and B are concordant with faults cutting the Pleistocene Gunchu Formation (see **Figure 3**). Trends C and D are recognized as deformation zones that branch off from the Iyo Fault and appear to be related with coastal stations showing extreme concentrations (414 and 489 counts for each measurement) of fractures (histograms in **Figure 7**). Such parallel trends aside, the phase *B* data tend to suggest stronger deformation along with the Iyonada Sea coast. Although numerous offshore faults have been found through previous studies (**Figure 2a**), the detailed structure of the shoreline remains ambiguous because research vessels cannot perform sounding surveys in very shallow water. The present results imply an offshore stepped extension of the Iyo Fault that provokes activity on the subordinate faults.

4.2 Actual deformation processes recorded in outcrops

As mentioned above, the Pleistocene Gunchu Formation possesses a steep homoclinal structure suggestive of strong neotectonic deformation. **Figure 8** represents the unconformity between the Izumi Group and the Gunchu Formation

Figure 8. Sketch of the unconformable relationship between the Cretaceous Izumi Group and the Pleistocene Gunchu Formation after [3]. See **Figure 7** for the outcrop location. Bedding attitudes for the Pleistocene unit imply syn-sedimentary structural growth.

first described by Itoh [3]. Note that the basal part of the Pleistocene gravel strata exhibits overturned bedding, which graduates upward into steep but normal bedding attitudes. Such a change indicates syn-depositional structural buildup. Another point is that the phase B data near this exposure (see **Figure 7** for its location) are in the gentle level of recent motions (tilting shallower than 30°). These geologic lines of evidence seem to suggest that a flexure zone developed under a compressive regime during the uplift of the hinterlands, roughly coinciding with the recent unconformable interface.

A sketch of important outcrops is presented in **Figure 9** (see **Figure 7** for the location). Steep tilting in its western part is likely to be affected by lateral motions on the adjacent Iyo Fault. It is notable that the Izumi Group in the central and

Figure 9. Sketch of an outcrop in which accumulation processes of neotectonic deformation are observed. See **Figure 7** for the outcrop location. Refer to the main text for the structural interpretation.

eastern parts of the outcrop shows overturned attitudes. Namely, as we move away from the active fault, the deformation of the strata seems to become stronger. This paradoxical phenomenon implies that an unreported zone of active contraction extends on the eastern side because the intensive signatures of phase B are confirmed within broadband around this observation point (see **Figure 7**).

An unconformable surface of the Izumi Group in this exposure is overlain by gravel-rich unconsolidated sediments. This unit seems to be gently inclined eastward, a tendency endorsed by the sedimentary structure of an intercalation of fine volcanic ash (**Figure 9**). Neotectonic activities on the MTLAFS thus resulted in severe deformation and exhumation of the Cretaceous basin fill, and the overlying fluvial deposits are significantly tilted under lingering tectonic stress.

4.3 Integrated neotectonic model

Figure 10 depicts an integrated model of neotectonic processes on a part of the MTLAFS, which is modified from the prototype submitted by Itoh [3]. First, an unknown transcurrent fault having a right offset from the Iyo Fault is postulated on the basis of active structures in the Iyonada Sea (**Figure 2**). Such a stepped

Figure 10. Schematic diagrams delineating the probable evolutionary history of the study area adjacent to an active transcurrent fault system. It is modified from Itoh [3] based on the present results.

morphology accompanied by propagation of fault termination enhanced activity on secondary faults bridging the primary strike-slip features [22]. Compartments divided by the subordinate faults were systematically tilted and rapidly buried by onlapping sediments (**Figure 10a**). Next, a rising contractional regime brought about progressive uplift of the hinterlands and seaward migration of the Pleistocene pull-apart sag. Strong tectonic stress eventually provoked steep tilting of the Gunchu Formation on a narrow flexure zone (see **Figure 10b**) and confined the deformation of the Izumi Group. The latest dextral motions on the MTLAFS may have induced reactivation of the crosscutting faults, which is inferred from the trends of recent intensive deformation (**Figure 7**).

This study has demonstrated that a long and complicated motion history of the MTL governs the architectural development of nearby geologic terranes. As it is a crustal break under the control of subduction modes of oceanic plates, the fault-related tectonics may have a wider influence over evolutionary processes for the island arc. For example, Itoh et al. [23] performed a volumetric analysis of the Iyonada Sea based on gravity anomalies and found a gigantic buried basin resting against a 4-km-deep scarp of the MTLAFS. Thus, a regional tectonic model of active margins should be built using multidisciplinary research to shed light on the deep interior of the earth.

5. Conclusions

1. Vigorous tectonic development of the southwestern Japan arc is illuminated in light of the motion history of an arc-bisecting fault, the MTL, which has been activated intermittently under transient subduction of oceanic plates since ca. 100 Ma. In its early stage, sinistral motions on the propagating fault produced an elongated pull-apart depression that was buried by the Cretaceous marine sediments of the Izumi Group. In contrast, the latest stage is characterized by dextral movements provoked by oblique convergence of the Philippine Sea Plate, which urged fault-parallel basin formation and massive uplift and erosion of the hinterlands.
2. The phase stripping method was applied to 720 points of structural data for the Izumi Group distributed along the MTL running through northwestern Shikoku Island. After removing an initial trend (east-plunging syncline), the present analysis succeeded in the isolation of a large amount of data suggesting considerable younger deformations, some of which are aligned parallel to the MTLAFS. Others, however, constitute linear trends in different directions, indicating unknown faults. Prominent trends near the coast of the Iyonada Sea are connected with faults cutting across the Pleistocene Gunchu Formation and are, therefore, regarded as active features.
3. Actual processes of structural growth were reconstructed based on outcrop observations. Geologic structures of the Izumi Group exposed within a zone of severe recent deformation imply the presence of an unreported reverse fault. Bedding attitudes of the Gunchu Formation are suggestive of syn-sedimentary tectonic disturbance. In this study, thus, the MTLAFS tends to be accompanied by recurrent contractional features, which may have been built up during episodic increases in compressive stress, reflecting fluctuations in convergent modes of the oceanic plates.
4. An integrated neotectonic model of architectural evolution in the study area was developed by assuming a right-stepping portion on the MTLAFS. Propa-

gation of dextral fault termination at such a structural singularity inevitably formed an active pull-apart basin divided by subordinate faults, which were promptly buried by the Quaternary clastics derived from uplifted hinterlands. A succeeding compressive regime triggered the seaward basin migration and eventual rollover of the recent basin fill. The latest dextral movements on the MTLAFS may have resulted in activity resuming on the basin-dividing faults.

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