Chapter 8

Neotectonic Intra-Arc Basins Within Southwest Japan — Conspicuous Basin-Forming Process Related to Differential Motion of Crustal Blocks

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http://dx.doi.org/10.5772/56588

1. Introduction

Southwest Japan is a continental sliver rifted during the Miocene opening of the Japan Sea [1]. Its post-rifting tectonic architecture is closely related to the mode of convergence of oceanic plates around the eastern Eurasian margin. It seems that neotectonic deformation in southwest Japan becomes increasingly intense from west to east, which has long been understood as a contraction regime caused by the westerly subducting Pacific Plate (e.g., [2]). Collision between the Eurasian and North American Plates around the eastern margin of the Japan Sea and the Itoigawa-Shizuoka Tectonic Line (Figure 1) is also responsible for the deformation trend [3]. Another remarkable structural trend, a late Neogene strong inversion along the backarc coast of the island arc, is sometimes related to the subduction of the Philippine Sea Plate [4,5]. The Philippine Sea Plate changed its convergent direction in the Quaternary [6], and enhanced right-lateral wrenching within southwest Japan [7].

The authors concentrate upon the Quaternary morphological features in the eastern part of the island arc, and describe conspicuous basin-forming processes in the study area. In a general context, we aim at comprehension of the regional tectonic zones controlling the vigorous formation of intra-arc basins, and at identifying the neotectonic domains divided by them. Geophysical information such as gravity anomalies [8] and reflection seismic data are utilized to visualize the deep interiors of the intra-arc basins and evaluate structural trends in the damaged upper crust surrounded by the tectonic zones. Closer observation of geologic structures leads us on the path to understand the formation processes of subordinate structures in the study area.

2. Description of major tectonic zones

2.1. Median Tectonic Line

The Median Tectonic Line (MTL) is the largest crustal break in southwest Japan, which bisects the island arc into the old terranes intruded by igneous rocks in the Inner Zone and partly metamorphosed accretionary complexes in the Outer Zone (Figure 1; [9]). It has a period of activity as long as 100 m.y. and highly complicated change in slip direction. In the following sections, we present a chronicle of the MTL activity based on previous research and original interpretation of geophysical data.

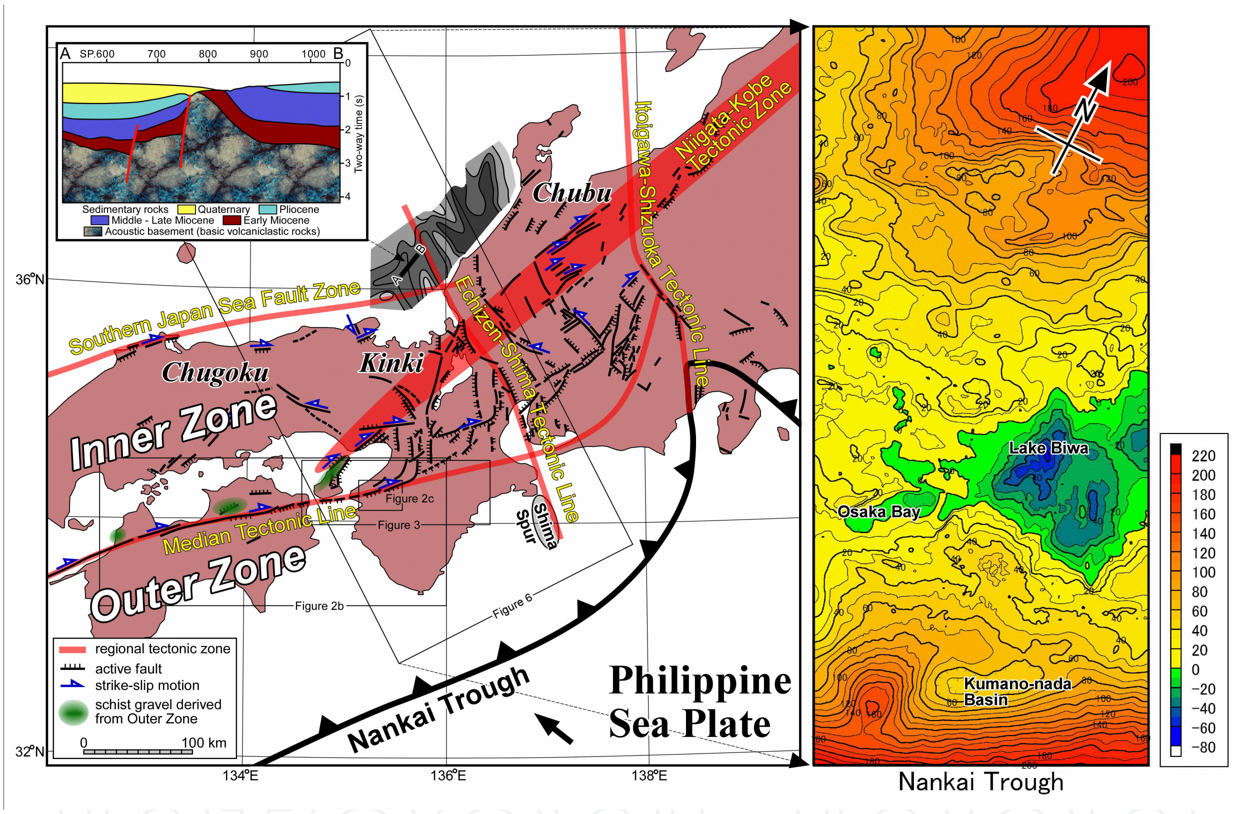

Figure 1. An index of the neotectonic regime in southwest Japan. Base map is after Huzita [2]. Gradation on backarc shelf showing onlapping sedimentation pattern and a seismic profile (shown inset) in the area are after Itoh et al. [5]. Influx of crystalline schist gravels is shown by green areas [22-24]. (Right) Bouguer gravity anomaly map. The Bouguer density is 2670 kg/m^3, and contour interval is 10 mGal. Gravity map is generated based on [8]

2.1.1. *Initiation of the regional fault zone*

Compiling reliable paleomagnetic data, Itoh et al. [5] reconstructed the Cretaceous to early Paleogene paleogeography around the eastern Eurasian margin (Figure 2a). They pointed out that the MTL constituted a larger fault zone together with the Central Sikhote Alin Fault, and had a left-lateral slip sense as a result of the quite rapid northerly motion of the Izanagi Plate [10]. Along the fault zone, conspicuous pull-apart basins were developed and buried by the

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Cretaceous silici-clastic rocks of the Izumi Group [11], which was deposited in an elongate basin (300 km long by 10~20 km wide) along the MTL with sinistral strike-slip movements (Figure 2b).

Wrenching deformation associated with the ancient left slip on the MTL is identified in the Outer Zone of the Kii Peninsula (Figure 2c). Wang and Maekawa [12] showed that the metamorphic grade in the Sanbagawa belt have an en echelon anticlinal trend along the MTL. The trend is a result of deformation after high-pressure metamorphism, the climax of which is assigned around the middle of Cretaceous [13]. It is noted that the most intensive post-metamorphic deformation zone does not coincide with the geologically determined MTL that runs upon the northern bank of the River Kinokawa. Hirota [14] found a remarkable discontinuity in the metamorphic grade around the Funaokayama bar within the River Kinokawa (Figure 2c), and regarded it as a tectonic block. Takasu et al. [15] argued, on the basis of chronological data, that the amalgamation of metamorphosed blocks had occurred during the late Cretaceous. A steep gradient in the gravity anomaly along the river also implies a concealed structure parallel to the surface MTL. Although the resolution is lower, the geomagnetic anomaly trend (Figure 3; [16]) supports a difference in upper crustal constituents along the same line as the density contrast.

2.1.2. Neotectonic activity

It is accepted that the MTL has been reactivated as a right-lateral fault since the late Neogene under the influence of the oblique subduction of the Philippine Sea Plate (e.g., [17]). Nakamura et al. [6] demonstrated that the oceanic plate shifted its convergent motion counterclockwise in the Quaternary, which resulted in vigorous slips on the MTL and westward transportation of the Outer Zone (e.g., [18]). However, when compared with the older stages, geomorphological features (e.g., [19]) suggest that the active segment of the MTL shrank during the late Quaternary. No active portion is identified in the eastern part of the Kii Peninsula (Figure 3), in which the geomagnetic anomaly contrast is also obscured. This is in contradiction to the plate subduction regime, and further study of the transient shift of MTL activity is necessary to solve this tectonic paradox. Another noteworthy point is that the MTL trace is characterized by frequent jogs and steps. A sounding survey in the Kii Channel [20] delineated a complex fault pattern that may cause great diversity in basin formation.

2.1.3. Episodic change of deformation mode

Subsurface structures delineated by reflection seismic data [21] suggest a different phase of the recent activities of the MTL. Figure 4 is a N-S (normal to the MTL) seismic profile of the northern bank of the River Kinokawa. Fault morphology is classified into high-angle flower structures, implying lateral motion, and north-dipping reverse faults, reflecting a complicated slip history. Amongst the structures, the most remarkable feature is the thrust at the bottom of the Cretaceous Izumi Group. Because it is underlain by recent sediments, a strong contraction episode in the Quaternary should be responsible for the structure.

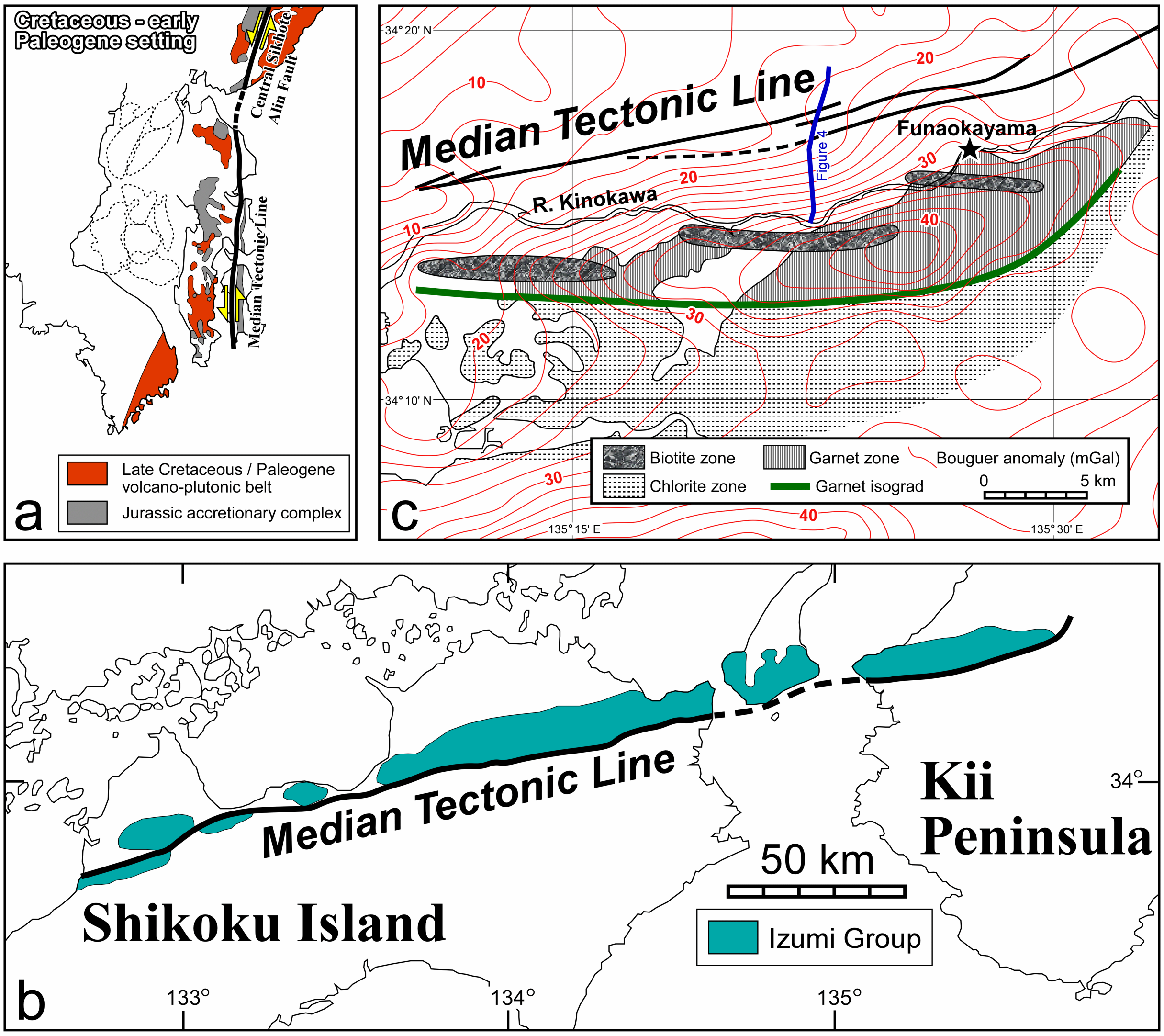

Figure 2. Incipient activity of the Median Tectonic Line (MTL). (a) Paleoreconstruction of the eastern Eurasian margin in the Cretaceous and early Paleogene stage [5]. (b) Distribution of the Cretaceous Izumi Group deposited in a series of pull-apart basins [11]. (c) Geologic features showing sinistral motion of the Median Tectonic Line in the Kii Peninsula. Metamorphic grade in the Sanbagawa belt is after Wang and Maekawa [12]. A star shows the Funaokayama bar in the River Kinokawa, where a remarkable gap in metamorphic grade was confirmed [14]. Mapped areas are shown in Figure 1

Provenance studies of the recent clastics on the northern flank of the MTL support the theory of a strong contraction phase in the Kii Peninsula. In some areas of the Pleistocene exposure, the frequent influx of schist gravels, apparently derived from the Sanbagawa belt in the Outer Zone (Figure 1), has been confirmed by many researchers (e.g., [22-24]). In contrast, Pleistocene sediments around Osaka Bay are lacking in such components in spite of the fact that the aforementioned metamorphic unit is widely distributed in the Kii Peninsula. The authors submit a hypothesis that the strong contraction phase provoked an inversion of the Cretaceous Izumi sedimentary basin along the MTL trace, and an E-W barrier (Izumi Mountains) prevented northward sediment transport through the late Quaternary.

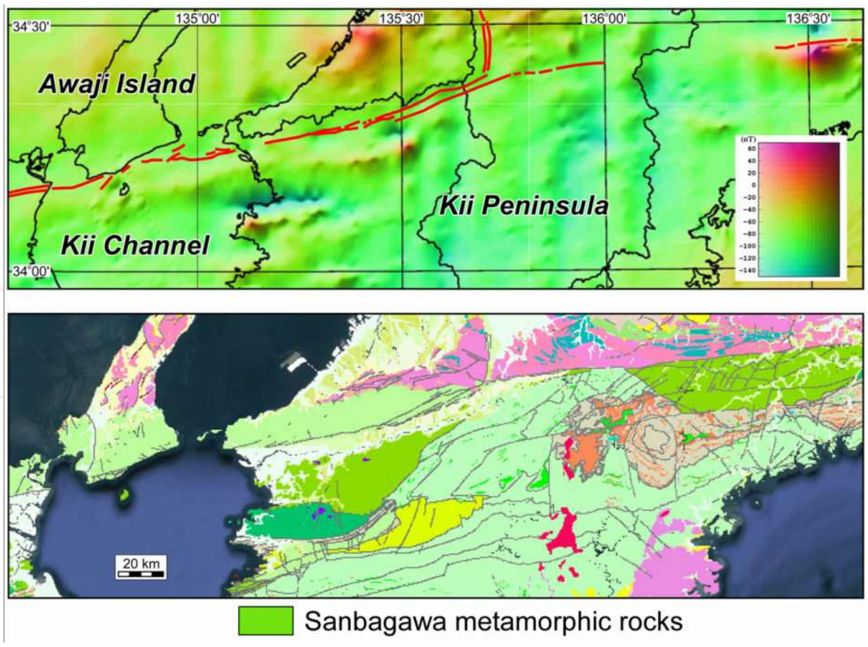

Figure 3. Recent active trace (red line) of the Median Tectonic Line around the Kii Peninsula, compiled after Yoshikawa et al. [20,21] and an active fault database [19]. See Figure 1 for mapped area. Base maps in upper and lower frames show geomagnetic anomaly [16] and geology [9], respectively

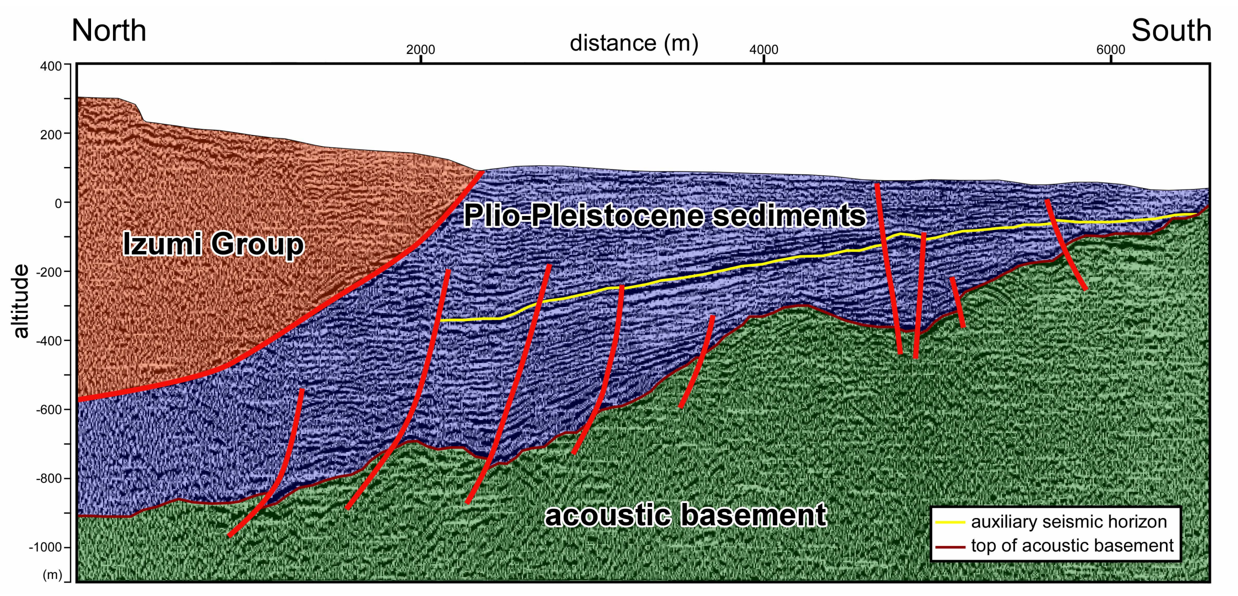

Figure 4. Geologic interpretation of a N-S depth-converted seismic profile across the Median Tectonic Line in the Kii Peninsula. Location of seismic line is shown in Figure 2. Original seismic data is after Yoshikawa et al. [21]

Visualization of subsurface structures in the forearc region implies that the contraction event has a broader impact upon the basin formation/deformation processes of southwest Japan. Takano et al. [25] stated that the Kumano-nada basin (Figure 1) suffered from an episode of contraction around the early Pleistocene, which became dormant in later periods. Thus the

MTL seems to have a much more complicated activation history than the common theory would suggest. This history may be a key to reconstructing the motion of the Philippine Sea Plate, which is not determined from global plate kinematics.

Basin morphology along the MTL shows a spatial variation under the Quaternary transient tectonic stress. Figure 5 presents a plan view of an active trace of the westernmost part of the MTL (upper) and the deep structure of recent sedimentary basins developed along the active segment, which is interpreted from reflection seismic data [26] (lower). It is obvious that the active MTL has a releasing bend around the Beppu Bay where countless secondary tensile faults develop. The volume of the pull-apart basin is estimated based on gravity data in this book (Itoh, Y., Kusumoto, S. and Takemura, K.). Deep structures interpreted from two seismic profiles with no vertical exaggeration indicate the following characteristics. (1) The youngest structural trend is a bunch of high-angle faults (with a so-called ‘flower structure’) implying strike-slip motion on the MTL fault system. (2) Temporal transition of the active fault trace is inferred from the migration of depocenters of the sedimentary basins. (3) Low-angle detachment in the acoustic basement, which was regarded as a material boundary in the upper crust [26], is clearly reactivated in an extensional sense as shown by the dragging deformation of the adjacent Plio-Pleistocene sediments.

A previous study [27] attributed the along-arc difference in deformation style (east, contraction; west, extension) to counterclockwise rotation of the forearc sliver in response to the relative motion of the Philippine Sea and Pacific Plates, and the backarc spreading of the Okinawa Trough. Further quantitative investigation of the three-dimensional structure of the island arc crust is necessary for constructing a probable tectonic model.

2.2. Niigata-Kobe Tectonic Zone (NKTZ)

Based on geodetic analyses, Sagiya et al. [28] described a NE-SW zone of deformation in southwest Japan (Figure 1), and named it as the Niigata-Kobe Tectonic Zone (NKTZ). It is characterized by right-lateral shear deformation [29], and obliquely crosses over the Itoigawa-Shizuoka Tectonic Line (ISTL; Figure 1) with pure reverse motions. As shown by Nakajima and Hasegawa [30], the NKTZ is a deeply rooted crustal weakness accompanied by a P-wave velocity anomaly in the mid-crust. Iio et al. [31] argued that the high water content of the lower crust, linked to dehydration of the subducting slab, is responsible for the formation of such a weak zone.

Paleomagnetic studies have shown that the NKTZ is not a short-lived feature but contributes to cumulative deformation of the island arc. Itoh et al. [32] compiled reliable paleomagnetic data around the eastern part of southwest Japan, and confirmed significant clockwise rotation on the NKTZ during the Quaternary. They pointed out that similar rotational events were identified on both flanks of the ISTL, and stated that the two crossing tectonic zones with different deformation senses may be alternately activated in response to fluctuation of the regional tectonic stress, which is a theory to comprehend the paradox of a geophysically-assessed low activity level of the ISTL showing geologic significance.

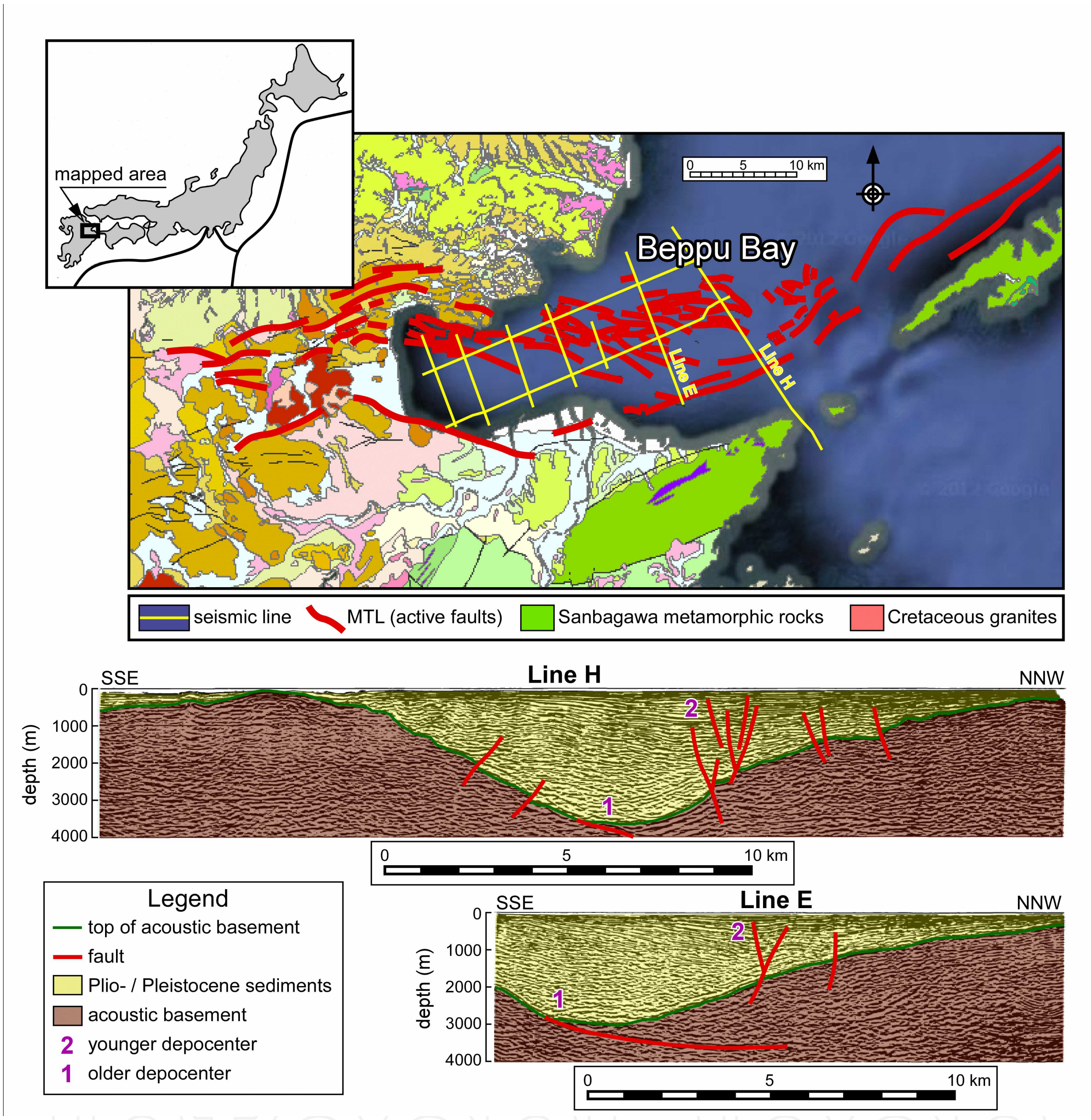

Figure 5. Upper: Westernmost part of active trace of the Median Tectonic Line after [9] and [27] with seismic line map [26]. Lower: Reinterpreted depth-converted seismic profiles without vertical exaggeration. Original seismic data is after Yusa et al. [26]

2.3. Echizen-Shima Tectonic Line (ESTL)

Huzita [33] stated that a triangular portion in the central Kinki district is characterized by intensive deformation and basin formation, and named it the 'Kinki Triangle'. The southern border of this tectonic area coincides with the MTL, and its western border roughly corresponds to the NKTZ. The tectonic context of the eastern border, however, has not been clearly discussed. Here, the authors attempt to redefine a tectonic line from the viewpoint of consistency in deformation trend including the forearc and backarc regions.

Itoh et al. [5] described the geologic structures of the backarc of southwest Japan. A sediment onlapping pattern depicts an inversion trend nearly normal to the elongation of the arc (Figure 1). They showed a seismic profile suggesting that the inversion developed from the Pliocene to Pleistocene. On the forearc side, the Shima Spur built up in early Quaternary [25]. These structural trends are linearly connected with onshore active faults, and constitute a regional zone of contraction. We regard it as a significant neotectonic boundary and name it the Echizen-Shima Tectonic Line (ESTL). At present, the origin of the ESTL is not fully understood. It probably has a close relation with the Miocene bending event in southwest Japan caused by the collision of the Izu-Bonin arc, the reason for this theory being that paleomagnetic studies [34,35] clarified that the hinge line of arc bending was located around the ESTL.

3. Neotectonic domains in southwest Japan

The authors have presented the characteristics of major neotectonic zones (lines) around the eastern part of southwest Japan. Next, we attempt to describe neotectonic domains bordered by these features. We identify the Chugoku, Kinki and Chubu domains from west to east (Figure 1).

The Chugoku domain is characterized by quite broad dextral wrenching and inactive basin formation. It is a crust sliver between the MTL and the Southern Japan Sea Fault Zone (SJSFZ). The SJSFZ is a reactivated right-lateral fault along the late Miocene backarc inversion zone [36]. Itoh and Takemura [7] pointed out that the recent absence of arc volcanism in southwest Japan has resulted in the homogeneous crustal strength and uniform strain rate of the fault-bounded sliver.

Among the geographically defined Kinki district, we take notice of the tectonic domain surrounded by the MTL, NKTZ and ESTL. It is a damage zone accompanied by countless faults and enormous intra-arc basins, which are delineated by low gravity anomalies (see Figure 1). The mechanism of paradoxical basin formation at a contraction step of the MTL is discussed in this book (Itoh, Y., Kusumoto, S. and Takemura, K.). After the incipient subsidence stage in the Pliocene, an accelerated strain rate during the Quaternary provoked rapid sedimentation. A geophysical view of the architecture of the crust and the general trend of subordinate structures within this domain are discussed in the next section.

The Chubu domain is bordered by the ISTL and ESTL, and subdivided by the NKTZ into northern and southern sectors. The northern Chubu sector seems to be under the influence of the backarc inversion zone of northeast Japan, and all the active faults show dominant reverse slip. In contrast, the southern sector is characterized by numerous conjugate faults suggestive of an E-W regional compression. Although large-scale intra-arc basins do not develop in this area, Itoh et al. [37] demonstrated that conspicuous small basins are formed around terminations and stepping parts of the strike-slip faults.

4. Discussion

4.1. Characteristics of gravity anomaly

We show a Bouguer gravity anomaly map for our study area in Figure 1. This Bouguer gravity anomaly map is based on gravity mesh data [8], and the Bouguer density is 2670 kg/m^3.

In this region, positive gravity anomalies are dominant, and there are conspicuous positive anomalies over the Pacific Ocean and the Japan Sea. The Bouguer gravity anomaly of the Japan Sea side is relatively flat, while the Pacific Ocean side has a large gradient (Figure 1). The Bouguer gravity anomaly (Δg_B) in a marine area is generally positive in an area with a deep water, this is inferred form the Bouguer gravity anomaly given by the following (e.g., [38]).

$$\Delta g_B = \Delta g_F - 2\pi G\left(\rho_w - \rho\right) D \tag{1}$$

Here, Δg_F, D and G are the free-air gravity anomaly, the depth of water and the universal gravitational constant, respectively; ρ_w and ρ are water density and surface crust density, and generally $\rho_w < \rho$. Consequently, it is expected that these positive gravity anomaly areas have deep water. In fact, the areas correspond to the subduction zone along the Nankai Trough and the back-arc basins in the Japan Sea. There are negative gravity anomalies indicating the existence of subsidence structures between these positive gravity anomalies, and the subsidence structures forming the negative anomalies would be due to intra-arc basins.

These negative anomalies correspond to the active tectonic zone during the Quaternary called the ‘Kinki Triangle’ [33], and it is divided into the Osaka Bay and Lake Biwa areas. Negative gravity anomalies around Osaka Bay and the Lake Biwa reach -15 mGal and -60 mGal, respectively.

It is known that negative gravity anomalies in the Osaka Bay area can be explained by sediments accumulated in and around Osaka Bay (e.g., [39,40]), and these negative gravities are divided by some active faults (Figure 1). In contrast, it is known that negative gravity anomalies in the Lake Biwa area can not be explained by the distribution of soft sediments in the lake (e.g., [41]). Nishida et al. [41] have suggested that depression of the Conrad surface or the existence of very low-density materials due to faulting is necessary to explain the gravity low reaching -60 mGal.

Figure 6 depicts the first order horizontal derivative of the Bouguer gravity anomalies larger than 2 mGal/km that is shown by color gradation with an interval of 1 mGal/km. The first order horizontal derivative of the Bouguer gravity anomalies is defined by the following equation.

$$\sqrt{\left[\frac{\partial g(x,y)}{\partial x}\right]^2 + \left[\frac{\partial g(x,y)}{\partial y}\right]^2} \tag{2}$$

Here, g(x, y) is the gravity anomaly on xy mesh data at a constant interval. Since the first order horizontal derivative of the Bouguer gravity anomaly emphasizes the shorter wavelength signals of subsurface structures, it is a good indication of a conspicuous density change and/or a large fault.

In Figure 6, high gradient anomalies greater than 2 mGal/km, except in the Lake Biwa area, have the same direction (roughly parallel to the Nankai Trough), and most of them in the land area correspond well with large faults or tectonic lines (Figure 1). The distribution of high gradient anomalies around Lake Biwa is very complex, and it could be considered that they reflect subsurface structures caused by extreme crustal activity including faulting during the Quaternary.

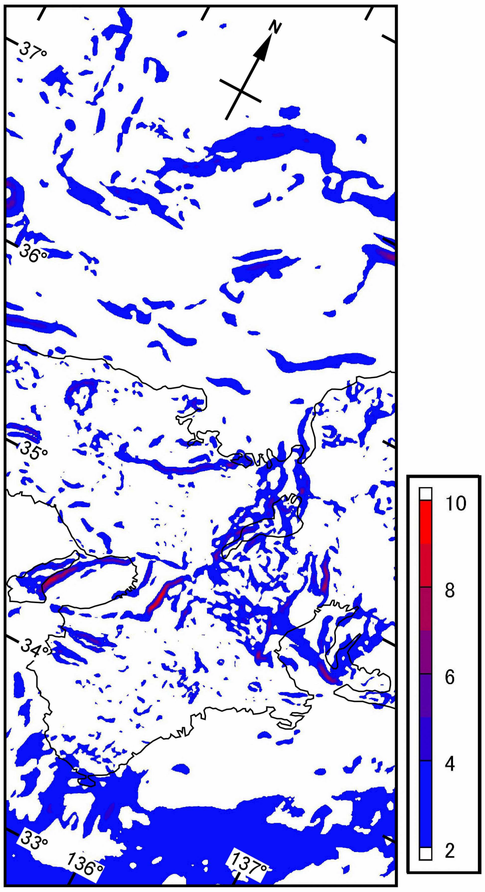

Figure 6. First order horizontal derivative of Bouguer gravity anomalies larger than 2 mGal/km, shown by color gradation with an interval of 1 mGal/km

4.2. Development of subordinate structure

As shown in the previous section, gravimetric analysis indicates that the crust of the Kinki domain is damaged under the influence of the complicated activity of surrounding tectonic zones. Numerous faults provoke the formation of intra-arc basins, among which Lake Biwa

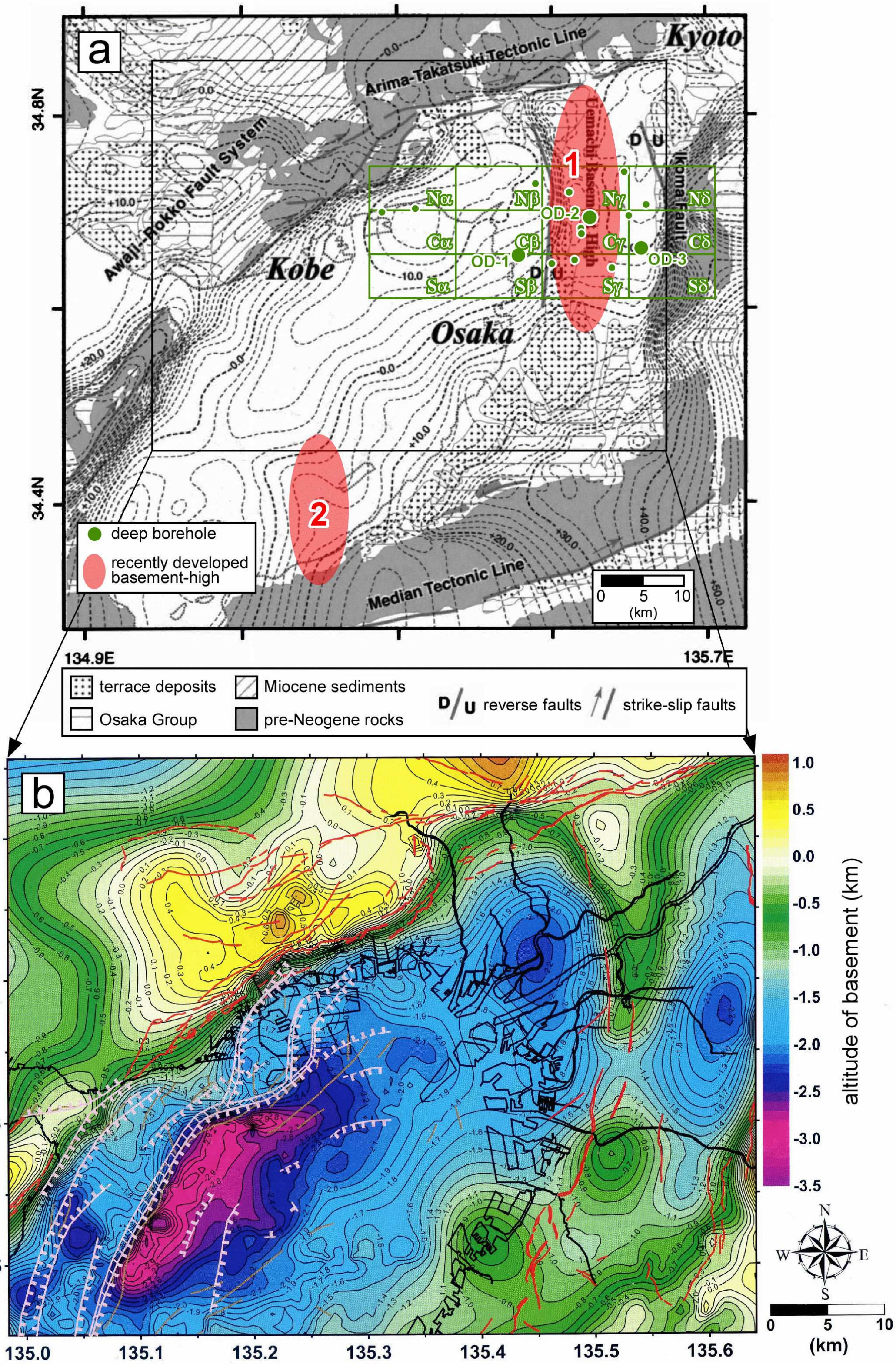

Figure 7. a) Bouguer gravity anomaly around the Osaka Bay at 2 mGal contour interval. The Bouguer density is 2670 kg/m^3. Green grid shows domains for calculation of sediment thickness [42]. (b) Altitude of basement around the Osaka Bay inferred from gravity data [45]

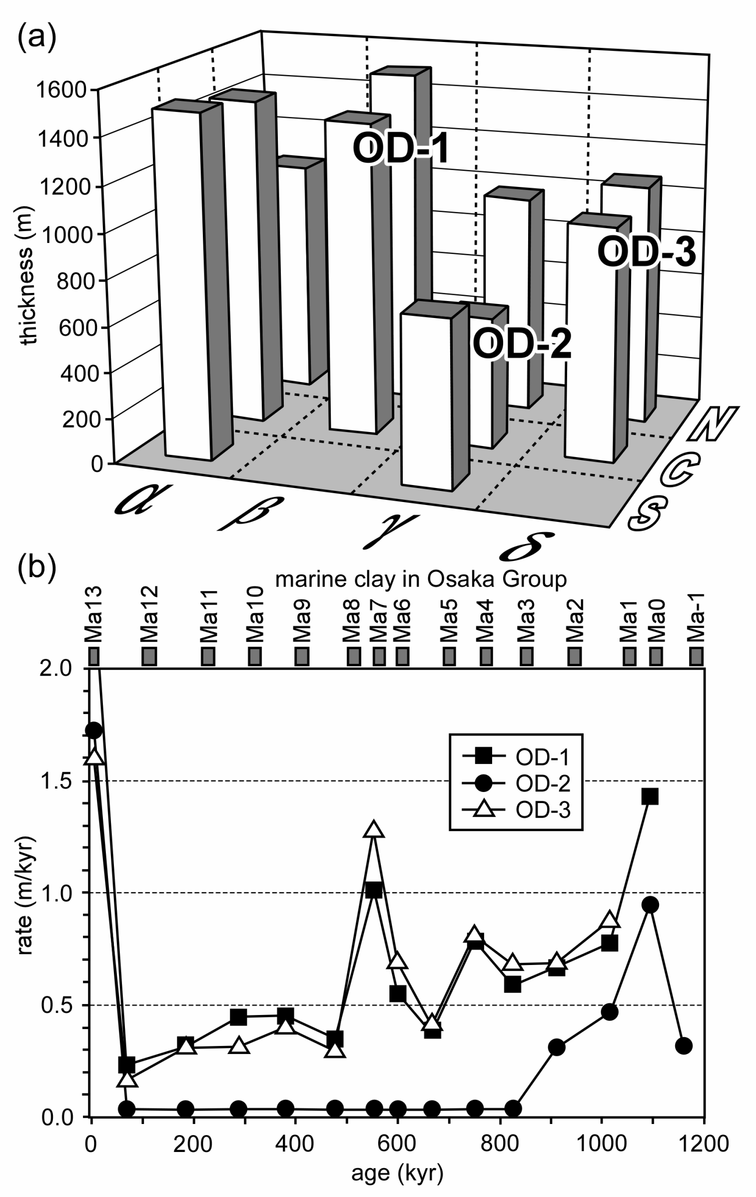

Figure 8. a) Sediment thickness diagram from the late Pliocene to early Pleistocene (from top of the basement to the Ma 2 marine clay intercalated in the Osaka Group) [42]. See Figure 7 for plan view and nomenclature of the analyzed domains. (b) Interval subsidence rates through the late Quaternary in the Osaka Plain [42]. See Figure 7 for locations of the selected boreholes

and Osaka Bay are the largest and most important for understanding the paleoenvironmental changes in southwest Japan. Takemura and others in this book present a comprehensive history of the Lake Biwa sedimentary basin.

It is noted that the majority of the subordinate faults have a N-S azimuth (Figure 1). Their activity results in the formation of N-S warping zones within the island arc as shown in Figure 7. Based on detailed well stratigraphy, Itoh et al. [42] showed that the largest warping in the Osaka sedimentary basin (Uemachi basement-high; 1 in Figure 7a) has been developing since the late Pliocene (Figure 8a), and episodically grew around 550 kyr, which is shown by

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synchronous acceleration of subsidence on the both flanks of the basement-high (Figure 8b). Similar events of crustal deformation are also confirmed in the Osaka Bay area. Itoh et al. [43] and Inoue et al. [44] indicated that a N-S warping (2 in Figure 7a) emerged around the mid-Quaternary and acted as a sedimentation divide in Osaka Bay. Basement altitude estimated from gravity (Figure 7b; [45]) implies that other subordinate structures emerged synchronous with the basin development. Thus, the differential motion of crustal blocks in a damage zone is closely related with complicated basin formation and conspicuous environmental changes.

5. Summary

A summary of basin-forming processes in an island arc was presented in connection with the development of a damaged area on an active plate margin. The Kinki district in southwest Japan has been a site of vigorous basin formation since the Pliocene. An accelerated Quaternary strain rate around the area is generally interpreted as a result of compressive stress linked to the westerly subduction of the Pacific Plate. Recent geodetic analyses demonstrated a NE-SW tectonic zone (Niigata-Kobe Tectonic Zone), which is an oblique trend of the geologically-detected active structure with a N-S azimuth (the Itoigawa-Shizuoka Tectonic Line). Based on the contrast in fault architecture and the subsurface structures depicted using geophysical methods, the authors define another cross-arc structural component, the Echizen-Shima Tectonic Line. Forearc deformation closely linked to activity of this tectonic line is discussed in a chapter of this book [46]. Westerly subduction of the Philippine Sea Plate has provoked the transcurrent motion of the forearc sliver and active faulting upon the along-arc Median Tectonic Line. Surrounded by these regional tectonic zones, the Kinki district is studded by countless subordinate faults and suffers from differential motion of crustal blocks, which results in great diversity of basin formation.

Acknowledgements

The authors are grateful to A. Noda for his constructive review. The early version of our manuscript was greatly improved based on his comments.

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