Evolutionary Models of Convergent Margins : Origin of Their Diversity

Chapter 3

Three-Dimensional Architecture of the Median Tectonic Line in Southwest Japan Based on Detailed Reflection Seismic and Drilling Surveys

Yasuto Itoh, Tomotaka Iwata and Keiji Takemura

Additional information is available at the end of the chapter

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Abstract

The subsurface morphology of an arc-bisecting tectonic zone has been unraveled by means of well-organized seismic investigation with the aid of borehole stratigraphic control. The Median Tectonic Line (MTL) active fault system in southwestern Japan, one of the world's largest intraplate transcurrent faults, is driven by the recent oblique subduction of the Philippine Sea Plate. Six tied seismic profiles covering the mountainous range, the southern foothill of which is truncated by the MTL, were used to visualize the Quaternary basins on both feet of the Izumi Mountains. North- and east-trending basement deformation was confirmed on the northern and southern sides of the watershed, respectively; this deformation reflects the spatial diversity in tectonic stress. Seismic data on the southern Izumi flank revealed a low-angle fault parallel to the MTL active fault system; this fault may be interpreted as a dormant structure that developed from 6 to 2 Ma under the intermittent increases of the compressive regime. A kink zone in the upthrown block of the thrust was identified on seismic profiles and continuously traced through field geological survey. This zone confirms the prevailing contractional phase related to the transient convergence mode of the oceanic plate.

Keywords: active fault, seismic survey, borehole, southwest Japan, Median Tectonic Line

1. Introduction

On convergent margins, the deformation and rearrangement of island arcs are often provoked by the oblique subduction of oceanic plates [1]. Located on the eastern Eurasian margin, the

Japanese Archipelago has been a site of vigorous tectonic events for more than hundreds of millions of years. Huzita contended that recent crustal deformation has been accompanied by frequent motions on basin-fringing active faults in his pioneering papers [2, 3]. He placed an emphasis on the role of the Median Tectonic Line (hereafter abbreviated as MTL), dextral motions on which have recurred during the Quaternary and bisect the southwestern Japan arc. Evaluation of its neotectonic activity has been established based on its geomorphological features [4, 5]. In the present chapter, the authors concentrate on the eastern part of the MTL running through the Kii Peninsula, where a comprehensive fault study was recently executed by the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT). Before the national project, detailed geologic surveys including the excavation of surface ruptures [6] have been used to describe the superficial deformation pattern along the fault, and a series of offshore [7] and onshore [8] seismic studies have been presented as useful profiles across the fault. As for the western half of the peninsula, a tectonic model has been proposed to strike a balance between the fault structure and its dominant motion senses [9]. However, the three-dimensional architecture of the MTL, one of the largest intraplate faults in the world, has never been addressed by means of detailed seismic data with a reliable stratigraphic control on deep boreholes; this theme was the focus of the present study.

2. Seismic surveys

The dataset used in this study consists of six tied seismic lines, two of which cross control boreholes. **Figure 1** delineates the study area, the reflection seismic array, and the boring locations.

In 1996, the National Research Institute for Earth Science and Disaster Resilience (NIED) conducted a seismic survey of the approximately 5300 m long K96-1 line along the southwestern coast of the Osaka Plain (**Figure 2**; [10]). During the shooting, 240 channels of geophones at 25 m intervals recorded the energy released from two vibrators (Y-2400) shot at 50 m intervals. The raw seismic data were stacked and then subjected to a poststack processing sequence to enhance the resolution.

In 1996, NIED conducted a seismic survey of the approximately 4800 m long K96-2 line that is connected to the K96-1 line at its northwestern end (**Figure 3**; [10]). During the shooting, 240 channels of geophones at 25 m intervals recorded the energy released from two vibrators (Y-2400) shot at 50 m intervals. The raw seismic data were stacked and then subjected to a poststack processing sequence to enhance the resolution.

In 1996, NIED conducted a seismic survey of the approximately 17,600 m long N96-1 line that runs through the Izumi Mountains and crosses the MTL (**Figure 4**; [11]). During the shooting, 240 channels of geophones at 25 m intervals recorded the energy released from four vibrators (Y-2400) shot at 50 m intervals. The raw seismic data were stacked and then subjected to a poststack processing sequence to enhance the resolution.

In 2006, MEXT et al. conducted a seismic survey of the approximately 22,200 m long Izumi line that runs through the Izumi Mountains and crosses the MTL (**Figure 5**; [12]). During the shooting, 555 channels of geophones at 40 m intervals recorded the energy released from four vibrators (HEMI-50) shot at 10 m intervals. The raw seismic data were stacked and then subjected to a poststack processing sequence to enhance the resolution.

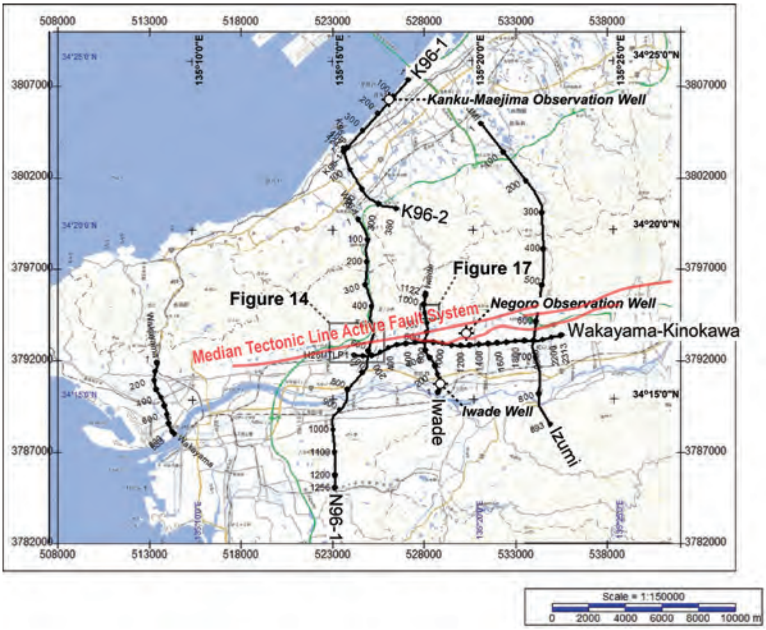

Figure 1. Index map of the seismic and drilling survey area. Common midpoint (CMP) numbers are attached to the seismic lines. Refer to the prologue of this section for regional tectonics.

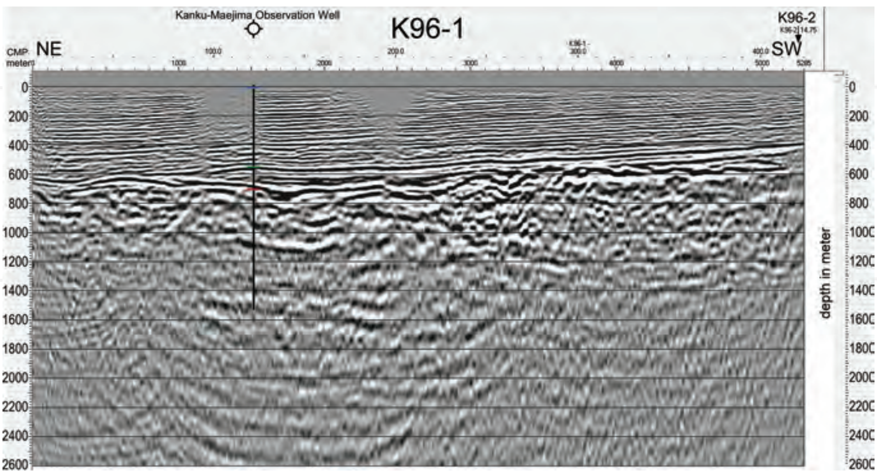

Figure 2. Raw seismic profile of the K96-1 line without vertical exaggeration [10]. See **Figure 1** for line location.

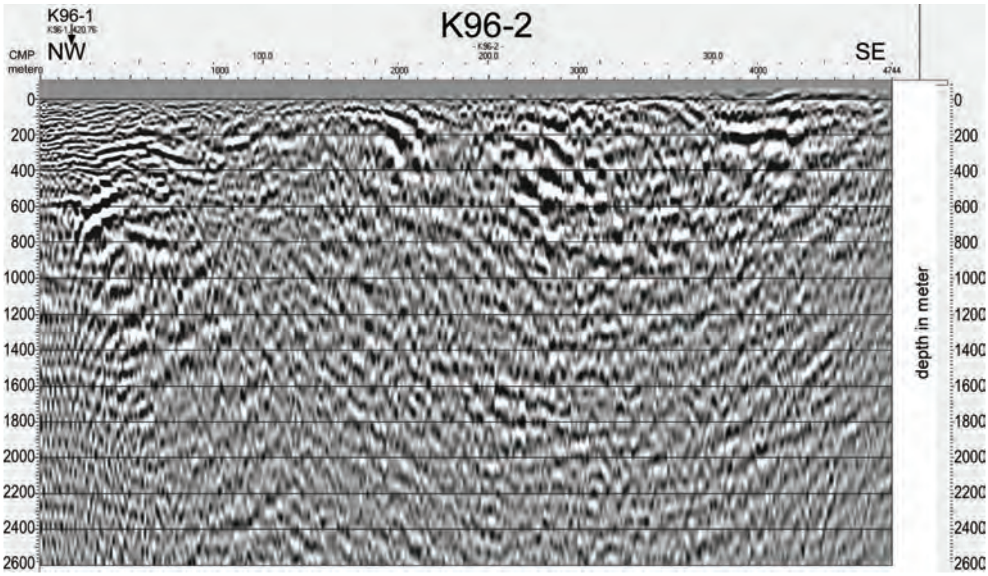

Figure 3. Raw seismic profile of the K96-2 line without vertical exaggeration [10]. See **Figure 1** for line location.

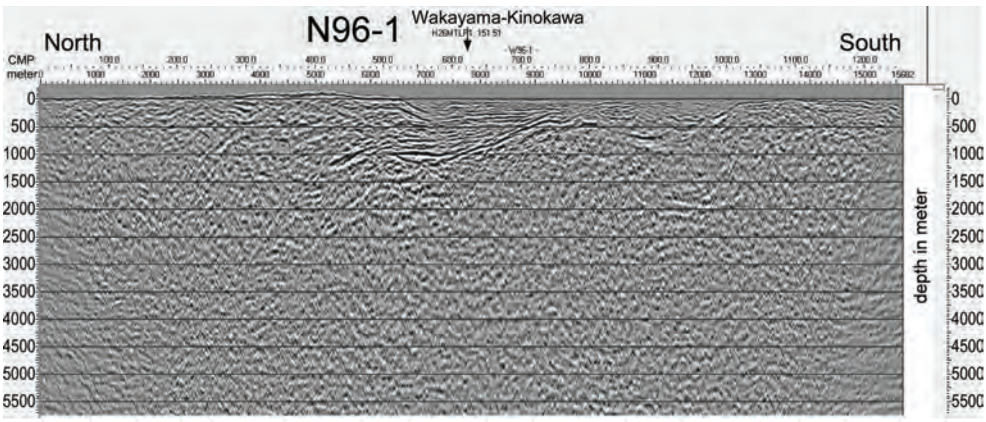

Figure 4. Raw seismic profile of the N96-1 line without vertical exaggeration [11]. See **Figure 1** for line location.

In 2014, MEXT and the Disaster Prevention Research Institute (DPRI) conducted a seismic survey of the approximately 5760 m long Iwade line that is located on the southern flank of the Izumi Mountains and crosses the MTL (**Figure 6**; [13]). During the shooting, a minimum of 100 channels of geophones at 10 m intervals recorded the energy released from one vibrator (EnviroVibe) shot at 10 m intervals. The raw seismic data were stacked and then subjected to a poststack processing sequence to enhance the resolution.

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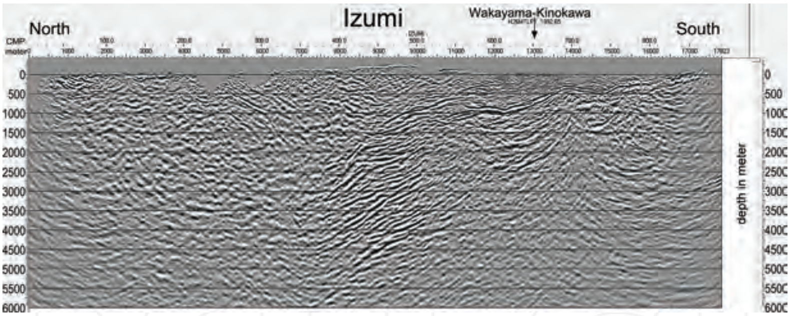

Figure 5. Raw seismic profile of the Izumi line without vertical exaggeration [12]. See **Figure 1** for line location.

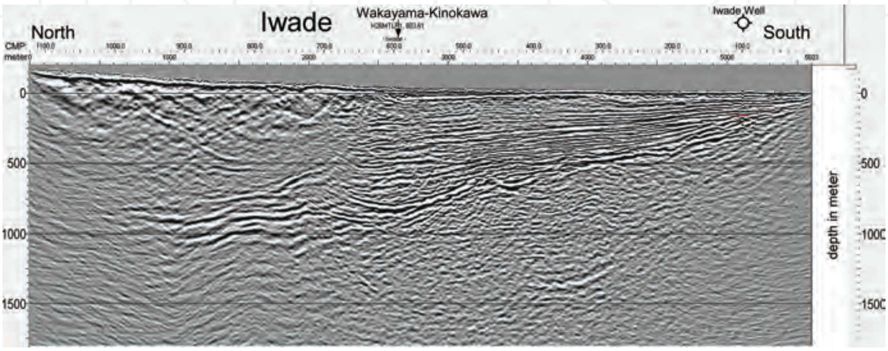

Figure 6. Raw seismic profile of the Iwade line without vertical exaggeration [13]. See **Figure 1** for line location.

In 2015, MEXT and DPRI conducted a seismic survey of the approximately 11,774 m long Wakayama-Kinokawa line, which runs parallel to the MTL and crosses the N96-1, Iwade, and Izumi lines (**Figure 7**; [14]). During the shooting, a minimum of 120 channels of geophones at 10 m intervals recorded the energy released from one vibrator (EnviroVibe) shot at 10 m intervals. The raw seismic data were stacked and then subjected to a poststack processing sequence to enhance the resolution.

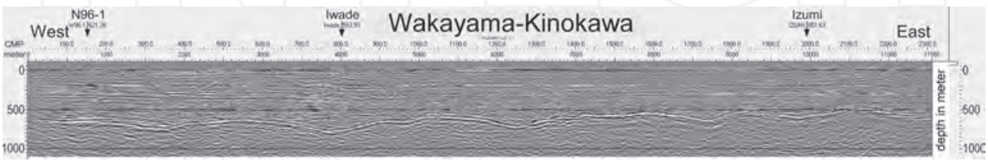

Figure 7. Raw seismic profile of the Wakayama-Kinokawa line without vertical exaggeration [14]. See **Figure 1** for line location.

3. Drilling surveys

3.1. Negoro Observation Well

The Negoro Observation Well was drilled vertically on the southern foothill of the Izumi Mountains (**Figure 1**). Continuous core samples were recovered during drilling and were identified as sheared sandstones and unconsolidated clastics intercalating a glassy volcanic ash (V290) from the ground surface to a depth of 137 m and from 137 to 625 m (TD), respectively (**Figure 8a**; [15]).

Mizuno et al. [15] assigned the upper consolidated unit to the late Cretaceous Izumi Group, which forms the watershed Izumi Mountains, and the lower loose unit to the Plio-Pleistocene Shobudani Formation. Plant macrofossils in the lower unit contained *Liquidambar* and *Pseudolarix* with last occurrences around the late Gauss Chron and early Matuyama Chron, respectively. The stratigraphic position of the unit was concordant with tephrochronology and paleomagnetic polarities confirmed on the same samples. As for the radiometric dating of the unconsolidated unit, fission-track and U-Pb ages of a surface ash sample taken near the drilling site were determined to be 1.33 and 1.50 Ma, respectively [16].

Contact between the lower (younger) and upper (older) units was regarded as a fault based on the presence of fault breccia and fault clay. The uppermost part of the Plio-Pleistocene unit (1 m thick) is sheared and tilted and suggests the occurrence of recent slips on the unit boundary. On the assumption that the discontinuity plane is connected to the Negoro-Minami Fault fringing the southern rim of the foothill, the reverse fault is estimated to dip approximately 30° northward. Additionally, an active fault was found on an outcrop adjacent to the drilling location [6], where the high-angle ENE-trending Negoro Fault with dominant dextral motion was confirmed.

In summary, the Negoro Observation Well provides the geometry of local active faults around the southern Izumi range and the age span of the recent fluvial basin developed along the MTL active fault system (see **Figure 1**).

3.2. Kanku-Maejima Observation Well

The Kanku-Maejima Observation Well was drilled vertically on the southwestern coast of the Osaka Plain, tied with the seismic K96-1 line (**Figure 1**). The lithologies of the penetrated strata were described based on cutting observations taken at depth intervals of 10 m and classified into upper unconsolidated Quaternary clastics and partly metamorphosed igneous rocks from the ground surface to 556 m and from 556 to 1535 m (TD), respectively (**Figure 8b**; [17]).

However, it should be noted that the upper part of the metamorphosed unit (556–700 m) is characterized by obvious stratification on the K96-1 line (**Figure 2**) and the top of the unit constitutes an aggradational surface of the overlying sediments. Thus, the authors interpret the equivocal section as crushed monomictic clasts originating exclusively from the Ryoke metamorphic rocks exposed on the northern flank of the Izumi range.

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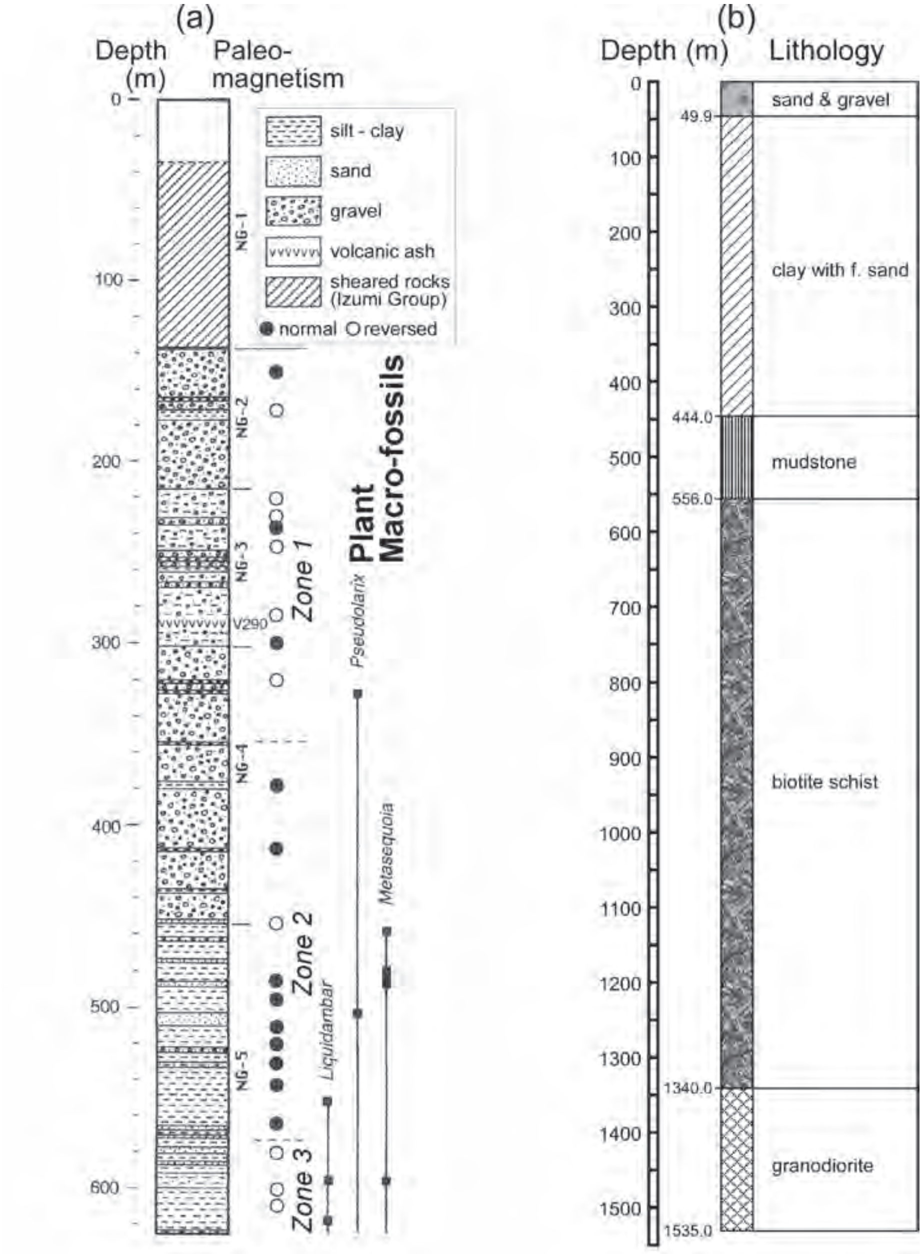

Figure 8. Geologic summaries of the (a) Negoro and (b) Kanku-Maejima Observation Wells [15, 16]. See **Figure 1** for drilling locations.

In summary, the Kanku-Maejima Observation Well provides the precise depths of the top of the acoustic basement (700 m) and the horizon of a drastic change in the clastic compositions, reflecting the progressive exhumation of the hinterland (556 m) on the K96-1.

3.3. Iwade Well

The Iwade Well was drilled vertically on the north bank of the Kinokawa River, tied with the seismic Iwade line (**Figure 1**). Continuous core samples and spot cuttings were recovered from intervals shallower and deeper than a depth of 189 m, respectively, and the strata were categorized into terrace deposits, Quaternary fluvial sediments, and Sanbagawa metamorphic rocks from the ground surface to 23 m, from 23 to 163 m, and from 163 to 300 m (TD), respectively (**Figure 9**; [18]).

A series of tephrochronological analyses that was executed for many dispersed ashes failed to correlate the ashes with widespread tephra. Although normal and reversed pDRMs were observed in the laboratory, unstable rock magnetic behavior during thermal treatments hindered the determination of polarity epochs. Fluvial sediments in the Iwade Well were correlated with the Plio-Pleistocene Shobudani Formation ad hoc [18] based on the stratigraphic study of the nearby Negoro Observation Well. However, it seems that a formal definition of the Shobudani Formation has not been established. Mizuno [19] defined the "Shobudani" unit as sediments that buried a fluvial basin along the MTL active fault system (see **Figure 1**), but the formation is assigned to three distant epochs, as he had previously suggested [15]. Recent U-Pb ages [16] obtained from volcanic ashes intercalated in the Shobudani Formation within the geologic map of Kokawa [6] showed a large scatter ranging from 0.26 to 1.50 Ma. In summary,

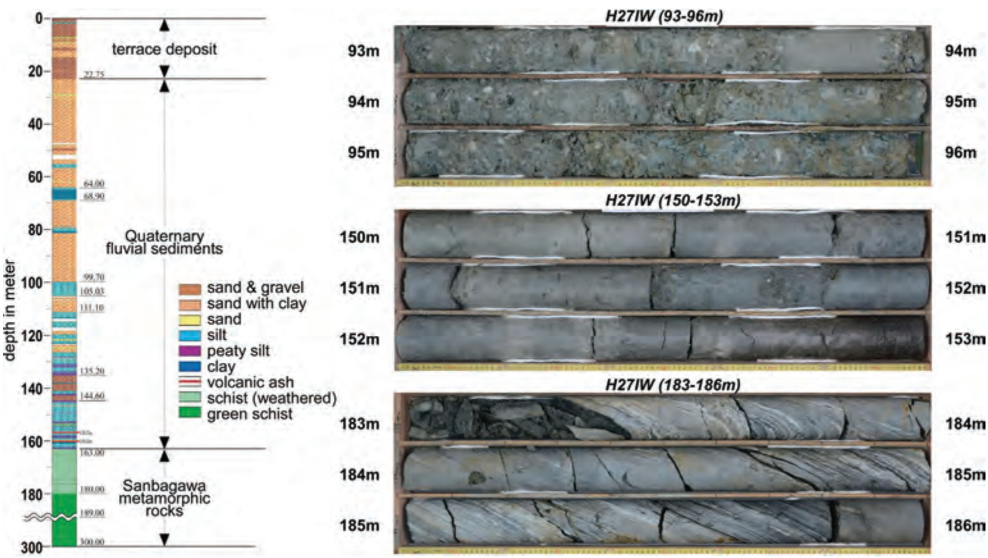

Figure 9. Geologic summary of the Iwade Well [18]. See **Figure 1** for drilling location.

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the "Shobudani" is an artifact or a hodgepodge of fluvial sequences along the MTL, and further chronological and sedimentological analyses should be made to obtain the definitive tectonic context of the sedimentary unit. Thus, the Iwade Well is simply referenced as an indicator of depth of the top of the acoustic basement on the Iwade line.

4. Geologic interpretation of seismic profiles

After exploring the stratigraphic information of boreholes in the study area, seismic interpretation was performed to obtain the subsurface structural architecture. In this section, a series of seismic features and their tectonic implications are presented.

4.1. K96-1 line

Figure 10 shows the results of the seismic interpretation of the K96-1 line; the top of the acoustic basement and the boundary between the lower metamorphosed clasts and the upper normal sediments are delineated as red and green lines, respectively.

It is noteworthy that the reflection terminations of the normal sediments are onlapping onto the lower unit surface in the southwestward direction. Such a tendency and the gentle tilt of the sedimentary units imply the recent uplift of the southwestern basin margin. This is a north-trending basement high discovered by means of gravity, seismic, and borehole investigation (**Figure 11**; [20–22]). The homoclinal tilting of the upper unit is suggestive of the episodic and possibly ongoing uplift of the mound accompanied by basement deformation.

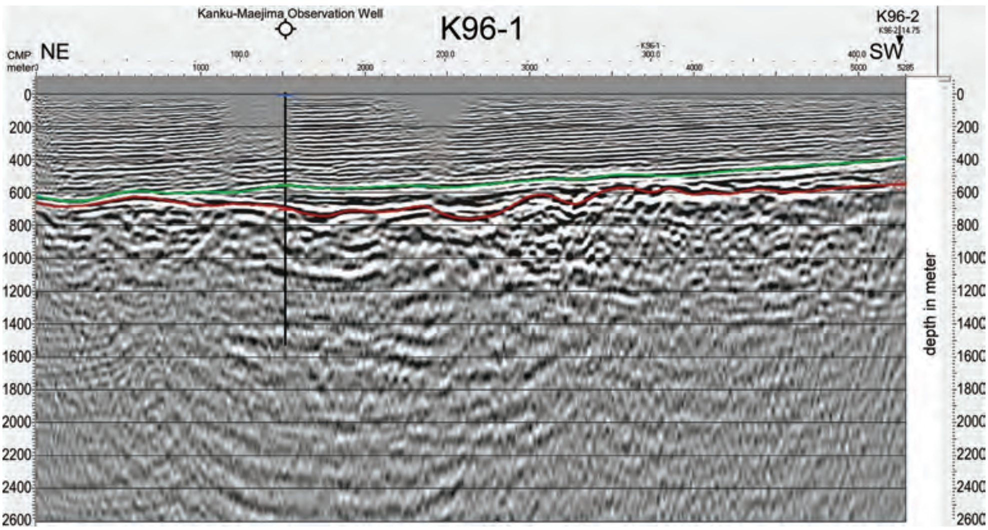

Figure 10. Interpreted seismic profile of the K96-1 line without vertical exaggeration. See **Figure 1** for line location.

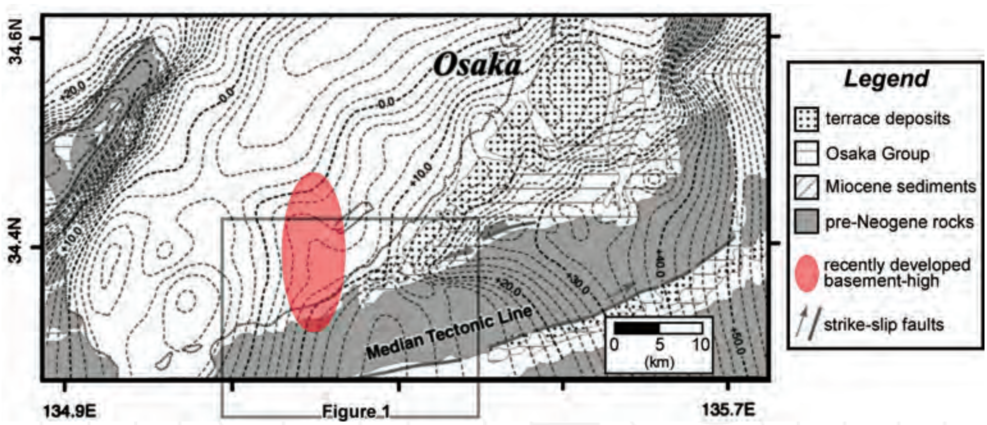

Figure 11. Regional basin morphological map of the southern Osaka Bay after Itoh et al. [20, 21]. Gravity contours are drawn at 2-mGal intervals.

4.2. K96-2 line

Regarding the K96-2 line, traceable seismic horizons are recognizable at its northwestern end, where the Cretaceous Izumi Group is covered by Quaternary sediments (**Figure 12**). The top of the acoustic basement (red in the downthrown block, maroon in the upthrown block) and the boundary between the metamorphosed clasts and normal sediments (green) are traceable from the K96-1 line. They are cut by two reverse faults, recent cumulative slips on which are unclear because the green horizon was not identified in the upthrown block.

A previous seismic interpretation [23] indicated that these faults are active faults parallel to the coastline. However, it seems that north-to-NNW-trending warping is a recent geomorphic feature around the northern foothill of the Izumi range [24], and one of the largest bumps coincides with the gentle uplift zone described on the K96-1 line. The presence of a superficial rupture on the K96-2 faults cannot be confirmed. In an effort to visualize the three-dimensional architecture of the Osaka sedimentary basin [25, 26], structural diversity that may reflect the transient convergence mode of oceanic plates (the Pacific and Philippine Sea Plates) has been recognized. The latest research [16] has presented a chronicle of the waxing and waning of neotectonic stresses and the varied structural development around the southern portion of the basin.

4.3. N96-1 line

On the southern side of the Izumi Mountains, only the top of acoustic basement is traceable through the four investigated sections. On the N96-1 line, the basement seismic horizon is shown as a red line in the downthrown block and a maroon line in the upthrown block, which is sandwiched between two faults (**Figure 13**). A kink zone in the Cretaceous Izumi Group was observed between the reverse faults.

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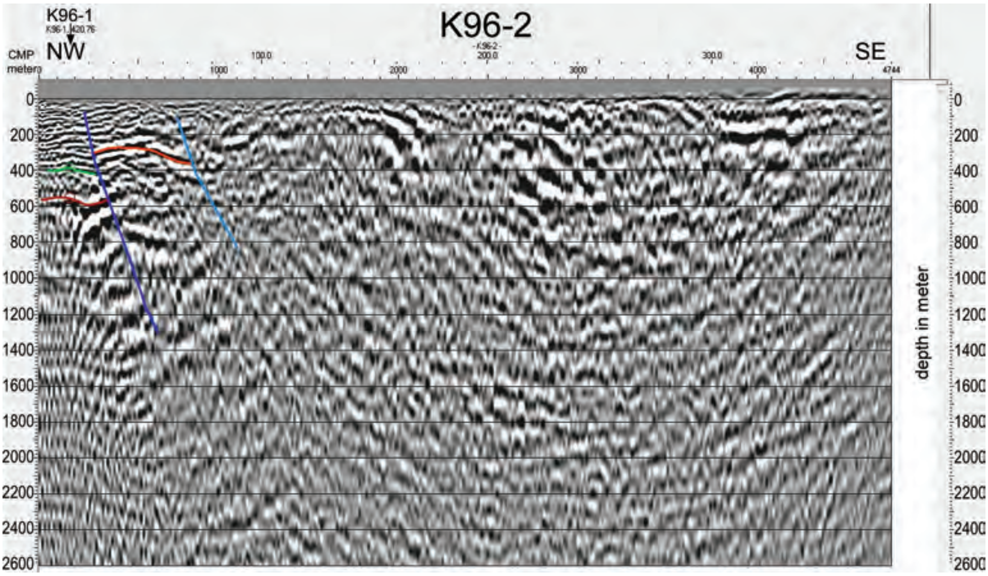

Figure 12. Interpreted seismic profile of the K96-2 line without vertical exaggeration. See **Figure 1** for line location.

The present field observation has indicated that the ENE-trending kink zone (parallel to the MTL) extends to the surrounding areas (**Figure 14**). First, it should be noted that the kink trend deviates from the original structure of a plunging syncline that developed after the initial deposition of the Izumi Group. Second, it is important that the kink is considerably distant from the active dextral trace of the MTL. In the present study, it was interpreted that the kink zone developed under the influence of compressive stress episodically raised from the Pliocene to early Pleistocene.

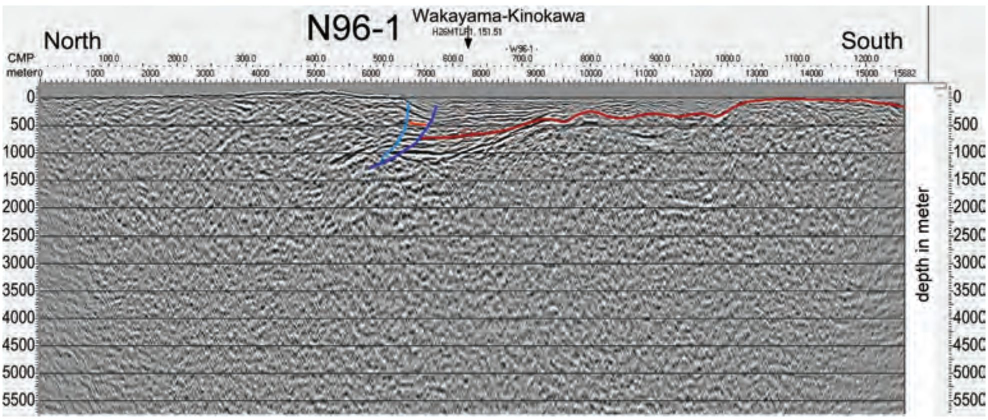

Figure 13. Interpreted seismic profile of the N96-1 line without vertical exaggeration. See **Figure 1** for line location.

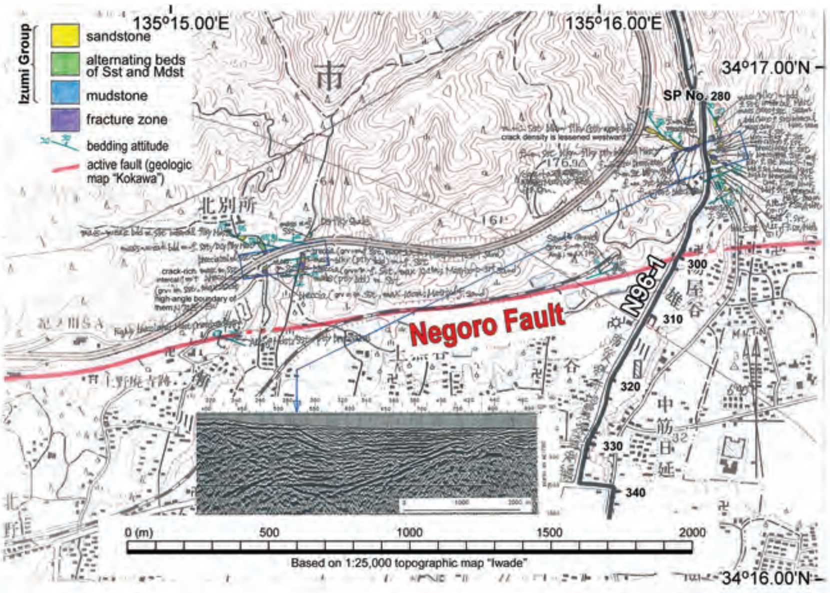

Figure 14. Field observation of a deformation zone along the N96-1 line. See **Figure 1** for mapped area.

4.4. Izumi line

On the Izumi line, a single low-angle fault and the top of acoustic basement were delineated (**Figure 15**). A half-graben buried by the Quaternary sediments is clearly shown on the profile.

On this seismic line, the deformation zone of the upthrown block of the thrust was not clearly identified.

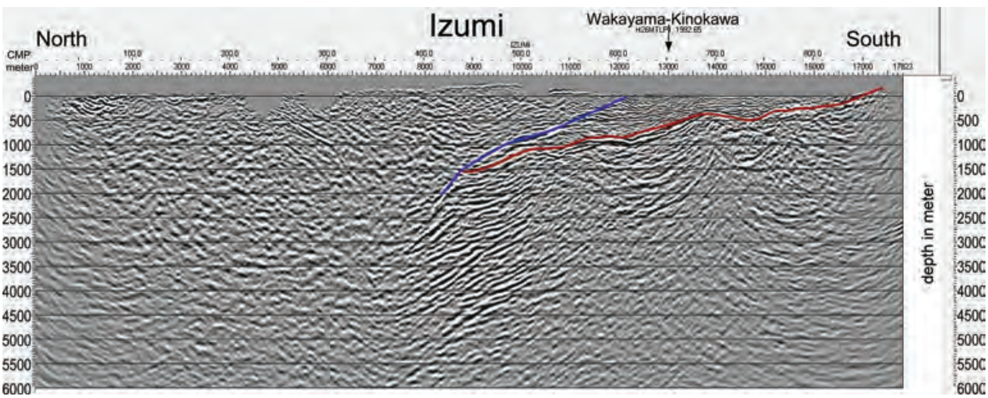

Figure 15. Interpreted seismic profile of the Izumi line without vertical exaggeration. See **Figure 1** for line location.

4.5. Iwade line

On the Iwade line, a single low-angle fault and the top of acoustic basement were delineated (**Figure 16**). A half-graben buried by the Quaternary sediments is clearly shown on the profile.

On this seismic line, the structure of the upthrown block of the thrust appears to be chaotic and to not contain a clear kink zone. As shown in **Figure 17**, the present field survey has revealed a divergent deformation zone adjacent to the Iwade line.

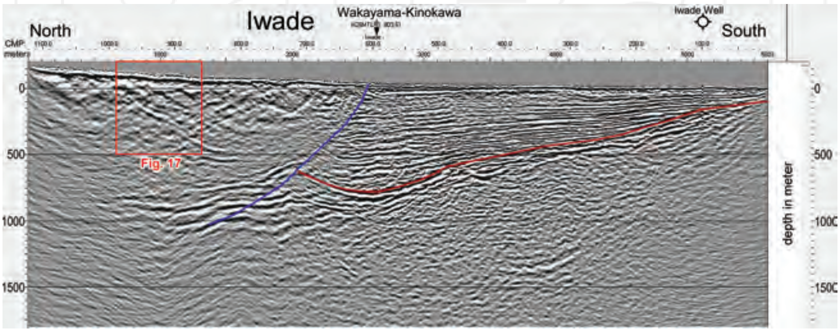

Figure 16. Interpreted seismic profile of the Iwade line without vertical exaggeration. See **Figure 1** for line location.

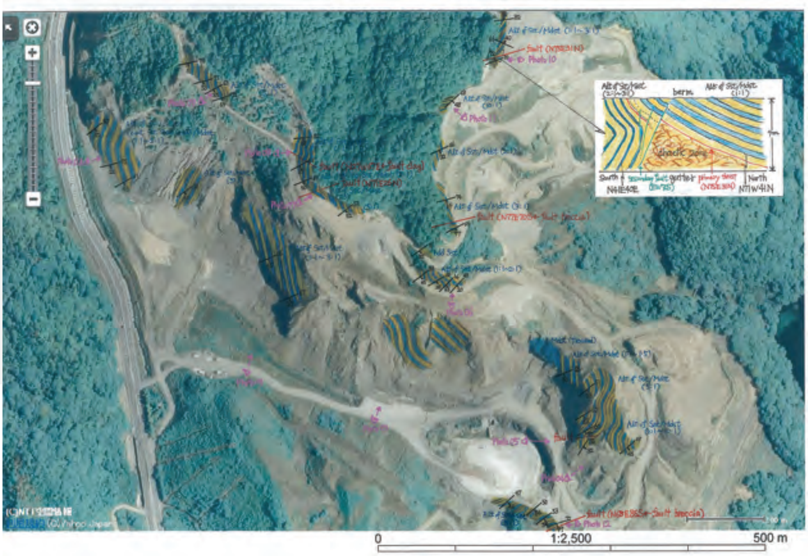

Figure 17. Field observation of a deformation zone along the Iwade line. See **Figure 1** for mapped area.

4.6. Wakayama-Kinokawa line

On the Wakayama-Kinokawa line, the gentle undulation of the top of the acoustic basement was delineated (**Figure 18**). As shown by the north-south seismic lines, the southern foothill of the Izumi range is characterized by a general ENE-trending structure that agrees with the topographic features. Hence, the discovered warping on the trend-parallel line implies the existence of subordinate crustal strain along the fault. Furthermore, the Quaternary sediments on the profile were observed to be nearly undeformed.

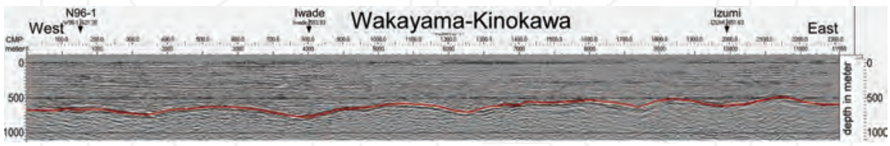

Figure 18. Interpreted seismic profile of the Wakayama-Kinokawa line without vertical exaggeration. See **Figure 1** for line location.

The basal heaves on the profile appear to correspond to uplifted areas of the southern foothill of the Izumi range. Although the flat attitudes of the recent sediments indicate that they do not have a direct relationship with the structural development processes, longstanding activities of the MTL since the Cretaceous may have developed similar wrenching trends along the fault. The gravity anomaly trend [27] shown in **Figure 19** implies that the most remarkable structural break lies under the present Kinokawa River, where a distinct gap in metamorphic grades in the Sanbagawa metamorphic complex was confirmed [28]. A similar crustal structure is also supported by the geomagnetic anomaly trend [29].

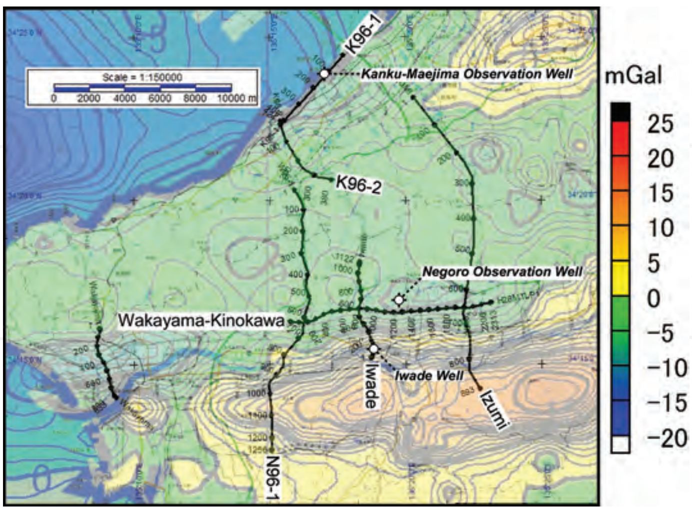

Figure 19. Overlaid images of geography and gravity anomaly trend [27] around the southern flank of the Izumi Mountains.

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5. Tectonic context of the unraveled structure along the MTL

The present 3-year geophysical and geological exploration along the MTL active fault system (see **Figure 1**) has clarified its detailed structure. **Figure 20** presents the first-ever images of the three-dimensional architecture around the MTL.

The MTL delineated through reflection seismic study is characterized by a low-angle feature, which should have reverse motion sense considering the shape of foreland basin and deformation of the Quaternary strata burying the depression. Sato et al. [9] have argued that the MTL was initiated as a subduction surface of the Izanagi Plate during the Early Cretaceous and became reactivated as a low-angle dextrally moving thrust during the Quaternary. Their intriguing scenario appears to ignore the presence of active high-angle right-lateral fault that is separate from and runs parallel to the remarkable thrust [6, 13, 14, 18]. Although such a hypothesis should agree with geological evidence, the low-angle model has some notable discrepancies. First, a high-pressure metamorphic belt is expected to develop on the upthrown block of the down-going slab, but the Sanbagawa metamorphic complex exists exclusively on the downthrown side of the thrust [30]. Second, the Cretaceous Izumi Group resting on the thrust is a series of turbidite sequences that buried a gigantic pull-apart basin [31], which should be formed not on a thrust but on the stepping part of high-angle lateral faults. As for the strange occurrence of a metamorphosed terrane, Sato et al. [9] proposed a conciliatory plot that the plate boundary jumped toward the ocean side as a result of the normal convergence of the Pacific Plate during the Late Cretaceous. Unfortunately, this is in disagreement with the coeval deformation history of an accretionary complex of the Shimanto Belt [32], which requires a nearby transcurrent fault. A regional paleogeographic reconstruction [33] showed that the MTL constituted a Cretaceous strike-slip break along the Eurasian margin together with the Central Sikhote Alin Fault. It is most probable that the low-angle fault on the seismic profiles has a younger origin unrelated to the Mesozoic transform boundary.

The most notable suspect in the extensive contractional event is the north-south shortening of southwestern Japan in the Late Miocene [34]. Although this tectonic deformation seems to be concentrated on the margin of the Japan Sea back-arc basin, the present thermochronological analysis based on the annealing of fission tracks in apatite and zircon separated from sandstones of

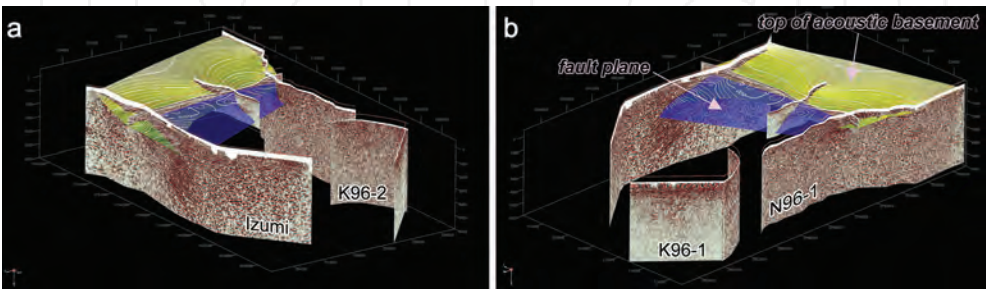

Figure 20. Bird's-eye views of the subsurface structural architecture around the Izumi Mountains from (a) the northeast and (b) the northwest based on reflection seismic interpretation. The moss green and semi-transparent blue surfaces represent the top of the acoustic basement and the most remarkable fault, respectively. See **Figure 1** for line locations.

the Izumi Group revealed that significant vertical exhumation of the sedimentary unit occurred near the end of the Miocene (Chapter 5). A sediment provenance study revealed crucial evidence of another epoch of contraction. Oka [35] noted that the lower part of the Quaternary strata exposed on the northern flank of the Izumi range contains a considerable amount of crystalline schist clasts derived from the Sanbagawa metamorphic complex, a fact that suggests that the emergence of the watershed Izumi Mountains occurred later than 3 Ma. This uplift event seems to have prevailed along the MTL [36] and to have been accompanied by the delayed deformation of the forearc [37]. The authors conclude that the remarkable thrust on the southern Izumi range developed between 6 and 2 Ma under the intermittent rise of compressive stress. Since then, the mountain-building activity has been dormant except for an episodic event that caused the uplift of the northern Izumi foothill [35] at ca. 1 Ma. This most recent incident may have been responsible for formation of the small fractures observed on the K96-2 line.

The recent reinforced dextral motion on the MTL is probably linked to a counterclockwise shift of the converging direction of the Philippine Sea Plate between 2 and 1 Ma [38], which provoked the wrench deformation of southwestern Japan [39], the migration of the forearc sliver [40], and the eventual crustal break on the back-arc shelf [41]. In an edited collection of the latest results of multidisciplinary studies on the mechanism of sedimentary basin formation [42], Itoh et al. [43] described a complicated subsurface structure in southwestern Japan related to the differential motion of fault-bounded crustal blocks. The evolutionary process of the MTL active fault system reflects the temporal shifts in the motion of the Philippine Sea Plate [44], and coming tectonic episodes (e.g., seamount subduction) may revitalize the Izumi thrust in the future.

6. Conclusions

The present integrated research has enabled the visualization of a thrust lying beneath the Izumi Mountains running parallel to the MTL active fault system, as presented in **Figure 21**.

With the aid of the stratigraphic control of three boreholes in the study area, seismic horizons were traced through the six tied reflection survey lines covering the watershed mountains, and the morphological characteristics of the Quaternary basins were successfully delineated on both flanks of the mountainous area. On the southern flank, the authors found a low-angle north-dipping fault, the up- and downthrown sides of which consist of the Cretaceous sedimentary rocks (Izumi Group) and unconsolidated fluvial sediments, respectively. Based on the subsidence pattern and the deformation mode of the infilled sediments of the recent asymmetric basin, it is clear that reverse slips are dominant on the fault. An ENE-trending continuous kink zone within the Izumi Group that has been detected on the seismic profiles and confirmed by geologic survey suggests the contractional deformation of the upthrown wedge. Considering the geomorphological features around the study area, the dextral movement on the MTL active fault system, which runs along the foothill margin to the south of the thrust, is likely to accommodate recent shear stress provoked by the oblique subduction of the Philippine Sea Plate. From the regional neotectonic context of the southwestern Japan arc, the dormant thrust likely evolved from 6 to 2 Ma, causing the uplift of the mountains under intermittent phases of north-south compression. At the present stage of tectonic history, the low- and high-angle crustal breaks act as material and mechanical boundaries, respectively.

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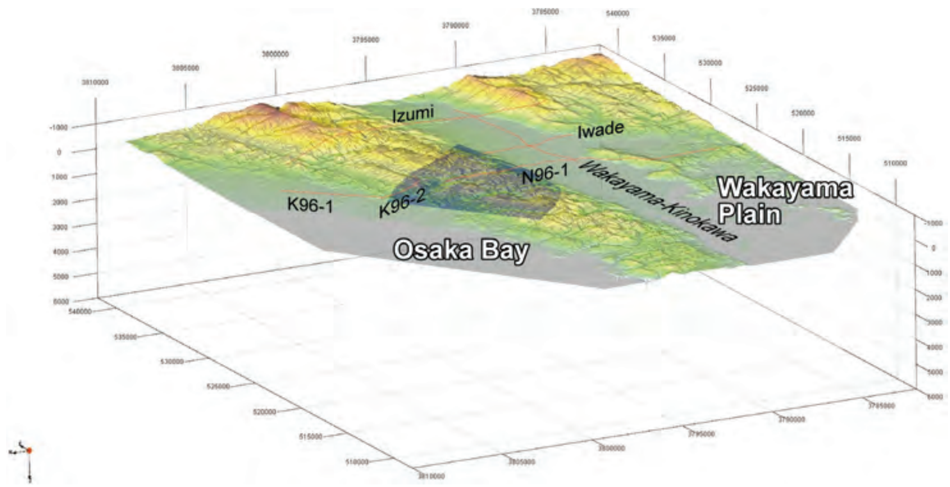

Figure 21. Bird's-eye DEM topographic map around the Izumi Mountains from the northwest. The most remarkable fault is shown as a semi-transparent blue surface. See **Figure 1** for line locations.

Among significant results of the authors' research, bird's-eye movies of three-dimensional fault architecture based on seismic interpretation and some original figures in this chapter are available at OPERA:Osaka Prefecture University Education and Research Archives (http://hdl.handle.net/10466/15058).

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Author details

Yasuto Itoh[1]*, Tomotaka Iwata[2] and Keiji Takemura[3]

*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

3 Institute for Geothermal Sciences, Kyoto University, Beppu, Japan

References

[1] Fitch TJ. Plate convergence, transcurrent faults, and internal deformation adjacent to southeast Asia and the western Pacific. Journal of Geophysical Research. 1972; 77: 4432-4460.

[2] Huzita K. The Quaternary tectonic stress states of Southwest Japan. Journal of Geosciences, Osaka City University. 1976; 20: 93-103.

[3] Huzita K. Role of the Median Tectonic Line in the Quaternary tectonics of the Japanese islands. Memoir of Geological Society of Japan. 1980; 18: 129-153.

[4] Research Group for Active Faults. The Active Faults in Japan: Sheet Maps and Inventories rev.ed. Tokyo: University of Tokyo Press; 1991.

[5] Okada A, Togo M, editors. Active Faults in Kinki. Tokyo: University of Tokyo Press; 2000. 395 p.

[6] Makimoto H, Miyata T, Mizuno K, Sangawa A. Geology of the Kokawa District, with Geological Sheet Map at 1:50,000. Tsukuba: Geological Survey of Japan, AIST; 2004. 89 p.

[7] Yoshikawa S, Kadosawa H, Mitsuhashi A, Iwasaki Y. Geological structure of the Median Tectonic Line in Tomogashima Strait area. Journal of the Japan Society for Marine Surveys and Technology. 1996; 8: 1-10.

[8] Yoshikawa S, Iwasaki Y, Ikawa T, Yokota H. Geological structure of the MTL in west Wakayama by reflection seismic study. Memoir of Geological Society of Japan. 1992; 40: 177-186.

[9] Sato H, Kato N, Abe S, Van Horne A, Takeda T. Reactivation of an old plate interface as a strike-slip fault in a slip-partitioned system: Median Tectonic Line, SW Japan. Tectonophysics. 2015; 644-645: 58-67.

[10] NIED (National Research Institute for Earth Science and Disaster Resilience). Report of Vibroseis and VSP Structural Survey Related to the Kanku-Maejima Boring Exploration by the Science and Technology Agency. Tsukuba: NIED; 1997.

[11] Kasahara K, Aoi S, Kimura H, Ikawa T, Kawanaka T, Mizohata S, Okamoto S. Subsurface structure derived from the seismic reflection survey around Median Tactonic Line at northwestern part of Wakayama. In: Abstracts of the Annual Meeting of Japan Geoscience Union. Tokyo: JpGU; 1998. SL-p019.

[12] MEXT (Ministry of Education, Culture, Sports, Science and Technology, Japan), ERI (Earthquake Research Institute, The University of Tokyo), DPRI (Disaster Prevention Research Institute, Kyoto University), NIED (National Research Institute for Earth Science and Disaster Resilience). Research for Crustal Structure of Metropolises (Project for Mitigation of Catastrophic Earthquake Disaster in Metropolises), Heisei 18 Fiscal Year Report. Tokyo: Research and Development Bureau, MEXT; 2007.

[13] MEXT (Ministry of Education, Culture, Sports, Science and Technology, Japan), DPRI (Disaster Prevention Research Institute, Kyoto University). Comprehensive Research and Survey for the Median Tectonic Line Fault System (Eastern Margin of Kongo Mountains – Southern Margin of Izumi Mountains), Heisei 25 Fiscal Year Report. Uji: DPRI; 2014.

[14] MEXT (Ministry of Education, Culture, Sports, Science and Technology, Japan), DPRI (Disaster Prevention Research Institute, Kyoto University). Comprehensive Research and Survey for the Median Tectonic Line Fault System (Eastern Margin of Kongo Mountains – Southern Margin of Izumi Mountains), Heisei 26 Fiscal Year Report. Uji: DPRI; 2015.

[15] Mizuno K, Tsukuda E, Takahashi M, Momohara A, Uchiyama T. Subsurface geology of the Wakayama Plain, southwestern Japan based on the deep boring survey. Journal of Geological Society of Japan. 1999; 105: 235-238.

[16] Itoh Y. Subsurface structure of Osaka sedimentary basin and its tectonic evolution. In: Itoh Y, Kusumoto S, Takemura K, editors. Research Frontiers of Sedimentary Basin Interiors: A Case Study and Methodological Review on an Oblique Convergent Margin. New York: Nova Science Publishers, Inc.; 2016. pp. 27-70.

[17] NIED (National Research Institute for Earth Science and Disaster Resilience). Report of the Kanku-Maejima Observation Well by the Science and Technology Agency. Tsukuba: NIED; 1997.

[18] MEXT (Ministry of Education, Culture, Sports, Science and Technology, Japan), DPRI (Disaster Prevention Research Institute, Kyoto University). Comprehensive Research and Survey for the Median Tectonic Line Fault System (Eastern Margin of Kongo Mountains – Southern Margin of Izumi Mountains), Heisei 27 Fiscal Year Report. Uji: DPRI; 2016.

[19] Mizuno K. Age and tectonic development of the Plio-Pleistocene sedimentary basins along the Median Tectonic Line, Southwest Japan. Memoir of Geological Society of Japan. 1992; 40: 1-14.

[20] Itoh Y, Takemura K, Ishiyama T, Tanaka Y, Iwaki H. Basin formation at a contractional bend of a large transcurrent fault: Plio-Pleistocene subsidence of the Kobe and northern Osaka Basins, Japan. Tectonophysics. 2000; 321: 327-341.

[21] Itoh Y, Takemura K, Kawabata D, Tanaka Y, Nakaseko K. Quaternary tectonic warping and strata formation in the southern Osaka Basin inferred from reflection seismic interpretation and borehole sequences. Journal of Asian Earth Sciences. 2001; 20: 45-58.

[22] Inoue N, Kitada N, Takemura K, Fukuda K, Emura T. Three-dimensional subsurface structure model of Kansai International Airport by integration of borehole data and seismic profiles. Geotechnical and Geological Engineering. 2012; DOI:10.1007/s10706-012-9568-4

[23] Kondo H, Sugito N, Yoshioka T, Tsutsumi H, Kimura H. Revisited spatial distribution of the Uemachi fault zone, Osaka, revealed by digital elevation models. Active Fault Research. 2015; 42: 1-34.

[24] Oka Y. The geomorphology and the crustal movements in the southeastern part of the Osaka Plain. Geographical Review of Japan. 1961; 34: 523-535.

[25] Itoh Y, Kusumoto S, Takemura K. Characteristic basin formation at terminations of a large transcurrent fault – basin configuration based on gravity and geomagnetic data. In: Itoh Y, editor. Mechanism of Sedimentary Basin Formation – Multidisciplinary Approach on Active Plate Margins. Rijeka: InTech; 2013. http://dx.doi.org/10.5772/56702

[26] Itoh Y, Kusumoto S, Takemura K. Tectonically controlled asymmetric basin formation and evolution: an example from an active plate margin. In: Veress B, Szigethy J, editors. Horizons in Earth Science Research, v14. New York: Nova Science Publishers, Inc.; 2015. pp. 123-141. https://www.novapublishers.com/catalog/product_info.php?products_id=57536

[27] Gravity CD-ROM of Japan, ver2, Digital Geoscience Map P-2 [CD-ROM]. Tsukuba: Geological Survey of Japan; 2004.

[28] Hirota Y. Geology of the Sambagawa metamorphic belt in western Kii Peninsula, Japan. Memoirs of Faculty of Science, Shimane University. 1991; 25: 131-142.

[29] Nakatsuka T, Okuma S. Aeromagnetic Anomalies Database of Japan, Digital Geoscience Map P-6. Tsukuba: Geological Survey of Japan; 2005.

[30] Wang CL, Maekawa H. Albite-biotite zone of the Sanbagawa metamorphic belt in the northwestern part of the Kii Peninsula, Japan. Journal of Mineralogy, Petrology and Economic Geology. 1997; 92: 43-54.

[31] Noda A, Toshimitsu S. Backward stacking of submarine channel-fan successions controlled by strike-slip faulting: The Izumi Group (Cretaceous), southwest Japan. Lithosphere. 2009; 1: 41-59.

[32] Tokiwa T. Timing of dextral oblique subduction along the eastern margin of the Asian continent in the Late Cretaceous: evidence from the accretionary complex of the Shimanto Belt in the Kii Peninsula, Southwest Japan. Island Arc. 2009; 18: 306-319.

[33] Itoh Y, Uno K, Arato H. Seismic evidence of divergent rifting and subsequent deformation in the southern Japan Sea, and a Cenozoic tectonic synthesis of the eastern Eurasian margin. Journal of Asian Earth Sciences. 2006; 27: 933-942.

[34] Itoh Y, Nagasaki Y. Crustal shortening of Southwest Japan in the Late Miocene. The Island Arc. 1996; 5: 337-353.

[35] Oka Y. The formation of the Izumi range and the Osaka Group. The Quaternary Research. 1978; 16: 201-210.

[36] Oka Y, Sangawa A. The formation of the sedimentary basin in the east of Inland Sea and the uplift of the Awaji Island, Japan. Journal of Geography. 1981; 90: 393-409.

[37] Takano O, Nishimura M, Fujii T, Saeki T. Sequence stratigraphic distribution analysis of methane-hydrate-bearing submarine-fan turbidite sandstones in the eastern Nankai Trough area: relationship between turbidite facies distributions and BSR occurrence. Journal of Geography. 2009; 118: 776-792.

[38] Nakamura K, Renard V, Angelier J, Azema J, Bourgois J, Deplus C, Fujioka K, Hamano Y, Huchon P, Kinoshita H, Labaume P, Ogawa Y, Seno T, Takeuchi A, Tanahashi M, Uchiyama A, Vigneresse J-L. Oblique and near collision subduction, Sagami and Suruga Troughs — preliminary results of the French-Japanese 1984 Kaiko cruise, Leg 2. Earth and Planetary Science Letters. 1987; 83: 229-242.

[39] Itoh Y, Takemura K. Quaternary geomorphic trends within Southwest Japan: extensive wrench deformation related to transcurrent motions of the Median Tectonic Line. Tectonophysics. 1993; 227: 95-104.

[40] Itoh Y, Takemura K. Mode of Quaternary crustal deformation of Kyushu Island, Japan. In: Shichi R, Heki K, Kasahara M, Kawasaki I, Murakami M, Nakahori Y, Okada Y, Okubo S, Ota Y, Takemoto S, editors. Proceedings of the 8th International Symposium on Recent Crustal Movement, CRCM'93, 6-11 December 1993, Kobe, Japan. Kyoto: The Local Organizing Committee for the CRCM'93; 1994.

[41] Itoh Y, Tsutsumi H, Yamamoto H, Arato H. Active right-lateral strike-slip fault zone along the southern margin of the Japan Sea. Tectonophysics. 2002; 351: 301-314.

[42] Itoh Y, editor. Mechanism of Sedimentary Basin Formation – Multidisciplinary Approach on Active Plate Margins. Rijeka: InTech; 2013. http://dx.doi.org/10.5772/50016

[43] Itoh Y, Takemura K, Kusumoto S. Neotectonic intra-arc basins within southwest Japan – conspicuous basin-forming process related to differential motion of crustal blocks. In: Itoh Y, editor. Mechanism of Sedimentary Basin Formation – Multidisciplinary Approach on Active Plate Margins. Rijeka: InTech; 2013. http://dx.doi.org/10.5772/56588

[44] Itoh Y, Kusumoto S, Takemura K. Evolutionary process of Beppu Bay in central Kyushu, Japan: a quantitative study of the basin-forming process controlled by plate convergence modes. Earth, Planets and Space. 2014; 66: 74. DOI:10.1186/1880-5981-66-74

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