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Neotectonics of Southwest Japan due to the right-oblique subduction of the Philippine Sea plate

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RESUMEN

La región antearco del suroeste de Japón está dividida en cinco regiones equivalentes denominadas unidades estructurales. Cada unidad es de 120 a 150 km de largo y está compuesta de una cuenca antearco bordeada por un alto estructural invertido en forma de L que se extiende a partir de cinco promontorios sobre la costa del Pacífico hasta la zona externa de la cresta que se encuentra a lo largo de la fosa de Nankai. Las unidades estructurales coinciden en dimensión y localización con las áreas fuente de terremotos de frontera de placa causados por cabalgaduras de bajo ángulo con una componente lateral derecha. Las características topográficas y estructurales han sido formadas fundamentalmente por acumulación de movimientos corticales y cosísmicos.

El segundo mar interior paleo-Seto, que existió al este del actual mar interior Seto durante el Plioceno al Pleistoceno Medio, estuvo compuesto de tres cuencas dispuestas *en-echelón* en sentido de mano derecha elongadas en dirección NE-SW, oblícuas a la Línea Tectónica Media (LTM). La evidencia paleogeográfica muestra que el segundo mar interior paleo-Seto era una zona de cillamiento lateral derecho asociada a fallamiento normal con componente lateral derecha de la LTM, de la misma manera que el actual mar interior Seto.

Estos movimientos neotectónicos característicos en la región antearco y a lo largo de la LTM son atribuídos a la subducción oblícua -derecha de la placa del Mar de Filipinas en la región de la fosa de Nankai desde el Plioceno Temprano hace 5 Ma.

PALABRAS CLAVE: Línea Tectónica Media, cuenca del Nankai, subducción oblícua, placa del Mar de Filipinas, suroeste de Japón, unidad estructural.

ABSTRACT

The forearc region of Southwest Japan is divided into five equivalent regions called structural units. Each unit is 120 to 150 km long and composed of a forearc basin fringed by an inverted L-shaped structural high extending from each of five promontories on the Pacific coast to the outer ridge zone along the Nankai Trough. The structural units coincide, in both dimension and location, with the source areas of plate-boundary earthquakes caused by low-angle thrusts with a right-lateral component. The topographic and structural features of the unit also correspond to the pattern of crustal movements associated with the earthquakes. From these facts, it is concluded that the structural units have been formed fundamentally by accumulation of coseismic crustal movements.

The second Paleo-Seto inland sea, which existed east of the present-day Seto inland sea in Pliocene to Middle Pleistocene time, was composed of three right-handed en-echelon basins elongated in the NE-SW direction oblique to the Median Tectonic Line. The paleogeographic evidence shows that the second Paleo-Seto inland sea was formed as a right-lateral shear zone in association with the right-lateral strike-slip faulting of the MTL in the same manner as the present Seto inland sea.

These characteristic neotectonic movements in the forearc region and along the MTL are attributed to the right-oblique subduction of the Philippine Sea plate at the Nankai Trough since the earliest Pliocene about 5 Ma.

KEY WORDS: Median Tectonic Line, Nankai Trough, oblique subduction, Philippine Sea plate, Southwest Japan, structural unit.

INTRODUCTION

The Philippine Sea is one of the largest marginal seas in the western Pacific, and it is subducting beneath the Eurasia plate along its northwestern boundary. The convergent plate boundary off Southwest Japan is called the Nankai Trough (Figure 1). The rate and direction of motion of the Philippine Sea plate with respect to the Eurasia plate are calculated based upon the fault-plane solutions of interplate earthquakes (e.g., Seno, 1977; Seno *et al.*, 1989). According to Seno *et al.* (1989), the relative motion along the Nankai Trough is 5 to 4 cm/yr in the direction of N50° W. Because the Nankai Trough strikes approximately N 60°E, the direction of the relative motion is deflected about 20° westwards from the direction perpendicular to the strike of the trough. Therefore, the Philippine Sea plate is subducting right-obliquely against the Nankai Trough with a right-lateral strike-slip component of relative motion.

Along the Nankai Trough, large plate-boundary earthquakes of magnitude 7.9-8.0 or greater have repeatedly occurred since A.D.684 (Usami,1987). The latest seismic

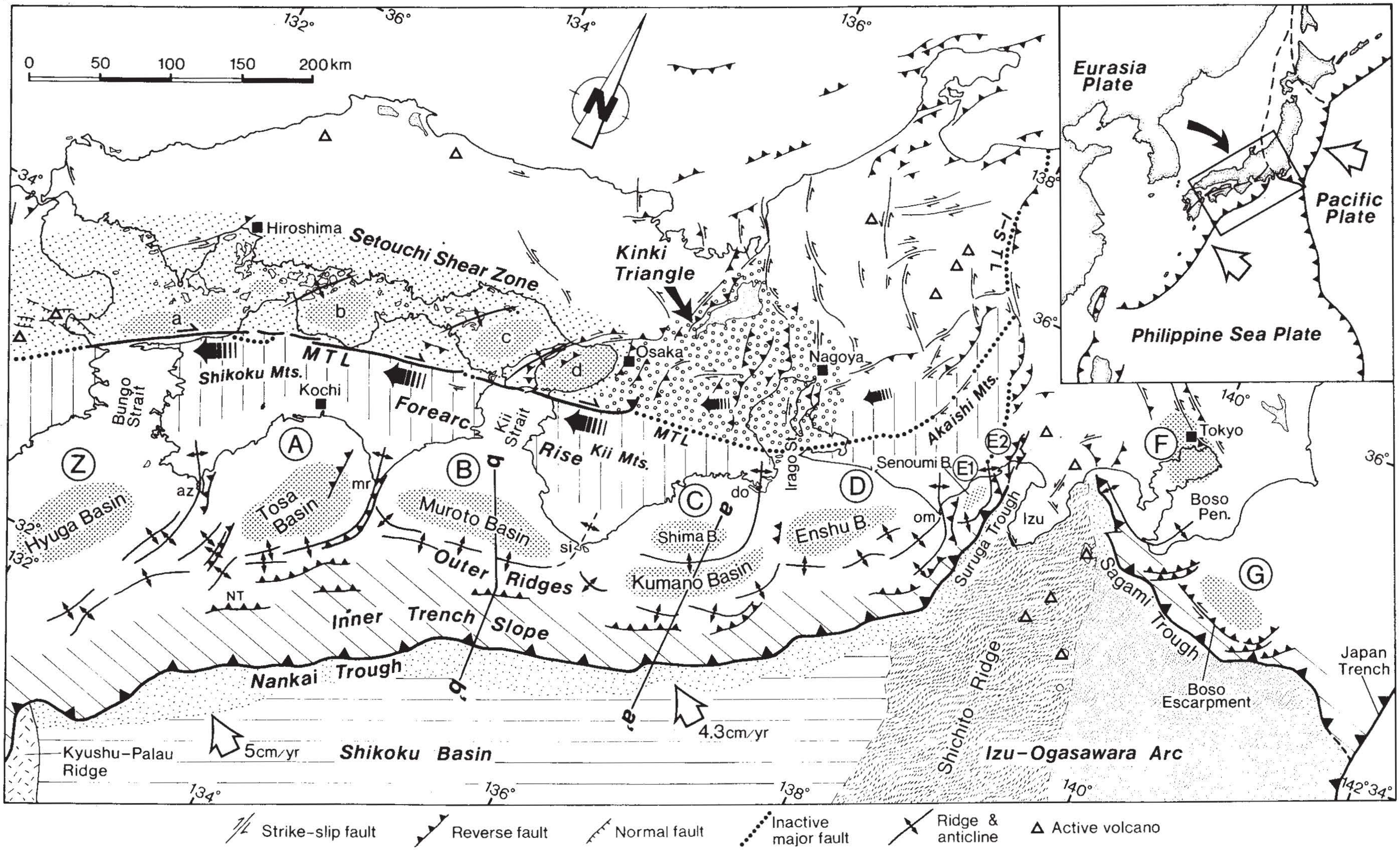


Fig. 1. Active tectonic map of Southwest Japan. Modified after Sugiyama(1992). Submarine geologic structures are simplified mainly from Okuda (1977), Okamura (1990) and Wakita *et al.* (1992). Arrows and numerical values in cm/yr on the Shikoku Basin show the directions and rates of the motion of the Philippine Sea plate relative to the Eurasia plate (after Seno *et al.*,1989). A~G and Z are structural units of the forearc region. Each unit, except for E2, consists of one or two sets of an inverted L-shaped structural high and a forearc basin. The capes on the highs are az: Cape Ashizuri, mr:C. Muroto, si: C. Shio, do:C. Daio, and om: C. Omae. The reverse fault labeled NT, off the Tosa basin, is a low-angle thrust reported by Kagami *et al.*(1983). Caudate arrows along the MTL (Median Tectonic Line) show the moving direction of the forearc sliver. The basins in the Setouchi shear zone (Seto Inland Sea) are a: Iyo nada(sea), b: Hiuchi nada, c:Harima nada, and d:Osaka Bay. I-STL in central Japan denotes the Itoigawa-Shizuoka Tectonic Line. The lines a-a' and b-b' show the locations of the geologic profiles shown in Figure 2.

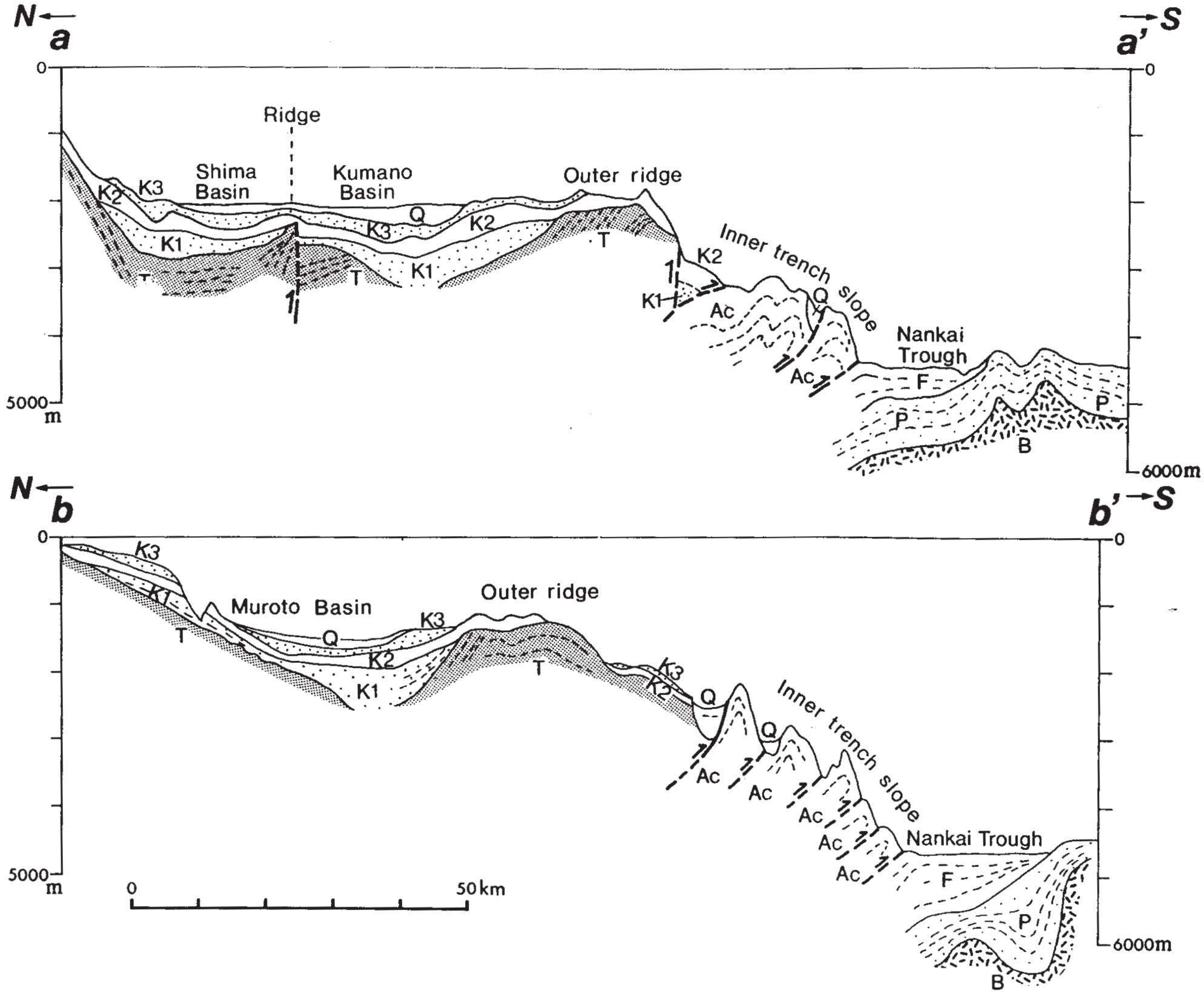


Fig. 2. Geologic profiles off Southwest Japan. After Okuda(1977). See Figure 1 for the locations of lines a-a' and b-b'. Ac:accretionary complex (mainly Pliocene to Quaternary), B:acoustic basement (oceanic basalt), F:trench-fill deposits (mainly Quaternary), K1~K3:forearc basin and slope deposits (Late Miocene to Pleistocene), P:pelagic sediments (Miocene to Quaternary), Q:forearc basin and slope deposits (Pleistocene to Holocene), T:basement rocks of outer ridge and forearc basin (mainly Miocene to Pliocene).

events occurred in 1944 and 1946. The fault planes causing these seismic events are determined underneath the Kumano and Enshu basins (Figure 1) for the 1944 Tonankai earthquake and underneath the Tosa and Muroto basins for the 1946 Nankaido earthquake, respectively (Ando, 1975, 1982; Ishibashi, 1981). Cape Muroto in Shikoku (Figure 3) was uplifted about 120 cm by the Nankaido earthquake, tilting landwards consistently with the northward-tilting deformation of marine terraces distributed around the cape (Figure 3-b,c; Okuda, 1950; Sawamura,1953; Miyabe, 1955). This strong geographic correlation of seismic source areas with forearc basins, and the consistency between coseismic crustal movement and marine terrace deformations, suggest that the accumulation of coseismic crustal movements plays an important role in the formation of forearc landforms of Southwest Japan.

When we consider the inland area of Southwest Japan (Figure 1), an E-W-striking transcurrent fault, the Median Tectonic Line (MTL), and an inland sea on the north of the MTL command attention. This inland sea, called the Seto inland sea, consists of four en-echelon basins which are separated by islands or island chains extending in an NE-SW direction (Figure 1). This characteristic landform strongly suggests that the Seto inland sea is a dextral shear zone associated with right-lateral strike-slip faulting of the MTL (Tsukuda, 1990). The area immediately east of the Seto inland sea, which was named the Kinki Triangle by Huzita (1962), seems to be controlled by tectonics quite different from that of the Seto inland sea, because geologic structures formed by E-W compression prevail in this area. The Kinki Triangle, however, was a freshwater and shallow-marine depositional realm called the second Paleo-Seto inland sea along the MTL in Pliocene to Pleistocene time. A large number of paleogeographic studies of the second Paleo-Seto inland sea (e.g., Kuwahara, 1985; Yoshida, 1992) have revealed that the inland sea was also composed of en-echelon basins with NE-SW-trending axes in its early stage of basin development. The paleogeographic evidence suggests that the second Paleo-Seto inland sea may have developed into the Kinki Triangle in relation to the right-lateral strike-slip faulting of the MTL since Pliocene time (Sugiyama, 1991).

This paper is aimed at linking the neotectonics of Southwest Japan with the right-oblique subduction of the Philippine Sea plate.

NEOTECTONICS OF THE FOREARC REGION OF SOUTHWEST JAPAN

Morphotectonic subdivision of the forearc region

The forearc region (or Outer Zone) of Southwest Japan, between the Nankai Trough and the MTL, is subdivided morphotectonically into four zones parallel to the Nankai Trough. From the offshore (trench) side, these are the inner (or landward) trench slope, outer ridge, forearc basin, and forearc (or outer zone) rise (Figure 1). The inner trench slope consists of accreted sediments of post-Miocene age, which have been deformed by landward-dipping imbricate thrusts and decollements (Figure 2; Kagami *et al.*, 1983; Moore *et al.*, 1990; Ashi and Taira, 1992). The outer ridge zone is mainly composed of Upper Miocene to Pliocene strata showing a composite anticlinal structure (Okamura and Joshima,1986). The forearc basin zone comprises six forearc basins separated by the N-S-trending promontories and spurs, and each basin is covered with non- or slightly-deformed Pleistocene to Holocene deposits. The forearc rise includes the Shikoku, Kii and Akaishi Mountains (Figure 1), where pre-Neogene rocks are widely distributed.

Geologic structure of the seismic deformation area

The forearc basin zone and outer ridge zone are collectively called the seismic deformation area, because geomorphic and structural characteristics of the two zones are considered to be a cumulative result of crustal deformations associated with plate-boundary earthquakes in the forearc region (Yoshikawa, 1968; Awata and Sugiyama, 1989). Crustal movements associated with great earthquakes extend into the forearc rise zone as shown by subsidence of the Shikoku Mountains at the time of the 1946 Nankaido earthquake (Figure 3-b; Sawamura, 1953; Thatcher, 1984). The coseismic subsidence is, however, contrary to the cumulative uplift of the forearc rise zone. Therefore, this zone is excluded from the seismic deformation area and its high elevation is attributed to interseismic or non-seismic uplifting (Figure 3-a; Yoshikawa *et al.*, 1981). The southern border of the seismic deformation area is located on the uppermost part of the inner trench slope, where there are large north-dipping thrust faults which are thought to be the upper tips of seismogenetic faults (Kagami *et al.*, 1983; Awata and Sugiyama, 1989).

1. Structure of the seismic deformation area along the Nankai Trough

The five N-S-trending structural highs extending from the promontories on the Pacific coast to the offshore spurs bend westwards and join the composite anticlinal structures of the outer ridge zone (Figures 1, 4; Okuda, 1977; Inoue and Honza, 1982). These structural highs show an inverted L-shaped trace as a whole, fringing on each of the forearc basins from the east and south. East of the inverted L-shaped structural highs, distinctive faults are distributed. ENE-WSW to E-W-striking faults are located on the south flank of the outer ridge (Figure 4). Seismic profiling revealed that most of the faults showing an upward displacement of the northern block are north-dipping reverse faults (Okamura, 1990). A remarkable low-angle thrust fault parallel to the Wadati-Benioff zone dipping 10~15° northwards is visible in a multichannel seismic reflection profile on the southern flank of the outer ridge off the Tosa basin (Kagami *et al.*, 1983). This fault, labeled NT in Figure 1, is situated close to the Nankai Thrust, an inferred causative fault of the 1946 Nankaido earthquake (Sawamura, 1953). On the other hand, on the eastern flanks of the southern spurs and capes, there are N-S-trending faults showing an upward displacement of the western blocks (Okuda, 1977; Okamura and Joshima, 1986; Okamura *et al.*, 1987). These faults are inferred to be reverse faults from an asymmetric anticlinal structure of the Muroto spur with a steep eastern limb and a gently-dipping western limb (Okamura, 1990).

Based on these structural features, the seismic deformation area along the Nankai Trough can be divided into five structural units (the realms A~D and Z in Figure 1), which are nearly equidimensional (120 to 150 km long in east-west) and have common morphotectonic characteristics (Awata and Sugiyama, 1989; Sugiyama, 1989). Each structural unit is composed of an inverted L-shaped structural high extending from the promontory to the outer ridge, frontal reverse faults, and a forearc basin bordered by the high (Figure 5). From this point of view, the realm C is considered to be a duplex structure composed by two structural units thrusted southwards (Figure1 and a-a' section of Figure 2).

Smaller-scale geologic structures characteristically present around the unit boundary are well investigated by seismic profiling in the vicinity of the Muroto and Ashizuri spurs which mark the boundaries between the units A, B and Z. The structures include a nose structure, folds with N-S-trending axes and megakink folds (Figure 4). The nose structure is a landward protrusion or landward-arching bend of all kinds of geologic structures parallel to the trench axis and is located at the boundary of units A and B. The N-S-trending folds are mainly found on the east of the spurs. As a result, the geologic structure in the western part of the structural units is more complicated than in the

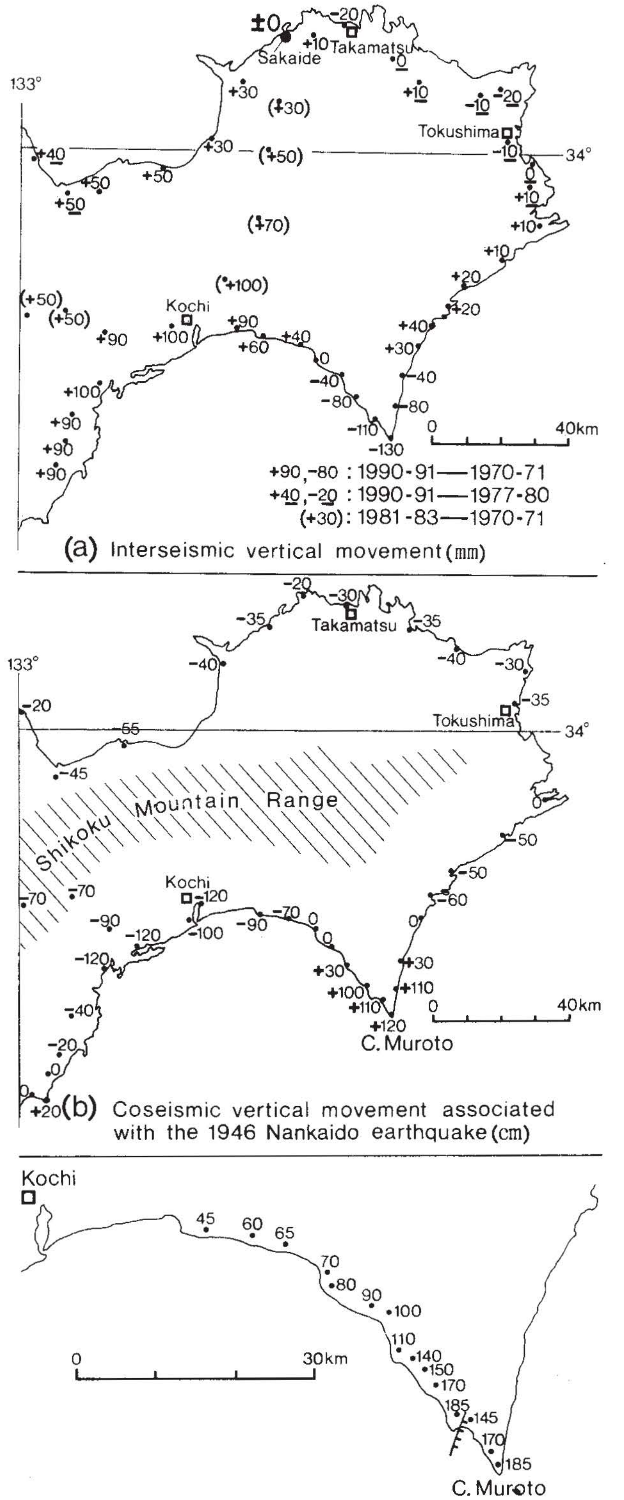


Fig. 3. Interseismic, coseismic and cumulative vertical crustal movements of eastern and central Shikoku. Interseismic vertical movement is after Geographical Survey Institute (1980, 1983, 1992) and values show the movements relative to the fixed point at Sakaide. Coseismic vertical movement is after Sawamura (1953) and Awata and Sugiyama(1989). Coseismic subsidence in northern Shikoku includes post-seismic movement due to viscoelastic deformation of the upper mantle propagating from the source area.

eastern part. The megakink folds occur on both sides of the Muroto spur with opposing rotational directions; megakink folds on the east of the spur rotate dextrally and those on the west sinistrally around the vertical axes.

2. Structures of the seismic deformation area along the Suruga and Sagami Troughs

Geologic structures similar to the structural units along the Nankai Trough are present along the Suruga Trough, the eastern extension of the Nankai Trough, and along the Sagami Trough beyond the Izu Peninsula (Figure 1).

The Senoumi basin, in the western part of Suruga Bay along the Suruga Trough, is bordered by an inverted L-shaped structural high extending from the Udo Hills through the Kuno spur to the north and south Senoumi banks (Figure 6). The Kuno spur has a composite anticlinal structure (Shiba *et al.*, 1990), and is bounded on the east by NW-SE-trending faults showing an upward displacement of the southwestern side (Maritime Safety Agency, 1978). The Senoumi banks are bordered on the east and south by steep cliffs which are inferred to be fault scarps. These morphotectonic features of the western Suruga Bay (the realm E1 in Figure 6) strongly resemble those of the structural units along the Nankai Trough. The dimension is, however, quite different; the realm E1 is approximately 40 km long, about one-third of the size of the structural units along the Nankai Trough. On the other hand, the realm E2 comprising the deep Suruga Bay and its coastal area (Figure 6) is characterized by a west-dipping imbricate structure formed by several active faults including the earthquake fault of the 1854 Ansei earthquake (Figure 6; Yamazaki, 1984, 1992). Thus, the realm E2, which also lies within the seismic deformation area, is strongly related to the inner trench slope.

Along the Sagami Trough, there are two other realms (F and G) which are equivalent to the structural units along the Nankai Trough (Sugiyama, 1990; Awata, 1992). The realm F, about 100 km long, includes the Boso Peninsula and Okinoyama bank chain in Sagami Bay as an inverted L-shaped structural high, and Tokyo Bay as a forearc basin (Figure 1). The realm G is situated along the Boso submarine escarpment and is approximately 80 km long. The detailed geomorphic and structural features of the two realms were described by Ogawa *et al.* (1989) and Ohkouchi (1990).

Formation mechanism of the structural unit

1. Low-angle thrusting with a right-lateral strike-slip component

The plate-boundary earthquakes along the Nankai Trough have been caused principally by dislocation along four fault planes which correspond in both location and dimension to the structural units A~D (Ando, 1975; Utsu, 1977). These four faults are inferred, on the basis of coseismic vertical and horizontal crustal movements, to be low-angle thrust faults with a right-lateral strike-slip component

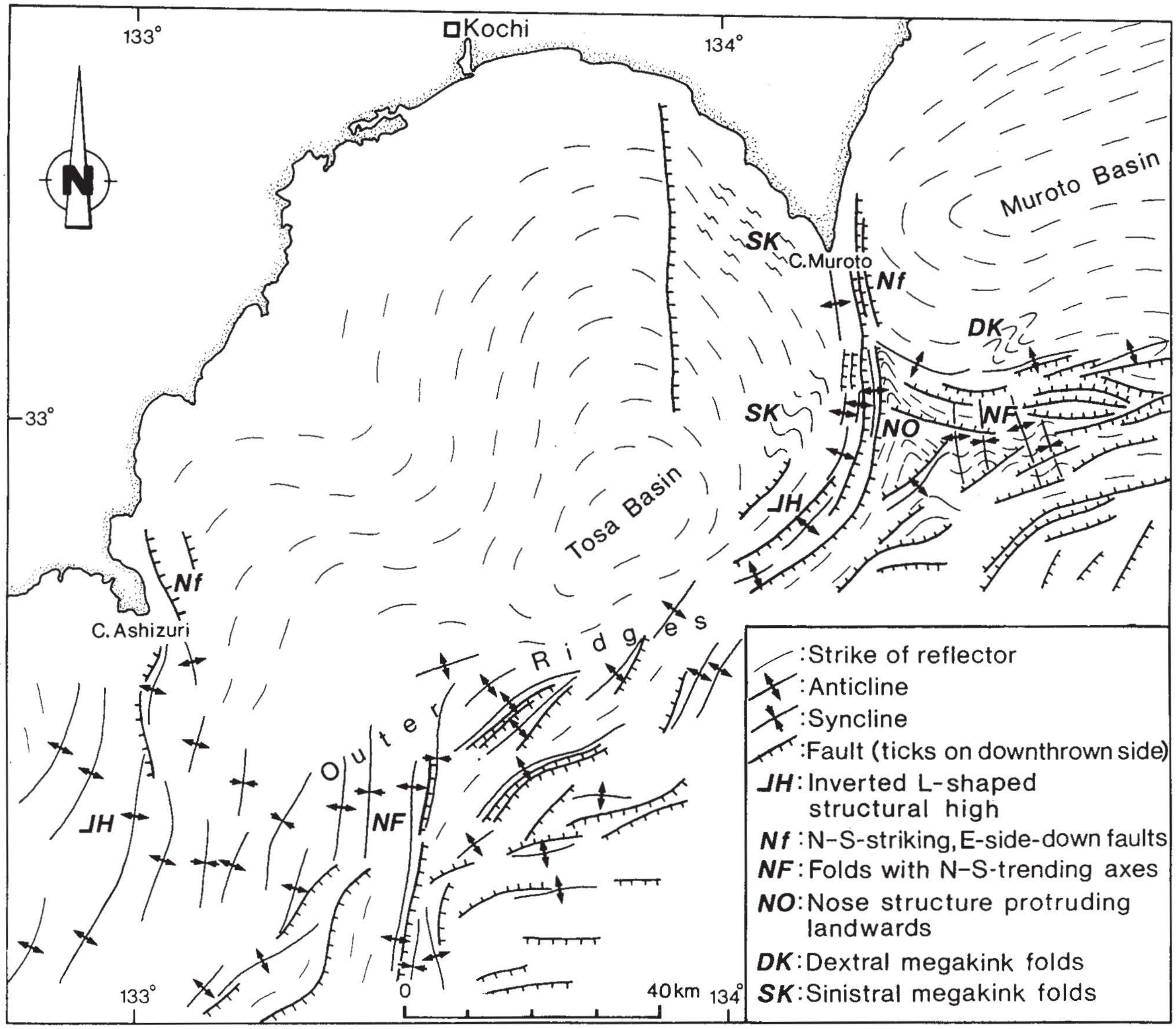


Fig. 4. Detailed geologic structures off Shikoku revealed by seismic profiling. Simplified after Okamura and Joshima (1986) and Okamura *et al.* (1987).

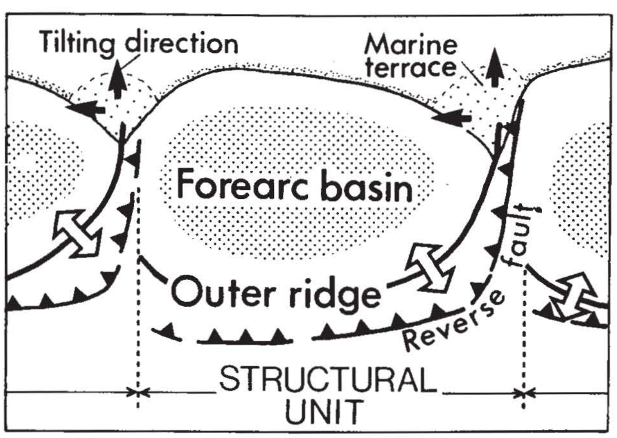


Fig. 5. Simplified topographic and structural features of the forearc structural unit along the Nankai Trough. After Sugiyama (1990).

(hereafter abbreviated to right-oblique thrust) (Ando, 1975, 1982; Ishibashi, 1981; Matsu'ura and Sato, 1975). In the case of a north-dipping right-oblique thrust, the main coseismic crustal deformations which occur at the Earth's surface due to the faulting are as follows (Figure 7-a):

(1) uplift along the southern and eastern margins of the fault plane.

(2) subsidence above the northwestern corner of the fault plane.

(3) E-W shortening along the eastern margin of the fault plane.

Comparing these deformations with the morphotectonic characteristics of the structural unit, (1) is correlative with the inverted L-shaped structural high extending from the promontory to the outer ridge, (2) with the forearc

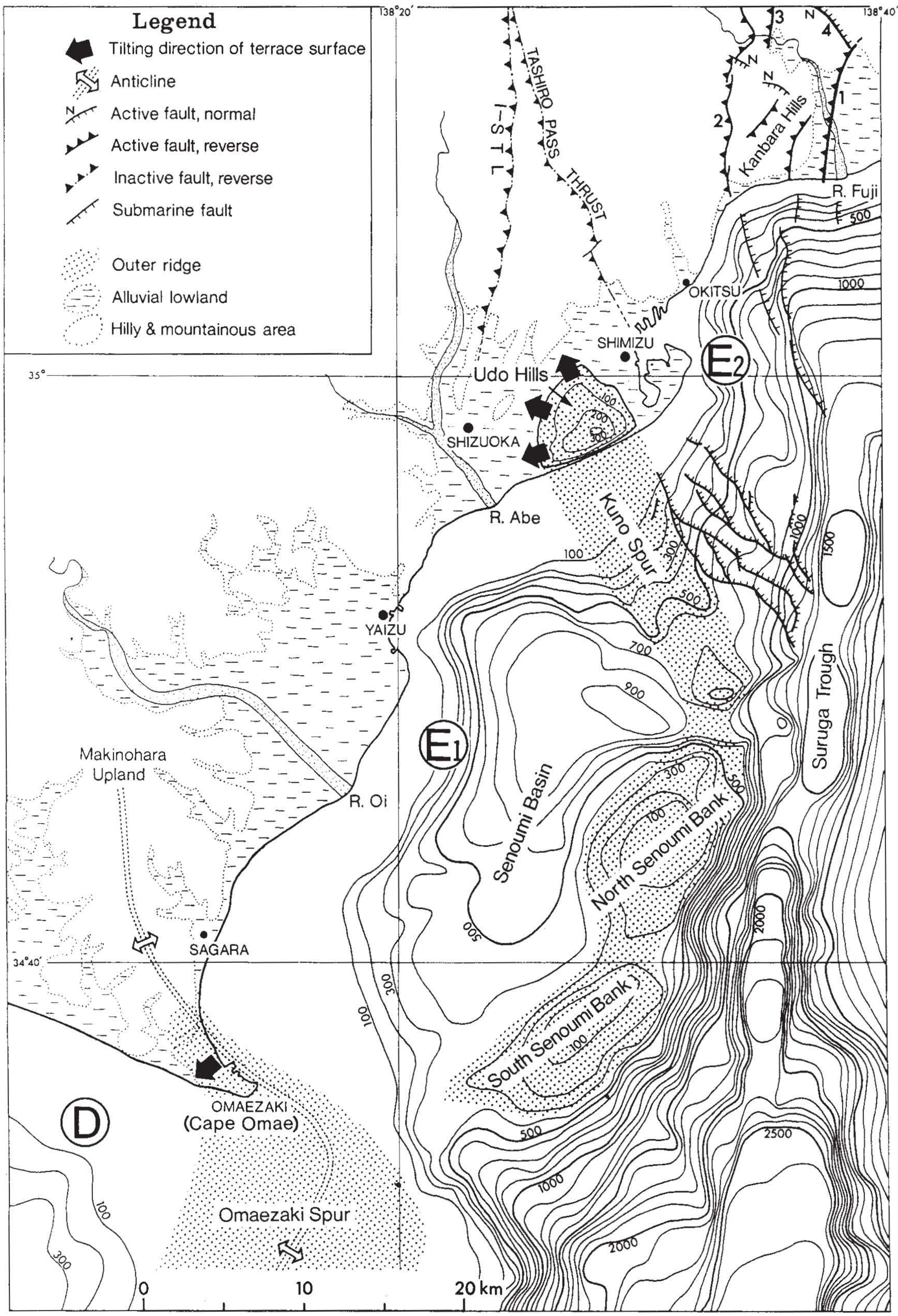


Fig. 6. Topography and geologic structure of the western and northern parts of Suruga Bay. After Sugiyama (1990). Bathymetric contours (in meters) are smoothed by restored contours method (valley width:2 km). D, E1 and E2 are structural units. The active faults around the Kanbara Hills are 1:Iriyamase fault, 2:Iriyama f., 3:Agoyama f., and 4:Omiya f.. The Iriyamase fault showed the east-side-down displacement at the time of the Ansei earthquake in 1854. I-STL denotes the Itoigawa-Shizuoka Tectonic Line. Submarine faults are after Maritime Safety Agency (1978).

basin, and (3) with the N-S-trending reverse faults and folds (Figure 7-a,b). Furthermore, both the uplift and E-W shortening along the eastern margin of the fault plane decrease northwards. The northward decrease of coseismic uplift is in agreement with the northward tilting of the marine terraces found at the promontories. The northward decrease of the E-W shortening is consistent with the nose structure protruding landwards and with the megakink folds showing opposite rotational directions on the east and west of the unit boundary (Sugiyama, 1989).

From these facts, Awata and Sugiyama (1989) and Sugiyama (1989) concluded that the major landforms and geologic structures characterizing the structural units along the Nankai Trough were formed fundamentally by the accumulation of coseismic crustal deformations due to the movement of north-dipping low-angle thrusts with a right-lateral strike-slip component.

2. Two types of plate-boundary earthquakes: an effect of reverse faulting at the eastern margin of the structural unit

Maemoku (1988a,b) and Maemoku and Tsubono (1990) have revealed, on the basis of radiocarbon dating of calcareous remains of organisms living in the tidal zone, that the elevated wave-cut benches at the capes of Ashizuri, Muroto and Shio have been formed at intervals ranging from 300 to 1500 years. These intervals are several times as long as the recurrence intervals of plate-boundary earthquakes (about 100~250 years). This fact suggests that along the Nankai Trough there are two types of great earthquakes which are equivalent to the Genroku-type and the Taisho-type earthquakes (Matsuda *et al.*, 1978) along the Sagami Trough.

In the case of Genroku-type earthquakes the coseismic uplift at the cape exceeds the subsidence and wave erosion in the period from one earthquake to the next, and consequently the elevated wave-cut bench is preserved (Figure 8). In the case of the Taisho-type earthquakes, the coseismic uplift at the cape is smaller than the interseismic subsidence and wave cutting; therefore the elevated bench is not preserved.

The Genroku-type earthquakes have been considered to be composite earthquakes caused by the combination of right-oblique thrusting at the plate boundary and reverse faulting within the Eurasia plate (Yonekura, 1979; Shimazaki, 1980). The intraplate reverse fault, however, has not been clearly evidenced. There are N-S-trending reverse faults along the meridional spurs bounding the structural units. If these faults slip concurrently with the movement of the north-dipping right-oblique major thrust, the uplift along the eastern margin of the structural units will be far larger if were caused only by the movement of the major thrust (Figure 7-a,c).

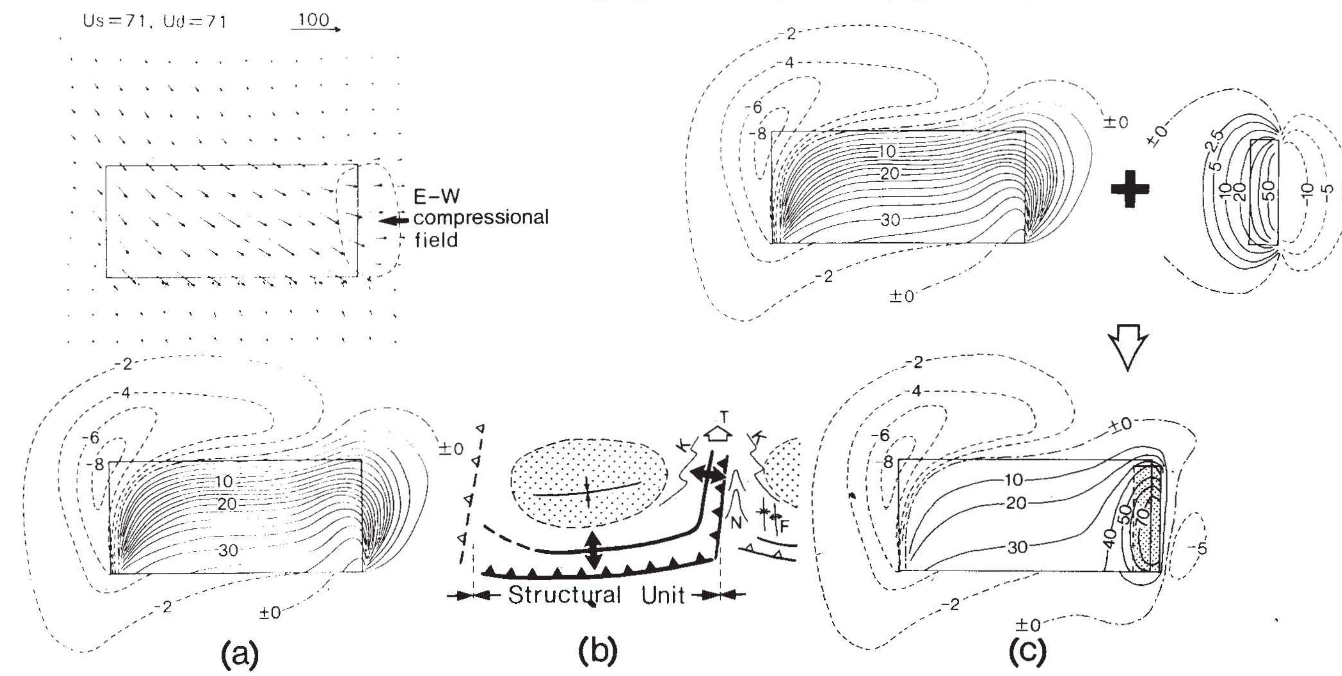


Fig. 7. Comparison of topographic and structural features of the structural unit with ground displacements due to the faultings. (a):horizontal and vertical displacements at the ground due to a right-reverse faulting under the following condition. The ratio of strike-slip to dip-slip is 1 to 1, inclination of the fault plane (quadrangle in the figure) is 30 degrees, and the upper edge of the fault plane (bottom side of the quadrangle) reaches the ground surface. After Ando(1985). For convenience'sake, the strike and dip of the fault plane are assumed to be E-W and north respectively, (b):topographic and structural features of the structural unit. F:folds with N-S-trending axes, K:megakink folds, N:nose structure protruding northwards, T: northward tilting of a marine terrace, (c):vertical displacement at the ground due to a right-reverse faulting accompanied by a reverse faulting at the eastern margin of the fault plane. The reverse faulting is under the following condition: the dip of the fault plane is 60 degrees west, and the dislocation of the fault is as large as the total dislocation of the right-reverse fault.

Consequently, the intraplate reverse faults which contribute to the formation of highly-elevated wave-cut benches at the time of the Genroku-type earthquakes are correlative with the reverse faults situated at the eastern margin of the structural unit (Awata, 1991; Sugiyama, 1992). Furthermore, the formation intervals of elevated wave-cut benches (300~1500 years) can be equated with the recurrence intervals of the Genroku-type earthquakes along the Nankai Trough.

3. Contribution of interseismic crustal deformations

The inverted L-shaped structural highs are largely below sea level, except for their northern tips (capes), and most of the N-S-trending spurs (composite anticlines) are plunging southwards (Okamura, 1990). This suggests that the interseismic or non-seismic subsidence of the seismic deformation area increases southwards and exceeds the coseismic uplift along the structural highs except for their northernmost parts (Sugiyama, 1992). The subsidence axes of the forearc basins are situated on the west of the meridional spurs, shifting southeastwards from the centers of subsidence caused by great earthquakes (Figure 7-a,b). Thus, we conclude that the subsidence of the forearc basins is related not only to the coseismic subsidence but also to the troughward-increasing interseismic subsidence inferred to be due to strain accumulation along the subduction zone.

4. Model for formation of the structural unit

The material presented in the previous sections leads to the generalized formation model of the structural unit illustrated in Figure 9. Morphotectonic elements characterizing the structural unit formed by the right-oblique subduction are summarized as follows (as viewed from offshore):

(1) an inverted L-shaped structural high or composite anticline fringing a forearc basin.

(2) reverse faults striking along the unit boundary and showing a relative uplift of the left block.

(3) a nose structure protruding landwards along the unit boundary, or landward protrusion of the structures parallel to the trench axis.

(4) folds or undulations with axes perpendicular to the trench axis on the right side of the unit boundary.

(5) dextral and sinistral megakink folds distributed on the right and left side of the unit boundary, respectively.

Elements (1), (2) and (4) are asymmetric relative to the unit boundary, while (3) and (5) are symmetric. It is reasonable, from the comparison of the structural unit with ground displacements due to the oblique thrusting (Figure 7), to regard the asymmetric features of the structural unit as a reflection of the lateral sense of the oblique subduction. Therefore, the left-oblique subduction is expected to form the structural unit composed of an L-shaped structural high and reverse faults showing a relative uplift of the right block along the unit boundaries (Figure 10). In this case, folds with axes perpendicular to the trench axis should be mainly formed on the left side of the unit boundary, while a nose structure and megakink folds would be formed in the same manner as the right-oblique subduction (Figure 10).

This formation model of the structural unit is applicable not only to a morphotectonic analysis of the recent subduction zones but also to a reconstruction of the interplate motions at ancient convergent plate boundaries. The author has applied this model to analysis of bending structures developed in the Tertiary strata in the forearc region of Southwest Japan (Sugiyama, 1989). The result of this analysis will be used later in relation to the beginning of structural-unit formation and right-oblique subduction.

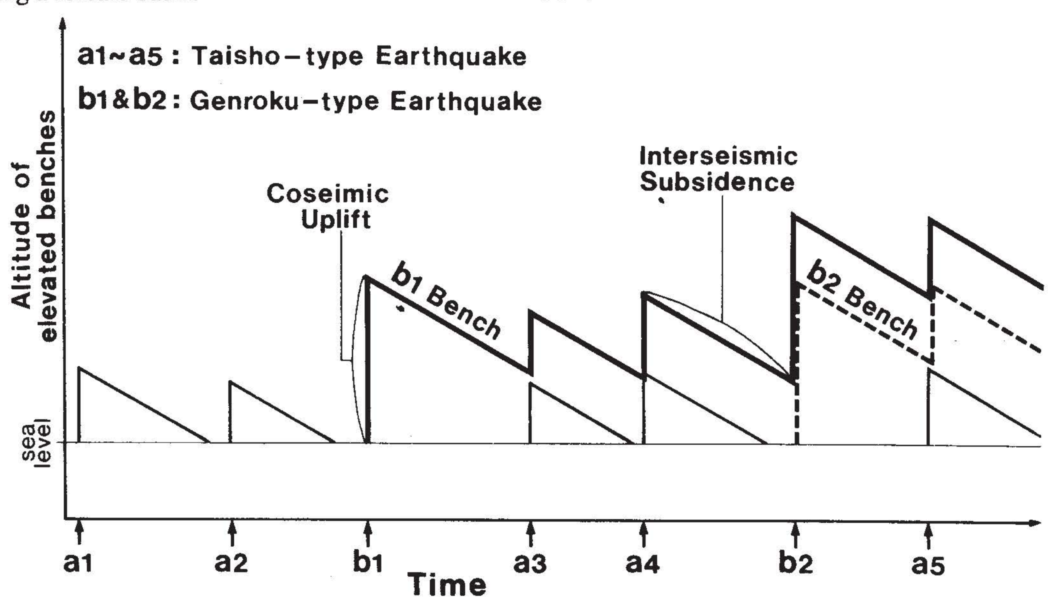


Fig. 8. Schematic formation model of elevated benches by coseismic uplifts associated with the Genroku-type earthquakes.

Plate-boundary earthquakes as reviewed from the structural unit model

A large amount of historical documents related to earthquakes and tsunamis have revealed that plate-boundary earthquakes along the Nankai and Suruga Troughs have repeatedly occurred at intervals ranging from 90 to 262 years (with an average interval of about 160 years) since A.D. 684 (Utsu, 1977). For the latest 1944 Tonankai and 1946 Nankaido earthquakes, seismological data as well as geodetic and tide-gauge data were obtained, and several fault models based on these data have been presented (e.g., Ando, 1975; Ishibashi, 1981). The source areas and fault models of the 1854 Ansei earthquake and earlier ones have been inferred from data such as earthquake damage, tsunami hazard and coastline changes recorded in historical documents (e.g., Hatori, 1976; Aida, 1981; Usami, 1987). Recently, the source areas of historical earthquakes were also inferred from liquefaction traces found at several archeological sites in Shikoku, Kii Peninsula and the coastal area of the Enshu sea (Sangawa, 1990).

On the basis of reviews of previous studies, the source areas of the successive great earthquakes are summarized in Figure 11. We discuss some of these earthquakes in the light of the structural unit model presented in this study.

1. Meio earthquake of 1498

The source area of the 1498 Meio earthquake has been assigned to off Tokai (structural units C and D) (e.g.,Utsu, 1977; Ishibashi, 1981). Liquefaction traces of the latest 15th century have been discovered at an archeological

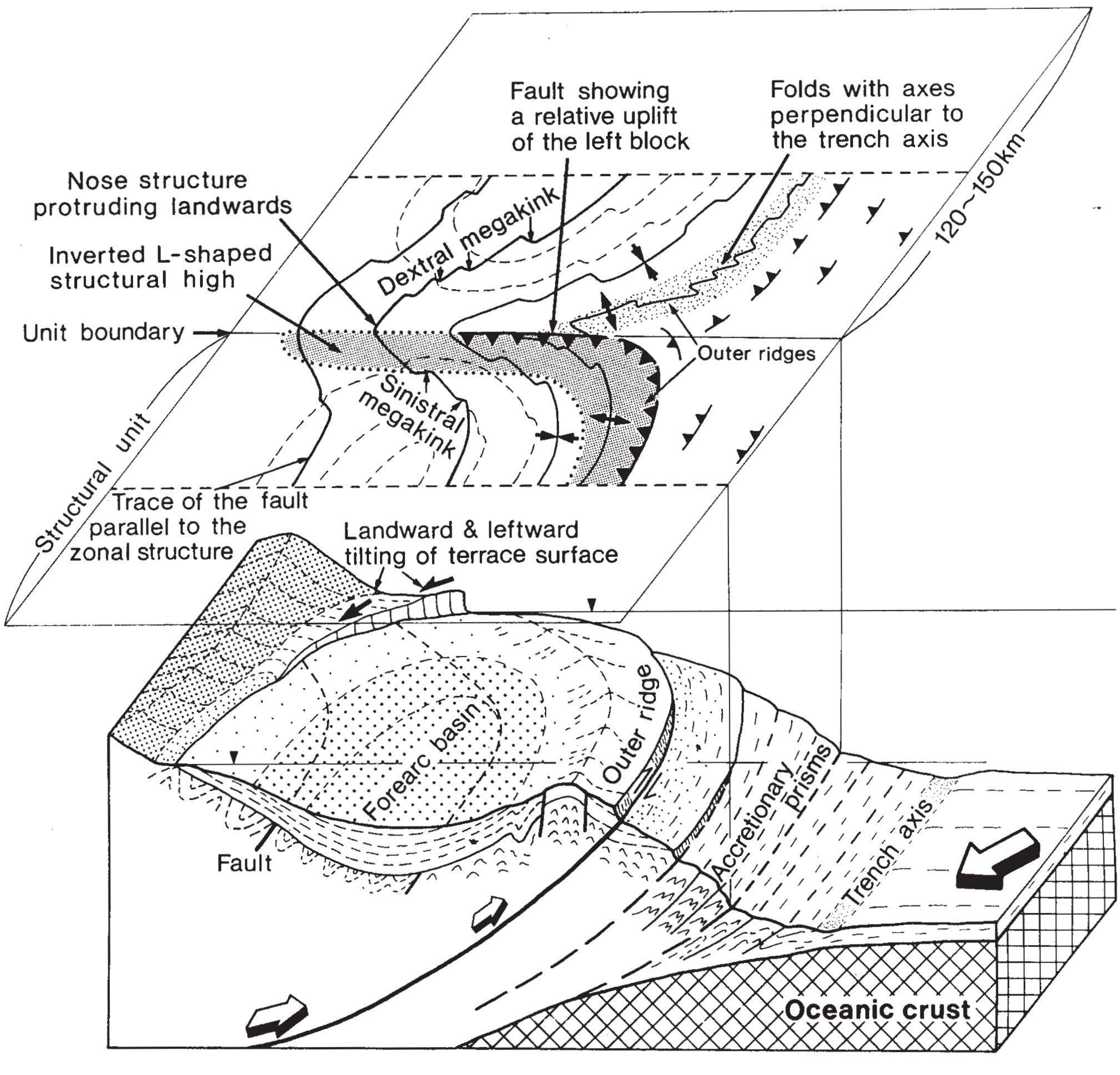


Fig. 9. Generalized formation model of topographic and structural features of the structural units formed by the right-oblique subduction. Modified after Sugiyama(1989).

site on the north coast of Tosa Bay in structural unit A (Sangawa,1990). This archeological evidence suggests that the fault movements causing the 1498 Meio earthquake extended into the structural unit A.

Although the southern part of Yaizu City on the west coast of the Senoumi basin (Figure 6) is known to have subsided at the time of this earthquake (Tsuji, 1980), a reasonable explanation for this subsidence has not been offered. According to the model presented in this study, however, the faulting of the structural unit E1 (right-oblique thrusting) should cause a subsidence of the west coast of the Senoumi sea. Consequently, it is inferred that the structural unit E1 also ruptured at the time of the Meio earthquake (Sugiyama, 1990).

2. Hoei earthquake of 1707

The Hoei earthquake is one of the largest earthquakes ever to occur in Japan, and its source area has been assigned to the wide region extending from structural unit A to E (e.g., Utsu, 1977). Recently, Hatori (1988), on the basis of newly collected tsunami data, revealed that waves, 3 to 5 m high, hit the coastal area of the Bungo Strait (Figure 1) at the time of the Hoei earthquake. A severely-shaked area registering intensity over 5 on the JMA scale also extended from southern Shikoku to western Kyushu (Usami, 1987). As tsunamis hitting this coastal area after the 1946 Nankaido earthquake were only 1 to 1.5m high, such a high tsunami, together with severe shaking in Kyushu, is considered to be evidence of faulting in structural unit Z at the time of the Hoei earthquake.

According to Maemoku (1988a) and Maemoku and Tsubono (1990), the youngest elevated wave-cut benches at Cape Muroto and C. Shio were formed within the last three centuries. Therefore, the latest Genroku-type earthquake along the Nankai Trough should have occurred within the last three centuries, being correlated to either the 1707 Hoei or the subsequent 1854 Ansei earthquake.

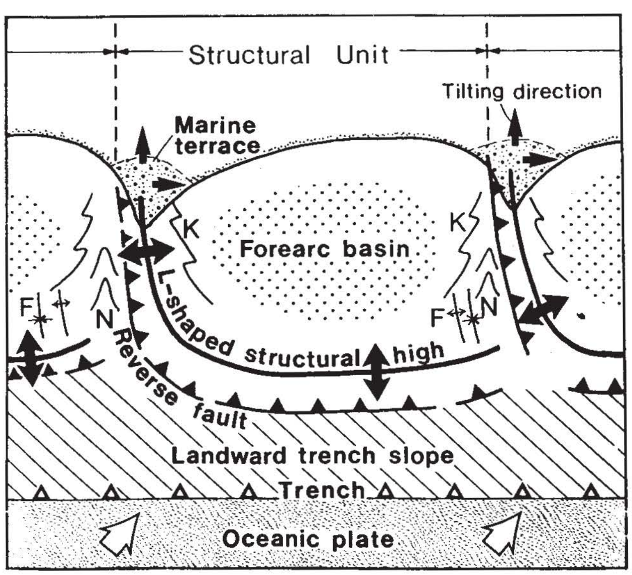


Fig. 10. Simplified topographic and structural features of the structural unit formed by the left-oblique subduction.

3. Ansei earthquake of 1854

The Ansei earthquake comprises two successive earthquakes; the Ansei Tokai earthquake assigned to the structural units C, D and E, and the Ansei Nankai earthquake assigned to the units A and B, which occurred 32hours later (Usami, 1987). In the Ansei Nankai earthquake, tsunamis 3 to 5 m high again hit the coastal area of the Bungo Strait (Hatori, 1988), and a severely-shaked area registering an intensity of over 4 on the JMA scale extended from the west coast of the Hyuga sea to northern Kyushu (Usami, 1987). These facts indicate that the structural unit Z also ruptured at the time of the Ansei Nankai earthquake.

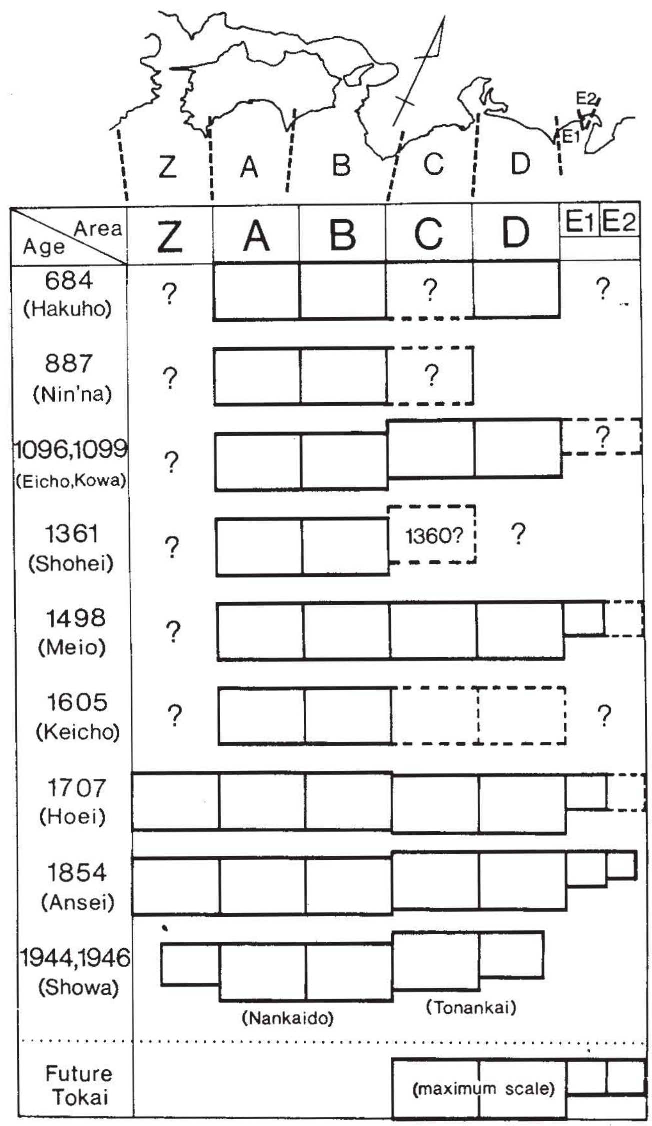


Fig. 11. Source areas of the successive plate-boundary earthquakes along the Nankai and Suruga Troughs. This figure was made on the basis of the reexamination of previous works on coseismic crustal movements, tsunami hazards and strong shaking caused by these earthqaukes, from the viewpoint of structural unit model. Solid-line rectangles show probable ruptured areas (fault planes), and broken-line rectangles show uncertain ones.

At the Ansei Tokai earthquake, the west coast of Suruga Bay and the coastal area of the Enshu sea east of the Tenryu River (Figure 12) uplifted while the area from Lake Hamana to Mikawa Bay subsided (Hatori, 1976; Ishibashi, 1984; Usami, 1987). The uplift was particularly large and attained 3m at Cape Omae and Udo Hills which are situated on structural highs of the unit D and E1 respectively, as well as at the eastern margin of the Kanbara Hills adjoining the Iriyamase Fault (Figure 6); one of the faults that ruptured during this earthquake (Ishibashi, 1984). These facts are quite consistent with our structural unit model.

4. Tonankai earthquake of 1944 and Nankaido earthquake of 1946

Iwata and Hamada (1986) have relocated the hypocenters of the main shock and aftershocks of the 1944 Tonankai earthquake on the basis of newly compiled seismogram data including some that had not been used yet. According to them, the hypocenter of the main shock is located at the depth of 40km in the westernmost part of structural unit C (Figure 12).Many aftershocks are distributed in the vicinity of the N-S-trending Shima spur, and some are scattered in structural unit D and around Cape Shio, with induced seismic activity in and around southern Izu Peninsula. From these epicentral distributions, structural units C and D are assignable, respectively, to a main source area and a subordinate source area of the Tonankai earthquake.

Although the 1946 Nankaido earthquake has been considered to be a result of faulting in structural unit B and subsequent rupturing of unit A (e.g., Gariel *et al.*, 1990), a coseismic uplift of about 1 meter is known to have occurred at Cape Ashizuri (Sawamura, 1953). A coseismic subsidence of the Hyuga basin is also inferred from the tide-gauge data of tsunamis (Hatori, 1974). These coseismic crustal movements suggest that the faulting also occurred in structural unit Z as well as in units B and A at the time of the Nankaido earthquake (Awata and Sugiyama, 1989). The faulting in unit Z at this time may have been restricted to its eastern part, because the Hyuga sea earthquakes of 1941 (M = 7.4) and of 1968 (M = 7.5) occurred respectively in the central and western parts of the unit Z.

Initiation of forearc neotectonics in Southwest Japan

As already stated, the forearc neotectonics of Southwest Japan is characterized by the formation of structural units due to an accumulation of coseismic and interseismic crustal deformations. Therefore, the beginning of the structural-unit formation can be regarded as the initiation of forearc neotectonics in Southwest Japan. The geologic data indicating the beginning of forearc neotectonics were obtained from the Sagara-Kakegawa area (land area of the structural unit D) and off-Shikoku area.

In the Sagara-Kakegawa area, forearc neotectonics dates back to the formation of the Megami anticline as an inverted L-shaped structural high, and of the Kakegawa basin which is an ancestor of the present Enshu basin (Sugiyama, 1989). The birth of these structures is marked by a basal conglomerate of the Kakegawa Group, distributed along the western flank of the Megami anticline (Figure 13). The conglomerate has been dated at about 4Ma

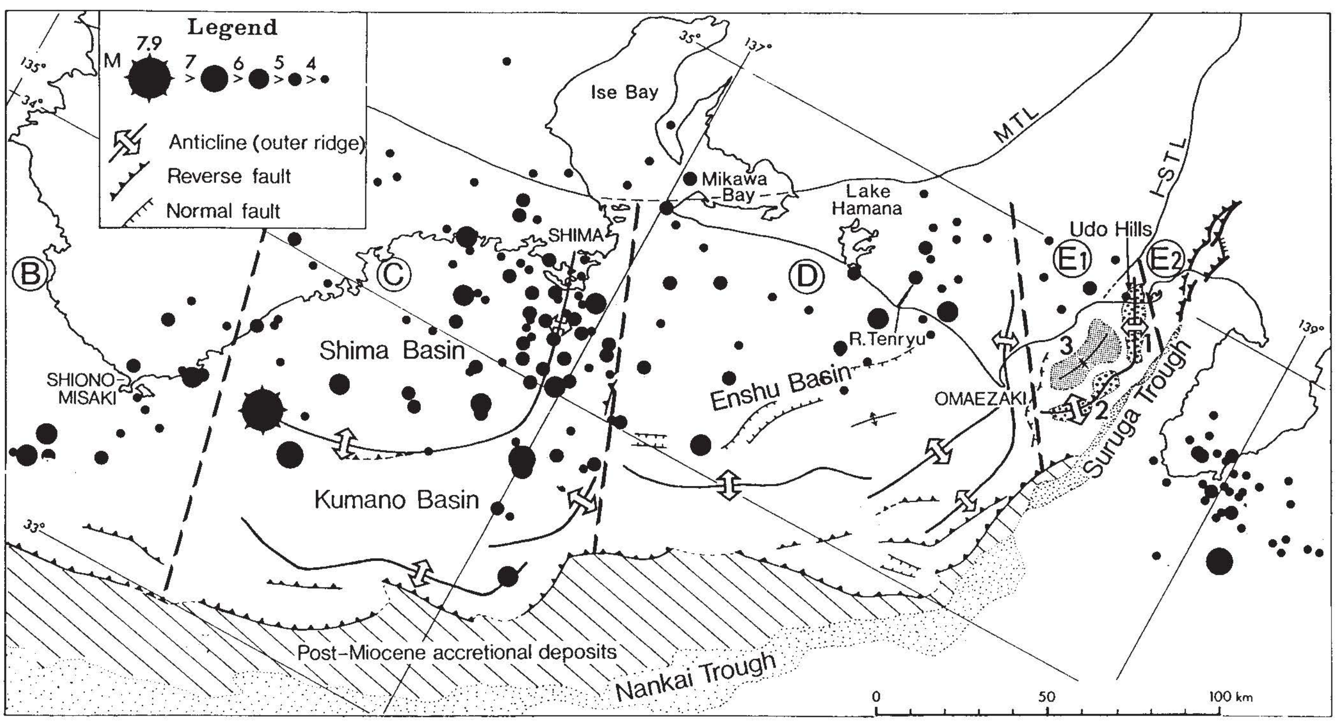


Fig. 12. Structural unit division of the off-Tokai region and epicentral distribution of earthquakes which occurred within 30 days after the 1944 Tonankai earthquake. After Sugiyama (1990). The location of epicenters is after Iwata and Hamada(1986). The topographic features in the unit E1 are 1: Kuno spur, 2: north and south Senoumi banks, and 3: Senoumi basin.

by fission-track dating of an intercalated tuff layer and by planktonic foraminiferal biostratigraphy of the Sagara and Kakegawa Groups (e.g., Ibaraki, 1986).

In the off-Shikoku area, forearc neotectonics began with the initiation of the uplift of the Muroto and Ashizuri spurs. According to Okamura and Joshima (1986), the tabular crown part of the Muroto spur is composed of upper Miocene and/or Pliocene strata showing almost no changes in thickness in the E-W direction and no conspicuous difference in deformation extent within the horizon. On both limbs of the spur, Pleistocene beds show a downward-increasing deformation and unconformably overlie the strata of Miocene to Pliocene age. Okamura and Joshima (1986) concluded on the basis of the above data that the uplift of the Muroto spur began within Quaternary time. Data indicating a similar distribution and deformation patterns of the Tertiary and Quaternary deposits have been obtained from the Ashizuri spur (Okamura *et al.*, 1987).

From these data it is inferred that the formation of the structural unit did not begin simultaneously through the forearc region, but began earlier in the eastern Sagara-Kakegawa area (about 4 Ma) and gradually extended westwards.

NEOTECTONICS OF THE SETOUCHI PROVINCE

The Setouchi Province (Ikebe, 1957) is an E-W-trending intra-arc depression north of the Median Tectonic Line (MTL) in Southwest Japan. The province was submerged to form a nonmarine to shallow-marine basin (inland sea) in Early Miocene and during Pliocene to Holocene times. The Miocene inland sea is called the first Paleo-Seto inland sea, while the Pliocene to Pleistocene one is the second Paleo-Seto inland sea, as distinct from the present-day Seto inland sea (Ikebe, 1957). This chapter deals with the active tectonics of the present-day Seto inland sea and with paleogeographic changes of the second Paleo-Seto inland sea in relation to the strike-slip faulting of the MTL.

Active tectonics of the present-day Seto inland sea

The present-day Seto inland sea is dominated by a basin-and-range (or ridge) topography composed of four basins and intervening islands or island chains extending in an NE-SW direction (Figure 1). Each of the basins has an elliptical shape elongated in an NE-SW direction at an angle of 30 to 45 degrees to the MTL. Thus the basins and ranges of the present-day Seto inland sea show a right-hand en-echelon arrangement oblique to the MTL (Figure 1).

Detailed geologic structures of basin-and-range landforms of the present-day Seto inland sea are visible in easternmost Osaka Bay and on Awaji Island. Osaka Bay is bounded to the west and the north by active faults featuring a subsidence of the bay relative to Awaji Island and the Rokko Mountains (Figure 14). NE-SW to ENE-WSW-trending faults in the Rokko Mountains are known to possess both right-lateral strike-slip and thrust components (Huzita and Kasama, 1982). A multichannel seismic profile across Osaka Bay clearly shows that the bay is a thrust-bounded basin filled with west-dipping deposits (Figure 15). Awaji Island, a ridge separating Osaka Bay from the Harima sea, displays a horst-like structure in its northern part (Figure 14; Mizuno *et al.*, 1990).

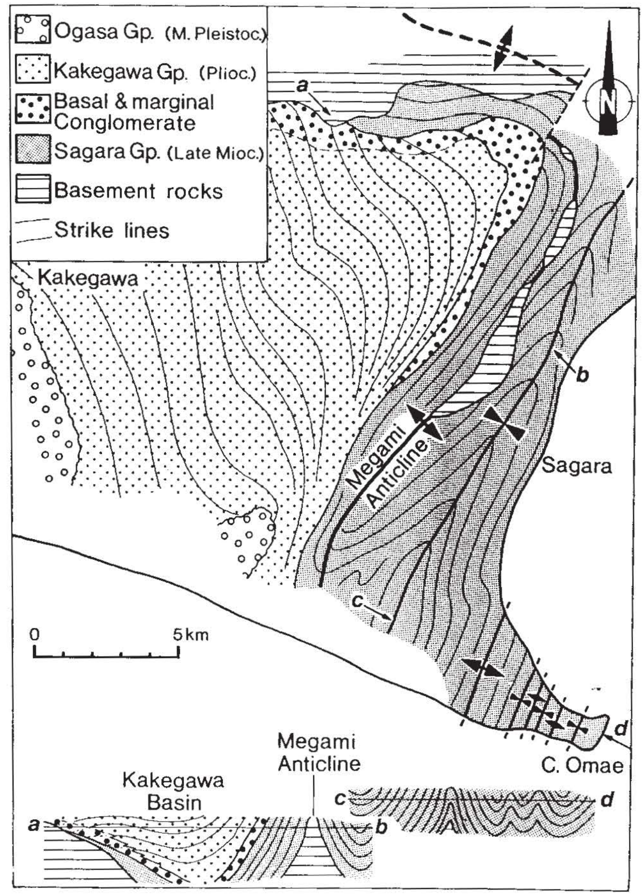


Fig. 13. Geological map of the Sagara-Kakegawa area. Modified after Sugiyama(1989).

These major landforms and geologic structures of the present-day Seto inland sea are consistent with structural features expected for a right-lateral shear zone (Kaizuka, 1975; Tsukuda, 1990). From this structural point of view, the inland sea is named the Setouchi (Seto inland sea) shear zone (Tsukuda, 1990). Trajectories of maximum horizontal compressive stress obtained from crustal earthquakes show dextral kinks at the northern and southern borders of the Setouchi shear zone (Figure 16). This supports the idea that the present-day Seto inland sea is a dextral shear zone which has been formed in association with the right-lateral strike-slip movement of the MTL (Tsukuda, 1990).

Figure 17 shows a generalized formation model of en-echelon basins and ridges along a major strike-slip fault from the above-mentioned data on the present-day Seto inland sea (Sugiyama, 1991).

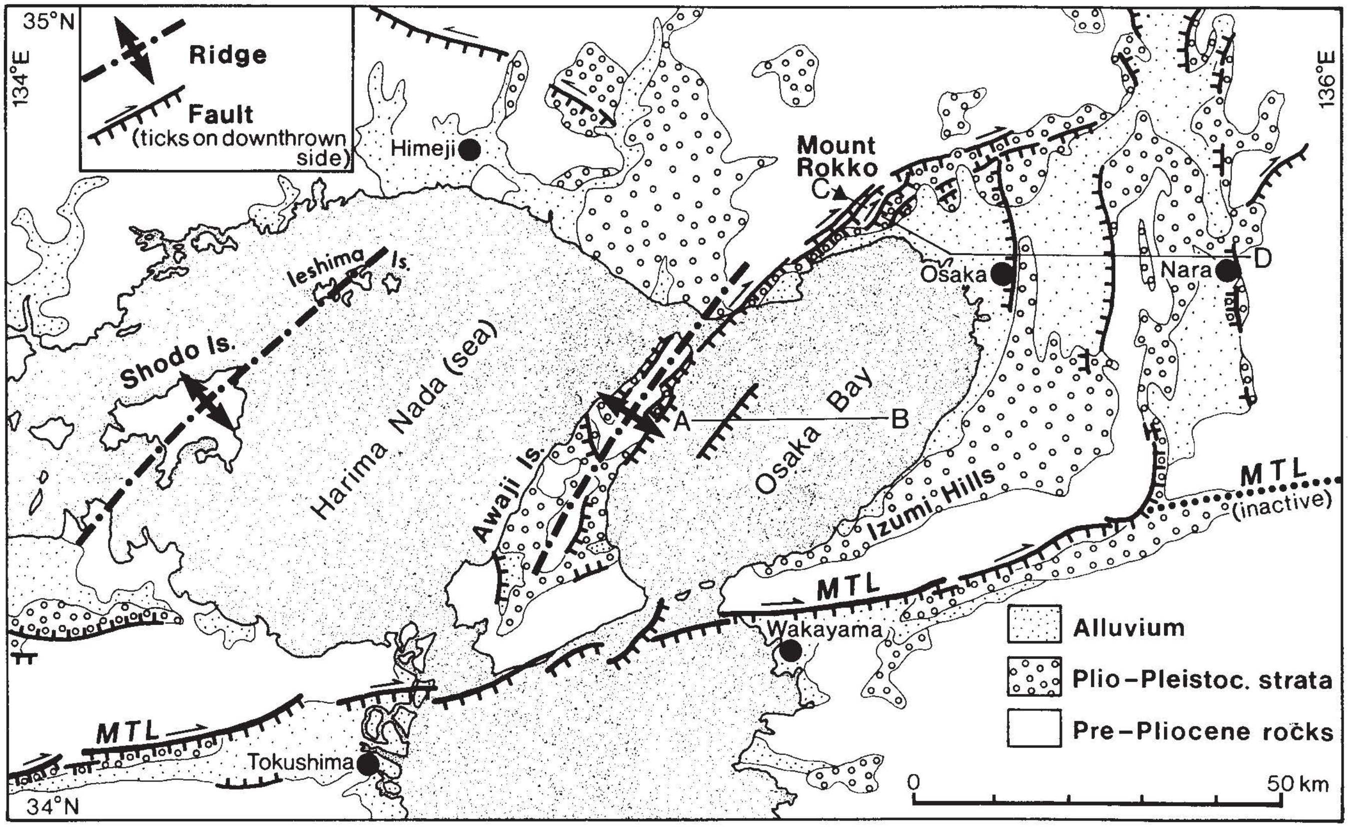


Fig. 14. Active tectonic map of the eastern Seto inland sea. Modified after Tsukuda(1992). The lines A-B and C-D show the locations of the geologic profiles shown in Figure 15.

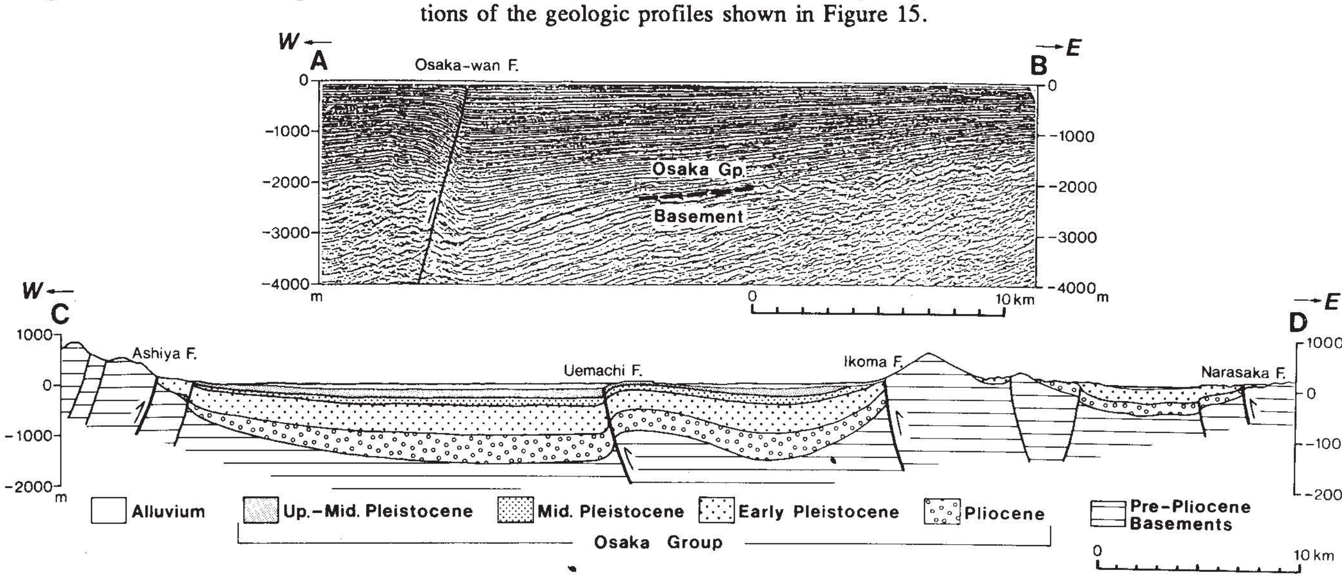


Fig. 15. Multichannel seismic reflection profile of Osaka Bay(A-B) and geologic profile of the Osaka area(C-D). The seismic reflection profile is after Iwasaki *et al.* (1990). The geologic profile of the Osaka area is after Itihara *et al.*(1991). See Figure14 for the locations of lines A-B and C-D.

Paleography of the second Paleo-Seto inland sea

Previous studies on the second Paleo-Seto inland sea (e.g., Kasama and Huzita, 1957; Huzita, 1962; Kuwahara, 1985; Yoshida, 1990) have revealed that the inland sea was composed of three main depositional basins; the Tokai, Kobiwako (Paleo-Biwa Lake) and Osaka basins from east to west.

In the following sections, the origin time and paleogeographic changes of these three basins are outlined on the basis of previous paleogeographic studies of each basin.

1. Origin of the depositional basins

Based on the tephrochronological and paleomagnetic studies of the deposits of the three basins in the second Paleo-Seto inland sea (e.g., Torii *et al.*, 1974; Otofuji *et al.*, 1975; Hayashida and Yokoyama, 1983; Kikkawa and Yoshikawa, 1990), the birth time of the basins is estimated at 4 to 5 Ma for the Tokai basin, 3.5 to 4 Ma for the Kobiwako basin and 3 to 3.5 Ma for the Osaka basin, respectively. The estimated ages of the basins are younger westwards. Some authors (e.g., Makinouchi *et al.*, 1983; Nakayama and Yoshikawa, 1990) state that the Tokai basin formed at 6.5 Ma or earlier on the basis of fission-track ages of volcanic ashes intercalated in the lower part of the Tokai Group (the deposits of the Tokai basin). However, the lower and middle parts of the Tokai Group are correlative to the Kakegawa Group in the forearc region, on the basis of chemical composition of intercalated volcanic ashes (Kikkawa and Yoshikawa, 1990). Furthermore, Mizuno (1992) completed a detailed tephrostratigraphy and paleomagnetic stratigraphy of the Setouchi Province, and showed that most fission-track ages of the Plio-Pleistocene volcanic ashes lacking other chronological data had been overestimated. We conclude that the Tokai basin in the second Paleo-Seto inland sea and the Kakegawa basin in the forearc region started to form at about the same time.

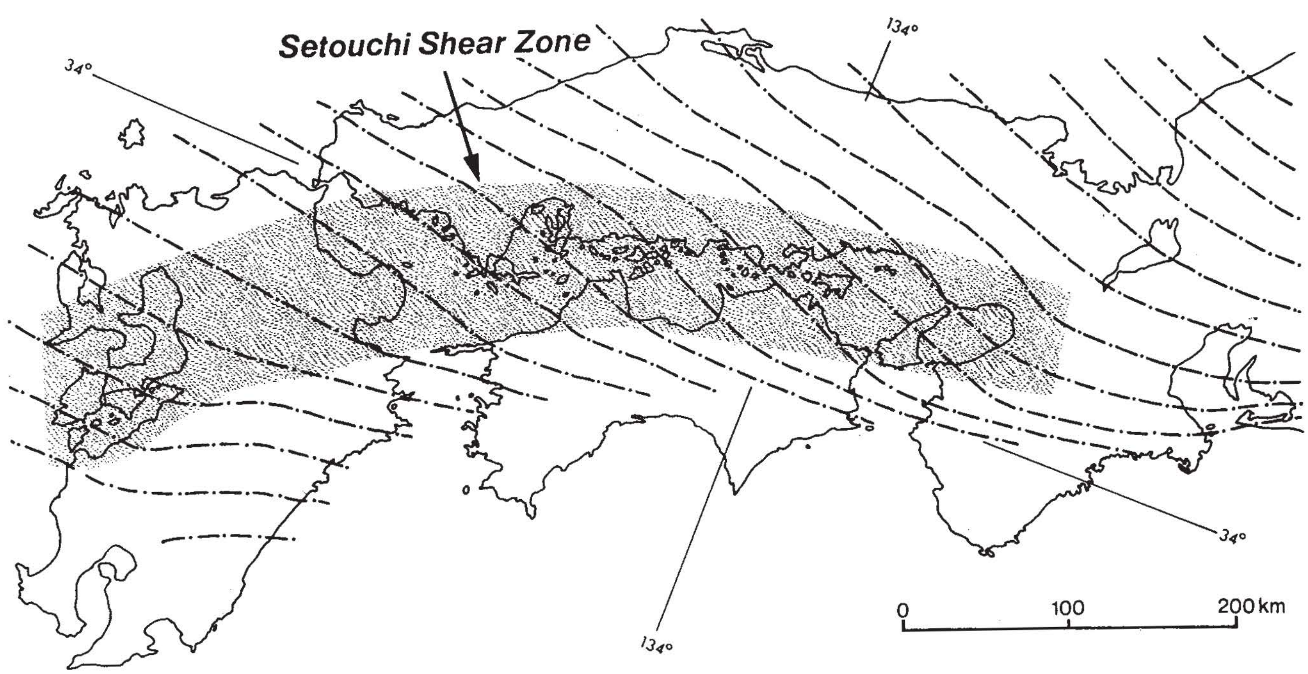


Fig. 16. Trajectories of maximum horizontal compressive stress obtained from focal mechanisms of crustal earthquakes. After Tsukuda(1992).

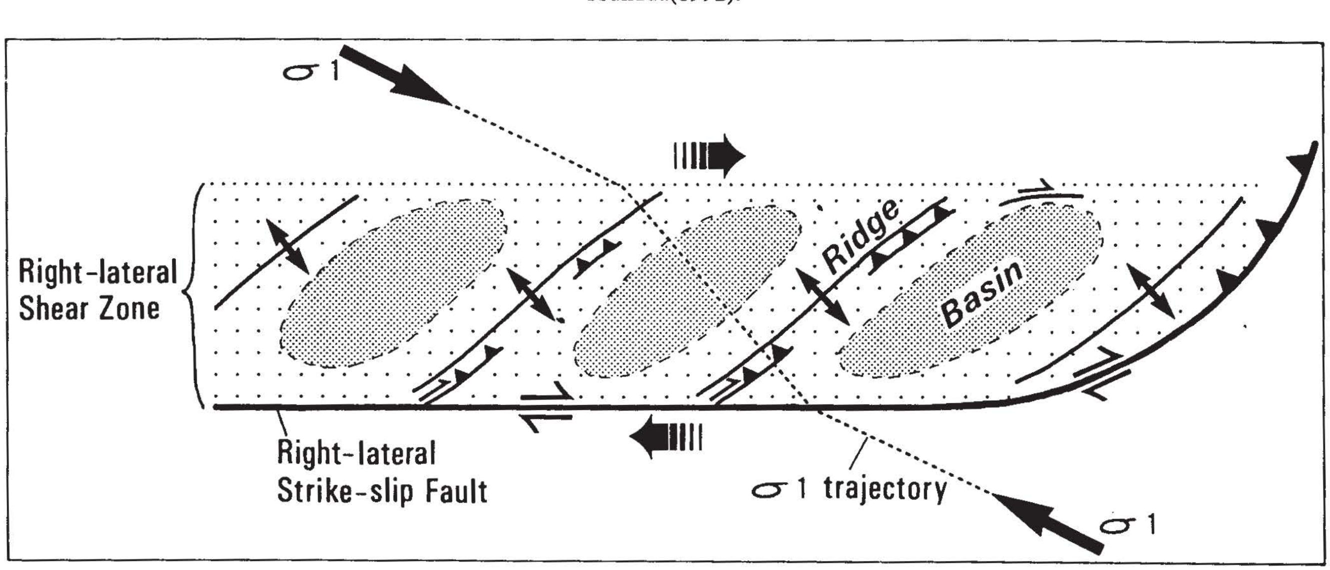


Fig. 17. Schematic formation model of right-handed en-echelon basins and ridges along a major right-lateral strike-slip fault. After Sugiyama(1991).

2. Paleogeographic changes of the depositional basins

1) Tokai basin

According to Kuwahara(1985), Makinouchi (1985) and Yoshida (1990), the Tokai basin originated in the southern area adjoining the MTL, with an elliptical shape elongated in the ENE-WSW to NE-SW direction (Figure 18-A). The depocenter gradually shifted to the north, changing the basin's elongation direction from NE-SW to N-S in association with the emergence of N-S-trending boundary ranges between the Tokai and Kobiwako basins (Figure 18-B, C). In early Pleistocene, the subsiding area was diminished by the increasing uplift of the N-S-trending ranges (Figure 18-D), and the former basin area was divided into several blocks tilted by N-S-trending thrusts and conjugate strike-slip faults with NE-SW and NW-SE directions. Since the Middle Pleistocene, the sea has cyclically invaded the last subsiding area (westward-tilting Nobi block) across the Irago strait, controlled by the glacio-eustatic sea level change (Figure 18-E).

2) Kobiwako basin

The Kobiwako basin (Paleo-Biwa Lake) had its origin in the Iga area immediately north of the MTL and migrated northwards to evolve into the present-day Biwa Lake (Figure 18-B~E; Kawabe, 1989). Kawabe (1989) has divided the northward-migrating history of the Kobiwako basin into four stages. From isopach maps, paleocurrent data and structure-contour maps of the Kobiwako Group by Kawabe (1989), it is inferred that the Kobiwako basin maintained an NE-SW-trending axis of subsidence at every stage, being regulated by NE-SW and N-S-trending structures such as faults and ranges.

3) Osaka basin

The most recent Osaka basin also originated in the southern part adjacent to the MTL (Figure 18-B), and developed into the present Osaka Bay with the first invasion of seawater about 1.2 Ma. Although the main deposits of the Osaka basin (Osaka Group) are present beneath the Osaka plain and Osaka Bay (Figure 15), these deposits also occur in the hilly areas along the southern and eastern margin of Osaka plain (Figure 14; Itihara *et al.*, 1986). This fact proves that the depocenter has retreated to the west or northwest. According to Huzita and Kasama (1982), the early Osaka basin in Pliocene time had an ENE-WSW-trending axis of subsidence, and the N-S-trending ranges bounded by east-dipping reverse faults in the eastern part became prominent in Middle Pleistocene.

Development mechanism of the second Paleo-Seto inland sea

1. Regularities in the development history of the basins

To summarize the above-outlined paleogeographic changes of the three basins in the second Paleo-Seto inland sea, we note the following regularities or common phenomena and processes in their history.

(1) The basin formation in the second Paleo-Seto inland sea began in its eastern part and extended progressively to the west.

(2) The basins had an elliptical shape elongated in the ENE-WSW to NE-SW direction, and were arranged in a right-handed en-echelon pattern at least in the early stages of development.

(3) The depositional centers of the Tokai and Kobiwako basins have migrated to the north. The depocenter of the Osaka basin also has retreated northwestward.

(4) In conjunction with the north or northwest shifting of the depositional area, N-S-trending structures such as ranges and thrusts were superposed from the south upon pre-existing ENE-WSW to NE-SW-trending structures bordering the early basins.

In addition, the active tectonics of the realm of the second Paleo-Seto inland sea (Kinki Triangle) is also characterized by the following:

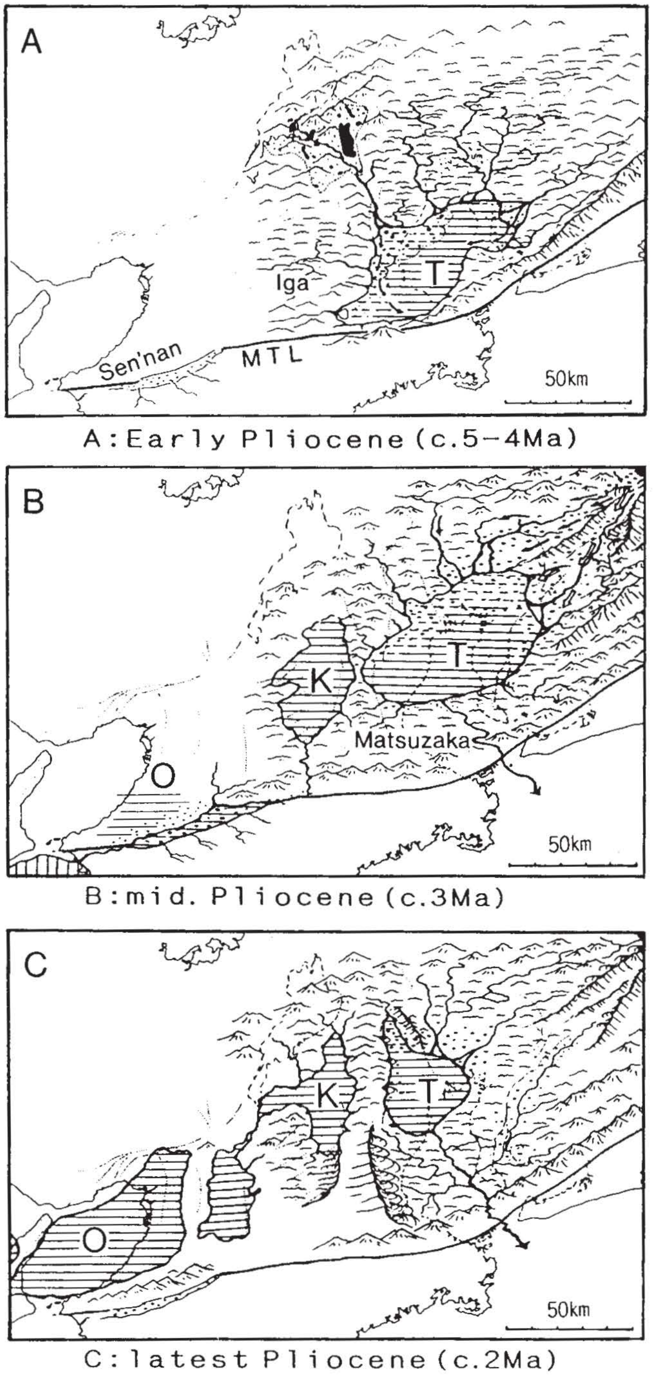
(5) The Tokai basin has changed into a domain of block movement controlled by N-S-trending thrusts and conjugate strike-slip faults in NE-SW and NW-SE directions reflecting an E-W compressive stress field. In the Osaka basin, by contrast, subsidence along an NE-SW-trending axis in the western part coexists with block movement controlled by N-S-trending thrusts in the eastern part (Figure 14). The active tectonics of the Kobiwako basin area is intermediate between those of the Tokai and Osaka basins, as evidenced by the survival of early basin structures (Biwa Lake) and the degree of development of N-S-trending structures.

2. Development model of the second Paleo-Seto inland sea in association with the migration of an active domain of the MTL

Among the above regularities recognized in the history of the second Paleo-Seto inland sea, (2) indicates that the inland sea was formed by the right-lateral shearing in the same manner as the present-day Seto inland sea. (1) together with the fact that the MTL south of the Kobiwako basin was active until the Early Pleistocene (Sangawa, 1986), suggests that the active domain of the MTL has migrated westwards. Furthermore, (3), (4) and (5) suggest that the southern border of the shear zone has shifted northward in association with the decline in activity of the eastern part of the MTL, and that the area seceding from the shear zone has been subjected to E-W compressive tectonic movement (Sugiyama, 1991).

Thus, the development of the second Paleo-Seto inland sea can be successfully explained by regarding the inland sea as a right-lateral shear zone along the MTL whose active domain has migrated to the west.

From the development history of the second Paleo-Seto inland sea, we obtain a generalized development model of en-echelon basins associated with the migration of an active domain of a large-scale strike-slip fault (Figure 19). In this model, the E-W change in active tectonics through the Setouchi Province is interpreted in terms of different stages



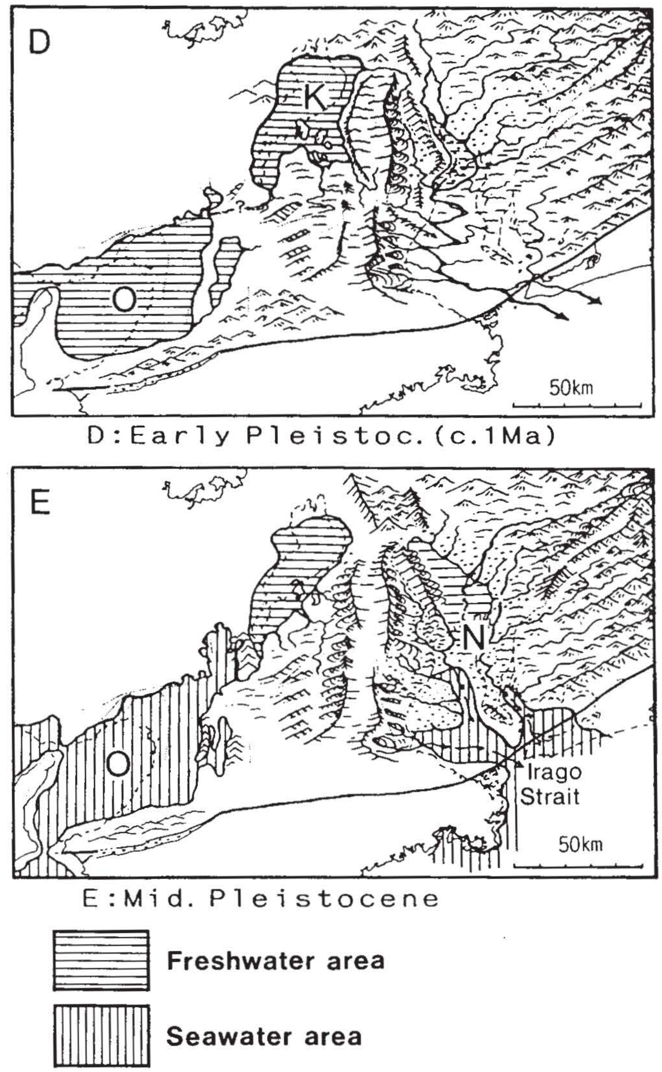


Fig. 18. Paleogeographic maps showing the progressive stages of basin development in the second Paleo-Seto inland sea. After Kuwahara(1985). T, K and O denote the Tokai, Kobiwako and Osaka basins, respectively, and N denotes the Nobi block.

of basin development. In other words, the Tokai and Lake-Biwa areas in the eastern part have reached a more advanced stage of basin development as compared with Osaka Bay and Harima sea.

Relation of the shear zone model with the conventional tectonic development model of the second Paleo-Seto inland sea

The tectonic development of the second Paleo-Seto inland sea has been explained by a superposition of two kinds of tectonic movements with different times and in a different stress field (e.g., Huzita, 1962, 1968; Kuwahara, 1968, 1985; Makinouchi, 1979, 1985). The first movemente is a basin formation or downwarping with an NE-SW to ENE-WSW-trending axis of subsidence in the Pliocene to Early Pleistocene. The next is a block movement which has been controlled by N-S-trending thrusts and conjugate strike-slip faults in NE-SW and NW-SE directions since the Middle Pleistocene.

By comparing these two kinds of tectonic movements with the basin development model shown in Figure 19, the earlier downwarping, which has been called the Chita movement (Makinouchi, 1979), is correlative to the right-lateral shear tectonics along the active MTL (e.g., in and around basin A in stage 1). On the other hand, the latter block movement, called the Rokko movement (Ikebe and Huzita, 1966) or the Sanage movement (Kuwahara, 1968), is correlated to the E-W compressive tectonics on the north of the MTL once it became inactive (e.g., in and around basin A" in stage 3).

The transition from the Chita to the Rokko movements has been attributed to a change in the regional stress field from N-S compression to E-W compression (e.g., Huzita, 1968; Huzita and Kasama, 1982). The shear zone model shown in Figure 19, however, does not require such a change of the regional stress field. More precisely, in the Chita movement or right-lateral shear tectonics stage, the maximum compressive stress in the shear zone is deflected to the N-S direction as shown in Figures 16 and 17. In the Rokko movement stage, an area seceding from the north-shifting shear zone is incorporated into the forearc region and translated westwards. The westward translation causes the collision of the seceding area with the shear zone area on the west, and a strong E-W compressive stress field develops in the collision area.

Therefore, the shear zone model of the Setouchi Province suggests the possibility that Southwest Japan has been in a constant stress field with maximum compression in the ESE-WNW direction since the birth of the Tokai basin 4 to 5 m.y. ago.

NEOTECTONICS OF SOUTHWEST JAPAN AS A RESULT OF THE RIGHT-OBLIQUE SUBDUCTION OF THE PHILIPPINE SEA PLATE

Comprehensive neotectonics of the forearc region and the Setouchi Province

The formation of structural units or right-oblique low-angle thrusts in the forearc region of Southwest Japan is interpreted as an elastic rebound of the forearc dragged downwards and westwards by the right-oblique subduction of the Philippine Sea plate. The right-lateral strike-slip faulting of the MTL and the formation of the Setouchi shear zone are attributable to the westward translation of the forearc region (forearc sliver) caused by the right-oblique subduction of the Philippine Sea plate (Seno, 1986; Tsukuda, 1990).

Consequently, the neotectonics of the forearc region and of Setouchi Province are comprehensively understood as arc-side reactions to the oblique subduction of the Philippine Sea plate. As pointed out by Fitch (1972) and Kaizuka (1975), the right-lateral strike-slip faulting of the MTL accommodates part of the relative motion between the Philippine Sea plate and the Eurasia plate.

Initiation of right-oblique subduction and change in motion of the Philippine Sea plate

As already stated, the structural units along the Nankai Trough began to form about 4 Ma and the basin-forming movement in the Setouchi Province also started 4 to 5 m.y. ago. This coincidence in the initiation time of forearc and backarc neotectonics suggests that the right-oblique subduction of the Philippine Sea plate or its effective action on Southwest Japan began 4 to 5 m.y. ago (Okada, 1980a; Sugiyama, 1991).

In the forearc region of Southwest Japan, except for the southern Fossa Magna (Figure 20) and the area along the Sagami Trough, regional uplift and interruption of sedimentation occurred in the Middle Miocene. The deposition restarted about 11 Ma in the Sagara area (Figure 13) and in the Miyazaki area (southeastern part of Kyushu Island). This fact suggests that the interaction of Southwest Japan with the Philippine Sea plate, which was weak in the Middle Miocene, recovered at about 11 Ma in order to submerge the forearc region (Sugiyama, 1992). The results of seismic reflection surveys off Shikoku (Okamura and Joshima, 1986; Okamura *et al.*, 1987) and the facies changes within the Upper Miocene Sagara Group (Mizuno *et al.*, 1987) indicate that there was a forearc slope which deepened monotonously toward the Nankai Trough without featuring outer ridges in the Late Miocene. Furthermore, in the Fujikawa area of the southern Fossa Magna and in the Miyazaki area, where the trench axis curves into a N-S trend, the geologic structures of the Upper Miocene strata indicate that left-oblique subduction was occurring (Sugiyama, 1989).

From these facts, it is inferred that the direction of motion of the Philippine Sea plate was deflected to the north in the Late Miocene (11 to 5 Ma), and that low-oblique subduction took place along the major part of the Nankai Trough while left-oblique subduction occurred at the east and west ends of the trough (Figure 20). Then the direction of motion of the Philippine Sea plate changed counterclockwise about 5 Ma, initiating right-oblique subduction along the Nankai Trough. The cause and process of this change of plate motion remain unsolved.

The change in motion of the Philippine Sea plate in Late Miocene to Pliocene times was also pointed out by Seno and Maruyama (1984). They concluded, on the basis of the volcanic front configurations in central Honshu during Miocene to Holocene times, that the motion of the Philippine Sea plate changed from north-northwestward to west-northwestward 10 to 5 m.y. ago. Their conclusion is consistent with ours, deduced from tectonic data of Southwest Japan.

Westward migration/extension of neotectonic movement

As already stated, the neotectonic movements of the forearc region of Southwest Japan and the Setouchi Province began earlier in their eastern parts and subsequently extended to the west. The cessation of faulting along the MTL also began earlier in the eastern part and has now reached the central part of Kii Peninsula (Okada, 1980b). What is the cause of this westward migration/extension of the neotectonic movements? The leading edge of the subducting slab has reached the backarc region across the MTL in the eastern area, where the MTL ceased

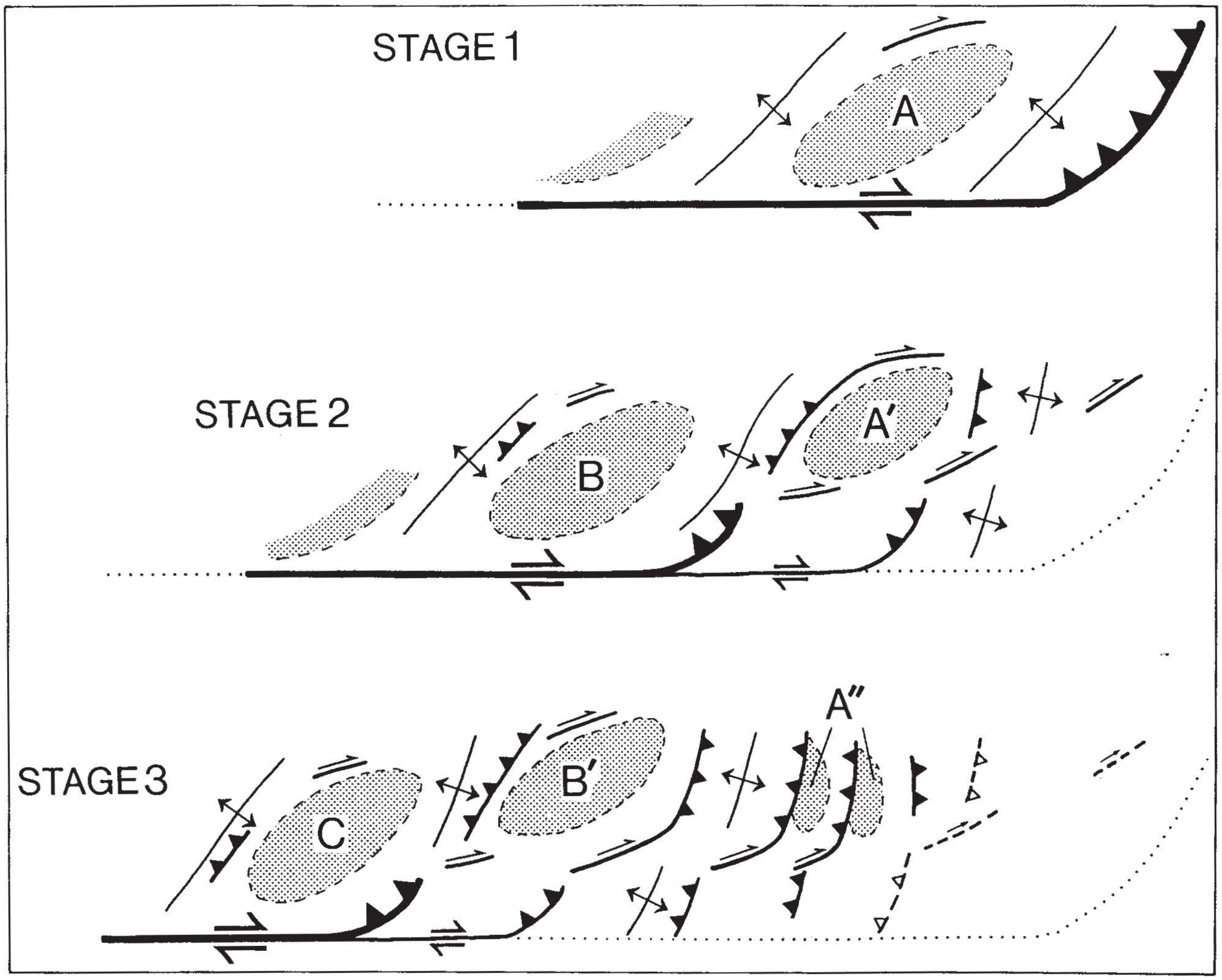


Fig. 19. Generalized model of basin development associated with the migration of active domain of a large-scale strike-slip fault from the development history of the second Paleo-Seto inland sea. After Sugiyama(1991).

its activity, while it still remains within the forearc region in the western Kii Peninsula and Shikoku, where the MTL is active (Figure 21; Shiono, 1980).

This fact leads us to hypothesize that, due to the westward-increasing distance between the Nankai Trough and the MTL (Figure 1), the strong coupling between the subducting slab and the forearc sliver, which causes the formation of structural units and the right-lateral faulting of the MTL, came into existence earlier in the eastern area. In the same way, the intrusion into the backarc side of the subducting slab, which interrupts the faulting of the MTL, also began earlier in the eastern area.

FUTURE RESEARCH

The neotectonic model of Southwest Japan presented in this paper is fundamentally based upon data on major landforms and submarine geology. Detailed submarine geological data for the construction of a tectonic model, however, have been obtained only for the off-Shikoku area and Suruga Bay in the forearc region, and only for Osaka Bay in the Setouchi Province. For the refinement of the neotectonic model of Southwest Japan, detailed research on submarine geology of unexplored and insufficiently-surveyed areas such as the Kumano basin in the forearc region and the Harima and Hiuchi seas in the Seto inland sea are necessary.

We may point out, finally, that a comparative study of the neotectonics of Southwest Japan and other oblique-convergent plate boundaries is indispensable for a deeper understanding of the tectonics of these specific regions. Morphotectonic features similar to those in Southwest Japan are visible in other oblique-convergent plate boundaries in the circum-Pacific region. In Sumatra and Kamchatka, where right-oblique subduction is occurring, there is a right-lateral transcurrent fault and a row of forearc basins bordered by an inverted L-shaped structural high extending from a promontory or peninsula to the outer ridge (e.g., Drummond *et al.*, 1981). It is suggested that the neotectonic model of Southwest Japan presented in this study may be useful for an understanding of the tectonics of these areas.

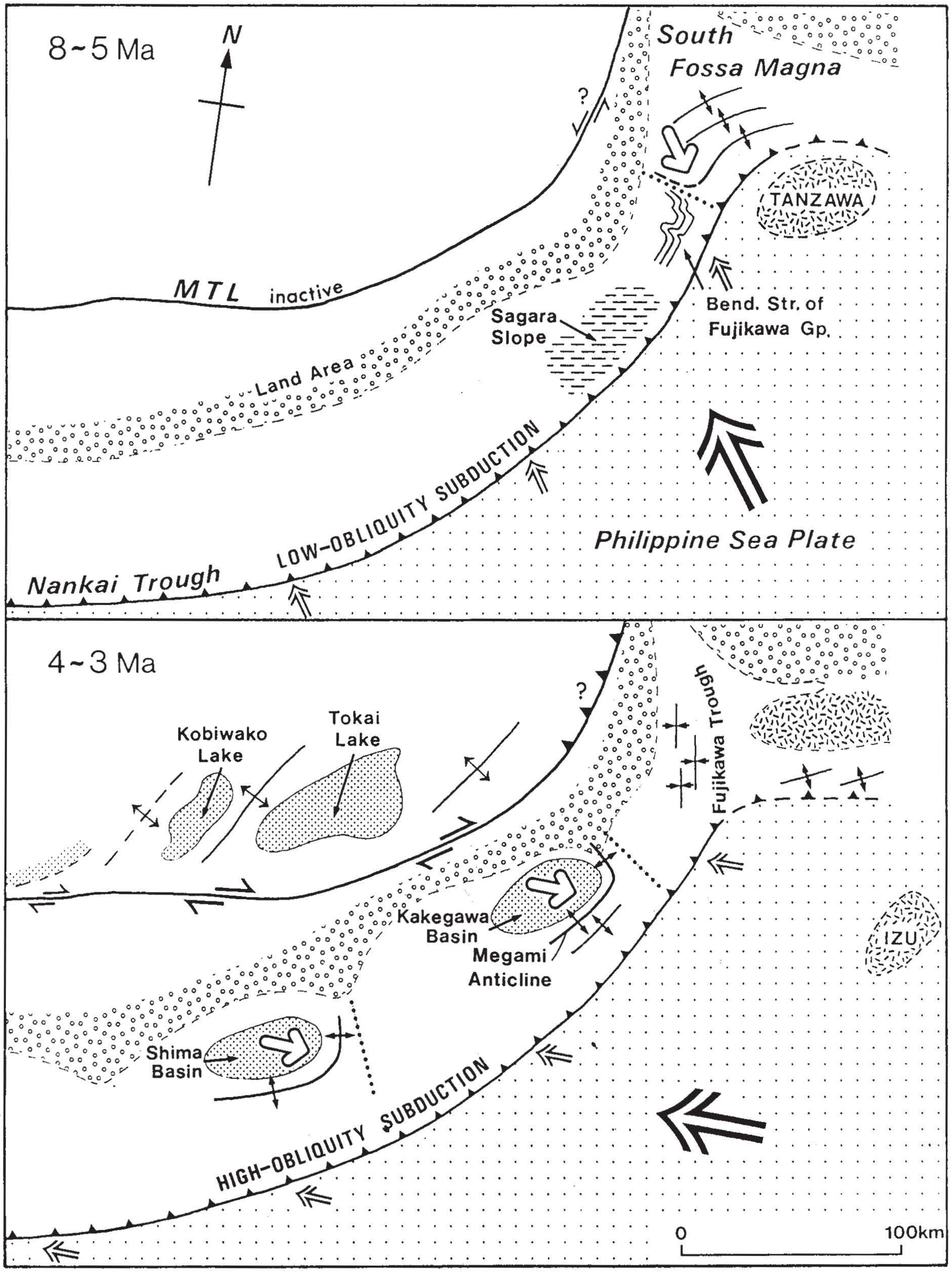


Fig. 20. Possible formation model of structural units in the forearc region and en-echelon basins along the MTL in relation to the initiation of right-oblique subduction of the Philippine Sea plate along the Nankai Trough. After Sugiyama(1991). Arrows in the South Fossa Magna (top figure) and in the Kakegawa and Shima basins (bottom figure) show the displacement direction of hanging walls of the causative faults of plate-boudary earthquakes.

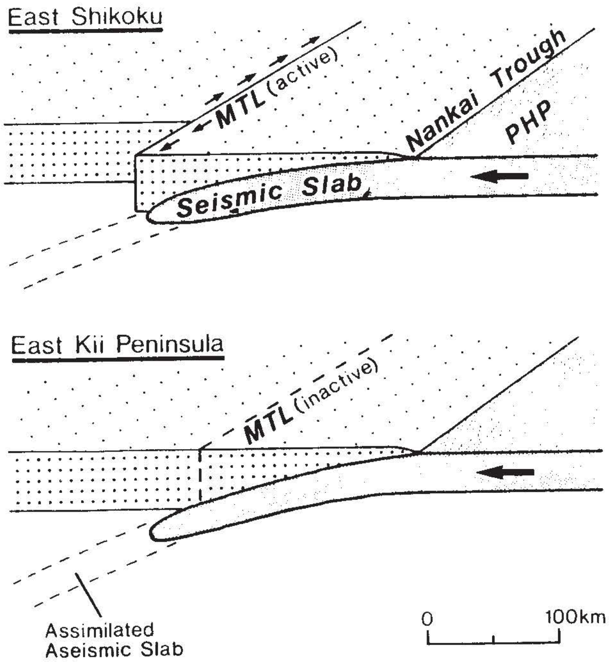


Fig. 21. Schematic figure showing the positional relation of leading edges of the seismic slab to the Median Tectonic Line in east Shikoku and east Kii Peninsula. Modified after Shiono(1992).

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