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CONTINENTAL SLOPE STRUCTURAL HIGH IGNEOUS ACTIVITY AND ITS BEARING ON THE GEOTECTONIC HISTORY OF THE PHILIPPINE SEA

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Some characteristic magmatism on the structural highs of continental slopes indicates initiation of subduction of a new, relatively warm slab. An instance is the plagio-granitic and tholeiitic magmatism that occurred on the Middle Miocene topographic and structural highs of the continental slope of the outer zone of Southwest Japan. It was simultaneous with the initiation of subduction of the new Shikoku Basin slab, just following the off-ridge volcanism in the basin. The magmas intruded upward through the remnant fissure of the transform fault which had separated the Southwest Japan arc from the Philippine Sea plate until the cessation of the Shikoku Basin opening.

Application of the idea of "continental slope structural high magmatism" to the igneous rocks of the Daito Ridge Group provides a new hypothetical scenario for the tectonic history of the Northern Philippine Sea. Late Cretaceous collision of the "Kuroshio Paleo-island" with the Japan arc resulted in suspension of northward subduction of the Paleo-Philippine Sea plate, temporal southward subduction of a part of the plate under the Paleo-Daito arc, and the structural high magmatism on the Amami Plateau, the present northernmost ridge in the Daito Ridge Group.

1. *Introduction*

Occurrence of "continental slope igneous complex" (SHIKI and MISAWA, 1979: or "forearc igneous complex," SHIKI and MISAWA, 1982) is one of the most significant findings in the recent studies on the structure and history of the continental slope-trench region.

Much recent information supports the essential part of the generalized structural model of the Japanese continental slope regions proposed by SHIKI and MISAWA (1979, 1980, 1982) except for a few minor points. Especially, the important role played by thrust movement, which is directly manifested by the tectonic activity of the Wadati-Benioff zone, is gradually being elucidated, though the idea of generation and intrusion of magma along the earthquake zone and the thrust fault is still hypothetical.

One the other hand, however, the idea of the "Nankai Structural High Magmatic Zone" and the "structural high magmatism" (MIYAKE and HISATOMI, 1985) or "forearc magmatism" (MIYAKE, 1985a) was derived from the study of the Shiono-Misaki (see Fig. 3 for location) igneous complex which was formed in a structural high belt of the Miocene age (MIYAKE and HISATOMI, 1985). The most interesting result of the study of the Shiono-Misaki complex was the marked resemblance in the petrochemical feature of its basaltic rocks with that of the Shikoku Basin off-ridge tholeiite.

The purposes of the present paper are as follows:

1) To stress the importance of "(continental slope) structural high igneous complex" and its bearing on subduction-collision tectonic history in the Western Pacific.

2) To discuss the geotectonic history of the Northern Philippine Sea, and hypothetical scenario for the change of tectonic setting due to a Late Cretaceous collision at the northern margin of the sea.

3) To provide some suggestion on the genetic history of the marginal seas and basins in the transitional zone.

2. *Continental Slope Structural High Igneous Complex*

Figure 1 shows the topographic and structural section and Fig. 2 shows the geological and geophysical section respectively, of the continental slope of Southwest Japan and Nankai Trough (SHIKI and MISAWA, 1980; SHIKI, 1982). Figure 2 was drawn based on many seismological and geological data including seismic profiling data and dredge samples (HADA *et al.*, 1982; HADA and SUZUKI, 1983a, b; HILDE *et al.*, 1969; KAGAMI, 1984, 1985; KAGAMI *et al.*, 1983; KIMURA,

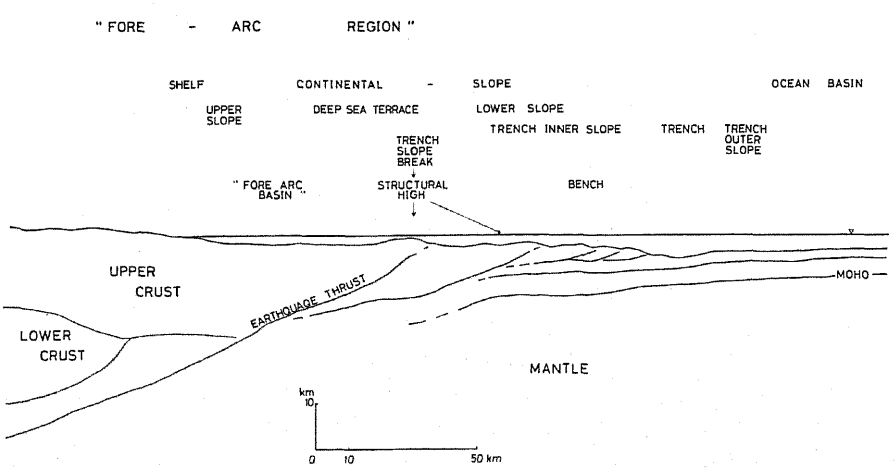

Fig. 1. Simplified topographical and structural section on the Outer Southwest Japan continental slope and Nankai Trough.

1979; KIMURA and OKANO, 1980; NASU *et al.*, 1982; OKANO and KIMURA, 1981; OKUDA, 1977; OKUDA *et al.*, 1979; SHIKI *et al.*,1971; TAMANO *et al.*, 1983; YOSHII *et al.*, 1973).

Several structural highs, forearc basins, and deep-sea terraces develop between the upper and lower continental slopes. The "(continental slope) structural high igneous complex" occurs exactly on these structural highs (MIYAKE and HISATOMI, 1985). A basaltic rock specimen was recently dredged from one of the structural highs off Shikoku (HONZA *et al.*, 1984). Many concealed igneous masses were suggested in the acoustic data and positive magnetic anomalies were found along modern structural highs (OKUDA *et al.*, 1978; OSHIMA *et al.*, 1980; WATANABE and HATTORI, 1980). The Shiono-Misaki igneous complex, cropping out onshore now, is an excellent example of the continental slope structural high igneous complex of past geological age.

Based on stratigraphic and sedimentological studies, HISATOMI and MIYAKE (1981) made it clear that a topographic barrier developed authochtonously with basin genesis, to dam up the sediments of the Miocene Kumano Group. The Shiono-Misaki igneous complex occurs on this topographic barrier of the Miocene age. This setting of the basin, the topographic high, and the igneous complex in Miocene time resembles well that of the modern age.

The Miocene upheaval zone through the Shiono-Misaki area is very close to one of the modern structural highs (Fig. 3). It suggests that the modern structural high has developed from one of the Miocene magmatic upheaval zones.

MIYAKE (1981, 1985a) examined the sequence of igneous activity and petrochemistry of the Shiono-Misaki igneous complex, and found that all of these igneous rocks are classified as non-alkaline rock. They are markedly low in potassium. All the petrochemical characters of the basaltic rocks of the Shiono-Misaki complex, that is, TiO_2 versus FeO/MgO ratio, titanium versus chromium, chondrite normalized rare earth element values, and K_2O versus SiO_2, have similarities to the off-ridge basalt (tholeiite) of the Shikoku Basin. They possibly were formed from the source material common with that of the Shikoku Basin off-ridge basalt, but by a rather smaller degree of melting than the latter. This must be noted together with the fact that the magmatism occurred just after the cessation of opening of the Shikoku Basin, that is 15–16 Ma (MIYAKE, 1981).

In the section of Fig. 2, the structural high rock might seem as if it had intruded along an inclined thrust from the deep place beneath the crust. However, it must be considered that no accretionary wedge existed in the Miocene time. The pass of magma intrusion in the Miocene time could be much closer to the Shikoku Basin and steeper. The figure shows present geological section after the accretion of sediments and deformation.

It can be pointed out that a transform fault separated the Southwest Japan arc from the Philippine Sea plate during the time of opening of the Shikoku Basin (Fig. 4). The off-ridge volcanism occurred at the end of the opening in the Shikoku Basin. It seems natural that the fissure, originated from the transform fault, provided the

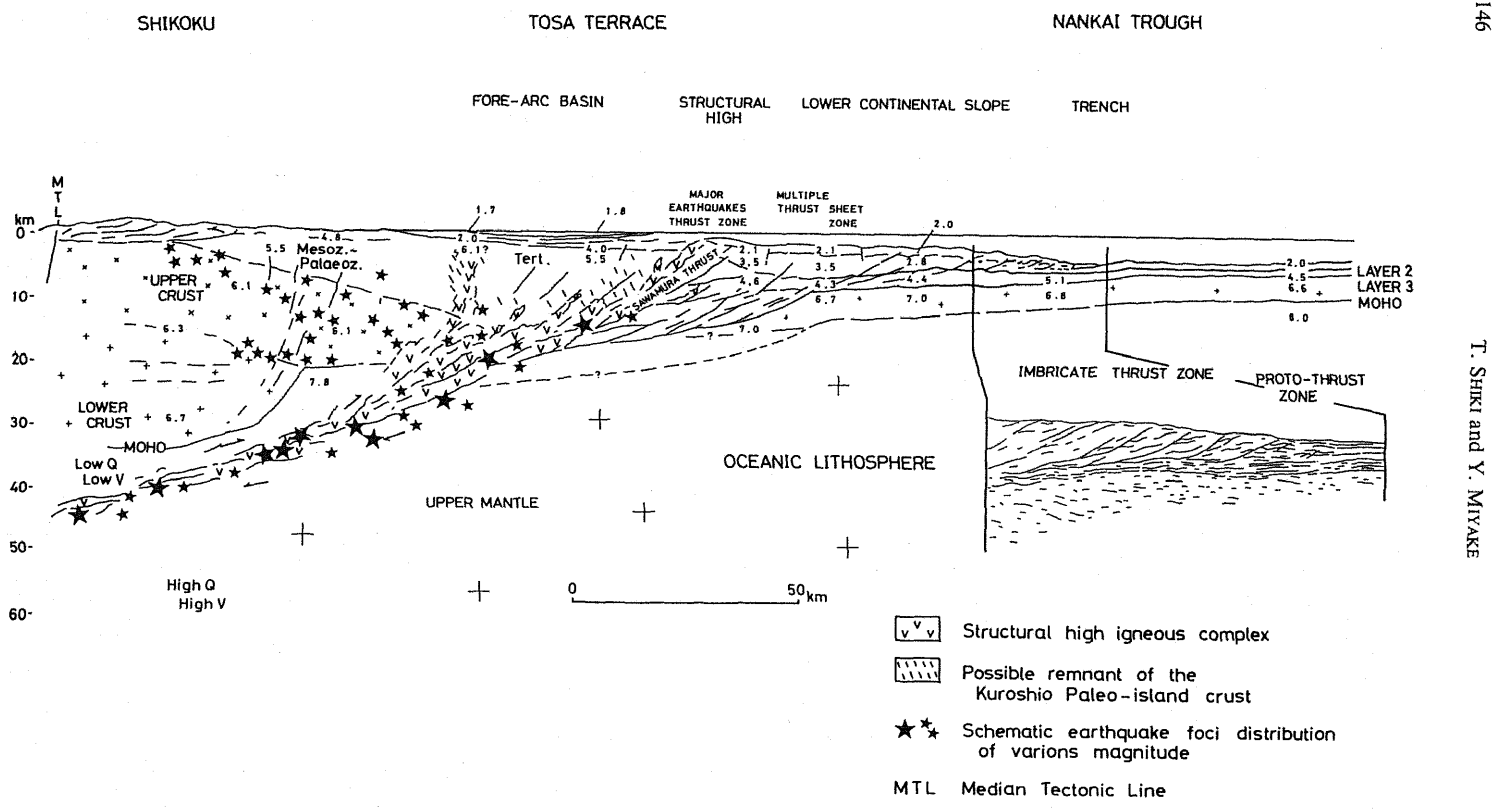
SHIKOKU
TOSA TERRACE
NANKAI TROUGH
FORE-ARC BASIN
STRUCTURAL HIGH
LOWER CONTINENTAL SLOPE
TRENCH
MTL
km
0
10
20
30
40
50
60
MAJOR EARTHQUAKES THRUST ZONE
MULTIPLE THRUST SHEET ZONE
Mesoz.~Palaeoz.
Tert.
UPPER CRUST
LOWER CRUST
MOHO
Low Q
Low V
High Q
High V
SANAGAWA THRUST
UPPER MANTLE
OCEANIC LITHOSPHERE
IMBRICATE THRUST ZONE
PROTO-THRUST ZONE
LAYER 2
LAYER 3
MOHO
0
50km
Structural high igneous complex
Possible remnant of the Kuroshio Paleo-island crust
Schematic earthquake foci distribution of varions magnitude
MTL Median Tectonic Line

Fig. 2

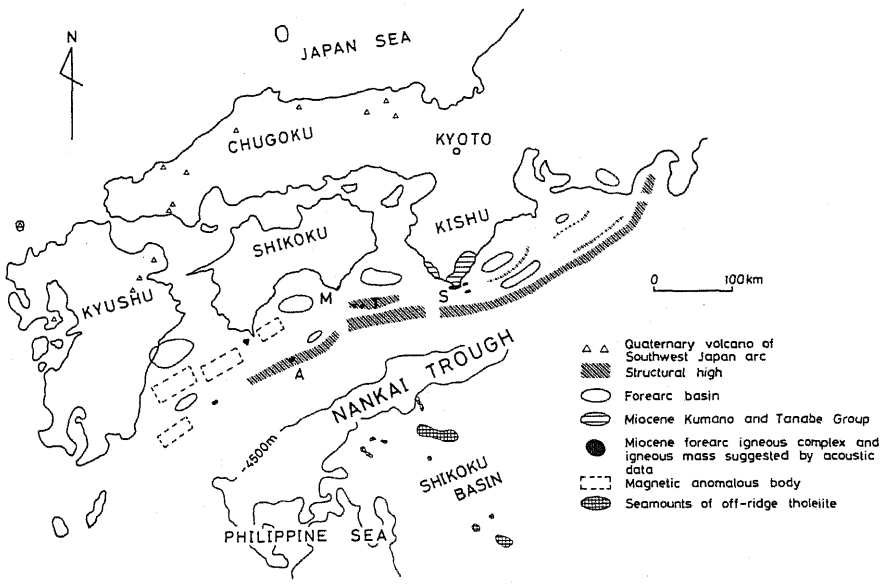

Fig. 3. Map showing the geologic setting of "continental slope structural high igneous complex." Modified from MIYAKE and HISATOMI (1985). S, Shiono-Misaki; M, Muroto-Misaki; A, Dredge station of basaltic rock.

pass of upward intrusion of magmas just before the initiation of subduction of the new slab of the Shikoku Basin (SHIKI, 1985). MIYAKE (1985b) discussed possible lateral intrusion of materials of the Shikoku Basin asthenosphere under the Southwest Japan arc lithosphere assuming relatively warm and light physical properties of the Shikoku Basin asthenosphere (Fig. 4).

In short, the Miocene continental slope structural high magmatism is a characteristic incident which records the initiation of subduction in the past. There are also reported igneous masses in some other modern continental slope structural highs, though their petrological characters are different from each other. Some of them consist of abyssal tholeiite gabbro and accompanied by low potassic acidic rocks (JAKES and MIYAKE, 1984; MIYAKE, 1985a).

Ophiolitic rocks such as abyssal tholeiite, gabbro, and amphibolite associated

Fig. 2. Geological and geophysical section across the Outer Southwest Japan continental slope, and Nankai Trough showing structure of crust and accretionary prism, earthquake foci distribution, and continental slope structural high igneous complex. Modified from SHIKI (1982). Seismic velocities are based mainly on seismic refraction information by HILDE *et al.* (1969); KIMURA (1979), KIMURA and OKANO (1980), and multi-channel seismic reflection data by NASU *et al.* (1982). Stars: Earthquake foci by OKANO and KIMURA (1981).

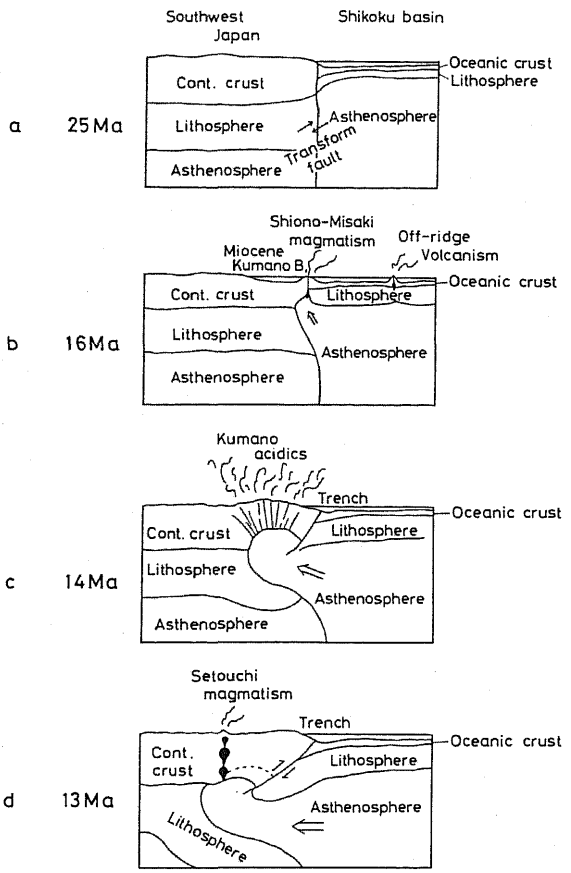

Fig. 4. Sketches of lateral intrusion process of the Shikoku Basin asthenosphere under the crust of Southwest Japan arc, and magmatism in the Miocene.

with granitic rocks occur in much older tectonic belts in the world. Permo-Triassic rocks in the Maizuru Belt and the Kurosegawa Belt in Southwest Japan (Fig. 5) are good examples. It should be pointed out that a large amount of granitic rocks of noticeable petrochemical character, that is, poor in potassium, low in initial $^{87}Sr/^{86}Sr$ ratio, were formed there. Some of the rocks have protoclastic texture (SHIKI and MISAWA, 1982).

Tectonic settings of the granitic and other rocks of these tectonic belts were discussed by several authors. MARUYAMA (1978), and HADA and SUZUKI (1983a, b) proposed the idea of occurrence of ophiolitic rocks along the suture zone between the island arc crust and the oceanic plate. A similar idea was presented by SHIKI (1978, 1982), and SHIKI and MISAWA (1979, 1980) in connection with subduction and accretion tectonics and activity of the Wadati-Benioff zone.

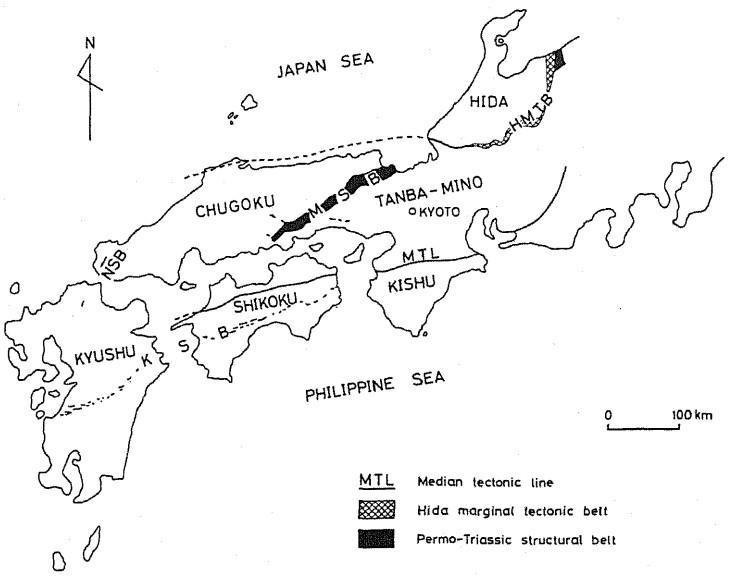

Fig. 5. Permian—Triassic structural belt in Southwest Japan. MSB, Maizuru Structural Belt; KSB, Kurosegawa Structural Belt; NSB, Nagato Structural Belt.

3. *Geotectonic History of the Northern Philippine Sea*

On the basis of a comprehensive study of numerous data of the Philippine Sea and the margin of Southwest Japan arc including the petrochemical character of rocks stated above, SHIKI (1985) proposed a hypothetical scenario for the geotectonic history of the Northern Philippine Sea. This scenario implies subduction of marginal sea floors which existed between the Southwest Japan arc and the Kuroshio Paleo-islands, and the Daito Paleo-islands.

As was reported by AOKI *et al.* (1975, 1976), SHIKI *et al.* (1977, 1979), potassium-poor granite and gabbro occur on the Amami Plateau, the northernmost member of the Daito Ridge Group. This granite has a notable resemblance with that of the Shiono-Misaki, that is, it is poor in potassium, low in initial $^{87}Sr/^{86}Sr$ ratio. This fact, together with its association with gabbro and marginal situation in the Daito Ridge Group Region, suggests the possibility that the rocks belong to the structural high igneous complex of the "Daito Ridge Group arc" (SHIKI, 1985).

High P and low T metamorphic rocks develop in the Daito Ridge, which forms the central part of the ridge group (MIZUNO *et al.*, 1975, 1976; SHIKI *et al.*, 1985). In the case of the Plagiogranite-bearing "ophiolitic rocks" of the Maizuru Belt and Sangun metamorphics, the former is situated on the outer side (ocean side). As pointed out by SHIKI (1985), if there is a similarity in tectonic setting between the Daito Ridge Group and the Maizuru Belt, the ocean basin (marginal sea basin) must have existed in the northern side of the ridge group, and the Cretaceous

subduction must have occurred southward from the north. This polarity of subduction is opposite to the general direction of the movement of the Philippine Sea plate during the time of spreading of the West Philippine Basin stated by many authors (e.g., KARIG, 1975; SENO and MARUYAMA, 1984; UYEDA and BEN-AVRAHAM, 1972). The southward subduction was an exceptional incident which happened following a collision at the southern margin of the Southwest Japan arc.

Modern geological structure and tectonic history of the continental slope of Southwest Japan and Nankai Trough have long been investigated. Here we introduce a pre-Miocene geotectonic model of 1) Continental slope structural high igneous activity at the beginning of subduction of the Shikoku Basin, and 2) collision of remnant of the "Kuroshio Paleo-islands" with the Southwest Japan arc.

Members of the Shimanto Research Group proposed that a piece of land had extended from the south of the Southwest Japan arc to the east of the Ryukyu arc from Late Mesozoic to Paleogene, judging from the direction of paleocurrent and the distribution of orthoquartzite gravels observed in the Shimanto Major Belt in Southwest Japan (HARATA and TOKUOKA, 1974; SUZUKI and TATEISHI, 1975). They named the land "Kuroshio Paleoland." However, no evident remnant crust of the Kuroshio Paleoland has been found in the Philippine Sea floor. Most probably, the remnant had collided and joined with the crust of the Southwest Japan arc and the Ryukyu arc as suggested by NAKAZAWA *et al.* (1983). Facies change of sediments of the Shimanto Major Belt through the Late Mesozoic to the Paleogene indicates such a tectonic event. Probable trench sediments appear in formations older than Santonian, whereas much coarser and younger sediments including end-olistostrome derived from the south reflect the upheaval of the southern provenance.

It must be noted that the inferred time of collision of the Kuroshio Paleo-island is very close to or correlative with that of the magma intrusion at the northern margin of the Daito Paleo-island arc. In this connection, the structural high magmatism is a special event which occurred only immediately prior to or at the initial stage of subduction of relatively warm oceanic plate.

Putting these pieces of information together, a hypothetical scenario, as shown in Fig. 6, can be proposed for the changes of the tectonic setting in the Northern Philippine Sea from the Late Cretaceous to the Miocene. Subduction of the unnamed part of the Paleo-Philippine Sea plate of the Mesozoic time (Kula plate?) was suspended when the Kuroshio Paleo-islands collided with the Japan arc. Subduction of a part of the plate to the south under the Paleo-Daito arc occurred in the Latest Cretaceous time.

The volcanic activities of the Paleocene and Earliest Eocene time on and near the Daito Ridge (MCKEE and KLOCK, 1980; OZIMA *et al.*, 1980; TOKUYAMA *et al.*, 1980) was related also with the subduction tectonics from the north. This subduction, together with older northward subduction, was related with the opening of the West Philippine Basin.

The southward subduction probably ceased soon. New subduction of the

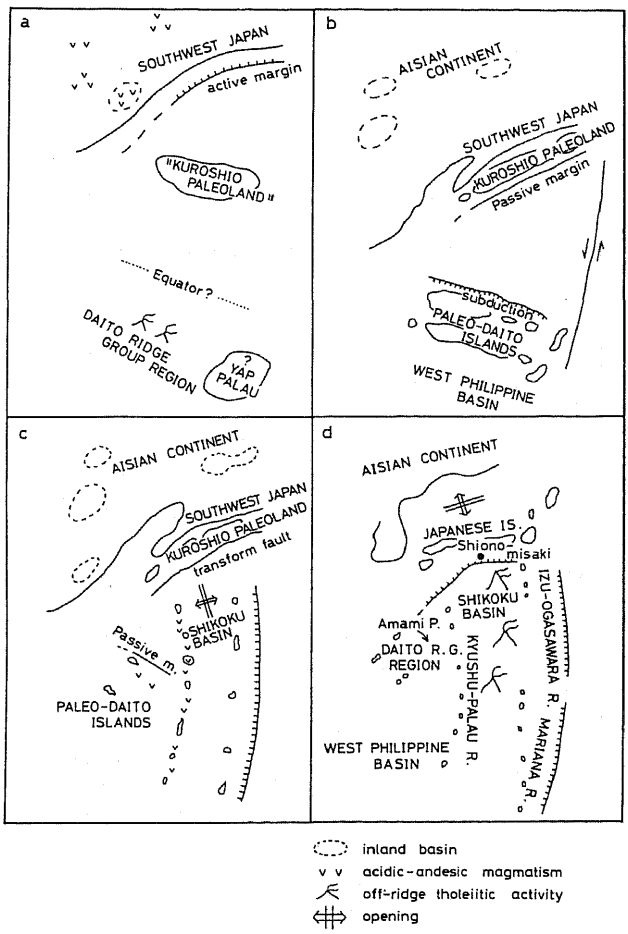

Fig. 6. Schematic scenario for change of the geotectonic setting of subduction in the Northern Philippine Sea. a, Late Cretaceous; b, Paleocene-Eocene; c, Oligocene; d, Middle Miocene. Modified from SHIKI (1985).

Philippine Sea plate began from the south to the north under the Kuroshio Paleo-island mass of the Southwest Japan arc.

Opening of the Shikoku Basin in the Oligocene and Early Miocene time has been well clarified (KOBAYASHI and NAKADA, 1978; KOBAYASHI, 1983). It was followed by off-ridge volcanism in the basin, subduction of the new slab of the Shikoku Basin, and upward intrusion of magma through the remnant fissure of transform fault of the Shikoku Basin opening.

It is noteworthy that the time of clockwise rotation of the Southwest Japan (almost 15 Ma; OTOFUJI and MATSUDA, 1983; OTOFUJI *et al.*, 1985, 1986) was very

close to that of the Shiono-Misaki igneous activity. Discussion of this problem, however, is beyond the purposes of the present paper.

After the consolidation of the Shiono-Misaki igneous complex, subduction zone shifted southward slightly, to the outer side of the complex. Thus, younger structural highs and structural high magmatic zone are situated slightly south of the older structural high.

In this paper, we stressed the importance of continental slope structural high complex ("forearc igneous complex") and provided a hypothetical scenario of the geohistory of the Northwestern Philippine Sea from the Late Cretaceous to the Present. It is clear that extensive further investigations and studies are required to check the hypothetical history stated above.

REFERENCES

AOKI, H., Y. KIM, M. ISHIKAWA, and R. EGAWA, Petrological results in the GDP Cruise, *Mar. Sci.*, **7**, 460–465, 1975 (in Japanese with English abstract).

AOKI, H., Y. KIM, Y. MISAWA, M. ISHIKAWA, and R. EGAWA, Some geological problems in the Shikoku-Philippine Basin, *Mem. Geol. Soc. Jpn.*, **13**, 393–398, 1976 (in Japanese with English abstract).

HADA, S. and T. SUZUKI, Tectonic environments and crustal section of the outer zone of southwest Japan, in *Accretion Tectonics in the Circum-Pacific Regions*, ed. H. Hashimoto and S. Uyeda, pp. 207–218, Terra Scientific Publishing Co., Tokyo, 1983a.

HADA, S. and T. SUZUKI, Accretionary melange of Cretaceous age in the Shimanto Belt in Japan, in *Accretion Tectonics in the Circum-Pacific Regions*, ed. H. Hashimoto and S. Uyeda, pp. 219–230, Terra Scientific Publishing Co., Tokyo, 1983b.

HADA, S., T. SUZUKI, K. OKANO, and S. KIMURA, Crustal section based on the geological and geophysical features in the outer zone of Southwest Japan, *Mem. Geol. Soc. Jpn.*, **21**, 197–211, 1982 (in Japanese with English abstract).

HARATA, T. and T. TOKUOKA, Kuroshio-paleoland, *Science* (Tokyo), **44**, 495–502, 1974 (in Japanese).

HILDE, T. W. C., J. M. WAGEMAN, and W. T. HAMMOND, The structure of Tosa terrace and Nankai trough off Southwest Japan, *Deep-sea Res.*, **16**, 67–75, 1969.

HISATOMI, K. and Y. MIYAKE, Upheaval movement and igneous activity in the Shionomisaki area, Kii Peninsula, Southwest Japan, *J. Geol. Soc. Jpn.*, **87**, 629–639, 1981 (in Japanese with English abstract).

HONZA, E., M. ARITA, Y. KINOSHITA, Y. OKUDA, and K. TAMAKI, Geological investigation of seas around Japan, *Chishitsu News*, **355**, 26–48, 1984 (in Japanese).

JAKES, P. and Y. MIYAKE, Magma in forearcs: Implication for ophiolite generation, *Tectonophysics*, **106**, 349–358, 1984.

KAGAMI, H., Accreted sedimentary wedges at trenches observed on multichannel reflection seismic records, *Chigaku Zasshi*, **93**, 43–51, 1984 (in Japanese).

KAGAMI, H., Internal structure of the accretionary wedge in the Nankai Trough off Shikoku, Southwest Japan, in *Formation of Active Ocean Margins*, ed. N. Nasu, K. Kobayashi, S. Uyeda, I. Kushiro, and H. Kagami, pp. 193–219, Terra Scientific Publishing Co., Tokyo, 1985.

KAGAMI, H., D. E. KARIG, F. AKIBA, C. J. BRAY, J. P. CADET, J. CHARVET, W. COULBOURN, K. FUJIOKA, H. KINOSHITA, M. LAGOE, T. H. LANG, J. K. LEGGETT, G. A. LOMBARI, N. LUNDBERG, T. MACHIHARA, R. MATSUMOTO, P. MUKHOPADHYAY, N. NIITSUMA, A. J. SMITH, C. L. STEIN, and A. TAIRA, In the orient Leg. 87 drills off Honshu & SW Japan, *Geotimes*, **28**, 15–18, 1983.

KARIG, D. E., Basin genesis in the Philippine Sea, in *Initial Reports of the DSDP*, Vol. 31, ed. D. C. Karig and J. C. Ingle, pp. 857–879, Washington (U. S. Government Printing Office), 1975.

KIMURA, S., Upper crustal structure in the Shikoku district, *Zisin*, *2*, **32**, 329–340, 1979 (in Japanese with English abstract).

KIMURA, S. and K. OKANO, Structure of the lower crust and the uppermost mantle in Shikoku Japan, *Zisin*, *2*, **33**, 157–168, 1980 (in Japanese with English abstract).

KOBAYASHI, K., Cycles of subduction and Cenozoic arc activity in the Western Pacific margin, in *Geodynamics of the Northwestern Pacific*, ed. T. W. C. Hilde and S. Uyeda, pp. 287–372, AGU/GSA Geodynamics Series, 9, 1983.

KOBAYASHI, K. and M. NAKADA, Magnetic anomalies and tectonic evolution of the Shikoku inter-arc basin, *J. Phys. Earth*, **S26**, 391–402, 1978.

MARUYAMA, S., The dismembered ophiolite belt, *Earth Sci.* (*Chikyu Kagaku*), **32**, 317–320, 1978 (in Japanese with English abstract).

MCKEE, E. and P. R. KLOCK, K-Ar ages of basalt sills from deep sea drilling project sites 444, and 446, Shikoku Basin and Daito Basin, Philippine Sea, in *Initial Reports of the DSDP*, Vol. 58, pp. 921–922, Washington (U. S. Government Printing Office), 1980.

MIYAKE, Y., Geology and petrology of the Shionomisaki igneous complex, Wakayama Prefecture, Japan, *J. Geol. Soc. Jpn.*, **87**, 383–403, 1981 (in Japanese with English abstract).

MIYAKE, Y., MORB-like tholeiites formed within the Miocene forearc basin Southwest Japan, *Lithos*, **18**, 23–24, 1985a.

MIYAKE, Y., Chemical variation among andesitic and basaltic rocks from Setouchi Province and its south, *Mem. Geol. Collab.*, No. 29, 153–164, 1985b (in Japanese with English abstract).

MIYAKE, Y. and K. HISATOMI, A miocene forearc magmatism at Shionomisaki, Southwest Japan, in *Formation of Active Ocean Margins*, ed. N. Nasu, K. Kobayashi, S. Uyeda, I. Kushiro, and H. Kagami, pp. 411–422, Terra Scientific Publishing Co., Tokyo, 1985.

MIZUNO, A., Y. OKUDA, and K. TAMAKI, Some problems on the geology of the Daito Ridges Region and its origin, *Geol. Stud. Ryukyu Isl.*, **1**, 177–198, 1976 (in Japanese with English abstract).

MIZUNO, A., M. NOHARA, Y. KINOSHITA, N. NAKAJIMA, Y. OKUDA, K. TAMAKI, and K. ISHIBASHI, Scientific data obtained by the Hakurei-Maru Cruise, with special reference to the results of bottom sampling and continuous seismic reflection profiling in the East of Okinawa, in *Geological Problems of the Philippine Sea*, ed. K. Nakazawa, pp. 105–111, Geological Society of Japan, 1975 (in Japanese).

NAKAZAWA, K., H. MATSUYAMA, and F. KUMON, Olistostrome stratigraphy in the Shimanto Belt and its formation mechanism, *Mar. Sci.*, **15**, 448–452, 1983 (in Japanese).

NASU, N., K. KOBAYASHI, M. OZIMA, I. KUSHIRO, Y. TOMODA, K. NAKAMURA, K. NAKAZAWA, H. KAGAMI, Y. TAKAYANAGI, H. OKADA, S. NAGUMO, S. MURAUCHI, S. UYEDA, H. KINOSHITA, and A. TOYAMA, Multi-channel seismic reflection data across

Nankai Trough IPOD-Japan Basic Data Series, 4, 34, 1982.

OKANO, K. and S. KIMURA, Structure of the Uppermost Mantle in Shikoku examined by using the velocity of seismic S waves, *Zisin, 2*, **34**, 95–104, 1981 (in Japanese with English abstract).

OKUDA, Y., 1 : 1,000,000 Geological map off outer Zone of Southwest Japan, Marine Geological Map Series, 8, Geol. Surv. Japan, 1977.

OKUDA, Y., M. KUMAGAI, and K. TAMAKI, Tectonic development of the continental slope and its peripheral area off Southwest Japan in relation to sedimentary sequences in sedimentary basins, *J. Assoc. Petroleum Technol.*, **44**, 279–290, 1979 (in Japanese with English abstract).

OKUDA, Y., K. TAMAKI, and M. JOSHIMA, Seismic reflection results. Investigation of continental margin of Southwest Japan, E. Inoue (ed.), *Geol. Surv. Jpn. Cruise Rep.*, **9**, 10–16, 1978.

OSHIMA, S., T. OZAKI, and K. ONODERA, Geomagnetic anomalies at sea around southwest Japan, *Rep. Hydrogr. Res.*, **15**, 33–54, 1980 (in Japanese).

OTOFUJI, Y. and T. MATSUDA, Paleomagnetic evidence for the clockwise rotation of Southwest Japan, *Earth Planet Sci. Lett.*, **62**, 349–359, 1983.

OTOFUJI, Y., A. HAYASHIDA, and M. TORII, When was the Japan Sea opened?: Paleomagnetic evidence from Southwest Japan, in *Formation of Active Ocean Margins*, ed. N. Nasu, K. Kobayashi, S. Uyeda, I. Kushiro, and H. Kagami, pp. 551–566, Terra Scientific Publishing Co., Tokyo, 1985.

OTOFUJI, Y., T. MATSUDA, and S. NOHDA, Brief review of Miocene opening of the Japan Sea: Paleomagnetic evidence from the Japan arc, *J. Geomagn. Geoelectr.*, **38**, 287–294, 1986.

OZIMA, M., T. TAKIGAMI, and I. KANEOKA, $^{40}Ar/^{39}Ar$ geochronological studies on rocks of Deep Sea Drilling Project Sites 443, 445, and 446, in *Initial Report of DSDP*, Vol. 58, pp. 917–920, Washington (U. S. Government Printing Office), 1980.

SENO, T. and S. MARUYAMA, Paleogeographic reconstruction and origin of the Philippine Sea, *Tectonophysics*, **102**, 53–84, 1984.

SHIKI, T., Structure and tectonics under the continental slopes of the Honshu Arc, *Tectonophys. EOS, Trans. Am. Geophys. Un.*, **59**, 1183, 1978.

SHIKI, T., The basement problem of the Japanese Islands—viewed from marine geology of the fore-arc regions, *Mem. Geol. Soc. Jpn.*, **21**, 297–307, 1982 (in Japanese with English abstract).

SHIKI, T., Further geological problems concerning the Northwestern Philippine Sea, in *Geology of the Northern Philippine Sea*, ed. T. Shiki, pp. 270–280, Tokai University Press, Tokyo, 1985.

SHIKI, T. and Y. MISAWA, A few problems concerning the structure under the continental slope and its origin, *Earth Sci. (Chikyu Kagaku)*, **33**, 208–240, 1979 (in Japanese with English abstract).

SHIKI, T. and Y. MISAWA, Geologic structure and tectonics under the inner slopes of the Nankai Trough and the Japan Trench, *Geotectonics*, **6**, 98–109, 1980 (in Russian).

SHIKI, T. and Y. MISAWA, Forearc geologic structure of the Japanese Islands, in *Trench-Forearc Geology: Sedimentation and Tectonics on Modern and Ancient Active Plate Margins*, ed. K. Leggett, Geological Society Special Publication, 10, pp. 63–73, Blackwell Scientific Publications, London, 1982.

SHIKI, T., Y. MISAWA, and I. KONDA, The Daito Ridge Group and the Kyushu-Palau

Ridge—with special reference to the tectonics of the Philippine Sea, *J. Phys. Earth*, **27**, Suppl., 113–124, 1979.

SHIKI, T., A. MIZUNO, and K. KOBAYASHI, Data listing of the bottom materials dredged and cored from the Northern Philippine Sea, in *Geology of the Northern Philippine Sea*, ed. T. Shiki, pp. 23–41, Tokai University Press, Tokyo, 1985.

SHIKI, T., Y. MISAWA, I. KONDA, and A. NISHIMURA, Geology and geohistory of the Northwestern Philippine Sea, with special reference to the results of the recent Japanese research cruises, *Mem. Fac. Sci. Kyoto Univ.*, **44**, 67–78, 1977.

SHIKI, T., H. KAGAMI, T. HARATA, I. KONDA, H. MITSUSHIO, J. NAKAMURA, K. NAKAZAWA, S. NISHIDA, H. SUZUKI, M. TATEISHI, T. TOKUOKA, and I. YOSHIMURA, Submarine geology off Kii Strait including the bank of Tosabae, *Mar. Geol. Jpn.*, 7, 1–28, 1971 (in Japanese with English abstract).

SUZUKI, K. and M. TATEISHI, The development of the Shimanto geosyncline and the Kuroshio Paleoland, *Mar. Sci./Mon.*, 7, 685–691, 1975 (in Japanese with English abstract).

TAMANO, T., T. TOBA, and Y. AOKI, Development of fore-arc continental margins and their potential for hydrocarbon accumulation, *Pet. Geol.*, **PD3**, 1–11, 1983.

TOKUYAMA, H., M. YUASA, and A. MIZUNO, Conglomerate and sandstone petrography, Deep Sea Drilling Project site 445, Philippine Sea, in *Initial Reports of the DSDP*, Vol. 58, pp. 629–641, Washington (U. S. Government Printing Office), 1980.

UYEDA, S. and Z. BEN-AVRAHAM, Origin and development of the Philippine Sea, *Nature*, **240**, 176–178, 1972.

WATANABE, S. and H. HATTORI, Magnetic properties and densities on rocks near Miyazaki City for evaluation of regional magnetic anomalies in south-eastern Kyushu, *Bull. Geol. Surv. Jpn.*, **31**, 105–136, 1980 (in Japanese).

YOSHII, T., W. J. LUDWIG, N. DEN, S. MURAUCHI, N. EWING, H. HATTA, P. BUHI, T. ASANUMA, and N. SAKAJIRI, Structure of Southwest Japan margin off Shikoku, *J. Geophys. Res.*, **78**, 2517–2525, 1973.