Okinawa Trough genesis: structure and evolution of a backarc basin developed in a continent

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The Okinawa marginal basin was opened by crustal extension into the Asian continent, north of the Taiwan collision zone. It is located behind the Ryukyu Trench subduction zone and the Ryukyu active volcanic arc. If we except the Andaman Sea, the Okinawa Trough is the only example of marginal backarc basin type, opened into a continent at an early stage of evolution. Active rifting and spreading can be observed. Synthesis of siesmic reflection, seismic refraction, drilling, dredging and geological field data has resulted in interpretative geological cross sections and a structural map of the Ryukyu–Okinawa area. The main conclusions of the reconstruction of this backarc basin/volcanic arc evolution are. (1) Backarc rifting was initiated in the volcanic arc and propagated along it during the Neogene. It is still active at both ends of the basin. Remnants of volcanic arc are found on the continental side of the basin. (2) There was synchronism between opening and subsidence of the Okinawa Trough and tilting and subsidence of the forearc terrace. The late Miocene erosional surface is now 4000 m below sea-level in the forearc terrace, above the trench slope. Retreat and subsidence of the Ryukyu trench line relative to the Asian continental plate, could be one of the causes of tilting of the forearc and extension in the backarc area. (3) A major phase of crustal spreading occurred in Pliocene times 1.9 My ago in the south and central Okinawa Trough. (4) En échelon rifting and spreading structures of the central axes of the Okinawa Trough are oblique to the general trend of the arc and trench. The Ryukyu arc sub-plate cannot be considered as a rigid plate. Rotation of 45° to 50° of the southern Ryukyu arc, since the late Miocene, is inferred. The timing and kinematic evolution of the Taiwan collision and the south Okinawa Trough opening suggest a connection between these two events. The indentation process due to the collision of the north Luzon Arc with the China margin could have provoked: lateral extrusion; clockwise rotation (45° to 50° according to palaeomagnetic data) and buckling of the south Ryukyu non-volcanic arc; tension in the weak crustal zone constituted by the south Ryukyu volcanic arc and opening of the south Okinawa Trough. Similar lateral extrusions, rotations, buckling and tensional gaps have been observed in indentation experiments. Additional phenomena such as: thermal convection, retreating trench model or anchored slab model could maintain extension in the backarc basin. Such a hypothetical collision–lateral backarc opening model could explain the initiation of opening of backarc basins such as the Mariana Trough, Bonin Trough, Parece Vela — Shikoku Basin and Sea of Japan. A new late Cenozoic palaeogeographic evolution model of the Philippine Sea plate and surrounding areas is proposed.

Keywords: Okinawa Trough; Ryukyu arc; Backarc basin; Rifting; Spreading; Taiwan; Collision

Introduction

The region situated between the Pacific Plate and Asian continent is made up of an intricate set of basins created in different periods and separated by active or inactive volcanic arcs, collision zones and blocks of micro-continents. The structural context, opening mechanisms and evolution of these basins can be quite different.

For example, the South China Sea is a basin which opened up on the edge of the Asian continent. The central oceanic zone, formed between 17 and 32 Ma (Taylor and Hayes, 1980), is bordered to the north and to the south by a zone of tilted and foundered blocks, formed from thinned and stretched Asian continental crust. No volcanic arcs can be observed on the edge of the oceanic zone, and the authors agree in considering that this basin is of the Atlantic type.

Another type of basin is constituted by the Mariana Trough (see *Figures 1* and *2*). This basin has been opening since the Pliocene, above a subduction zone, in the convergence area of two oceanic plates. It is at present opening behind an active volcanic arc, and it separates the Mariana Ridge from the Western Mariana Ridge. The latter forms a remnant arc. The two ridges meet to the north at present, forming the Bonin Ridge. Prior to basin opening they formed only one ridge, and it is

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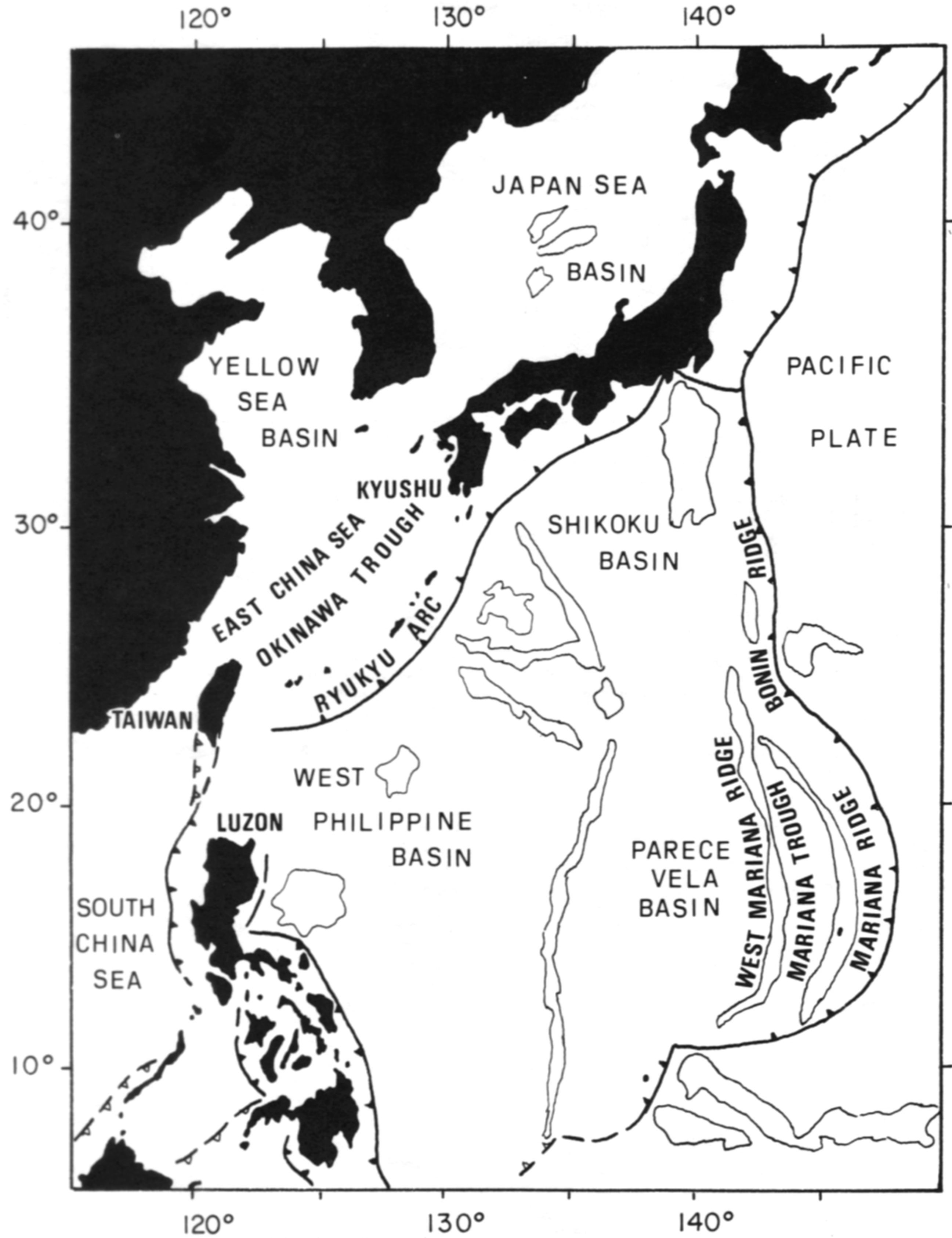


Figure 1 Location map of Okinawa Trough, Ryukyu arc and vicinity

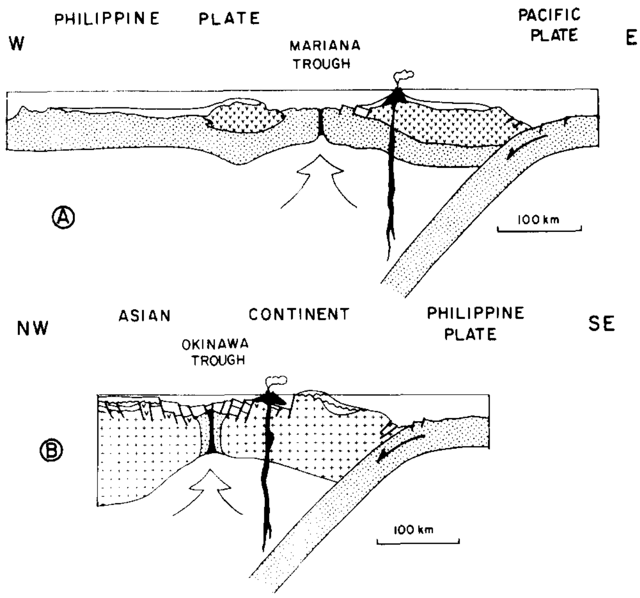


Figure 2 Comparison between (A) Mariana backarc model in an oceanic environment and, (B) Okinawa backarc model in a continental environment

considered that the Parece Vela basin and the Shikoku Basin have had the same type of opening.

The third type of marginal basin is the Okinawa Trough (see *Figures 1* and *2*). It opens by crustal extension into the Asian continent, parallel to the Philippine–Asian plate boundary. The basin is located behind the Ryukyu Trench subduction zone and the Ryukyu active volcanic arc. However, there also exists a non volcanic ridge and an island between the Okinawa Trough and the trench. This ridge represents an elongated piece of the continental Asian margin, with Palaeozoic and Cenozoic sediments which drifted by the opening of the backarc basin (*Figure 2B*).

Basins of the Okinawa marginal basin type are thought to have existed in ancient oceans but to have disappeared due to collisions, as in the Alpine chain or the Himalayas. In Southeast Asia, the Sea of Japan, the Sulu Trough, the Banda Sea or the Andaman Sea could represent this type of marginal basin. If we except the Andaman Sea with a complex oblique opening, the Okinawa Trough is the only example in the world of an active marginal backarc basin type, opening into a continental boundary, at a early stage of evolution. The end of the rifting period and the beginning of the spreading period can be observed at present. The structure and evolution of the Ryukyu Arc and Okinawa backarc basin provide an example for the evolution of this marginal type of basin.

Other interesting features in this area can be attributed to the effects of collisions, i.e. collision between the Kyushu–Palau Ridge, the Amami Plateau and the Ryukyu Arc; collision between the North Luzon volcanic arc and the Asian margin in the Taiwan area.

Our study was carried out by using a number of seismic profiling surveys, including unpublished multi-channel survey data in the Ryukyu Arc, Okinawa Trough and East China Sea areas (*Figure 4*), as well as results of a geological field study in Taiwan, Okinawa and Ryukyu. This was checked against and completed with geological and geophysical data published about these regions. The complete geophysical data analysis and conclusion on the structure and evolution of the Okinawa Trough have been carried out by one of the co-authors (Kimura, 1985).

Geographic setting

The Ryukyu Arc extends from Taiwan to Kyushu (*Figure 3*). It is bordered by the Ryukyu Trench to the south and the Okinawa Trough to the west. From the islands to the trench, the 150 km wide forearc zone is composed of a gently dipping slope, a forearc terrace and the trench slope break, around 3000 m below sea-level, with a steep inner wall (*Figures 3* and *6*).

The Okinawa Trough extends from northeast of Taiwan to Kyushu. It is divided into several sub-basins (*Figure 3*). The deeper one (2270 m) to the south is the South Okinawa Trough. To the northeast the basin is shallower and wider, and is called the Central Okinawa Trough, Amami Basin, Tokara Sub-Basin and North Okinawa Trough. To the southwest, Taiwan mountains reach 3931 m in height.

Geophysical data and interpretation

The Ryukyu Trench is the boundary between the Philippine Sea Plate and the Eurasian Plate. The Wadati–Benioff zone extends from the Ryukyu Trench beneath the Ryukyu arc to a depth of between 200 and 300 km (*Figure 9*), at an angle of 40° to 50° in the deeper part.

Shallow seismicity beneath the Okinawa Trough is clearly distinguishable from the earthquakes in the Wadati–Benioff zone, and the focal mechanism solutions indicate a subhorizontal tension axis oriented in the N-S or NNW-SSE direction (Eguchi and Uyeda, 1983). The eastward dip of the Wadati–Benioff zone dipping from the Luzon Trench beneath the Luzon volcanic arc becomes almost vertical around the east coast of Taiwan (*Figure 9*).

Models of instantaneous relative plate motion of the Philippine Sea Plate, with respect to the Eurasian Plate are calculated using the slip vector of focal mechanism solutions for shallow thrust-type earthquakes which occurred at the interface of the two plates, beneath the arc trench system. According to Seno's model (1977), the pole locations are at 45.5° $\pm$3.7°N, 15.2° $\pm$5.4°E, and the angular velocity is 1.20 $\pm$0.12 degrees Ma^{-1}.

The direction of relative plate motion between the Philippine Sea Plate and the Eurasian Plate is roughly WNW-ESE (*Figure 10*), and this enables us to assume that the spreading or rifting behind the Ryukyu trench is much smaller than the convergent rate at this trench. However, in the Okinawa Trough, south of the Okinawa Basin, Kimura (1985) found a recent oceanic crust spreading at a rate estimated at 2 to 3 cm $year^{-1}$ (half spreading).

Since the Eocene, the Philippine Plate has been surrounded by subduction zones, so that the plate rotation vectors of the Philippine Sea Plate with respect to the Eurasian Plate could not be established precisely in the past. Results of seismic refraction studies around the Okinawa Trough were compiled by Kimura (1983 and 1985). The general crustal structure, inferred from these refraction studies (Murauchi *et al.*, 1968; Ludwig *et al.*, 1973; Leyden *et al.*, 1973; Lee *et al.*, 1980), is continental around the Okinawa Trough, below both

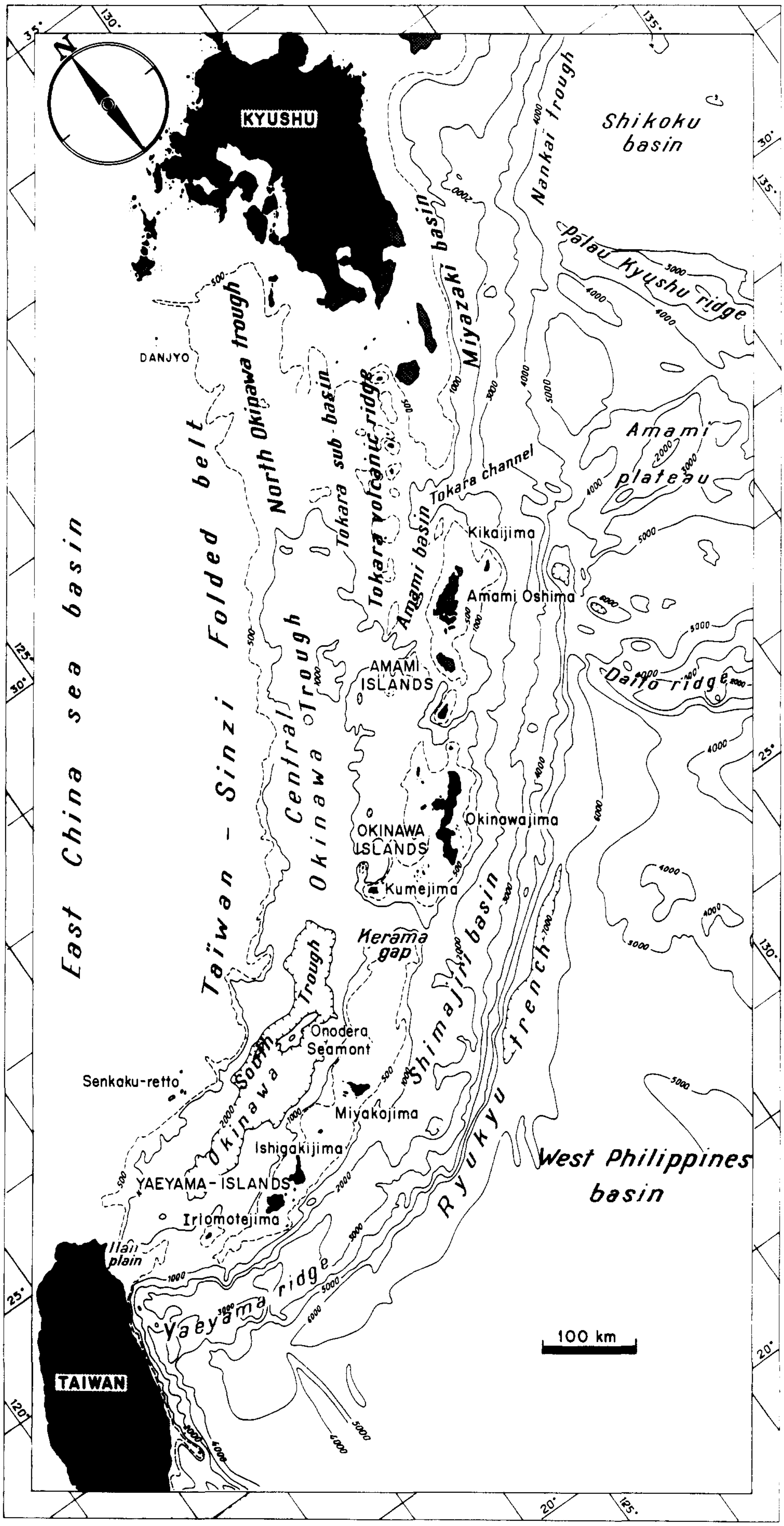


Figure 3 Physiographic map of Ryukyu Arc and Okinawa Trough area. Bathymetry from Mammericks *et al.*, 1976

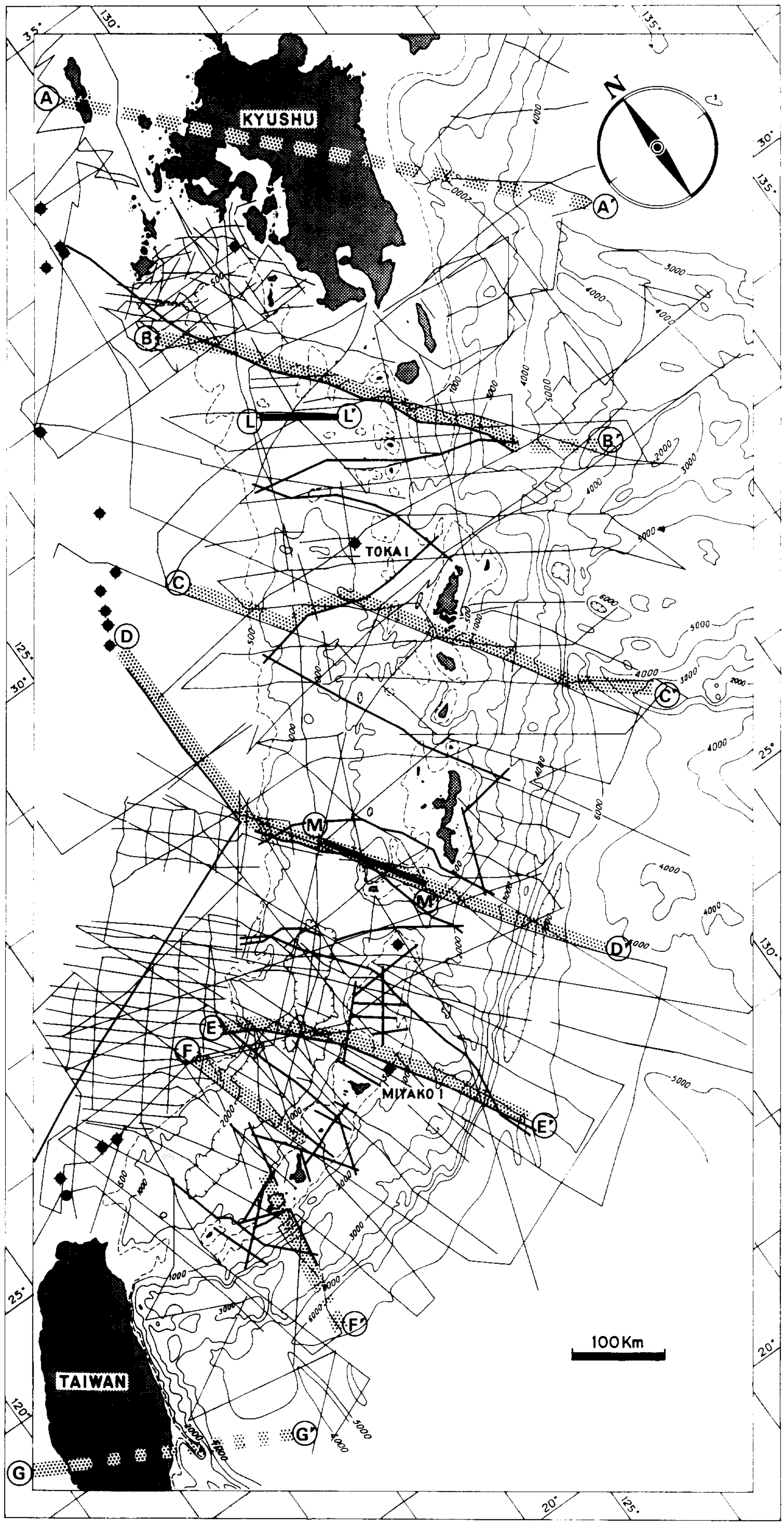


Figure 4 Location map of seismic reflection profiling records used for this study (for origin and examples cf. Kimura, 1985). Thin lines represent single-channel and thick lines multi-channel profiling tracks. Dotted lines AA' to GG' are the location of the interpretative geological cross-section (*Figure 6*). Hachured lines LL' and MM' are sections (*Figure 8*). Solid circles show oil wells

the Ryukyu arc and the continental shelf. However, the mantle is about 17 km deep beneath the central rift of the South Okinawa Trough. This oceanic or thinned continental crust beneath Okinawa Trough is also supported by gravity data (Segawa, 1976; Muakami, 1976; Lee *et al.*, 1980).

In the southern half of the basin, linear magnetic anomalies are nearly parallel to the strike of the structural belts. Calculations of the magnetic anomaly of the central rift show a zone which may have been spreading since the early Pleistocene −1.9 Ma ago (Kimura, 1985). The high heat flow also suggests that the age of the Okinawa Trough may be as young as 2 Ma (Lu *et al.*, 1981).

In the northern half of the Okinawa Basin, local magnetic anomalies suggest that intrusions occurred in the trough. However, it is not certain whether the lithosphere is oceanic or thinned continental.

Many single-channel reflection profiling surveys have been carried out around the region (Wageman *et al.*, 1970; Kimura *et al.*, 1975, 1979, 1980; Honza, 1976; Herman, 1978; Lee *et al.*, 1980). Well developed graben structures with many normal faults have been observed all along the Okinawa Basin. Some intrusions into the sedimentary layers are also obvious.

Aiba and Sekiya (1979) and Nash (1979) presented a geological and structural interpretation of the area based on multi-channel seismic surveys and oil drilling.

Structures of the Ryukyu Arc–Okinawa Trough area

The structural map (*Figure 5*) and interpretative geological cross-sections (*Figure 6*) summarize the main structures observed on seismic profiles and deduced from field geology, drilling or dredging. For the thickness of the post late Miocene sediments, a single time-to-depth conversion scale was used for the whole area (*Figure 5*).

From Taiwan to Kyushu, several structural zones more or less parallel to the trench are observed (*Figures 5* and *6*). They are: subduction complex zone, forearc terrace, non-volcanic island arc, active volcanic arc, Okinawa backarc basin, Taiwan–Sinzi folded belt, East China Sea Basin. In each zone, lateral structural variations are considerable.

Philippine Sea Basins and Ryukyu Trench

The depth and morphology of the Ryukyu Trench and the Nankai Trough are closely related to the age and structure of the subducted Philippine Sea plate.

The Shikoku basin was formed by interarc spreading during the late Oligocene (30 Ma) to early Miocene (16 or 18 Ma). Its average depth is 4500 m and reaches 4800 m in the Nankai Trough.

The Kyushu Palau Ridge is a remnant volcanic arc which, according to the sampling, was active until the mid Oligocene. In the collision zone south of Kyushu, the trench depth is < 4500 m.

The age of the West Philippine Basin is considered to be Eocene. Its average depth is about 5500 m. Only a few sediments cover the oceanic crust. A similar Eocene age for the crust was obtained by deep sea drilling on the NW-trending Oki–Daito Ridge. The deepest part of the Ryukyu Trench, over 7000 m, is observed south of Okinawa island (*Figures 3* and *6*; sections D and E), but in the collision zone with Amami Plateau, the depth reaches only 4500 m (*Figures 3* and *6*; sections B and C).

The Subduction Complex Slope

Except in the southwestern area along the Ryukyu Trench, accreted sediments do not morphologically form a ridge, i.e. Barbado Ridge or Java Ridge, but a subduction complex slope, as along the Nankai Trough (Ocean Research Institute, University of Tokyo, 1982). This is probably partly due to the low sediment supply coming from islands. In the southwestern area of the Ryukyu Trench towards Taiwan, a sedimentary ridge is observed with en échelon WSW–ENE compressional structures (Yaeyama Ridge, *Figures 5* and *6*; section F).

Non-volcanic Ryukyu Island Arc, Forearc Basins and Forearc Terrace

The pre-late Miocene substratum of the central and north Ryukyu islands is the prolongation of the geological outer zones and southwestern zones of Kyushu, Shikoku and Honshu. This substratum is very different from the one observed in the southern islands (Yaeyama archipelago) which shows some similarity with Taiwan.

Central and Northern Ryukyu pre-late Miocene formations. The two geological cross-sections southwest of Kyushu and across Okinawa give a good summary of the pre-late Miocene substratum (*Figure 7*). Older slightly metamorphosed sediments are late Palaeozoic or Mesozoic. Southeastward of these metamorphosed formations and parallel to the present margin, Cretaceous to early Miocene Aquitanian sediments have been interpreted as an accretionary complex (Taira *et al.*, 1981; Sakai, oral communication), formed during the northward subduction of the Philippine Basin, prior to the middle Eocene change in the Pacific Plate's motion. After this event and during the opening of the Shikoku Basin (late Oligocene to Burdigalian), the movement along this margin is considered to have been oblique subduction or transcurrent faulting. This formation disappears southward between Okinawajima and Miyakojima.

A compressional tectonic event with southeastward thrusting occurred in eastern Kyushu after the Aquitanian (around 23 Ma) and before the Serravalian acidic intrusive volcanism (around 13 Ma). The reason for this event is not clear: the possibilities are collision with Palau Kyushu ridge, or with oceanic plateaus north of the Western Philippine Plate or change of the plate motion.

A strong erosional event affected the whole island arc–forearc region before the late Miocene–Pliocene transgressive neritic facies. Angular unconformity has been observed also on seismic lines below the forearc basin sediments (*Figure 6*; sections B and D). This seems to prove that this area was under subaerial or aerial conditions in the middle or late Miocene.

Southern Ryukyu Pre-Latest Miocene Sediments – Comparison with Taiwan. In the Yaeyama islands (*Figures 3* and *6*; section F), the late Palaeozoic is composed of green schists including glaucophane

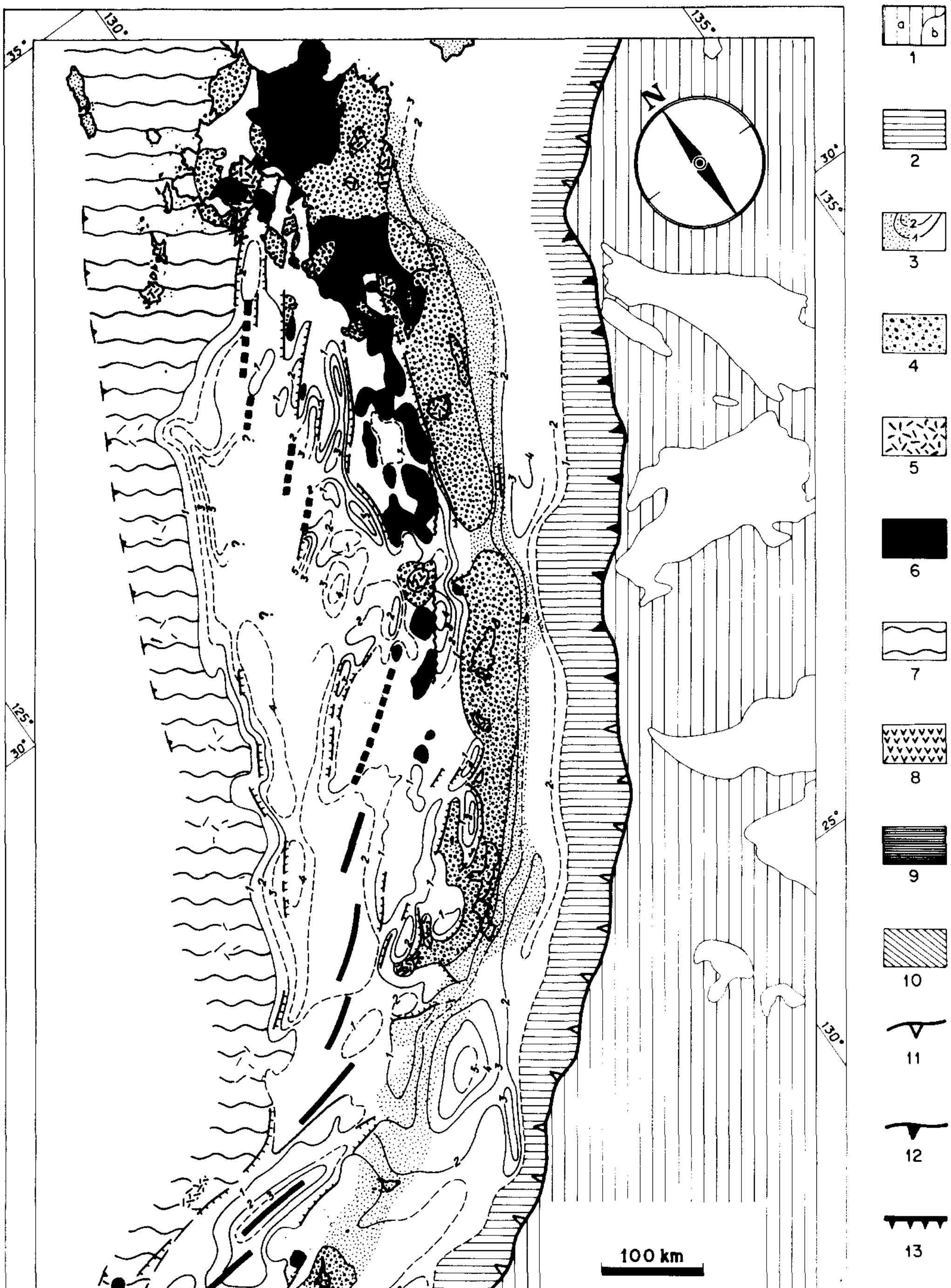
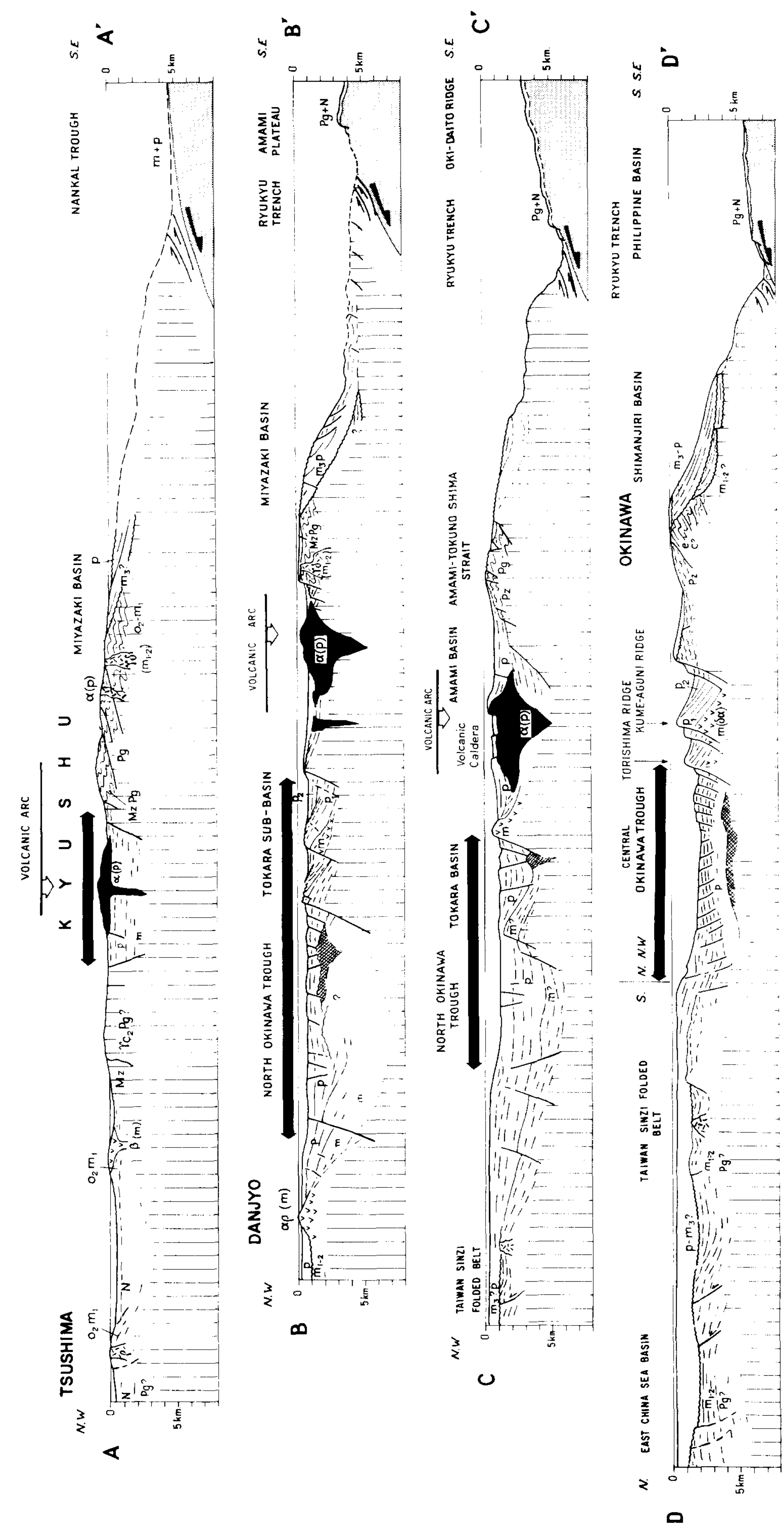


Figure 5 Geological and structural map of Ryukyu Arc, Okinawa Trough, Taiwan and vicinity. (1) Philippine Basin, (a) oceanic crust area; (b) oceanic ridge or plateau. (2) Trench slope and accretionary complex. (3) Post late Miocene basins, with contour map of the latest Miocene–Pliocene and Quaternary sediments. Numerals show the thickness in km. A time–depth conversion scale is given on the figure. The dotted zone shows the extension of the Pleistocene erosional surface, cutting and eroded sediments. (4) Pre-late Miocene sediment and metamorphic rocks. (5) Early to middle Miocene igneous rocks (Green Tuff formation). (6) Pleistocene to recent volcanism (Ryukyu volcanic arc). (7) Taiwan–Sinzi Folded Belt. (8) Luzon–Taiwan volcanic arc. (9) Palaeogene sediments, Taiwan central range. (10) Neogene sediments, Taiwan central range. (11) Subduction zone. (12) Collision zone. (13) Eastern Taiwan suture zone. (14) Normal fault. (15) Reverse fault. Thrust fault. (16) Anticline structure. (17) Okinawa Trough central grabens: lines represent spreading centre; dotted lines rifting centre


A
N.W
TSUSHIMA
KYUSHU
VOLCANIC ARC
MIYAZAKI BASIN
NANKAI TROUGH
S.E
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DANJYO
NORTH OKINAWA TROUGH
TOKARA SUB-BASIN
VOLCANIC ARC
MIYAZAKI BASIN
RYUKYU TRENCH
AMAMI PLATEAU
S.E
B'
C
N.W
TAIWAN SINZI FOLDED BELT
NORTH OKINAWA TROUGH
TOKARA BASIN
VOLCANIC ARC
Volcanic Caldera
AMAMI BASIN
AMAMI-TOKUNO SHIMA STRAIT
RYUKYU TRENCH
OKI-DAITO RIDGE
S.E
C'
D
N.
EAST CHINA SEA BASIN
TAIWAN SINZI FOLDED BELT
S. N.W
CENTRAL OKINAWA TROUGH
TORISHIMA RIDGE
KUME-AGUNI RIDGE
OKINAWA
SHIMANJIRI BASIN
RYUKYU TRENCH
PHILIPPINE BASIN
S. S.E
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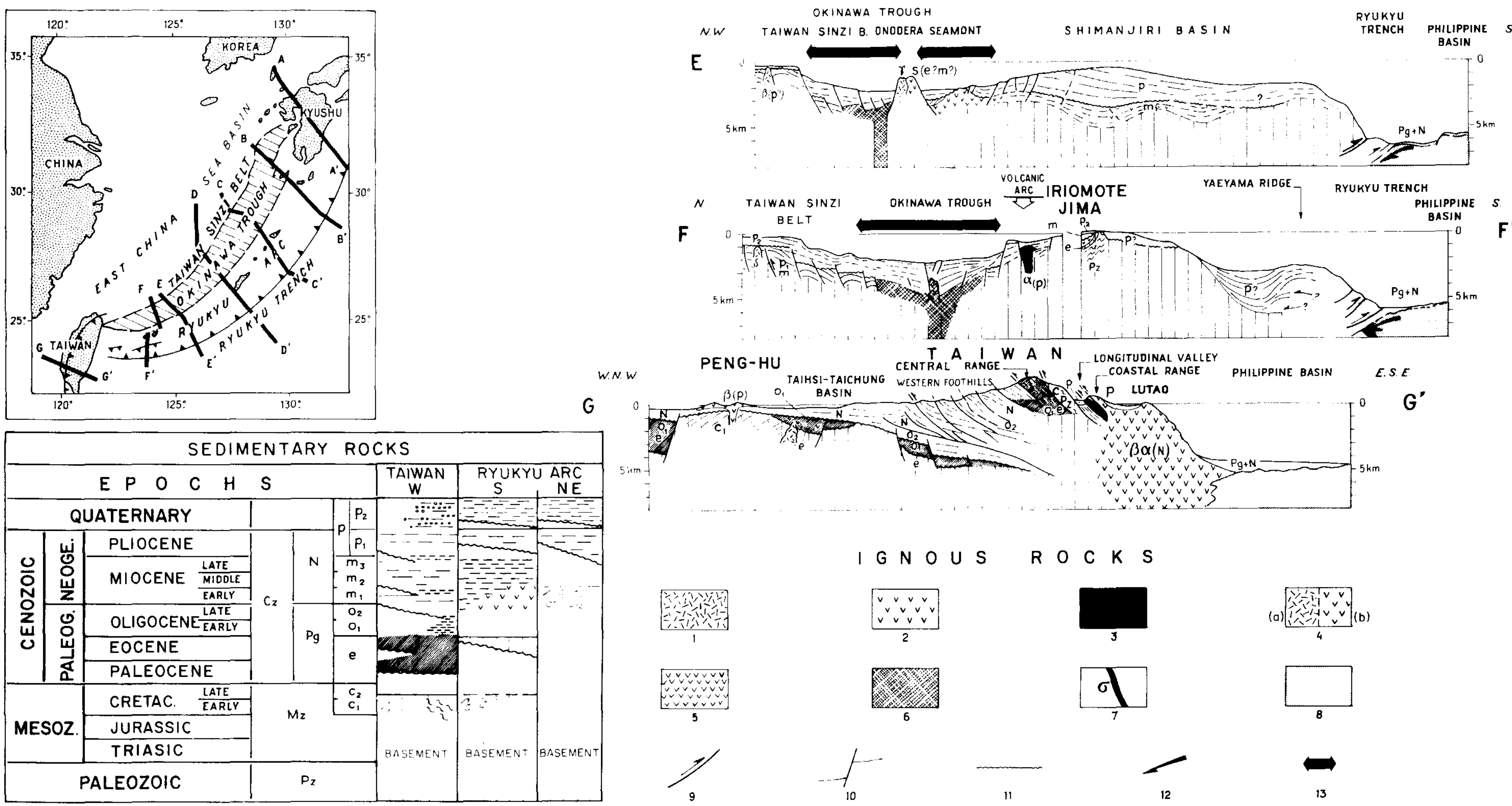

Figure 6 Interpretative geological cross-sections based on geological data and seismic interpretation. Locations are shown in *Figure 4*. (1) Intrusive rocks; γ, granite; δ, diorite. (2) Extrusive rocks; ρ, rhyolite; α, andesite; β, basalt. (3) Pleistocene to recent Ryukyu volcanic arc igneous rocks. (4) Miocene igneous rocks: (a) intrusive; (b) extrusive. (5) Miocene to Pleistocene Taiwan–Luzon volcanic arc igneous rocks. (6) Inferred Pleistocene oceanic. (7) Eastern Taiwan suture zone Lichi melange with ultramafic. (8) Philippine Sea oceanic crust, oceanic ridge or plateau. (9) Thrust fault. (10) Normal fault. (11) Unconformity. (12) Subduction. (13) Okinawa Trough

schist facies with NW-SE trend of fold axes (Kizaki, 1979; Nakagawa *et al.*, 1982). Rhyolite intrusion (47.5 ±3 Ma) conglomerates and calcareous littoral Eocene sediments are conformably covered with andesite flows and pyroclastic rocks. The pre-late Miocene is composed of littoral sandstones with mudstone, pyroclastics and a few coal beds, although its precise age has not yet been ascertained.

East of Miyakojima, exploration well 'Miyako 1' penetrated this formation. Below the Pliocene unconformity (NN 13), the lower part of the section was dated late Burdigalian and Langhian (NN 4, NN 5, Aiba, oral communication).

In Taiwan, metamorphic basement rocks exposed in the Central Ranger (*Figures 5* and *6*, section G) are composed of meta-sediments and meta-volcanics deformed during the late Mesozoic orogenesis (Ho, 1982). Two metamorphic belts have been recognized with blueschist and greenschist facies, with the occurrence of glaucophane, as in southern Ryukyu islands.

In western Taiwan, late Palaeocene carbonates, tuffs and shallow water or paralic sediments transgressed and unconformably covered metamorphic Palaeozoic and early Cretaceous sediments (Huang, 1978). Early Eocene silty marl with alkaline volcanism and acidic intrusions (45, 50, 55 Ma; in Ho, 1982) infilled half grabens.

Late Eocene and early Oligocene time correspond to a regression with a major unconformity; the sediments are called the 'lower coal bearing formation'. A marine transgression began during the middle Oligocene (NP 23, Huang, 1979). Two regressions with 'coal bearing formation' deposits occurred during the early Miocene (NN 2), and late Miocene (NN 10 and NN 11, Huang, personal communication). They could correspond to the Neogene littoral facies observed in southern Ryukyu.

Miyazaki and Shimanjiri Forearc Basins, central and northern Ryukyu. After the middle to earliest late Miocene erosional event, a thick marine series was accumulated in central and northern Ryukyu and constituted the Shimanjiri and Miyazaki Basins (*Figures 3, 5* and *6*; sections A, B, C, D, E). These late Neogene sediments (Shimanjiri group) are more than 5000 m thick between Okinawajima and Miyakojima (*Figure 5*). Above the unconformity, the Shimanjiri group is well developed in southeastern Kyushu and Okinawajima (*Figure 5*). Late Miocene neritic sediments with conglomerates, silts and sandstones (NN 10 or N 16 in Okinawajima, Ujiié, oral communication; N 17 in

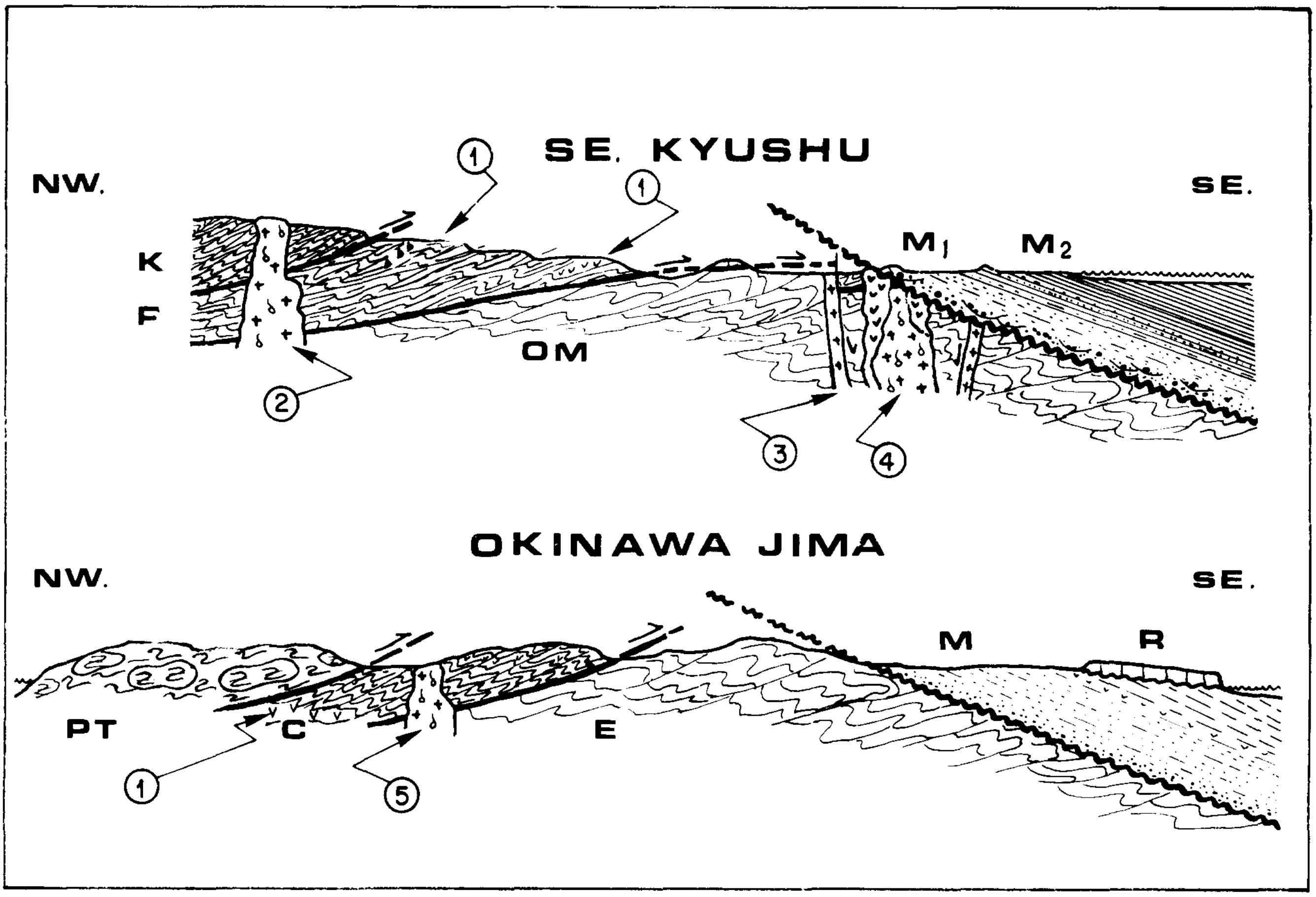

Figure 7 Idealized structural and stratigraphic relationships of the pre and post late Miocene in the forearc islands. *In southern Kyushu,* compression and thrusting took place between the Aquitanian and early Serravalian: K, Cretaceous to Eocene metamorphosed shales and sandstones; P, Palaeogene to early Oligocene slightly metamorphosed shales and turbidites including (1) basalts and radiolarians; OM, late Oligocene to early Miocene (Aquitanian) folded and slumped turbidites with blocks, interpreted as accretionary sedimentary complex; M1, Late Miocene (?) fluviomarine conglomerates and sandstone; M2, Plio-Pleistocene turbidites; 2, granodiorite, 14 Ma; 3, granodiorite dike around a caldera, 13 Ma; 4, Ryodorite tuff and conglomerates, 13 Ma. *Across Okinawajima*: PT, weakly metamorphic Permo-Triassic rocks; C, late Cretaceous (?), philites, sandstones; 1, meta andesite and meta basalt; E, Eocene flysch with folds and slumps interpreted as accretionary sedimentary complex; M, Late Miocene (N16 or NN10) coastal conglomerates and sandstones, followed by Pliocene–early Pleistocene upper slope silty clays with sandstones and tuffs; R, Pleistocene Ryukyu limestone; 5, diorite, 12 Ma

Miyakojima, Ujiié and Oki, 1974; NN 13 Miyako 1 borehole, Aiba oral communication) are followed by turbiditic deposits in Kyushu or silty clay and sandstone upper slope deposits in Okinawajima. This upper formation is early Pliocene (post NN 11 in Okinawa, around 6 Ma) to early Pleistocene. In this formation south-eastward prograding structures are observed on seismic lines. This indicates a tilting of the forearc since 6 Ma. The late Miocene unconformity is now 4000 m below sea-level in the forearc terrace zone (*Figure 6*; sections B, D and E).

The Pleistocene erosional surface is observed all along the arc (*Figure 5*). It is also affected by normal faulting and southeastern tilting (*Figure 6*; sections B and C). Perhaps due to collision and compression to the west and northwest of the Amami plateau, the sediments of the forearc basin are disturbed (*Figure 6*; section B), the forearc terrace is uplifted (Kikaijima island east of Amami Oshima island) and the Pleistocene erosional surface is tilted (*Figure 6*; section C).

Transversal depressions and normal faulting are also observed along the arc (*Figure 5*).

South Shimanjiri Basin and Yaeyama Ridge, south Ryukyu. South of the Yaeyama Gunto Islands, the structures of the forearc are completely different from those observed along the central and northern Ryukyu arc. The main structures are oriented E–W or ESW–WNW.

Below the forearc terrace, the basin is very thick with more than 5000 m of sediments. The age of the basin is uncertain; it may be post-late Miocene. The layers form a large syncline onlapping a late Miocene or pre-Neogene erosion surface (*Figure 6*; section F). Deeper horizons are imbricated in the northward thrust of the sedimentary Yaeyama ridge. The Yaeyama ridge is a sedimentary compressional ridge, with en échelon anticline structures.

The geographic position, the recent age of this structure and the thick pile of sediments involved in the northern thrust faults could be correlated with the sediments and structures observed in the eastern Taiwan coastal range (*Figure 6*; section G). In the coastal range the northwestern prolongation of the Luzon volcanic arc was covered with more than 4000 m of middle Pliocene to Pleistocene conglomerates and terrigenous material (Chi *et al.*, 1981). They were deposited after collision with the Asian Margin during the uplifting and erosion of the Central Range. These sediments and this volcanic substratum have been thrust to the west-northwest. Structures of the Coastal Range plunge to the north below the sea.

A thick sedimentary pile on the oceanic crust or a high sediment supply from the continent is a necessary condition for building a thick accretionary prism along an active margin. This situation occurred in the Ryukyu Trench near the Taiwan collision zone, since the beginning of uplift and erosion of the Central Range. Thus we interpret the Yaeyama ridge as a sedimentary wedge similar to the Barbados ridge (*Figure 6*, section F-F'). This ridge has progressively grown during the collision. The tectonic of this ridge is linked to the subduction process but is also complicated by the progressive collision of the North Luzon volcanic ridge with the chinese margin.

Recent and active volcanic arc

Recent and active volcanic activity align above the 80 to 120 km depth of the Wadati–Benioff zone (*Figure 9*), at a distance of between 160 to 250 km from the trench. Along the Ryukyu Arc, volcanic activity is located between the non volcanic island arc and the deep Okinawa Trough, but is west of the first escarpment fault, in a large half graben (*Figures 5* and *6*; section B, C, F). Most of the recent volcanoes are located in Kyushu and North Ryukyu (*Figure 9*). Toward the southeast boundary of the Wadati-Benioff zone, north

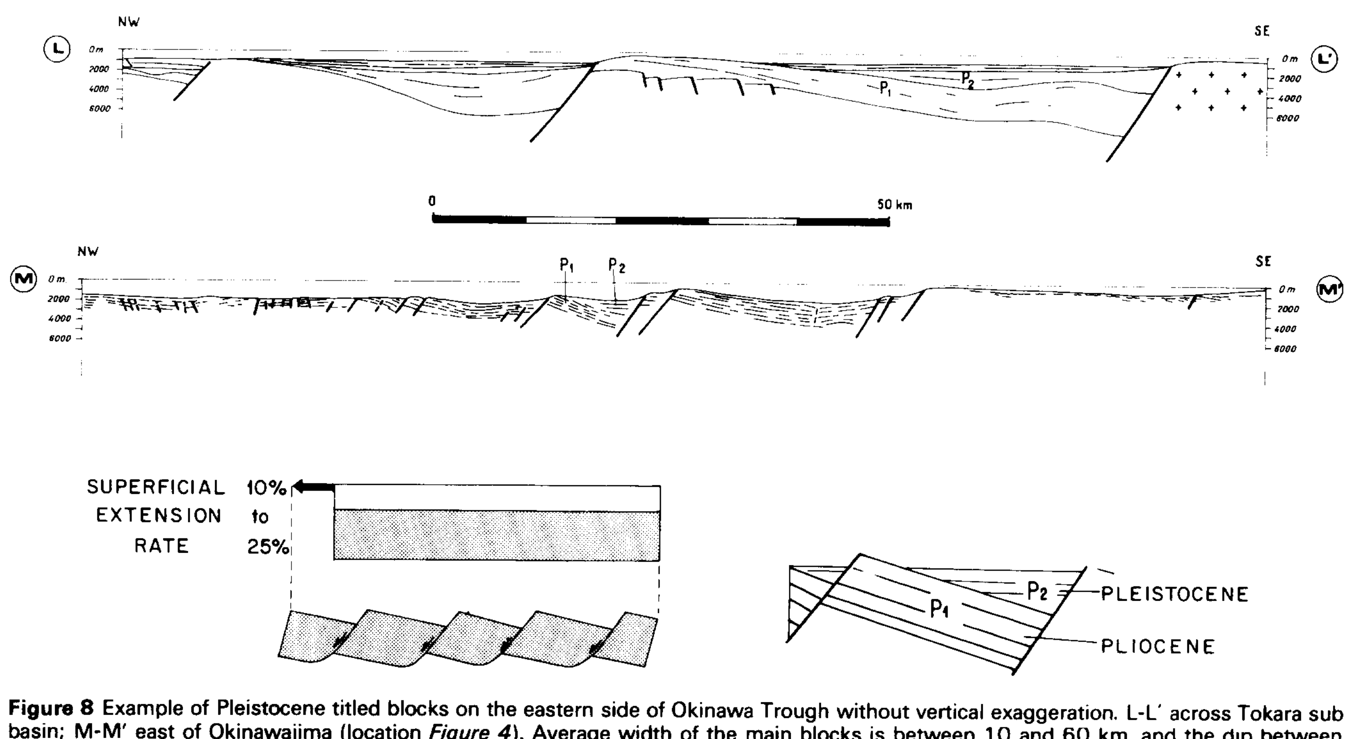

Figure 8 Example of Pleistocene titled blocks on the eastern side of Okinawa Trough without vertical exaggeration. L-L' across Tokara sub basin; M-M' east of Okinawajima (location *Figure 4*). Average width of the main blocks is between 10 and 60 km, and the dip between 10 and 20°. Calculated Pleistocene superficial extentional rate is between 10 and 25%

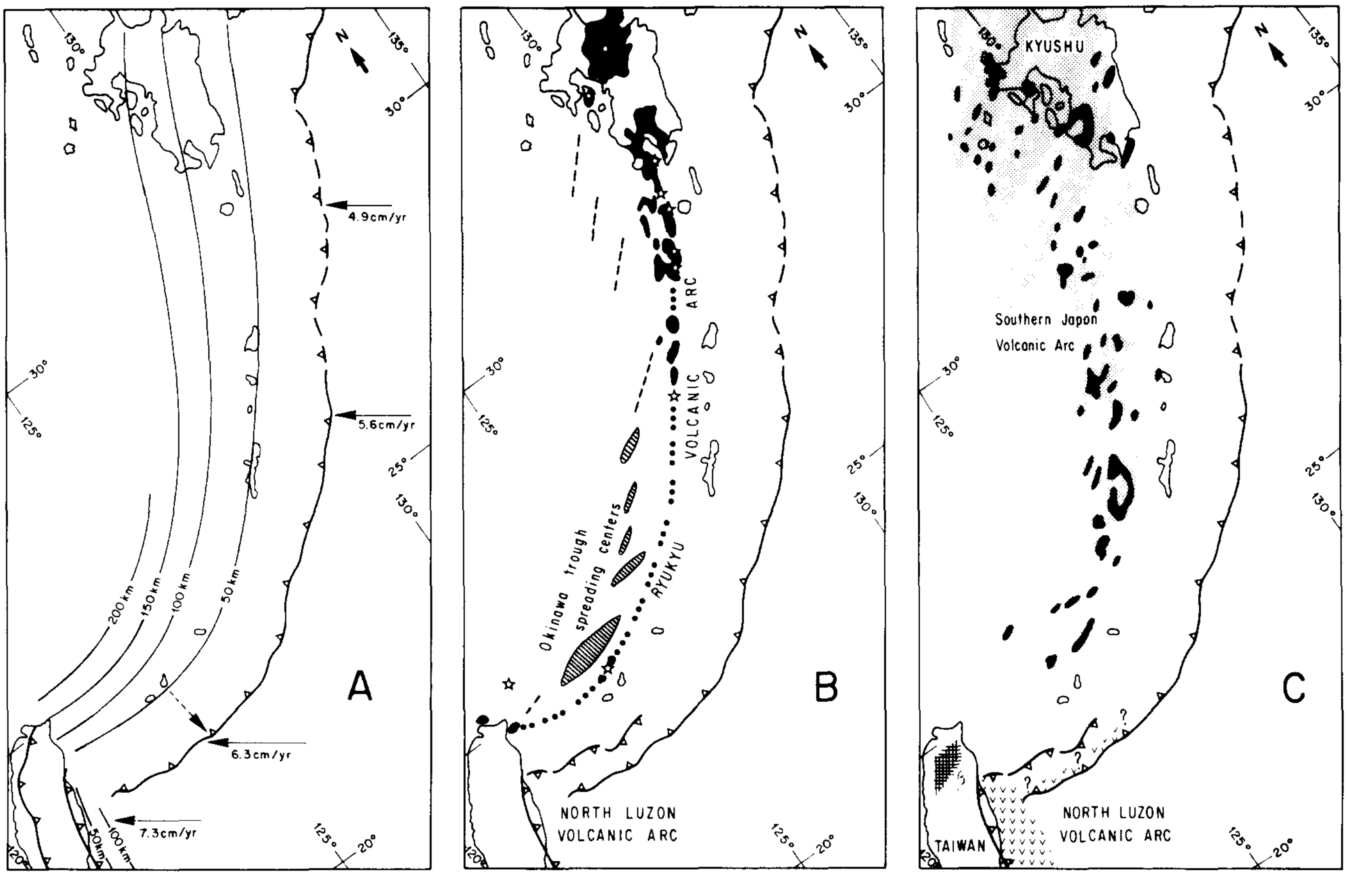

Figure 9 Seismotectonic and position of the Neogene volcanism in Taiwan-Ryukyu area. (A) *Seismotectonic map* with isodepth contours of the deep seismic zone, based on the seismicity map (in Eguchi and Uyeda, 1983). Arrows at the trench show the relative plate motion of the Philippine Sea plate with respect to the Eurasian plate, based on the model of Seno (1977). Dashed arrows show the relative motion of the South Ryukyu arc with respect to the Eurasian plate according to the spreading rate in the Okinawa trough (Kimura, 1984). (B) *Pleistocene and Present magmatic activity*: in black, Pleistocene an active volcanoes (stars) related with the Ryukyu volcanic arc, black points line represent the Ryukyu andesite volcanic front; V, are the Taiwan–Luzon volcanic arc; dashed zones and broken lines arc inferred latest Pliocene–Pleistocene oceanic intrusive and basalts (backarc spreading) and central rifts, respectively. (C) *Miocene and Pliocene magmatic activity*: shaded area is the extension of the Mio-Pliocene igneous activity (Southern Japan volcanic arc), in black the main Miocene–Pliocene intrusions, volcanoes, outcrops or tectonically tilted up igneous rocks; V, are the north Luzon volcanic zone; early and middle Miocene basalts of Taiwan

of Taiwan, recent calc-alkaline volcanism is observed.

Okinawa Trough

The Okinawa Trough is a backarc depression extending from the Ilan Plain in northeastern Taiwan to Beppu Shimabara Graben in Kyushu (*Figure 10*). The total width of the basin ('Great Okinawa Trough', Kimura, 1985) reaches a maximum of 230 km in the northern part. The Okinawa Trough ('inner graben', Kimura, 1985) has a width of about 50 to 100 km. According to seismic reflection lines, the total sediment thickness above the acoustic substratum reaches a maximum of 3000 to 4000 m in the south, but can exceed 7000 or 8000 m in the north.

Except in the south (*Figure 6*; section F), the basement structure is symmetrical and sedimentation shows prograding features on the western side. The arc side of the basin contains southeastern dipping half-grabens, 10 to 80 km wide (*Figure 6*; sections B, C, D, E). The dip of the main half-grabens is generally between 10° and 20° (*Figure 8*). According to onlapping features, the age of the tilting is generally Pleistocene, but the main and secondary faults are still active today. Structure of the continental side of the basin changes from southeast to northeast. Near Taiwan the slope is affected by numerous canyons and channels which cover Pleistocene half-graben structures (*Figure 6*; section F). In the south and south central area, the slope is steep and the central graben is bounded by a main fault (*Figure 6*; sections E and F). In the north, the slope dips gently and is covered with a thick pile of onlapping and prograding sediments (*Figure 6*; sections B, C). These sediments and the basement are affected by numerous growth faults and normal faults, some of them westward dipping.

The central basin or graben is an en échelon structure bounded and affected by numerous normal faults, most of them still active today.

In some cases, several graben features are observed on the same transverse across the basin (multirifting). This is why the exact location of the central rift is not always clear in the Central and North Okinawa Trough. To the northeast toward Kyushu, the main basin branches into minor half-grabens (Amami Basin, Tokara sub-basin). The average trend of the grabens and faults changes from south to north, from WSW-ENE in the South Okinawa Trough to SSW-NNE near Kyushu (around 45° between these trends).

The second common feature of the Okinawa Trough is the presence of intrusions and volcanism from different ages (*Figure 9*). Late Miocene, Pliocene or Pleistocene volcanisms covered the metamorphic

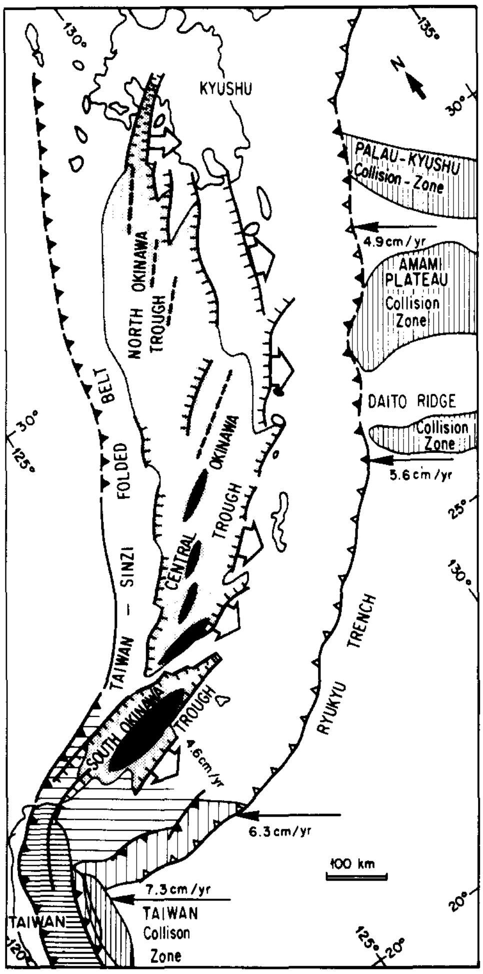

Figure 10 Tectonic index map of the Taiwan–Ryukyu–Okinawa regions. Shaded area is the Okinawa Trough bounded by the main normal fault escarpments; black area and broken lines are inferred latest Pliocene–Pleistocene oceanic intrusive and basalts (backarc spreading) and central rifts, respectively; large harrow, extension in the backarc area with velocity for the south Okinawa Trough. Close vertical lines area are the ridges, plateaux, or volcanic island arc, which collided with the Asian continental margin. We correlated compressive structures of the eastern Taiwan coastal range with anticlines and trusts of Yaeyema ridge. Lines with open triangles are the Ryukyu trench subduction zone. Lines with black triangles are the collision zone or thrust front. Close vertical line area is the Taiwan thrust zone with, in the middle, the Lishan fault. The large horizontal line is the area affected by Pliocene–Pleistocene South Okinawa opening. Arrows at the trench show the relative plate motion of the Philippine Sea plate with respect to the Eurasian plate, based on the model of Seno (1977)

basement and interfinger with the sediments in the eastern or northeastern area (Tokara sub-basin, Amami Basin, Southwest Okinawa; *Figure 6*; sections B, C, D). For example, near southern Kyushu, crests of half-grabens outcrop on islands, and the substratum is composed of Miocene or recent volcanism. Same features are observed in the small islands, west of Okinawajima. The basement of tilted blocks (*Figure 6*; section D) is composed of Miocene to Pliocene (17.5 to 4.5 Ma) tuffs, lava flows and calc-alkaline dikes of andesite and basalt in Kumejima, or andesite and dacite in Agunijima (5 Ma; Yuzo Kato, oral communication). Oil well Toka 1 in the Tokara Basin penetrated a pre-Miocene basement, unconformably overlain by late Miocene pyroclastics and lavas (K/A 6 Ma; Nash, 1979).

In the South Okinawa Basin, a dredge sample of diorite and andesite from the slope of Onodera Seamount (Kato, 1982) is correlated with Eocene or Miocene igneous rocks outcropping southward on Yaeyama islands. This volcanism could be correlated with the large Miocene magmatic event which affected a wide zone along southern Japan. Another kind of volcanism could be the intrusions observed in the central rift zone in the Okinawa Trough, which could correspond to the new oceanic crust described by Kimura in 1985 (*Figure 9*).

Along the 1300 km length of the Okinawa Basin, only one oil well Toka 1 in the Tokara sub-basin penetrated the whole sediment series (Nash, 1979). In the Tokara area, above the late Miocene pyroclastics and lavas, a thick clastic sandy shale was deposited in the Pliocene-early Pleistocene sequence. These sediments interfinger in place with volcanics. The horizons of this sequence are deposited in a large half-graben and cover and infill the substratum and volcanic sequences.

Tilting with 'onlap fill' configuration and erosion on the top of the crest blocks occurred during the Pleistocene (Nash, 1979). This late Miocene-early Pliocene phase of fragmentation and subsidence with a new Pleistocene phase of tilting of the blocks seems to be representative of the central and northeastern Okinawa Basin areas, according to seismic reflection data. The north Okinawa Basin is very thick, sporadically more than 8000 m. Only minor and local unconformities are observed and the stratigraphy is uncertain. According to seismic interval velocity and acoustic characteristics, we believe that the Miocene could be present in this basin.

In the South Okinawa Trough only Pleistocene sediments covered the central graben.

Taiwan–Sinzi Folded Belt and East China Sea Basin

Below the East China Sea, late Miocene regional unconformity is observed. This unconformity corresponds to a strong erosional event, except in the centre of the East China Sea Basin and toward Taiwan, where horizons are parallel and the unconformity is not well defined. Late Miocene (?), Plio–Pleistocene shallow marine shales and sandstones covered the unconformity. Below the unconformity, thick Neogene continental or coastal marine sediments were deposited in the East China Sea Basin. This basin was connected during late Oligocene and Neogene periods with the Taihsi Taichung Basin on Taiwan (Sun, 1981). As in western Taiwan, the Palaeogene could be present below the Neogene in some areas.

Toward the Yellow Sea before the unconformity, Neogene normal faulting and subsidence affected the area. A few transcurrent faults with folds and compressional structures have been observed just before and after the late Miocene regional unconformity. This compressional event is certainly connected to the Himalayan collision (Tapponnier and Molnar, 1976).

The Taiwan–Sinzi Folded Belt (Emery *et al.*, 1969) is an elongated structure, extending parallel to the Okinawa Basin from northeastern Taiwan (Sun, 1981) or the Senkaku islands to the Danjyo islands. In the Senkaku islands, Miocene sandstone, siltstones and

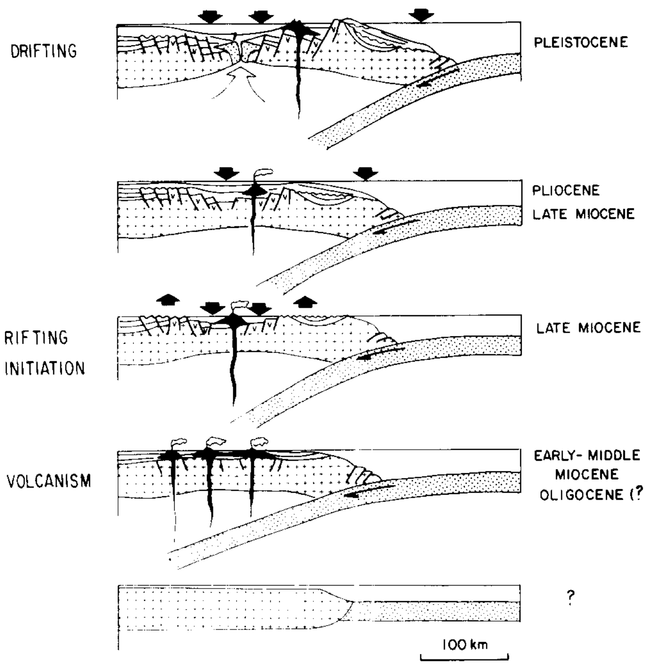

Figure 11 Sketch of evolutionary stages in the Central Okinawa Trough Backarc rifting was initiated in the volcanic arc. Notice the subsidence of the forearc terrace during the rifting and spreading of the backarc. Drifting started 1.9 Ma ago in the South Okinawa Trough and probably also in the central Okinawa Trough. We correlated this event with the collision in Taiwan area

conglomerates are intercalated with thin coal beds and intruded by diorite. Miocene 'Green Tuff' volcanics also outcrops west of Kyushu in the Danjyo Gunto islands. Short-period magnetic anomalies (Emery *et al.*, 1969) attest to the presence of igneous intrusive and extrusive rocks (Green Tuff formation?) between these two island archipelagos.

In the central and northern area below the late Miocene unconformity, the sediments are very tectonized and the structure is not discernible from the seismic reflection data. This tectonized zone is probably composed of Palaeogene and Neogene sediments and volcanics, folded and faulted. It seems that prior to the late Miocene, normal faulting was rejuvenated with reverse movement and northwestward thrust (*Figure 6*; section D). This local compressional event is observed along the western side of the central and north Taiwan-Sinzi Folded Belt (*Figure 10*).

Almost similar but more recent structures occurred in the South Taiwan-Sinzi Folded Belt near Taiwan (*Figure 5*; section F). Late Pliocene thrusts and folds, north of the Ilan Plain in Taiwan extend to the east in this belt. Since about 2 Ma crustal extension with volcanism was active in the Ilan Plain and along the north of the Okinawa Trough near Taiwan.

The Taiwan-Sinzi folded belt is a complex structure which now corresponds to an elongated basement high, parallel to the Okinawa Trough. It was intruded by Neogene igneous rocks and recent volcanism near Taiwan. This volcanism appears to be related to arc volcanic activity but is now in a position of a remnant arc behind a backarc basin. Compressional events and erosion are not of the same age in the north and in the south, but in both regions thrusts are toward the continent. In the south the compression is clearly related to the Pliocene Taiwan collision and thrust belt. But compression, thrust and uplift were stopped by the western propagation of the Okinawa Trough's Pleistocene extension into the Taiwan folded belt.

Discussion and conclusions

The structural evolution of the Okinawa Trough and Ryukyu Arc are linked to several geodynamic processes. These are: volcanism with backarc rifting and spreading; the timing of extension and subsidence of the backarc basin and the tilting and subsidence of the forearc; the kinematics of the opening in the backarc basin and deformation of the arc as a function of collisions.

Neogene volcanic activity, relations to rifting, spreading and Taiwan collision

The extension of Neogene volcanism is summarized on the map in *Figure 9*. The map clearly indicates two magmatic provinces; the Taiwan province related to the South China Sea margin and collision with the North Luzon volcanic arc, and the Ryukyu province which is related to the Philippine Sea subduction and Okinawa Trough opening.

As along the South China passive margin in central Taiwan, early and middle Miocene alkaline basalts were interbedded in the sediments. The eastern Taiwan middle Miocene pillow basalts (NN 5; Huang *et al.*, 1979) are associated with ultramafic rocks and are incorporated in the 'Lichi Mélange'. These rocks are considered to be slices from the South China Sea transform fault incorporated in the Taiwan–Luzon collision zone complex, along the longitudinal valley (*Figure 6*, section G). In the eastern coastal range and islands, early Miocene to Pleistocene calcalkaline volcanism occurred in the northern prolongatin of the Luzon volcanic arc. This volcanic ridge collided with the South China margin during the Plio–Pleistocene (*Figures 10* and *14*). Its width is very small (around 50 km) compared to its width farther south at the latitude of Luzon (300 to 350 km).

The northern Taiwan Pleistocene andesitic volcanoes (*Figure 9*) have been interpreted as the extension of the Ryukyu volcanic arc system (Ho, 1982). The Ilan plain, the terminus of the southwestward prolongation of the Okinawa Basin extensional regime, subsides in this volcanic belt. Kueishantao island, off Ilan plain, is an active andesitic volcano (*Figures 9* and *10*). The same feature is observed in the northeastern terminus of the Okinawa Trough, in the Beppu-Shimabara Graben in Kyushu, where the Unzen and Aso active volcanoes are located in the central graben of the Okinawa Trough. Therefore, rifting is initated in both cases and is in progress in a highly active arc volcanism. The break up of the arc occurs in the volcanic front so that Okinawa Marginal Basin rifting is a typical 'interarc basin opening' (*Figure 11*).

Rifting is in progress just along the volcanic front. Pleistocene to Recent volcanoes are located between the non-volcanic arc and the central Okinawa Trough, but inside the extensional zone (*Figures 5, 6* and *9*). The distribution of the Pleistocene and active volcanoes is not uniform along the Ryukyu arc. Most of these volcanoes are along the North Okinawa Basin, and only a few have been observed south of the Okinawa Trough (*Figure 9*).

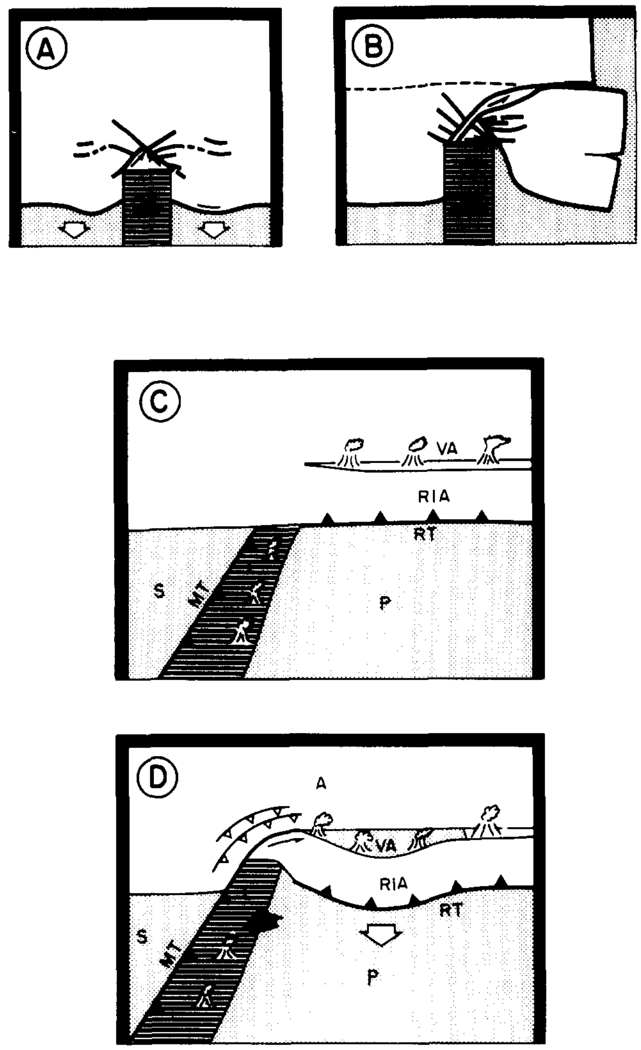

Figure 12 (A) and (B) Plane indentation experiment using plasticine with horizontal anisotropy (Peltzer, 1983). (C) and (D) Analogy of the deformation in the Taiwan-South Okinawa Trough areas. (A) *Bilaterally confined*. Rotation of layers occurred on both sides of the indent. Buckling is observed along the free horizontal boundary. Horizontal tensional gaps are observed on both sides. (B) *Unilaterally confined*. Deformation became asymmetrical. The left lateral fault that originates at the left tip of the indent grows and curves out to join one of the horizontal discontinuities of the model (interface between two layers of plasticine). This fault guides the extrusion and rotation of blocks and terminates in a wedge-shaped gap. (C) *Schematic boundary conditions* before the north Luzon Island arc–Asian Continent collision: L, Luzon island arc (indent); MT, Manilla Trench (free boundary); P, Philippine sea oceanic crust; S, South China Sea oceanic crust; A, Asian continent; VA, Ryukyu Volcanic arc (weak crustal zone); RT, Ryukyu Trench (free boundary); RIA, Ryukyu Island arc. (D) Deformation observe after the collision and indentation process of the north Luzon Island arc with the Asian continent. SOT, South Okinawa Trough; T, Taiwan; LF, Lishan fault.

The distribution of late Miocene-Pliocene volcanism, deduced from a few island outcrops and seismic interpretations, is not precise. Most of this volcanism seems to be located east and northeast of the Okinawa Basin.

More interesting is the distribution of early to middle Miocene volcanism prior to the main Okinawa rifting phase (*Figure 9*). Mostly in the central and northern region and also all along southern Japan, Miocene volcanism and related acidic rocks affected a wide zone. This volcanic, pyroclastic and intrusive event is called the 'Green Tuffs' episode. The intrusion is 100–150 km inland from the Nankai Trough and Ryukyuu Trench, and is believed to have been caused by subduction and melting with continental material. This wide volcanic zone was probably due to the low dip angle of the subducted slab or due to subduction of the oceanic ridge or transform zone (*Figure 14*). The age of these rocks ranges from early Miocene (21 Ma, in Bowin and Reynolds, 1975) to middle Miocene or late Miocene (6.8 Ma, in Takahashi, 1981). As for the terminus of the recent extensional regime, the late Miocene rifting of the Okinawa Basin occurred along the volcanic arc around 9 to 6 Ma ago (*Figure 11*). The remnant of the early to middle Miocene volcanic arc can be found rifted on the continental side of the basin in the Taiwan-Sinzi Folded Belt.

We can postulate that, along the active margin, changes in thermal and mechanical properties of the crust in the overriding plate are due to the ascent of magma in the volcanic arc zone. Backarc rifting was then initiated along the volcanic front, because the crust is weaker along the volcanic arc. The same features have been observed in the Mariana Trough opening.

Age of the Okinawa Trough, temporal relation between extension and subsidence of the Okinawa Trough and Ryukyu Forearc Basin

After the wide middle Oligocene regression and erosion which affected the whole China Shelf, large-scale subsidence with local extension may have occurred, especially in the East China Sea Basin. The Okinawa Trough was buried by sediments and igneous material due to Neogene igneous activity. If the thick sedimentary pile observed in the North Okinawa Trough is partly from Miocene age, subsidence in that area could be synchronous with the Japan Sea opening. We suggest that this small basin could be a southwestward en échelon graben linked to the Japan Sea drifting (*Figure 14*).

Extensional movements associated with volcanism occurred in the late Miocene–Pliocene (Nash, 1979). Some geologic evidences suggest spreading of the north Okinawa Trough in the Miocene, but the crustal structure and magnetic anomalies are not well known. This rifting and crustal extension was of major importance in the area, involving subsidence and the formation of depocentres all along the Okinawa Trough. Prior to the latest Miocene-Pliocene main subsidence, on both sides of the basin a strong erosional event affected the area. This erosion took place around 9 Ma to 6 Ma ago. In Taiwan, the regression which corresponds to the 'upper coal bearing formation' is also dated around NN 10–NN 11 (T.C. Huang, personal communication) and is considered to be a major eustatic sea-level change. But the two elongated high eroded zones on both sides of the basin could also be due to the uplift of the two shoulders of the central graben. This is a common feature in continental rift zones.

In the forearc basin zone, along the Ryukyu Arc, late Miocene-Pliocene subsidence took place after the erosional event, but without any extension. Sedimentary and seismic features show a progressive eastward tilting of the basin. The late Miocene unconformity is currently 4000 m below the forearc terrace bordering the trench. Similar subsidence of the forearc terrace was discovered by deep sea drilling on IPOD legs 56 and 57, near the Japan Trench east of Japan. This example shows that the subsidence of the forearc terrace bordering the trench is synchronous with the opening of the backarc Japan Sea Basin.

According to Seno and Maruyama's model (1983), the change in the Philippine Plate motion could have occurred at an imprecise date between 10 and 4 Ma ago. We believe that this event could be correlated with the beginning of the subsidence of the Ryukyu forearc and Okinawa backarc basin < 9 Ma ago. Therefore, the subsidence of the forearc terrace bordering the trench could be linked to the subsidence of this trench, i.e. the change of the slab dip during or after the change in the Philippine Plate motion? (*Figure 14*).

A second major phase of crustal stretching occurred after the latest Pliocene times, 1.9 Ma (Kimura, 1984) and was of major importance in shaping the area. En échelon cracks occurred along the axis of the Okinawa Trough. Magma may have ascended through the rift during lower Pleistocene in the South and Central Okinawa Trough (*Figure 9*). The location of the spreading centres is distinct from the location of previous ascending volcanic arc magma (*Figure 11*). Spreading has been active since 1.9 Ma ago in the south or central Okinawa Trough, but the north Okinawa Trough is only in a rifting stage (Kimura, 1984). In the terminal Pleistocene a new crustal stretching with active normal faulting and magmatic intrusions was again observed.

In the eastern side of the basin, east-dipping Pleistocene half-grabens subside, with synchronous subsidence of the forearc. The retreat and subsidence of the Ryukyu trench line in relation to the Asian continental plate could be one of the causes of the tilting of the forearc and extension in the backarc area (*Figure 11*).

The retreating-trench model or anchored-slab model can be used to explain extension in a backarc area. But for the initiation of the opening of backarc basins, an additional phenomenon linked to collision can be used to explain the timing and the kinematics of the opening.

Kinematics of the extension in the backarc basin and deformations of the island arc in relation to collision

Rifting and the beginning of spreading in the Okinawa Trough occurred along en échelon normal faults producing grabens, half-grabens and typical rift structures. Multi-rifting occurred, especially in the northern half of the basin. Contrary to wide oceanic spreading systems, transform faults perpendicular to rifts or grabens are not observed. Along the island arc, oblique extensional features were noticed, i.e. Tokara Channel, Kerama gap (*Figures 5* and *10*).

The opening is not synchronous along the 1300 km of Okinawa Trough. Rifting in the North Okinawa Trough predominantly occurred probably in the early or middle Miocene. Pleistocene spreading seems to be mostly active in the Central and the South Okinawa Trough. During the Miocene the boundary between the Philippine Sea plate and the South China Sea was a transform zone or a subduction zone (Luzon arc). Along the Asian continental margin this boundary was situated at the end of the Miocene Ryukyu volcanic arc,

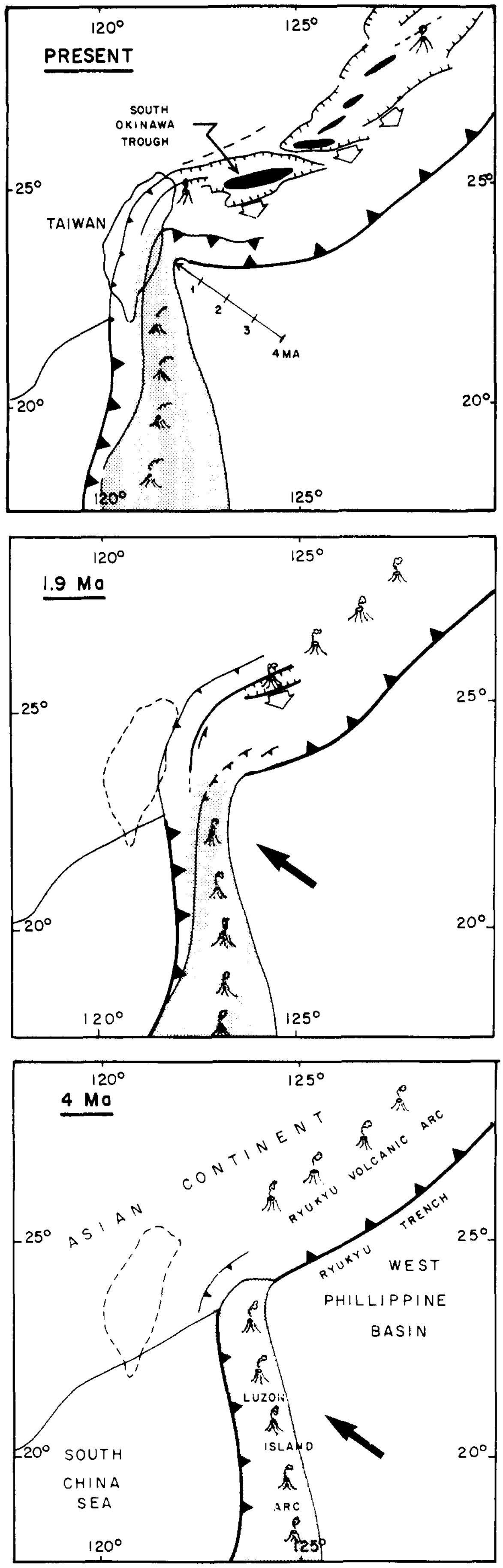

Figure 13 Structural evolution of the north Luzon Island arc–Taiwan Collision Zone, and Ryukyu Island arc–South Okinawa Trough opening. A collision/lateral backarc basin opening model. Symbols are the same as in *Figure 12*

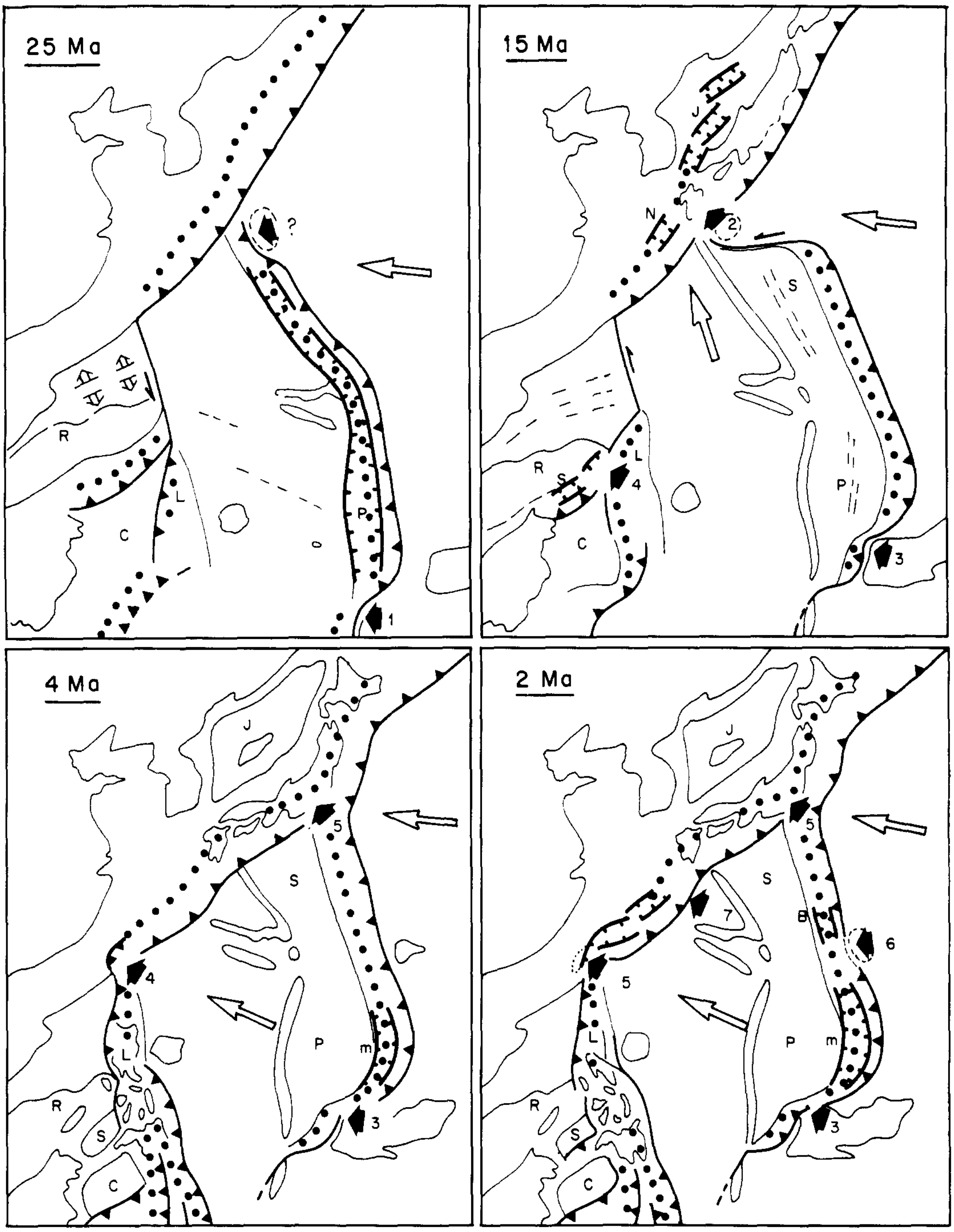

Figure 14 Palaeogeographic reconstruction of the Philippine Sea at 25 Ma, 15 Ma, 4 Ma, 2 Ma ago, based on the collision/lateral backarc basin opening model. The Pacific plate was moving westward with respect to hotspots since the middle Eocene (43 Ma). The motion of the Philippine Sea with respect to Eurasia at the triple junction change from northwestward to west northward 10–5 Ma ago (Seno and Maruyama, 1984). Continents, volcanic and oceanic ridges contours is shown (see *Figure 1*). R, L, S, C, N, J, P, S, M, B, denotes Reed Bank – North Palawan continental block, Luzon island arc, Sulu Trough, Celebes Sea, North Okinawa Trough, Japan Sea, Parece Vela Basin, Shikoku Basin, Mariana Trough, Bonin Trough, respectively. Broken lines indicate extinct ridges. Thrust symbols denote active trenchs and thrusts, black points active volcanic arcs. Solid arrows indicate the collisions: 1, 2, 3, 4, 5, 6, 7, 8, indicate Mapia Ridge, Palau Kyushu and inferred oceanic ridge, Caroline Ridge, North Luzon island arc, Uzu-Bonin volcanic arc, Ogasawara plateau, Amami plateau Palau Kyushu Ridge, Philippine mobile belt, collision zones respectively. Graben symbols indicate lateral backarc basin opening

east of the Yaeyema compressional ridge (*Figures 3, 9, 13* and *14*).

The rapid acceleration of the sedimentation rate in the coastal range of Taiwan and the reworking of continental material during the middle Pliocene, are thought to reflect the growth of the island of Taiwan, along the Luzon Island Arc, during the oblique collision. According to such arguments, Chi *et al.* (1981) estimated that the Luzon island arc on the Philippine Sea plate began to collide with the Chinese continental margin 3.5 to 4.0 Ma ago (*Figures 13* and *14*).

In Taiwan, shortening due to an indentation process could be estimated at 150 to 200 km, lateral to the collision, second stage of drifting of the South Okinawa Trough occurred 1.9 Ma ago and stopped the uplift and compression on both sides of the Trough. The Pleistocene extension was 30 to 50 km in the central part of the South Okinawa Trough, and decreased to the West toward the Ilan plain in Northern Taiwan. The conjugated movement of the relative extension in the Okinawa Trough and bending due to collision in northern Taiwan has produced a clockwise rotation of southern Ryukyu (Yaeyema Islands) since the middle Pliocene. Palaeomagnetic studies also support this conclusion. Okinawajima has had negligible rotation and latitude motion since the Eocene (5° clockwise) in contrast to the 45–50° of clockwise rotation and negligible latitude motion since the Miocene in the southern Ryukyu islands (Jarrard and Sasajima, 1980). The rotation of the southern Ryukyu, the non-parallel alignment of a rifting and spreading trend and the extensional features along the arc, strongly support the conclusion that there is no single finite pole of rotation for the opening of the Okinawa Trough. Thus the Ryukyu arc sub-plate can not be considered as a rigid plate.

Hypothetical collision/lateral backarc basin opening model

The succession of structural events and the kinematic evolution of the Taiwan collision and the South Okinawa Trough opening suggest a link between these two events. Intracontinental deformations and rotation movements, associated with widespread seismicity, have been interpreted as a consequence of continental collision (McKenzie, 1972; Molnar and Tapponnier, 1975). In order to simulate evolution in time of intracontinental deformations produced by collision and indentation processes, an analogic experimental approach has been used (Tapponnier and Molnar, 1976; Tapponnier, 1977; Tapponnier *et al.*, 1982; Peltzer, 1983).

Interesting features occurred in plane indentation experiments on anisotropic blocks of plasticine (Peltzer, 1983). In such experiments the influence of free lateral boundaries and anisotropy has a profound influence on the deformation pattern. The experiments suggest (*Figure 12*): compression and shortening in front of the indenter; lateral extrusion and rotation of blocks; buckling along the free surface; tensil gap occurring along interlayer discontinuities parallel to the free surface.

In these models free boundary conditions are supposed to be the subduction zones. Before the collision along the Asian Continental Margin, on both sides of the Luzon Island arc, the boundary conditions were asymmetric (*Figure 12*). The subduction zone exists only along the Ryukyu arc, the South China margin was a passive margin. The second peculiar asymmetric feature was the existence of the Ryukyu volcanic arc. This line of magmatic ascent constitutes a weak zone in the Asian continent, parallel to the subduction zone.

The indentation experiment suggests that collision of the north Luzon island arc with the Asian continental margin during the Pleistocene could have been provoked (*Figure 13*): first, compression and thrusts on the continental side; then, during the early Pleistocene, by reverse lateral faults. Faults originated at the left tip of the indenter, grow and curve out to join the discontinuity constituted by the Ryukyu volcanic arc. One of these postulated faults could be the Lishan fault in central Taiwan. The nature of this accident which separated two major tectonic zones of the central range is controversal (Ho, 1981). Its trajectory could have been deformed by recent thrust movements. This fault curves to the northeast to join the Ilan Plain and the South Okinawa Trough which have been tensional features since the early Pleistocene.

Movements into the Asian margin involve the succession of lateral extrusion and rotation of the south Ryukyu–Yaeyema island block and the bending of the Ryukyu island arc. These deformations were counterbalanced by N–S tensional axes trending into the Ryukyu volcanic arc. Intra-arc stretching, initiated during the early Pleistocene, explains the opening of the south Okinawa Trough (*Figure 13*). After the opening initiation, the volcanic arc activity was situated only in the extremity and along the external zone of the marginal basin. But the volcanic activity stops on the continental side (remnant arc).

In the northeastern Taiwan area the rift propagated to the west into the folds, thrusts and uplift zone generated at the beginning of the collision during the Pliocene. In that area the stress regime changed suddenly from compression to extension in the latest Pliocene–early Pleistocene. This explains the folds and the northwestward thrust faults found near Taiwan on the continental side of the Okinawa Trough in the Taiwan–Sinzi folded belt.

The collision lateral backarc basin opening model presented here is compatible and could be superimposed on more classical models or phenomena to explain the opening of backarc basins. Thermal convection, the retreating trench model or the anchored slab model could maintain active spreading in Backarc basins. But for the South Okinawa trough stretching initiation, this model is more convenient to explain the chronology and kinematics of the deformations.

It might be interesting to see whether the initiation of opening of other backarc basins in the world correspond or not to an indentation process so as to generalize the hypothetical 'collision/lateral backarc basin opening' model. Unfortunately for most of the backarc basins we examined, the chronology of the events is not so precise as the chronology in the Taiwan–Ryukyu area (hundreds of thousands of years). In this region the structural process seems more clear because it is at an early stage of evolution.

Figure 14 suggests a late Cenozoic palaeogeographic reconstruction of the Philippine sea, modified from Seno and Maruyama (1984) based on the collision/

lateral backarc basin opening model. Looking at the present position of backarc basins related to collision zones in the Philippine sea and surrounding area, we can notice a close relation between these two kinds of structures.

- The Okinawa Trough is bounded to the south by the north Luzon island arc collision and to the north by the Amami Plateau-Palau Kyushu Ridge collision zone.
- The Bonin Trough, recently opened, is bounded to the south by the Ogasawara plateau collision zone.
- The Mariana Trough, open since the Late Miocene (?)-Pliocene, is bounded to the south by the Caroline ridge and to the north by the Ogasawara plateau collision zone..
- The Parece Vela Basin was open from the Oligocene to middle Miocene. It is bounded to the south by the Mapia Ridge and Carolina Ridge collision zones. The Pacific-Philippine plate's convergence rate is considered to be very slow in this area.
- The Shikoku Basin was open from latest Oligocene to early-middle Miocene. Its northern boundary disappeared in the Nankai subduction zone. It must be a transform zone joining the Izu-Bonin volcanic arc to the Palau-Kyushu remnant arc
- The opening age of the Sulu Trough is unknown. We speculate that there was a relation between the north Palawan-Philippine mobile belt collision (Lower Middle Miocene) and the opening of the Sulu Trough.
- The opening of the Sea of Japan by rotation of South Japan took place during the Middle Miocene and may have been stopped by collision with Izu-Bonin Ridge. We speculate that there was a relation between this opening and the compression and thrusts which occurred in Kyushu between the Burdigalian and early Serravalian (*Figure 7*). Collision with north Kyushu-Palau Ridge or an oceanic plateau, now subducted, can explain the compression and the lateral opening of the Sea of Japan.

Conclusions

This regional study of the Taiwan Ryukyu area allows us to draw the following conclusions.

(1) Subduction, and associated arc volcanic activity preceded backarc basin opening.

(2) We suggest that collision and indentation processes provoked lateral extrusion, rotation and buckling of the island arc, and initiated the opening of the backarc basin. Inactive compressional features, such as folds, uplift and thrust toward the continent can be observed on two sides of the backarc basin near the collision area. After the initiation of the opening, thermal convection, the retreating trench model or the anchored slab model could maintain active spreading in Backarc basins.

(3) Opening of the backarc basin occurred and propagated into the weak crustal zone constituted by the active volcanic arc. After the rifting of the backarc basin, the active volcanic front was located near the main boundary fault. The remnant of the volcanic arc should be found on the continental side of the basin. It seems that the beginning of the backarc spreading observed in the central and southern Okinawa Trough corresponds to a relative minimum in the activity of the volcanic arc.

(4) The original width of the continental elongated fragment which drifted from the continent is defined by the volcanic arc–trench distance. In this fragment which drifted from the continent we recognized: a complex subduction zone above the trench; a forearc slope and terrace, with only a few extentional features with a sub-aerial erosional surface covered by sediments: an uplift and eroded non volcanic island arc; a rifting zone with volcanic arc activity.

(5) The opening and subsidence of the marginal basin and the tilting and subsidence of the forearc terrace above the trench slope were synchronous.

(6) En échelon rifting and spreading trending structures in the central graben could be oblique to the general trend of the arc.

(7) Most of the structures found in a backarc basin, opened by crustal extension into a continent, are also observed in intra-oceanic backarc basins.

(8) A late Cenozoic palaeogeographic evolution model of the Philippine Sea Plate based on the hypothetical collision/lateral backarc opening model is proposed.

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