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THE OKINAWA TROUGH: GENESIS OF A BACK-ARC BASIN DEVELOPING ALONG A CONTINENTAL MARGIN

JEAN LETOUZEY [1] and MASAAKI KIMURA [2]

Institut Français du Pétrole, Boite Postale 311, 92506 Rueil Malmaison Cedex (France)
[2] *Department of Marine Sciences, College of Science, University of the Ryukyus, Senbara 1, Nishihara, Okinawa 901.01 (Japan)*

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ABSTRACT

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The Okinawa Trough is the only example of a marginal back-arc basin type at a young stage of evolution that developed along a continental margin. The first phase of crustal stretching and subsidence occurred during late Miocene–early Pliocene times. A second major phase occurred after the latest Pliocene or early Pleistocene, with en échelon rift axes along the axes of the Okinawa Trough, oblique to the general trend of the arc and trench. Crustal separation and active spreading has occurred in the central and southern Okinawa Trough, but the north Okinawa Trough is only in a rifting stage. The development of the basin has several correlations with the general tectonism of the arc system:

(1) There was a synchronism between opening and subsidence of the Okinawa Trough and tilting and subsidence of the fore-arc terrace.

(2) Back-arc rifting was initiated in the volcanic arc and propagated along it during the Neogene. Remnants of a volcanic arc are found on the continental side of the basin. The beginning of the back-arc spreading observed in the central and southern Okinawa Trough correspond to a relative minimum in the activity of the volcanic arc.

(3) The timing and kinematic evolution of the Taiwan collision and the south Okinawa Trough opening suggest a connection between these two events. Such a collision-lateral back-arc opening model could explain the initiation of the opening of back-arc basins, but additional phenomena such as thermal convection, retreating trench model or anchored-slab model are indispensable to maintain extension in the back-arc basin.

INTRODUCTION

The Okinawa marginal basin opened by crustal extension in the Asian continent, parallel to the Philippine–Asian plate boundary, north of the Taiwan collision zone (Fig. 1). It is located behind the Ryukyu Trench subduction zone and the Ryukyu active volcanic arc (Fig. 2).

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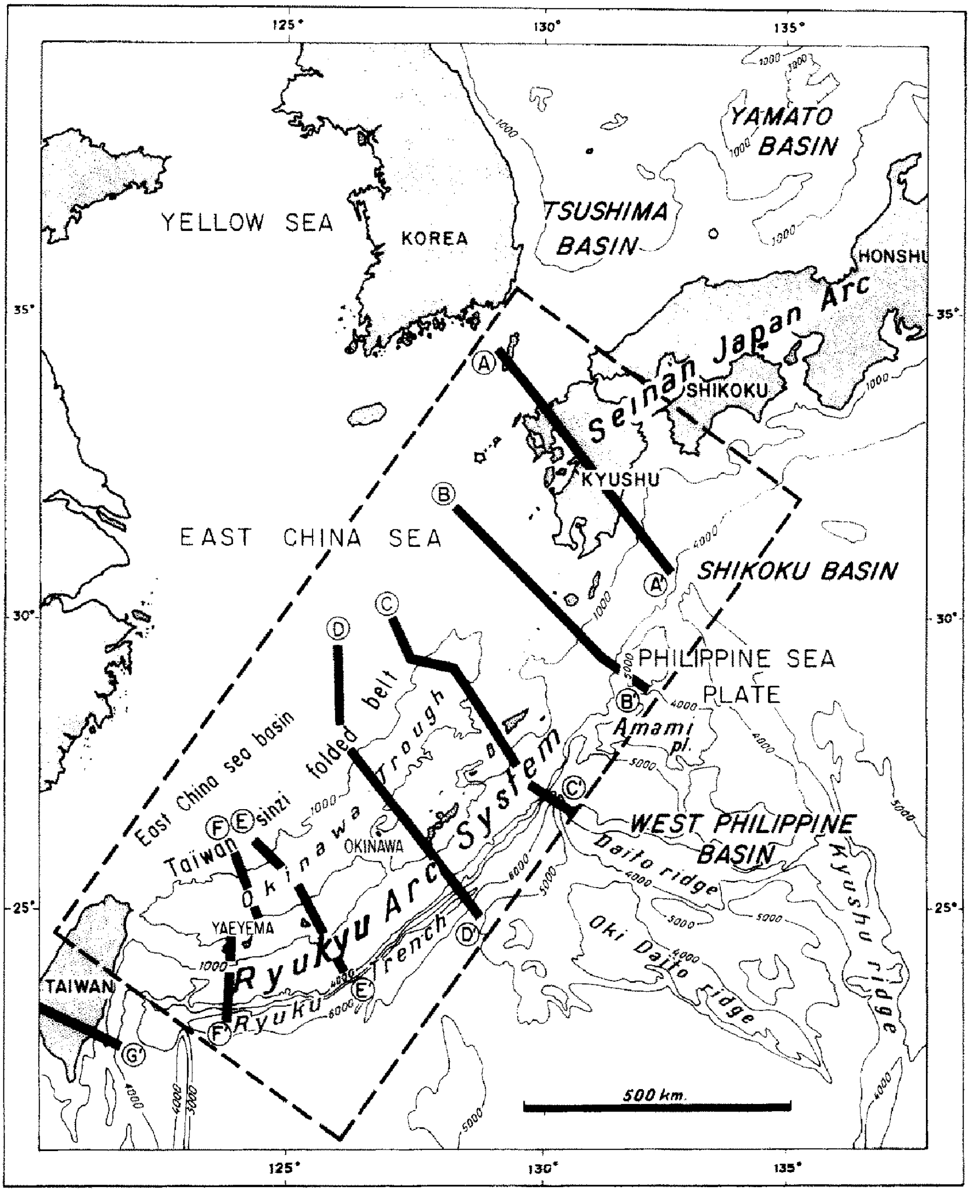


Fig. 1. Location map of Okinawa Trough, Ryukyu arc and vicinity. *AA′–FF′*—location of the interpretative geological cross-sections of Fig. 5. Area of study is outlined by dashed box.

If we except the Andaman Sea, with a complex oblique opening, and the Tyrrhenian Sea, the Okinawa Trough is the only example in the world of an active marginal back-arc basin type, opening along a continental boundary, at a young stage of evolution. The end of the rifting period in the northern Okinawa Trough

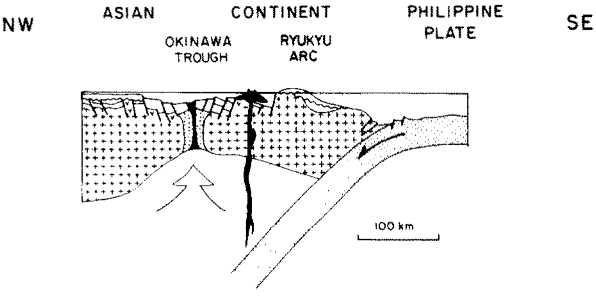


Fig. 2. Idealized cross section of the Okinawa Trough–Ryukyu arc.

and the beginning of the spreading period in the central and southern Okinawa Trough can be observed at present.

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, as well as results of geological field trips in Taiwan, Okinawa and Kyushu. The complete geological and geophysical data analysis and conclusions on the structure and evolution of the Okinawa Trough and Ryukyu arc were published in previous papers (Letouzey and Kimura, 1985; Kimura, 1985).

Some specific problems concerning the structure and evolution of the Ryukyu arc and Okinawa back-arc basin could give some ideas and answers about the origin and evolution of intra-continental marginal back-arc basins. Three topics will be discussed: (1) the temporal relation between extension and subsidence of the back-arc basin and the tilting of the fore-arc; (2) the relations between arc volcanism, rifting and spreading; and (3) the connection between collision and lateral opening of a back-arc basin.

STRUCTURE OF THE OKINAWA–RYUKYU AREA

The Ryukyu arc is a convex structure extending from Taiwan to Kyushu. It is bordered by the Ryukyu Trench, from which a Wadati Benioff zone extends beneath the arc to a depth of between 200 and 300 km. Acording to Seno's model of instantaneous relative plate motion, the convergent rate between the Philippine Sea plate and the Eurasian plate varied from 4.9 to 7.3 cm/y along the arc (Fig. 3). Since the Eocene, the Philippine plate has been surrounded by subduction zones, so that the plate motion vectors of the Philippine Sea plate with respect to the Eurasian plate could not be determined precisely in the past.

The Okinawa Trough extends from northeast of Taiwan to Kyushu (Fig. 1). The deeper part to the south is called the South Okinawa Trough. From refraction studies (Murauchi et al., 1968; Ludwig et al., 1973; Leyden et al., 1973; Lee et al.,

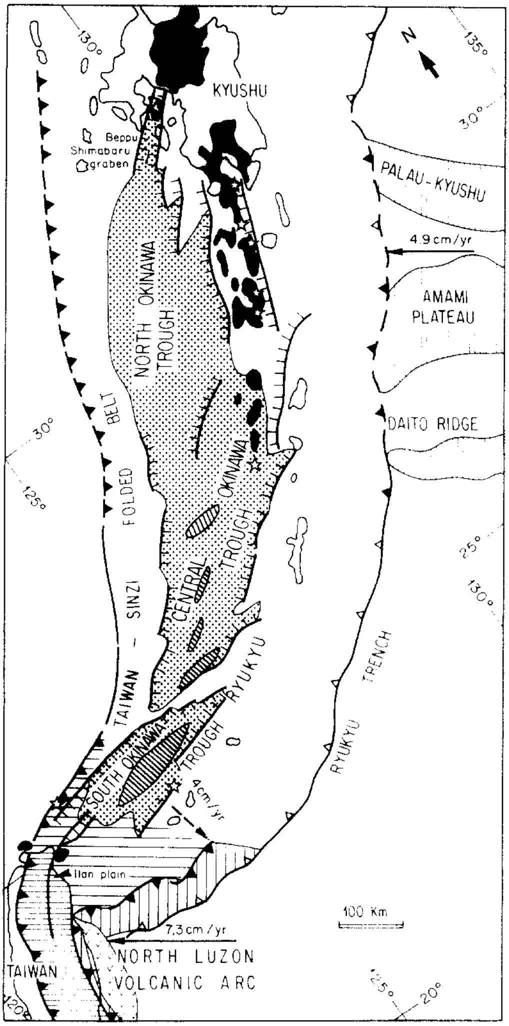


Fig. 3. Tectonic index map of the Taiwan–Ryukyu–Okinawa regions. Shaded area is the Okinawa Trough bounded by the main normal fault escarpments. Dark shaded area are inferred latest Pliocene–Pleistocene oceanic intrusives and basalts (back-arc spreading) respectively. In black, Pleistocene and active volcanoes (stars) related to the Ryukyu volcanic arc, V's denote the Taiwan–Luzon volcanic arc. Close vertical lines area are the ridges, plateaus, or volcanic island arc, which collided with the Asian continental margin. We correlated the compressive structures of the eastern Taiwan coastal range with anticlines and thrust of Yaeyama ridge. Lines with open triangles are the Ryukyu trench subduction zone. Lines with black triangles are the collision zone or thrust front. The close horizontal 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 Taiwan compression. 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, 1985).

1980; compiled by Kimura, 1983 and 1985) and gravity data (Segawa, 1976; Murakami, 1976; Lee et al., 1980), the general crustal structure is continental around the Okinawa Trough, below both the Ryukyu arc and the continental shelf. However, the mantle is about 17 km deep beneath the central rift of the South Okinawa Trough. The high heat flow also suggests that the age of the South Okinawa Trough may be as young as 2 Ma (Lu et al., 1981). In this area sea-floor spreading is inferred from linear magnetic anomalies (Herman et al., 1978; Lee et al., 1980). From correlations between magnetic anomalies and magnetic reversal time scale, Kimura (1985) suggests that in the central part of the South Okinawa Trough spreading initiated in the early Pleistocene (around 1.9 Ma ago). Average half spreading rate has been 2 cm/y. The North Okinawa Trough is only in a rifting stage (Letouzey and Kimura, 1985; Kimura, 1985).

Many single-channel reflection profiling surveys have been carried out in the Okinawa Trough (Wageman et al., 1970; Kimura et al., 1975, 1979, 1980; Honza, 1978; Herman et al., 1978; Lee et al., 1980).

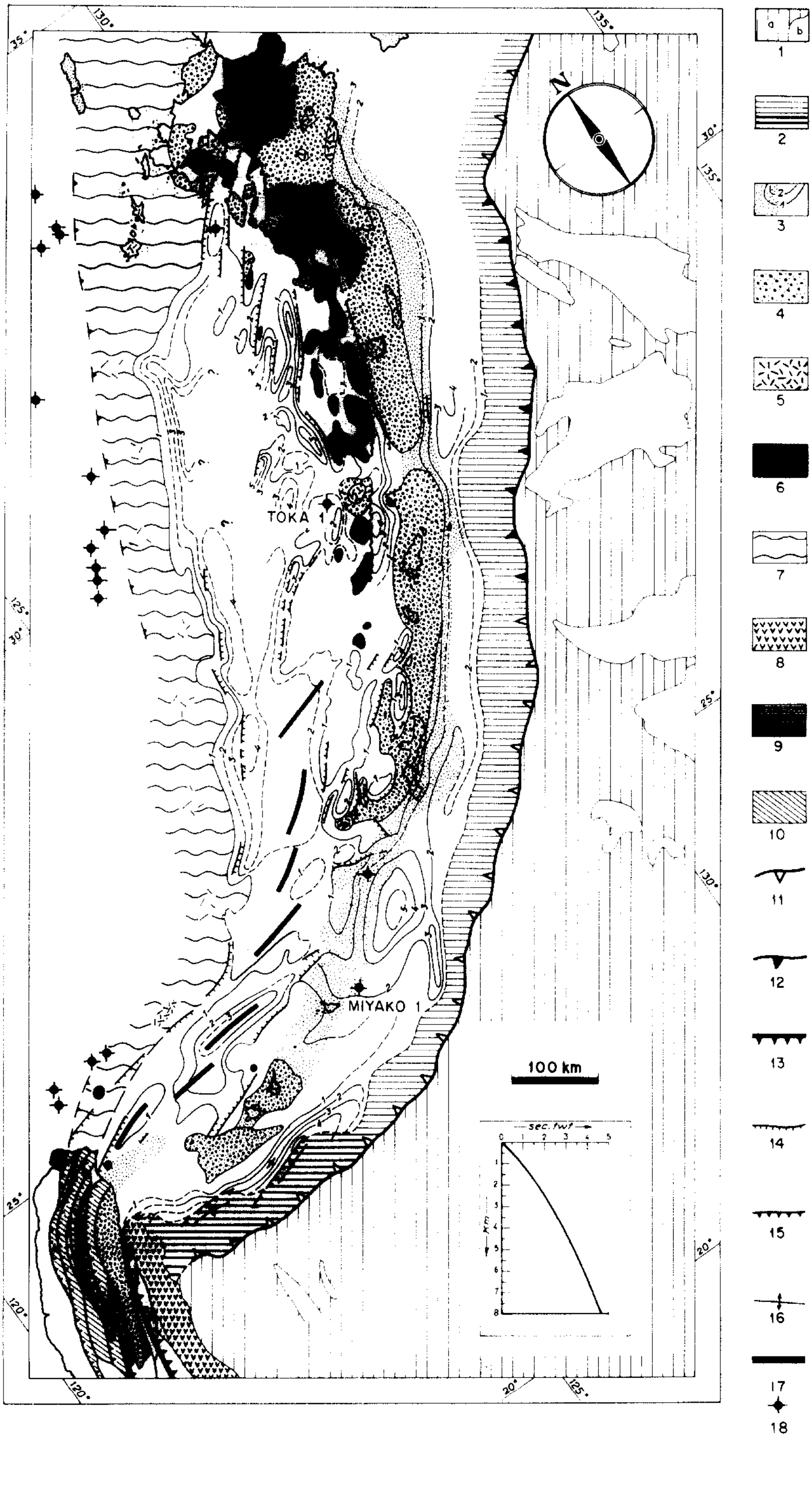
Aiba and Sekiya (1979), Nash (1979) and Letouzey and Kimura (1985) presented a geological and structural interpretation of the area based on multi-channel seismic surveys.

The structural map (Figs. 3 and 4) and interpretative geological cross-sections (Fig. 5) summarize the main structures observed on seismic profiles and deduced from field geology, oil drilling or dredging (Letouzey and Kimura, 1985).

AGE OF THE OKINAWA TROUGH, TEMPORAL RELATION BETWEEN EXTENSION AND SUBSIDENCE OF THE OKINAWA TROUGH AND RYUKYU FORE-ARC BASIN

The pre-late Miocene substratum of the central and North Ruykyu Islands (Figs. 4 and 5) is the prolongation of the geological outer zones and southwestern zones of Kyushu, Shikoku and Honshu, with slightly metamorphosed late Paleozoic and Mesozoic sediments. Cretaceous to Eocene or early Miocene (Aquitanian) sediments have been interpreted as an accretionary complex, formed during the northward subduction of the Philippine Basin (Taira et al., 1981; T. Sakai, oral commun., 1983). Probably related to Philippine Sea plate subduction, a compressional tectonic event with southeastward thrusting occurred in eastern Kyushu after the Aquitanian sediments were deposited (around 23 Ma) and before the Serravalian acidic intrusive volcanism (around 13 Ma). Cenozoic formations related to the Japan active margin are not observed in the southern Ryukyu Islands; Paleogene and Neogene sediments in these islands (Yaeyema Islands) show some similarity with Taiwan and South China Sea passive margin deposits.

As in western Taiwan, the Paleogene could be present beneath the Neogene in some areas of the present East China Sea, or Taiwan–Sinzi fold belt. After the widespread middle Oligocene regression and erosion which affected the whole China shelf, large-scale subsidence with local extension may have occurred, especially in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the East China Sea Basin. This basin was connected during late Oligocene and Neogene periods with the Taishi Taichung Basin on Taiwan (Sun, 1981). Thick Neogene continental or coastal marine sediments were deposited in the East China Sea Basin (Aiba and Sekiya, 1979).

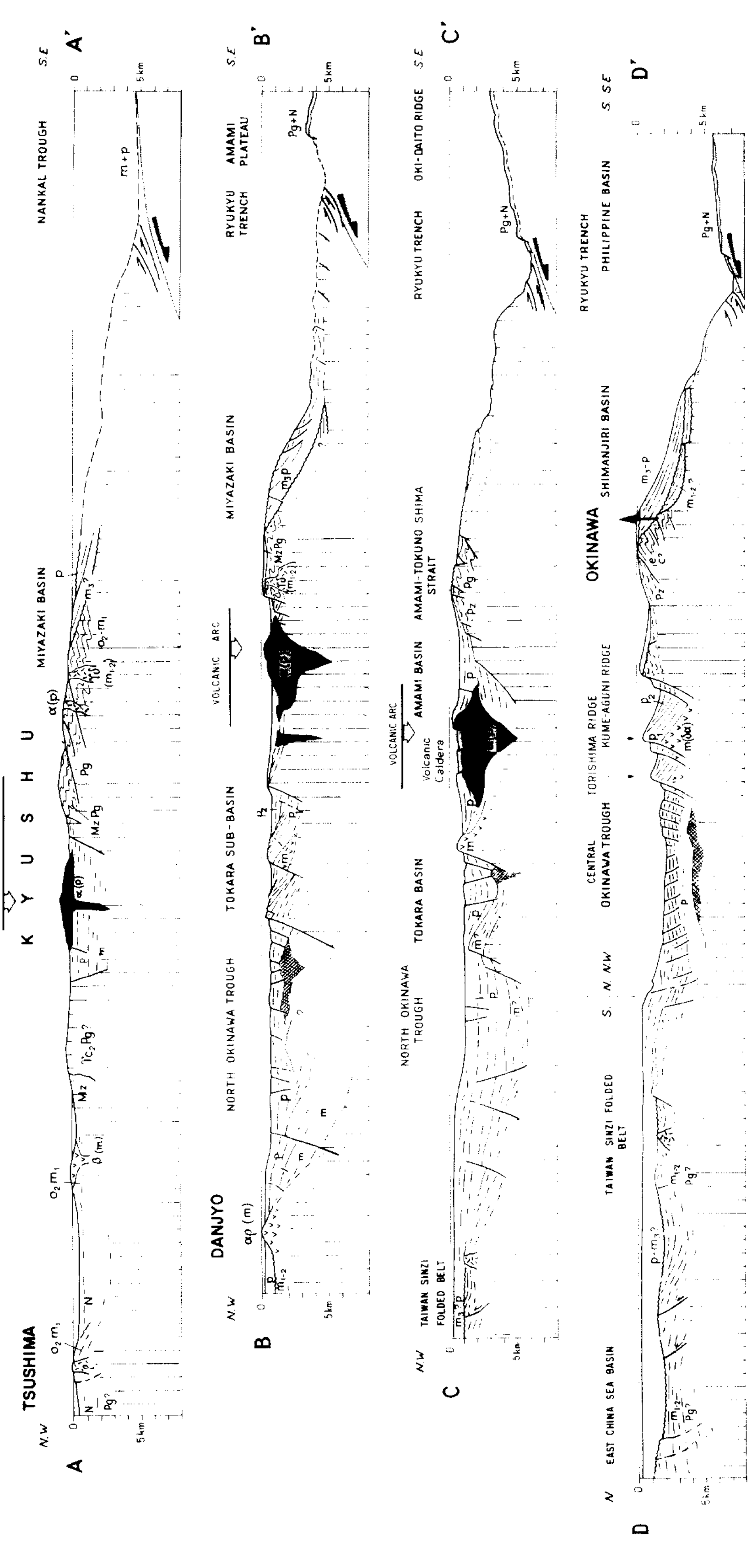
The central and north Okinawa Trough was also buried by sediments and igneous material due to Neogene igneous activity. The North Okinawa Basin is very thick, sporadically more than 8000 m (Fig. 5B, section BB′). Only minor and local unconformities are observed and the stratigraphy is uncertain. According to seismic interval velocity and acoustic characteristics, we believe that the Miocene and perhaps some Paleogene could be present in this basin. We can then suggest that this small basin could be a southwestward en échelon graben linked to the Japan Sea drifting (Fig. 6).

Prior to the latest Miocene–Pliocene main subsidence, on both sides of the present Okinawa Trough a strong erosional event affected the area. This erosion took place around 9 to 6 Ma ago (Letouzey and Kimura, 1985). In Taiwan, the regression which corresponds to the "upper coal bearing formation" is also dated around NN10–NN11 (T.C. Juang, pers. commun., 1983).

This late Miocene regional unconformity, probably due mostly to the eustatic regression, is observed beneath the whole area of the East China Sea. This unconformity corresponds to a strong erosional event, except in the center of the East China Sea Basin and toward Taiwan where horizons are parallel and the unconformity is not well defined.

In the central and northern Taiwan Sinzi fold belt below the late Miocene unconformity, the sediments are very tectonized and the seismics are not clear. This structure is probably composed of Paleogene and Neogene sediments and volcanics, folded and faulted. On the seismic profiles, it seems that prior to the late Miocene, normal faulting was rejuvenated with reverse movement and northwestward thrust

Fig. 4. Geological and structural map of the Ryukyu arc, Okinawa Trough, Taiwan and vicinity from Letouzey and Kimura (1985). *1* = Philippine Basin: *a*—oceanic crust area *b*—oceanic ridge or plateau; *2* = trench slope and accretionary complex, thick lines are the Yaeyama Ridge; *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, on the arc side of the Okinawa Basin, 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 fold belt; *8* = Luzon–Taiwan volcanic arc; *9* = Paleogene 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 spreading center; *18* = oil wells.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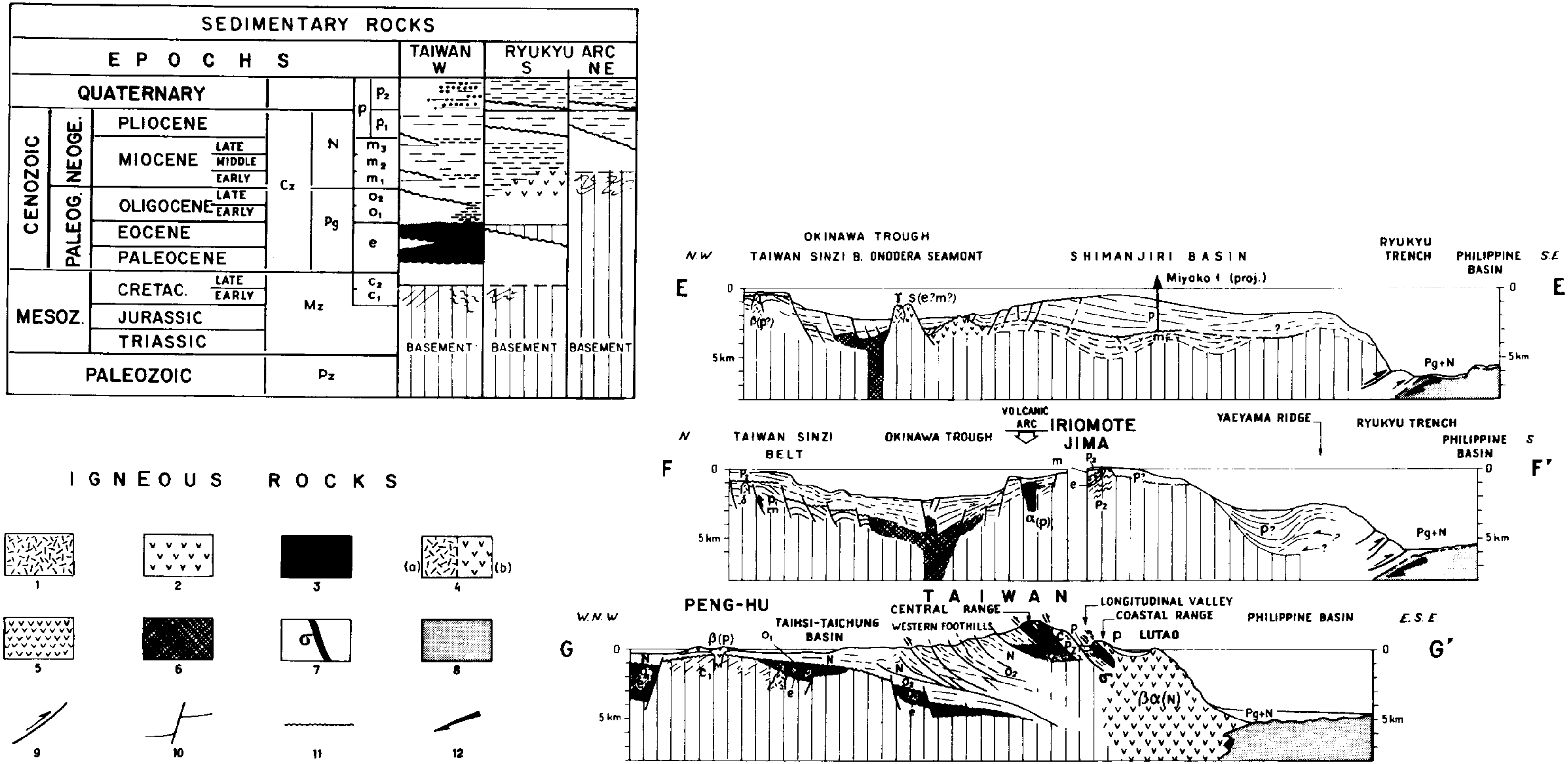

Fig. 5. Interpretative geological cross-sections based on geological data and seismic interpretation. Location is shown in Fig. 1. *1* = intrusive rocks: γ—granite; δ—diorite; *2* = extrusive rocks: ρ—rhyolite; α—andesite; β—basalt; *3* = Pleistocene to recent Ryukyu volcanic-arc igneous rocks; *4* = Miocene igneous rocks: *a*—intrusive, *b*—extrusive; *5* = Miocene–Pleistocene Taiwan–Luzon volcanic-arc igneous rocks; *6* = inferred oceanic or thinned continental crust; *7* = eastern Taiwan suture zone Lichi mélange with ultramafics; *8* = Philippine Sea oceanic crust, oceanic ridge or plateau; *9* = thrust fault; *10* = normal fault; *11* = unconformity; *12* = subduction.

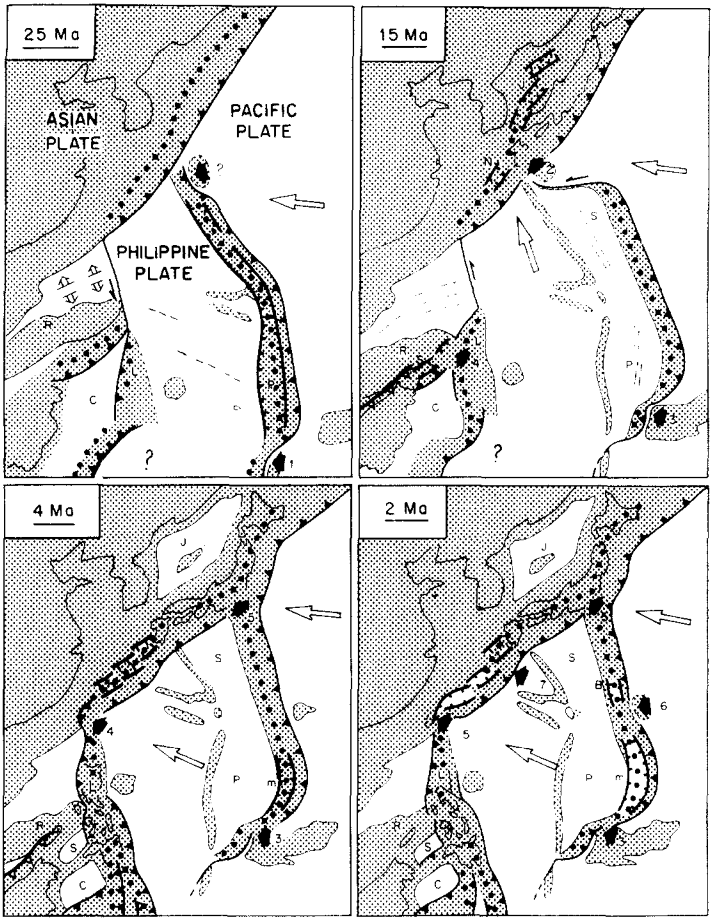

Fig. 6. Paleogeographic reconstruction of the Philippine Sea 25, 15, 4 and 2 Ma ago, based on the collision-lateral back-arc basin opening model. The Pacific plate has been moving westward with respect to hotspots since the middle Eocene (43 Ma). The motion of the Philippine Sea with respect to Eurasia at the triple junction changed from NW to WNW 10–5 Ma ago (Seno and Maruyama, 1984). Shaded areas are continents, volcanic and oceanic ridges. Letters denote: *R*—Reed Bank–North Palawan continental block, *L*—Luzon island arc, *S*—Sulu Trough, *C*—Celebes Sea, *N*—North Okinawa Trough, *J*—Sea of Japan, *P*—Parece Vela Basin, *S*—Shikoku Basin, *M*—Mariana Trough, and *B*—Bonin Trough, respectively. Broken lines indicate extinct ridges. Thrust symbols denote active trenches and thrusts, black points active volcanic arcs. Solid arrows indicate the collisions: *1*—Mapia Ridge, *2*—Palau Kyushu and inferred oceanic ridge, *3*—Caroline Ridge, *4*—North Luzon island arc, *5*—Izu–Bonin volcanic arc, *6*—Ogasawara plateau, *7*—Amami plateau–Palau–Kyushu Ridge, *8*—Philippine mobile belt, collision zones, respectively. Graben symbols indicate lateral back-arc basin opening.

(Fig. 5, section DD′). This compressional event is also observed locally below the Yellow Sea, beneath sub-horizontal late Miocene (?)–Plio-Pleistocene shallow marine shales and sandstone which covered the unconformity.

Since the late Miocene, extension has been localized in the Okinawa Trough, parallel to the Ryukyu active margin. The late Miocene–Pliocene and early Pleistocene crustal extension was of major importance in the area, involving subsidence and the formation of depocenters all along the Okinawa Trough.

Along the 1300 km length of the Okinawa Basin, only one well, Toka 1 (Fig. 4), has penetrated the whole sediment series. This drilling was located in the rifted zone along the North Okinawa central depression. In this area, a thick clastic sandy shale formation was deposited above the Cretaceous (?) substratum and some late Miocene pyroclastics and lavas (Nash, 1979). These Pliocene to Quaternary sediments interfinger in place with volcanics.

As along the western margin of the Okinawa Trough, a strong erosional event affected the whole island arc–fore-arc region before the late Miocene or early Pliocene. This angular unconformity has been observed in some islands or boreholes but also on seismic lines below the fore-arc basin sediments. Late Miocene neritic sediments with conglomerates, silts and sandstones NN10 or N16 in Okinawajima (H. Ujiié, oral commun., 1983), N17 in Miyakojima (Ujiié and Oki, 1974), NN13 (Miyako 1, borehole; J. Aiba, oral commun., 1983) are followed by turbiditic deposits in Kyushu or silty clay and sandstone upper-slope deposits in Okinawajima. This upper formation is early Pliocene (post NN11 in Okinawa, around 6 Ma) to early Pleistocene. From water drillings in Okinawa Island and outcrops in Kyushu the basal unconformity of this formation has been tilted toward the southeast (Fig. 5, sections AA′, DD′). This late Miocene unconformity or its lateral equivalent seismic horizon are now 4000 m below sealevel in the fore-arc terrace zone (Fig. 5, sections BB′, DD′, EE′). On seismic profiles the lower part of the seismic sequence show parallel or onlapping features, whereas the upper part show southeastward prograding structures. These different observations indicate a subsidence and a tilting of the fore arc since 6 Ma but without any extension.

A second major phase of crustal stretching occurred after the latest Pliocene times. En échelon cracks occurred along the Okinawa Trough. Tilting with "onlap fill" configuration and erosion on the top of the crest blocks occurred during the Pleistocene in the eastern margin (Nash, 1979). In the North Okinawa Trough, only a few local recent intrusions have been observed, and this area is only in the rifting stage. Magma may have ascended through the rift during the early Pleistocene in the south and central Okinawa Trough (Fig. 5). In the south Okinawa Trough the total sediment thickness above the acoustic substratum reaches a maximum of 3000 to 4000 m (Figs. 4 and 5). According to seismic correlations with the northeast Taiwan Shelf (Letouzey and Kimura, 1985) and the age of the spreading (Kimura, 1985), only Pleistocene sediments covered the oceanic central graben. In the latest Pleistocene a new crustal stretching, with active normal faulting and magmatic intrusions into the central grabens, was again observed.

A Pleistocene erosional surface is observed all along the arc (Figs. 4 and 5). This erosional surface outcrops in some islands and was covered by reefal limestones. It is also affected by normal faulting and southeastern tilting (Fig. 5, sections BB′ and CC′).

Thus it seems we observe a synchronism between the opening and subsidence of the Okinawa marginal basin and the tilting and subsidence of the fore-arc terrace above the trench slope. Similar subsidence of the fore-arc terrace was discovered by deep-sea drilling on IPOD legs 56 and 57, near the Japan Trench, east of Japan. We can notice that, in this example too, the subsidence of the fore-arc terrace bordering the trench is synchronous with the opening of the back-arc Japan Sea Basin. Retreat and subsidence of the Ryukyu trench line, relative to the Asian continental plate ("retreating trench" model or "anchored slab" model), could be one of the causes of the tilting of the fore arc and extension in the back-arc area.

CORRELATION BETWEEN ARC VOLCANISM, RIFTING AND SPREADING

Miocene–Pliocene volcanism—First extensional phase

The extension of the Neogene volcanism clearly indicates four magmatic provinces: in the Taiwan area the alkaline volcanism related to the South China Sea passive margin and the calc-alkaline volcanism of the North Luzon arc, and in the Ryukyu area the volcanism is related to the Philippine Sea subduction with the arc volcanism and the back-arc spreading intrusions (Figs. 3, 4, 5 and 7).

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 (NN5, Huang et al., 1978) are associated with ultramafic rocks and are incorporated in the "Lichi Mélange". These rocks have been considered to be slices from the South China Sea transform fault incorporated in the Taiwan–Luzon collision zone complex, along the longitudinal valley (Chi et al., 1981). In the eastern coastal range and islands, early Miocene and Pleistocene calc-alkaline volcanism occurred in the northern prolongation of the Luzon volcanic arc. This volcanic ridge collided with the South China margin during the Plio-Pleistocene (Fig. 6).

Along the central and northern Ryukyu Arc and southern Japan, Miocene volcanism and related acidic rocks affected a wide zone. This volcanic, pyroclastic and intrusive event is called the "Green Tuffs" episode (Fig. 7). The intrusion is 100–150 km inland from the Nankai Trough and Ryukyu Trench, and is believed to have been caused by subduction. The age datings 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). In the Okinawa Trough area the distribution of Miocene–early Pliocene volcanism (Fig. 7) is deduced from a few island outcrops, drilling, magnetism and seismic interpretation. Southward extensions of Miocene acidic intrusives outcrop along the non-volcanic Ryukyu Island Arc, in and around Okinawa and the northern islands. Pyroclastic rocks were penetrated by exploration

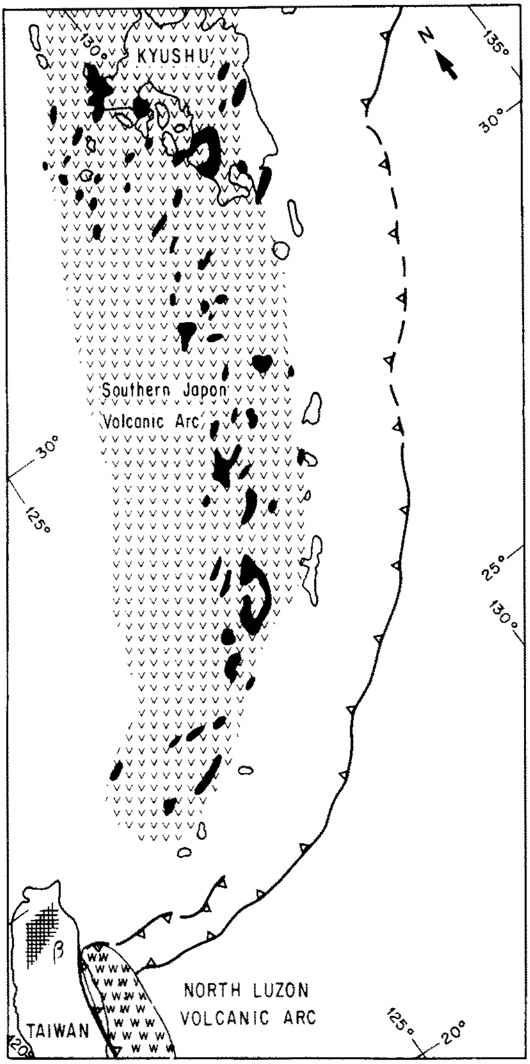

Fig. 7. Miocene and Pliocene magmatic activity: V's denote the extension of the Mio-Pliocene igneous activity (Southern Japan volcanic arc), in black the main Miocene–Pliocene intrusions, volcanoes, outcrops or tectonically uptilted igneous rocks; W's denote the north Luzon volcanic zone; early and middle Miocene basalts of Taiwan.

wells "Miyako 1" (Fig. 4 and Fig. 5, section EE′) below the Pliocene into late Burdigalian and Langhian (NN4, NN5, J. Aiba, oral commun., 1983). In the Okinawa Trough, late Miocene, Pliocene or Pleistocene volcanic rocks covered the metamorphic basement and interfinger with the sediments in the eastern or north-eastern area (Fig. 5, sections BB′, CC′, DD′). For example, near southern Kyushu, crests of half-grabens outcrop on islands, and the substratum is composed of

Miocene or to recent volcanic rocks. The same features are observed in the small islands, west of Okinawa. The basement of tilted blocks (Fig. 5, section DD′) is composed of Miocene to Pliocene (17.5–4.5 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 commun., 1983). 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).

Pleistocene to recent volcanism, second extensional phase in the Okinawa Trough

In connection with the arc–continent collision in Taiwan and spreading in the Okinawa Trough, the volcanic activity changed during the Pleistocene time.

Perhaps due to compressive stress, the west Taiwan (Peng-Hu Islands) alkaline volcanic activity stopped after the Pliocene collision. Volcanism is now inactive in the eastern Taiwan Coastal Range, which is the tectonized northern prolongation of the active Luzon volcanic arc (Fig. 5, section GG′). In this range the more recent volcanic rocks are found interbedded with Pleistocene conglomerates.

In the Ryukyu–Okinawa area, related to the Philippine subduction province, since the early Pleistocene two distinct aspect of intrusive and volcanic activity have been observed: extrusion of oceanic crust and extrusive volcanic arc activity (Fig. 3).

From heat-flow values, refraction velocity and linear anomalies, Herman et al. (1978) and Lee et al. (1980) concluded that the South Okinawa Trough is floored by sea-floor spreading basalts. Kimura (1985) extends these oceanic areas to the central Okinawa Trough (Fig. 3). From correlations between magnetic anomalies and the magnetic reversal time scale, he proposes that the crustal separation has been occurring since early Pleistocene time (around 1.9 Ma ago). The average half spreading rate is estimated as about 2 cm/year.

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 (Figs. 3, 4 and Fig. 5, sections BB′, CC′). The distribution of the Pleistocene and active volcanoes is not uniform along the Ryukyu arc. Most of these volcanoes are in Kyushu and along the North Okinawa Basin which is only in the continental rifting evolution stage. Along the central and southern Okinawa Trough where spreading has been active since the Pleistocene, the volcanic arc is not active, except a submarine volcanic explosion around 70 years ago near Iriomiote Island (Fig. 4 and Fig. 5, section FF′). The northern Taiwan Pleistocene andesitic volcanoes (Figs. 3 and 4) have been interpreted as the extension of the Ryukyu volcanic arc system (Ho, 1982) above the southeast boundary of the Ryukyu Benioff Zone. Kueishantao Island, off the northeastern Taiwan Ilan plain (Figs. 3 and 4), is an active andesitic volcano. The Ilan plain is the terminus of the southwestward prolongation of the Okinawa Basin extensional regime. The same feature is observed in the northeastern terminus of the Okinawa Trough, in the Beppu–Shimabara

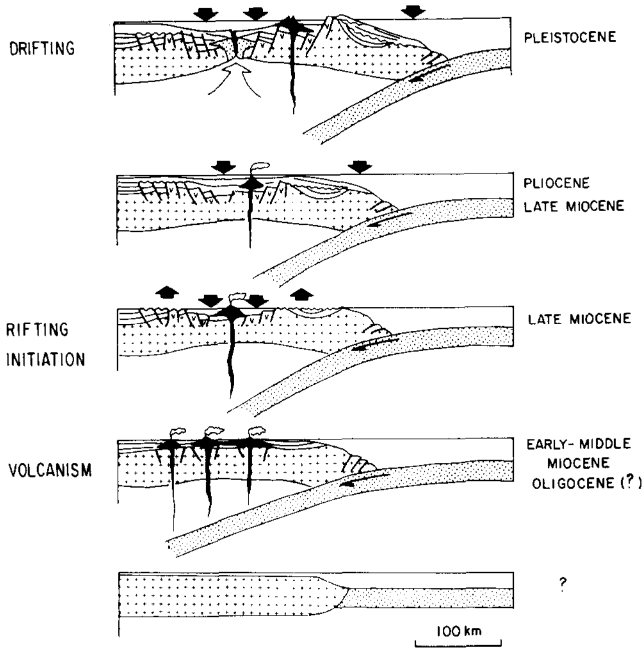

Fig. 8. Sketch of evolutionary stages in the central Okinawa Trough. Back-arc rifting was initiated in the volcanic arc. Notice the subsidence of the fore-arc terrace during the rifting and spreading of the back arc. Drifting started 1.9 Ma ago in the south Okinawa Trough and probably also in the central Okinawa Trough. We correlated this event with the collision in the Taiwan area.

graben in Kyushu, where the Unzen and Aso active volcanoes are located in the central graben of the Okinawa Trough (Figs. 3 and 4).

In summary, the break-up of the volcanic arc and the rifting of the back arc occurred and progressed in the active volcanic-arc zone. Inactive volcanism (remnant arc) should be found on the continental side of the back-arc basin. The Okinawa Marginal Basin rifting is a typical "inter-arc basin opening" (Fig. 8). It seems that the beginning of the back-arc spreading in the central and southern Okinawa Trough, corresponds to a relative minimum in the activity of the nearby volcanic arc.

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. Back-arc rifting was then initiated along the volcanic front, because the crust is weakest along the volcanic arc. The same features have been observed in the Mariana Trough opening.

CONNECTION BETWEEN THE TAIWAN COLLISION AND THE OPENING OF THE SOUTH OKINAWA BACK-ARC BASIN

The southern islands of the Ryukyu (Yaeyama Islands, Fig. 1) do not show any sedimentological and magmatic evidence of the late Paleogene–early Neogene

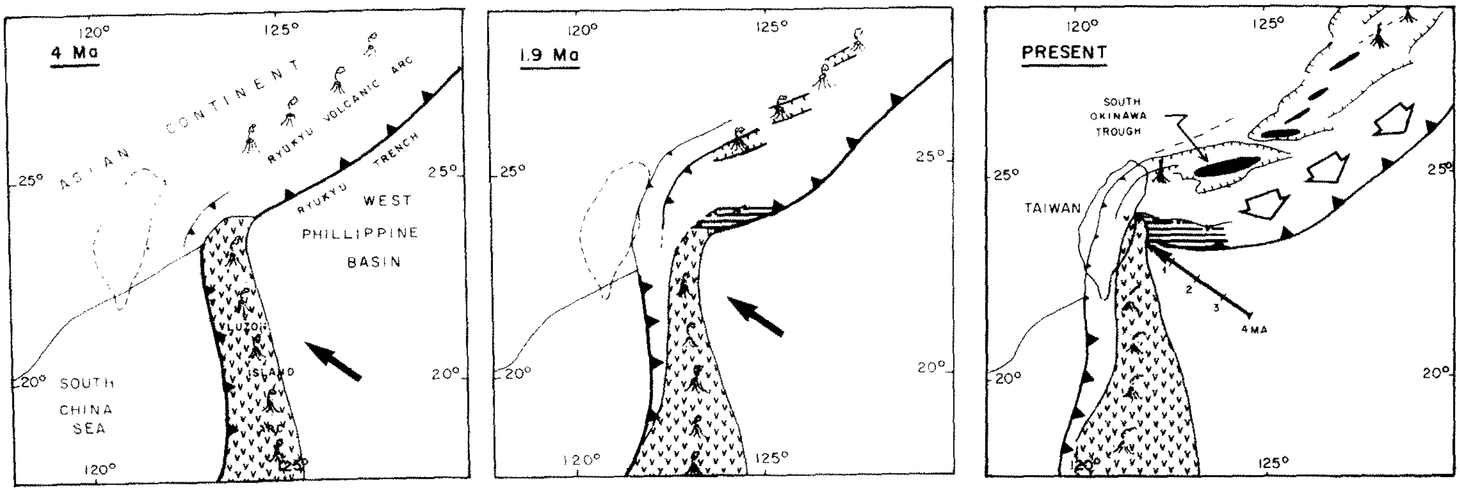

Fig. 9. Structural evolution of the north Luzon island arc–Taiwan collision zone, and Ryukyu island arc–south Okinawa Trough opening. A collision/lateral back-arc basin opening model.

The line of Miocene magmatic ascent of the Ryukyu volcanic arc, constitutes a weak zone in the Asian continent. The indentation process due to the collision of the north Luzon island arc with the Asian continental margin could have been provoked: (1) compression and thrusts on the continental side, (2) lateral extrusion and bending of the Ryukyu island arc. These deformations were counterbalanced by N–S tensional axes trending into the Ryukyu volcanic arc, (3) thermal convection, trench retreating hypothesis or the anchored hypothesis could develop and maintain active spreading in the back-arc Okinawa Trough.

Ryukyu subduction (Letouzey and Kimura, 1985). We suggest that the Miocene southern boundary of the subducted Philippine plate below the Ryukyus was situated southeast of the Yaeyama Islands, east of the present Yaeyama Ridge (Fig. 9).

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 3.5–4.0 Ma ago (Fig. 9).

Due to the rapid uplift and erosion of the Central Range in Taiwan, large amounts of sediments were deposited around Taiwan. 3000 and 4000 m of Pleistocene to recent sediments were trapped in the South Okinawa Trough (Letouzey and Kimura, 1985). More than 4000 m of middle Pliocene to Pleistocene conglomerates and terrigenous material covered the north Luzon volcanic arc (Chi et al., 1981). 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. On the eastern side of this structure, sediments coming from the Taiwan collision were also deposited in the Ryukyu Trench. We interprete the Yaeyama Ridge (Fig. 4 and Fig. 5, section FF′) as a compressional sedimentary wedge similar to the Barbados Ridge (Letouzey and Kimura, 1985). Due to uplift and erosion of the Taiwan Central Range, this ridge has progressively grown during the collision (Fig. 9).

The Taiwan–Sinzi fold belt is a complex structure which now corresponds to an elongated basement high on the continental side of the Okinawa Trough (Figs. 1, 3, 4 and Fig. 5, sections BB′–FF′). From seismic profiles interpretation north and south of this belt compressional eroded structures, trending parallel to the Okinawa Trough, were covered with flat-lying sediments. In both cases thrusts are toward the continent. But compressional events and erosion do not have the same age: Miocene in the north; Plio-Pleistocene near Taiwan. In the south the compression is clearly related to the Pliocene Taiwan collision. From seismic profiles late Pliocene thrusts and folds north of the Ilan Plain in Taiwan extend to the east in this belt (Fig. 4) and can be observed eroded below the flat-lying Pleistocene sediments (Fig. 5, section FF′).

Since around 2 Ma extension with volcanism has been observed in the Ilan Plain and along the north of the Okinawa Trough near Taiwan. Normal faulting and tilted blocks linked to the south Okinawa rifting affected the Plio-Pleistocene erosional surface. Movements along these faults seems to be synchronous with the postulated Pleistocene spreading in the South Okinawa Trough.

In summary, in the northeastern Taiwan area, the rift propagated to the west into the folds, thrusts and uplift zone generated at the beginning of 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 fold belt (Fig. 9).

The Pleistocene extension in the central part of the South Okinawa Trough could be estimated at 30 to perhaps more than 50 km. This extension decreased to the west toward the Ilan plain in northern Taiwan. Shortening due to collision in northern Taiwan has been estimated at 150–200 km (Suppe, 1980; Chi et al., 1981). These conjugated movements of extension and compression must have produced a clockwise rotation of the southern Ryukyu arc since the middle Pliocene. Paleomagnetic 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).

COLLISION AND BACK-ARC 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 motions produced by collision and indentation processes have been studied by seismology (McKenzie, 1972; Molnar and Tapponnier, 1975) and analogy with indentation experiments (Tapponnier and Molnar, 1976; Tapponnier, 1977; Tapponnier et al., 1982; Peltzer, 1983). In such experiments the influence of free lateral boundaries and anisotropy has a profound influence on the deformation pattern. Some experiments or models (Peltzer, 1983) suggest compression and shortening in front of the indenter. But with lateral free surfaces, lateral extrusion, rotation of blocks, buckling or tention gaps could be observed.

Lateral to the Taiwan collision the Ryukyu subduction zone can be considered as a free boundary. The line of magmatic ascent of the Ryukyu volcanic arc constitutes a weak zone in the Asian continent, parallel to the subduction zone. The indentation experiment suggests that the collision of the north Luzon island arc with the Asian continental margin during the Pleistocene could have been provoked (Fig. 9), first compression and thrusts on the continental side, then during the early Pleistocene the beginning of lateral extrusion and the bending of the Ryukyu island arc. These deformations were counterbalanced by N–S tensional axes trending into the Ryukyu volcanic arc. For the south Okinawa trough's stretching initiation, this model is convenient to explain the chronology and kinematics of the deformations near Taiwan. But, we believe it is not sufficient to maintain the stretching into the back-arc basin along the whole 1200 km, and only other factors such as thermal convection, the trench retreating hypothesis or the anchored hypothesis could maintain active spreading in back-arc basins.

It might be interesting to see whether the initiation of the opening of other back-arc basins in the world corresponds or not to a collision process such as in the Taiwan Okinawa model. We propose in Fig. 6 a paleogeographic reconstruction of the Philippine Sea, modified according to Seno and Maruyama (1984), in which we suggest a connection between collisions and back-arc basin opening.

(1) 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.

(2) 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. Bonin Trough, recently opened north of this plateau.

(3) The Parece Vela Basin was open from the Oligocene to middle Miocene. It is bounded to the south by the Mapia Ridge and Caroline Ridge collision zones. The Pacific–Philippine plates convergence rate is considered to be very slow in this area.

(4) The Shikoku Basin was open from latest Oligocene to early–middle Miocene. Its northern boundary is unknown because it disappeared in the Nankai subduction zone. It must be a transform zone joining the Izu–Bonin volcanic arc to the Palau–Kyushu remanent arc before the Nankai subduction.

(5) 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 its opening.

(6) 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 the 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. Collision with the north Kyushu–Palau Ridge or an oceanic plateau, now subducted, can explain the compression and the lateral opening of the Sea of Japan.

CONCLUSIONS

From the evolution of the Ryukyu arc and Okinawa Trough area the following general aspects concerning back-arc basin opening can be retained:

Collision and indentation processes could initiate the opening of a back-arc basin. But additional phenomena such as thermal convection, retreating trench model or anchored-slab model are indispensable to maintain extension in the back-arc basin. These latter phenomena could explain the tilting and subsidence of the fore-arc terrace, above the trench slope, which is synchronous with the opening and subsidence of the fore-arc basin.

The rifting and the spreading of the back-arc basin occurred and propagated into the weak crustal zone constituted by the active volcanic arc. The beginning of back-arc spreading seems to correspond to a relative minimum in the activity of the volcanic arc.

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