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Early Pleistocene birth of the Okinawa Trough and Ryukyu Island Arc at the northwestern margin of the Pacific: evidence from Late Cenozoic planktonic foraminiferal zonation

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Abstract

Widespread development of the upper Pleistocene Ryukyu Limestone suggests the occurrence of prototypes of the Okinawa Trough and Ryukyu Island Arc, backarc-basin and forearc at the northwestern margin of the Pacific, before its deposition. Prior to the deposition, however, bathyal sediments of the Shimajiri Group were distributed over the arc region. On southern Okinawa Island, this group is divided into 11 planktonic foraminiferal zones, some of which may be not globally valuable but regionally useful, ranging in age from late Pliocene to earliest Pleistocene. This zonal scheme is applied to zoning 421 outcrop samples and a geologic map is successfully obtained. The map indicates the development of many faults that cut only the Shimajiri Group but not the overlying Ryukyu Limestone and majority of these faults run in perpendicular to the arc extension. Similar faults are also recognized in the lower Pliocene to lowermost Pleistocene Shimajiri Group on Miyako Island (southern Ryukyu Island Arc), in a submarine seismic profile, which was correlated with well stratigraphy, at the east of Miyako Island, and in the upper Pliocene to lowest Pleistocene Somachi Formation on Kikai Island (northernmost central arc). The structures observed in the Shimajiri Group and its equivalent may have been formed by an upward warping of the arc region associated with subsidence of the trough region. Considering the pre-Shimajiri basement geology as a whole, therefore, it is concluded that the initial appearance of this backarc basin and forearc occurred after the deposition of the Shimajiri and before that of the Ryukyu Limestone during the late Pleistocene ($\sim$1.7–0.5 Ma).

1. Introduction

The Ryukyu Island Arc extends about 1200 km between the southern Japanese Islands and Taiwan at the northwestern margin of the Pacific and is now fringed by coral reefs because the >2000 m deep Okinawa Trough traps enormous amounts of terrigenous materials from the Chinese Continent (Fig. 1). Terrigenous supply prohibits the flourishing of reef-building corals due to suffocating coral polyp itself and to shading solar light for symbiont algae. The coral reef development was initiated during late Pleistocene and formed the Ryukyu Limestone. Before the Ryukyu Limestone deposition, however, no reefal facies was developed but the Shimajiri Group of bathyal sediments was broadly developed.

This drastic paleoceanographic change from bathyal to coral reef environments should have been caused by the initial formations of the Okinawa Trough backarc basin and also of the Ryukyu Island Arc after the deposition of the Shimajiri Group and before that of the Ryukyu Limestone. To validate this hypothesis (Ujiié, 1980), the geological structure of the Shimajiri Group must be clarified. The Okinawa Trough has

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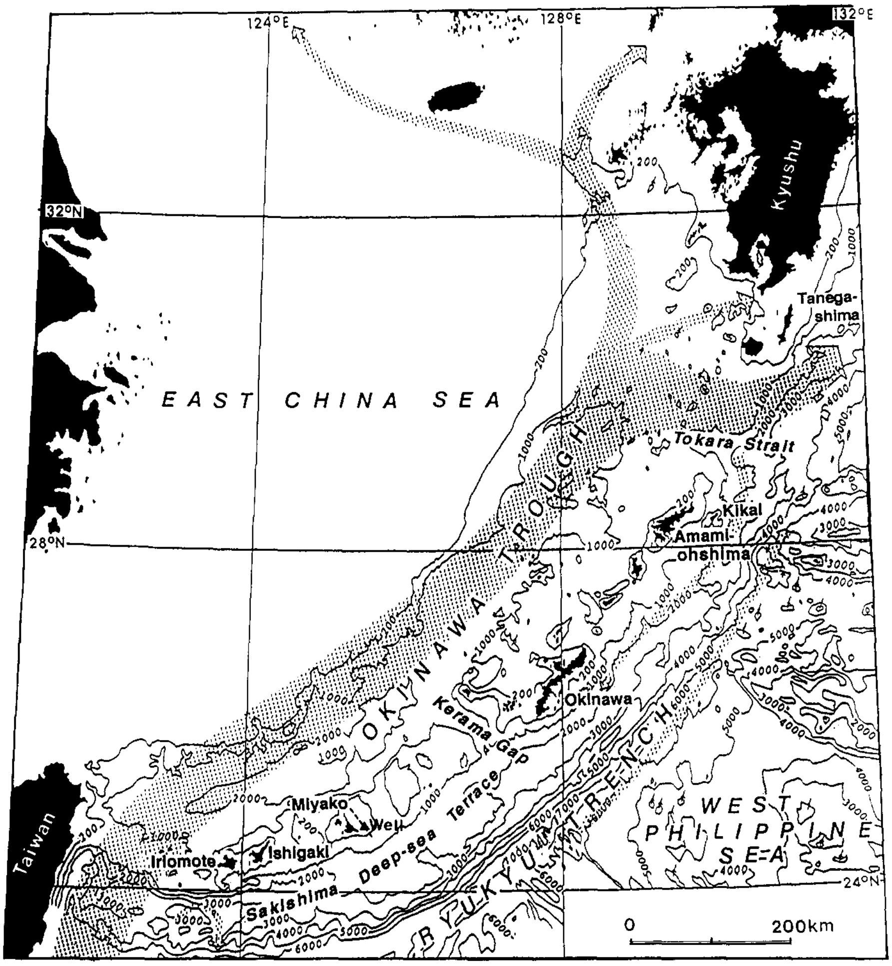

Fig. 1. Physiographic map of the studied region. Stippled arrows show the Kuroshio Current system; bathymetric contour lines in meters.

been of interest to many earth scientists, particularly after the finding of active hydrothermal vents at its central graben (e.g., Kimura et al., 1988; Halbach et al., 1989). Continuing submarine surveys, however, have concentrated in the central areas of the trough, where sedimentation rate is too fast so that no information concerning the Shimajiri Group equivalent has not been obtained. Oil companies have also interested in the Okinawa Trough and its surrounding region for prospecting petroleum and natural gas resources and obtained many seismic profiles. Some results were merely summarized as large-scaled isopach maps of the Shimajiri Group and other layers by Aiba and Sekiya (1979) and Nash (1979). The majority of these profiles, however, were not published so that their stratigraphic interpretations could not be evaluated. At least their stratigraphic correlations were not precise because of the paucity of submarine drilling (up to three).

Fortunately, however, the Shimajiri Group is well exposed on the southern half of Okinawa Island. Although the exposed rocks are composed essentially of massive mudstone and then ordinary field survey cannot reveal the geological structure, the mudstone is plentiful in well-preserved planktonic microfossils so that the Shimajiri Group can be divided into many fossil zones based on integrated knowledge of planktonic microbiostratigraphy. The zonation of a number of outcrops scattered on surface may clarify the geologic structures. Similar procedure is made on the Shimajiri Group equivalents on Miyako Island, southern Ryukyu Arc, and on Kikai Island at the northern end of the central Ryukyu Arc.

2. Geographic setting

The Ryukyu Island Arc extends for about 1,200 km between Taiwan and Kyushu, southern end of the Japanese Islands and is separated from the East China Sea shelf by a backarc basin, Okinawa Trough (Fig. 1). The arc can be divided into three segments (northern, central and southern arcs) by the Tokara Strait and Kerama Gap, respectively. The northern and central arcs face directly the Ryukyu Trench, while the southern arc faces the trench beyond the Sakishima Deep-sea Terrace that has a rugged surface deepening from ~2000 m at the northeast to ~4000 m at the southwest.

The Kuroshio Warm Current crosses the southern end of the Ryukyu Island Arc, flows northeastwards along the northwestern margin of the Okinawa Trough and passes away eastward through the Tokara Strait.

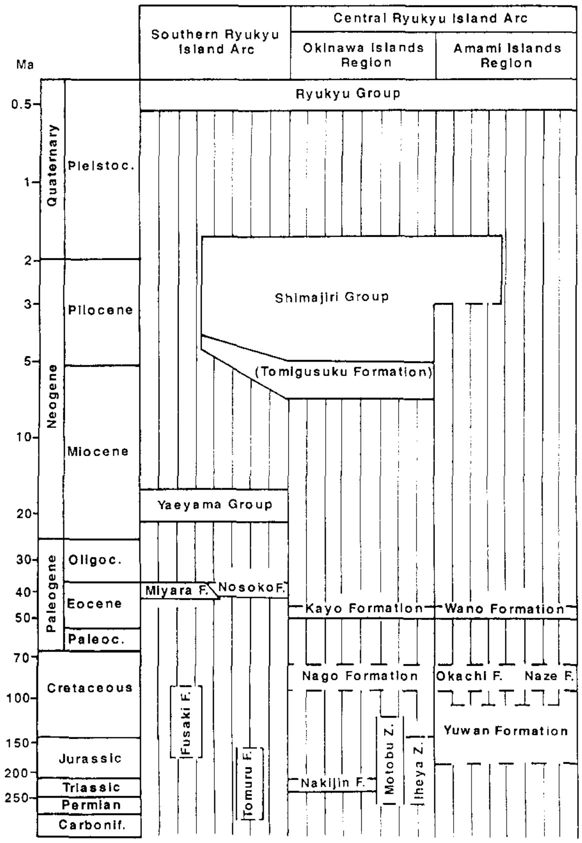

Fig. 2. Stratigraphic correlation chart.

3. Brief notes on basement rocks

The basement rocks are here assigned to rocks formed before the deposition of the Shimajiri Group, because these rocks were incorporated into the continent or continental shelf complex during a large time gap of sedimentation; ~36 m.y. in the central Ryukyu Island Arc and ~6 m.y. in the southern arc (Fig. 2).

4. Central Ryukyu Island Arc

In the central arc (particularly in the Okinawa Islands region), the basement rocks consist of five zones resulting from accretionary processes analogous to the Outer Belt of Southwest Japan (Ujiié and Nishimura, 1992). The innermost (northwesternmost) belt, called the Iheya zone, is represented by large-scaled folding, axes of which were inclined northwestward at high angle. Anticlinal cores are composed of Permian chert, while synclinal portions mostly of Jurassic sandstone-predominant layers according to field survey and radiolarians (Ujiié and Oba, 1991). On Ie Island at the southeasternmost site within this zone, the earliest Cretaceous accretionary prism overthrusted on by a Triassic through upper Jurassic pelagic chert mass that remains as a prominent peak in the middle of this island.

Rather gently inclined Nakijin Formation is developed at the southeast of the Iheya Zone beyond a channel. The lower half of this formation consists of recrystallized limestone, whereas the upper half is composed of Carnian fossil-bearing marly limestone associated with shale, a thin bed of chert and andesite sills (Ishibashi, 1988).

The Nakijin Formation has been regarded as to thrust on the Motobu Zone at the southeast. The Motobu Zone also contains many northwesterly inclined thrusts and sheared zones and represents an early? Cretaceous olistostromal complex. Olistoliths of Permian to Triassic limestones, cherts and greenstones are included in Valangian to Barremian radiolarians-bearing matrix (Fujita, 1980).

At the southeast of the Motobu Zone, black phyllite dominant facies is broadly developed as the Nago Zone. Although this zone was extensively sheared owing to the facies, good exposures along a few deep gorges show the development of many northwesterly inclined thrusts. Hashimoto and Nakagawa (1978) distinguished there four formations depending upon the insertions of greenrocks (restricted on the northwestern area) and of sandstone layers and presumed many faults running in northeast to southwest, i.e., perpendicular to the zonal structure trend. Unfortunately, however, the detailed map has not yet been published.

As the outermost zone, the Kayo Formation is well exposed on sea-cliff faced to the Philippine Sea. This zone is typical forearc thrust-fold belt composed of trench-filled turbidite (Ujiié, 1989). Intercalated debris flow deposits contain numerous black slate chunks, a few orthoquartzite pebbles, and rarely fragments of *Nummulites* belonging to lower Lutesian species (Suzuki and Ujiié, 1985). The Kayo Formation is thus dated as Middle Eocene age because these fragmental nummulites were not aggregated as limestone chips but always isolated implying nearly synchronous supply from continental shelf to trench bottom where the Kayo Formation was deposited.

Equivalents to the Kayo Zone can be traced far northeastward as the Wano Formation on Amami-ohshima, as the Kumage Group on Tanegashima (northern Ryukyu Island Arc), and as the older Shimanto Belt in Southwest Japan. Contrast to Southwest Japan, the younger Shimanto Belt (e.g., Taira et al., 1989) is not observed on land of the Ryukyu Island Arc. Whether the younger Shimanto Belt and the later sediments were not deposited in the arc region or obducted, cannot be decided at present.

So far as the land-based geology is concerned, I postulated that the above-mentioned five step subduction–accretion process ceased during late Eocene time and may have been incorporated to the continent until the marine transgression depositing the Shimajiri Group which started at $\sim$8 Ma. During the $\sim$36 m.y. time-gap, this newly built continent was peneplaned. Evidence of this peneplanation has remained as a ridge-line with the same altitude in mountainous region of the northern half of Okinawa Island and also as an entrenched meander which should have flowed on a large land mass like continent. This meander has been retained as a $\sim$4 km long and $\sim$150 m broad channel between the Unten Port and Haneji Inland Sea on northern Okinawa, because the area is composed of hard basement rocks belonging to the Motobu Zone.

5. Southern Ryukyu Island Arc

In contrast to the central Ryukyu Island Arc, pre-Tertiary basement rocks on Ishigaki and Iriomote Islands of the southern Ryukyu Island Arc are composed of a high-pressure metamorphic rocks (Tomuru Formation) and a weakly metamorphosed olistostromal complex (Fusaki Formation) which was overthrust by the Tomuru Formation. Based on white mica K–Ar age determinations, Nishimura et al. (1990) considered that metamorphism occurred during the Late Triassic to Early Jurassic for the Tomuru Formation and during Early Cretaceous for the Fusaki Formation. This pair can be correlated to that of the high P/T Suo metamorphic rocks and the olistostromal Kuga Group in Yamaguchi Prefecture in the Inner Belt of Southwest Japan (Isozaki and Nishimura, 1989), respectively, from analogous lithology, metamorphism ages and geologic structures. Basement rocks comparable to the Outer Belt of Southwest Japan are not exposed on the southern Ryukyu Island Arc but postulated to occur beneath the Sakishima Deep-sea Terrace. Ujiié (1985b) and Isozaki and Nishimura (1989), therefore, estimated a dislocation between basement rocks of southern and central arcs by a left-lateral slip fault along the Kerama Gap.

Pre-Tertiary basement on Ishigaki and Iriomote Islands is unconformably covered with the Miyara Formation which consists essentially of reefal limestone containing Priabonian larger foraminifera such as *Nummulites saipanensis*, *Pellatispira madraszi*, and so on (Ujiié and Miyagi, 1973). These upper Eocene neritic layers dip gently ($< \sim 30°$) southwestwards. The upper sandy facies of the Miyara Formation is conformably overlain by volcaniclastic rocks of the Nosoko Formation which contain altered dacitic to andesitic lava and dikes (Shirao et al., 1976). Part of the Nosoko experienced weak contact metamorphism by the early Miocene Omoto granitic stock (Kizaki, 1985). These rocks and formations are limited in the Ishigaki Island region in contrast to the Yaeyama Group.

The coal-bearing Yaeyama Group is broadly distributed over the southern Ryukyu Island Arc including its northern sea-bottom near Miyako Island. An oil-prospecting well at the east of Miyako Island revealed that a ~ 30 m thick limestone is intercalated between two coal-bearing layers belonging to the Yaeyama Group (Tsuburaya and Sato, 1985; Fig. 8). This limestone is plentiful in Burdigalian larger foraminifera (Ujiié, 1986). Late Early Miocene epicontinental sediments of the Yaeyama Group are gently ($< 20°$) inclined everywhere indicating that the southern Ryukyu Arc has not been affected by strong crustal movement. Even after the Shimajiri Group sedimentation started beyond a ~ 6 m.y. gap, a large area of the Ishigaki to Iriomote Island region has continuously been emerged until the present so that a Miocene-type wild cat has survived in native forests of Iriomote Island.

6. Shimajiri Group

The Shimajiri Group was recognized throughout the Ryukyu Island Arc under the name of Shimajiri Beds by Hanzawa (1935). This predominantly mudstone unit is gently inclined ($< \sim 4°$ in average) and separated into blocks by faults. Besides, most of this group is un-conformably covered with the Ryukyu Limestone (= Riukiu Limestone of Hanzawa, 1935). For a micropaleontologic study of the Shimajiri Group, therefore, I chose Okinawa, Miyako and Kikai Islands where many outcrop samples and a considerable number of well cores were available.

The Shimajiri Group is best exposed on the southern half of Okinawa Island, although the majority of outcrops consist of homogeneous mudstone rich in microfossils. Tanaka and Ujiié (1984) obtained a standard calcareous nannoplankton and planktonic foraminiferal biostratigraphic sequence from southern Okinawa Island. The sequence ranges from CN9a to CN13a of the Okada and Bukry (1980) nannoplankton zonation and also from N16 to N22 of Blow's (1969) planktonic foraminiferal zonation. A good correlation was recognized between both zones, even though there are some discrepancies between the respective zone boundary ages assigned by Haq (1983) for nannoplankton zonation and the corresponding foraminiferal one. This problem is not discussed here, because the main purpose of this paper is to clarify the geologic structures of the Shimajiri Group based on planktonic foraminiferal zoning of numerous spot samples from scattered surface outcrops. Calcareous nannoplankton is inadequate for such work, since the younger occurrences of these minute fossils due to reworking make it difficult to define true first or last appearance datum levels so far as spot samples are concerned.

7. Planktonic foraminiferal zonation

Tanaka and Ujiié (1984) obtained a biostratigraphic sequence (Fig. 3) of the Shimajiri Group (~ 1800 m total thickness) on the southern Okinawa Island based upon 52 samples from outcrops for the upper half and 20 samples from a natural gas prospecting well (Ryusei Well No. 2; R2 in Fig. 5) for the lower half, the majority of which is developed underground. Concerning 47 species, subspecies and varieties of planktonic foraminifera, Ujiié (1985a) indicated their stratigraphic ranges with logarithmic expression of relative abundances. Nearly all the taxa were also

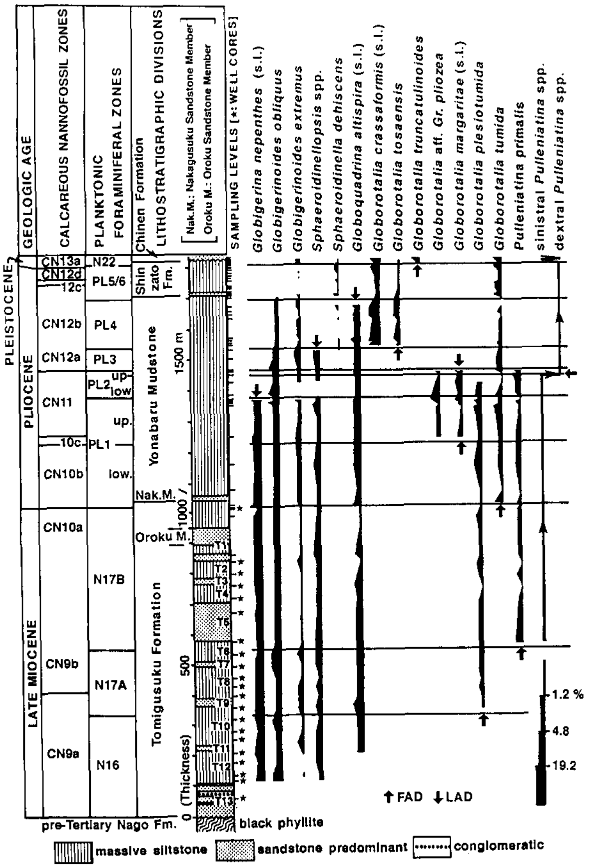

Fig. 3. Standard section of the Shimajiri Group along with stratigraphic ranges of index planktonic foraminiferal taxa. Calcareous nannoplankton zones after Tanaka and Ujiié (1984); sample levels modified from Tanaka and Ujiié (1984) and Ujiié (1985a).

illustrated as SEM micrographs along showing their morphologic variations.

As a result, 11 planktonic foraminiferal zones were distinguished as indicated in Fig. 3, where stratigraphic positions of sampling levels for the Yonabaru and Shinzato Formations shown by Tanaka and Ujiié (1984) and Ujiié (1985a) were here corrected, because it became evident that this sampling route obliquely crosses nine faults after a detailed geologic map was accomplished by Ujiié (1988). The zoning is based on the following datum levels (in ascending order):

(1) First appearance datum (FAD) of *Globorotalia plesiotumida* Blow and Banner at the N16/N17 boundary of Blow (1969).

(2) FAD of *Pulleniatina primalis* Banner and Blow. Kennett and Srinivasan (1983) subdivided N17 into N17A and N17B by this datum.

(3) FAD of *Globorotalia tumida* (Brady) at the N17/ N18 boundary.

(4) FAD of *Globorotalia margaritae* Bolli and Bermúdez. This datum can divide PL1, the lowermost unit of Berggren's (1973, 1977) Pliocene subdivision, into the lower and upper subunits at least in the Shimajiri section. This species is closely associated with *Globorotalia* aff. *Gr. pliozea* of Ujiié (1985a) in exhibiting almost simultaneous first and last appearances. Since the latter species occurs rather abundantly, its finding makes it easy to recover *Gr. margaritae*, which is rather rare, from added samples.

(5) Last appearance datum (LAD) of *Globigerina nepenthes* Todd between PL1 and PL2.

(6) Rapid shift from left- to right-coiling populations in the *Pulleniatina*-complex within PL2, which is thus subdivided into the upper and lower subunits. This shift occurred just above the Cochiti Event of the Gilbert Epoch in piston cores from the equatorial East Pacific Ocean by Hays et al. (1969) who also reported LAD of *Globigerina nepenthes* at the upper boundary of the Cochiti Event. In the Shimajiri section, however, there is a distinct lag in stratigraphic positions between LAD of *G. nepenthes* and the *Pulleniatina* coiling shift due to the much faster sedimentation rate in the Shimajiri Group. Saito (1976) recognized this shift slightly above the upper boundary of the Cochiti in piston cores from equatorial Indian, East Pacific and Atlantic Oceans, respectively, although it occurs slightly below the boundary in another core from the equatorial East Pacific. Saito (1976) also indicated coiling fluctuation of *Pulleniatina*-complex during the Matuyama Epoch. For the Shimajiri section, however, the right-coiling populations predominated throughout after the shift in PL2 until the the base of N22 so that it was easy to discriminate this event in spot samples from scattered outcrops.

(7) LAD of *Globorotalia margaritae* between PL2 and PL3.

(8) FAD of *Globorotalia tosaensis* Takayanagi and Saito at the upper limit of N19. In the Shimajiri Group, FAD of *Gr. tosaensis*, whose

occurrence is usually rare, is almost always associated with FAD of its "ancestor", *Globorotalia* (*s.l.*) *crassaformis* (Galloway and Wissler) that is usually abundant. After finding *Gr. crassaformis*, therefore, I could easily recover the presence of *Gr. tosaensis* from added samples.

(9) LAD of *Sphaeroidinellopsis* spp. at the PL3/PL4 boundary. This boundary just fits with the N19 base in the Shimajiri section same as the definition by Berggren (1973, 1977). Lately, however, Berggren (1984) correlated the PL3/PL4 boundary with the N19/N20 boundary. The latter boundary was assigned by the first appearance datum of *Neogloboqaudrina acostaensis pseudopima* (Blow) according to Blow (1969) but has been doubted by authors (e.g., Brönnimann and Resig, 1971; Ujiié, 1975) as well as in this study.

(10) LAD of *Globoquadrina altispira* (Cushman and Jarvis) between PL4 and PL5.

(11) FAD of *Globorotalia truncatulinoides* (d'Orbigny) between PL6 and N22. This datum is associated with a tentative shift from right- to left-coiling *Pulleniatina* populations.

The Pliocene subdivisions by Berggren (1973) are based on the last appearance datum planes of five taxa so that there may remain a problem of how to discriminate the difference between a phylogenetic disappearance and a "postponed" occurrence due to reworking. For the Shimajiri section, however, the last appearances of three index taxa were expressed by abrupt disappearances just after their continuous and abundant occurrences (Fig. 3) and PL1/PL2, PL2/PL3 and PL4/PL5 boundaries were thus well defined. Different from these, PL5/PL6 boundary defined by LAD of *Globorotalia miocenica* Palmer was not observed, because this species is an equatorial Atlantic species (Kennett and Srinivasan, 1983; Bolli and Saunders, 1985). Instead, PL1 and PL2 were subdivided into upper and lower subunits by FAD of *Gr. margaritae* and by coiling shift in *Pulleniatina*-complex, respectively. Including N17 subdivision to A and B, therefore, 11 planktonic foraminiferal zones were distinguished as summarized in Fig. 3.

Recently the accuracy of such planktonic foraminiferal datum levels as mentioned above has been discussed on the basis of their correlation with paleomagnetic stratigraphy in deep-sea drilling cores taken by DSDP and ODP projects (e.g., Weaver and Clement, 1987; Dowsett, 1989; Hills and Thierstein, 1989; Jenkins and Gamson, 1993). Strikingly diachronous first and last appearance datum level of *Globorotalia margaritae* were pointed our by Weaver and Bergsten (1991). This first appearance datum level was regarded as one of the Miocene/Pliocene boundary markers by Bolli and Saunders (1985), while the same datum is here used for subdividing PL1 into two subunits in the Shimajiri section. Similar, but in less extent, diachrony was indicated for the LAD of *Globigerina nepenthes*, LAD of *Globoquadrina altispira*, FAD of *Globorotalia tosaensis*, FAD of *Globorotalia truncatulinoides*, or FAD of *Globorotalia tumida* by Weaver and Clement (1986), Dowsett (1989), and Hills and Thierstein (1989).

When these events were observed in a single core treated by these authors, however, their successive occurrences are always in order. It suggests that the events are useful for zonation within a somewhat restricted region. The eleven datum levels used here, therefore, are available to subdivide the Shimajiri Group and also two drilling cores at DSDP Sites 292 and 296, both from the West Philippine Basin (Ujiié, 1975; Keller, 1979). The reasonableness of this procedure will be demonstrated by a fact that stratigraphic thickness of each planktonic foraminiferal zone observed in the standard section is maintained nearly throughout Okinawa Island as shown below.

8. Geologic Structure of the Shimajiri Group

8.1. Okinawa Island

The Shimajiri Group is well developed on the southern half of Okinawa Island. The Tomigusuku Formation, the lower half in ca. 1800 m total thickness, consists of alternation of seven sandstone-predominant layers and six mudstone-predominant layers. These layers were numbered from T1 to T13 (odd number means sandstone-rich layer; even number mudstone-rich layer) in descending order, respectively, by Okinawa Natural Gas Prospecting Group (1971) and effectively used for correlation between seven natural gas prospecting wells (Natori and Kageyama, 1987). This complete sequence was recovered in Ryusei Well No. 2 (R2 in Fig. 5), and has been traced to an adjacent well (RW), which was drilled in 1991 for hot-spring prospecting, by Ujiié. Only two top layers (T1 called the Oroku Sandstone Member and its subjacent T2) are exposed on surface in several areas separated one another. The Oroku Member consists usually of rather massive fine- to medium-grained sands and exceptionally shows slumping structure (Fig. 4b). The upper half of the Shimajiri Group is divided into the Yonabaru Mudstone and Shinzato Formation. The Nakagusuku Sandstone Member occupying the base of the former formation consists of turbidite sands with ~3–8 m (exceptionally ~40 m) thickness and is distributed over the studied region for ~40 km distance in leaving slumping structure at many places (Fig. 4c). The Shinzato Formation is also composed of mudstone, even though Makino and Higuchi (1967) called it the Shinzato Tuff, and separated only by a basal coarse-grained sand through pumiceous sand to pumiceous tuff bed from the Yonabaru Mudstone. This basal bed is variable in lithofacies and thickness in different places. The top of the Shinzato Formation is exposed only on Chinen Peninsula, where the muddy facies of the Chinen Formation of the Ryukyu Group overlies with a submarine erosion surface (Tanaka and Ujiié, 1984). The majority of the Ryukyu Group consists of reefal facies and covers the various horizons of the Shimajiri Group, sometimes accompanying with calcareous sand facies of the Chinen Formation.

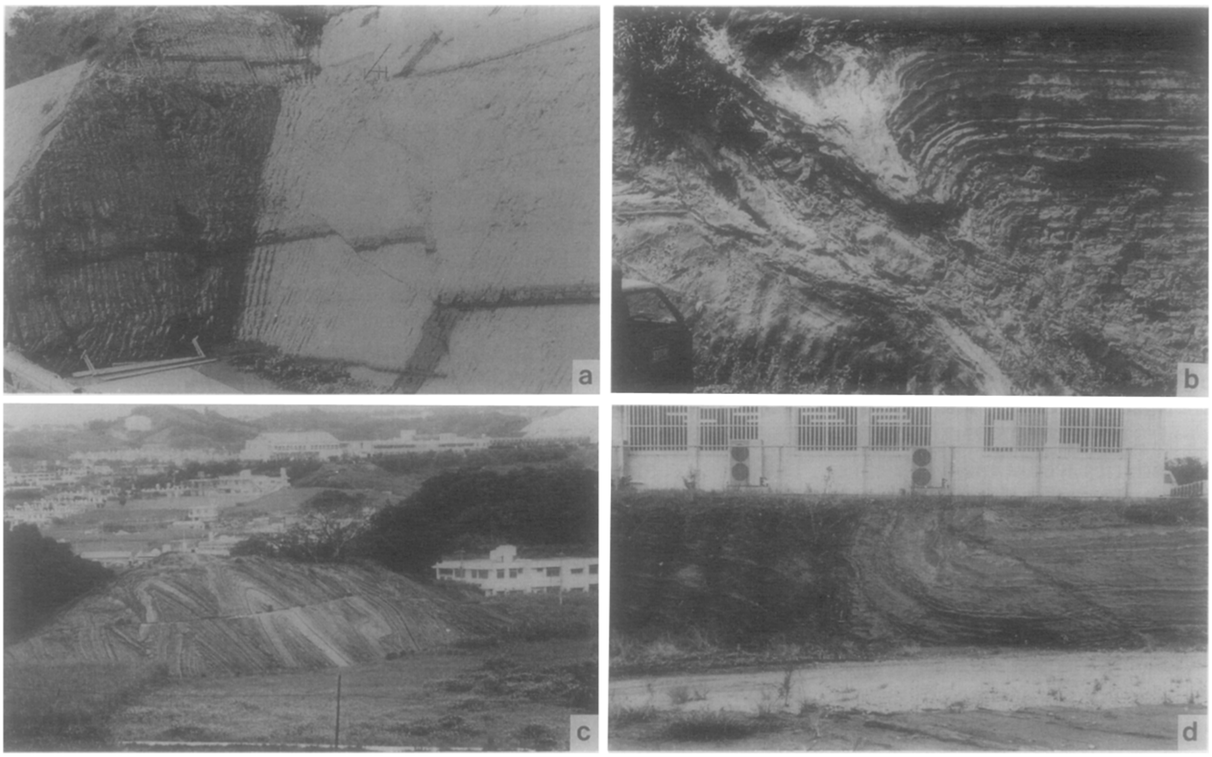

Fig. 4. Representative outcrops of the Shimajiri Group. a. Basal part of the Yonabaru Mudstone showing conjugated minor faults that clearly cut thin volcanic ash beds (close to the University campus). b. Thrust-like fault caused by submarine sliding in the Oroku Sandstone Member (location indicated as α in Fig. 6). c. Large-scaled slumping structure observed in the Nakagusuku Sandstone Member (δ). d. Normal fault bounded the mudstone-rich facies (left side) from sandstone-rich facies (right side) of the Oroku Member (β). By a ground construction performed after publication of the geologic map (Ujiié, 1988), this fault was exposed just on the northern extension of a fault presumed by the dislocation of planktonic foraminiferal zone boundaries.

The Shimajiri Group broadly exposed on surface is composed of massive mudstone with numerous (over a hundred?) and thin (usually less than ~ 1 cm) volcanic ash beds, glass shards of which are not useful for correlation because of progressed decomposition. Besides, many small conjugate faults are well developed particularly in the lower part (Fig. 4a). The general dip of the Shimajiri Group is less than $\sim 5°$ as shown in Fig. 5 for an example and its strike is in NE–SW.

Fortunately, however, mudstone of the Shimajiri Group is always plentiful in well-preserved planktonic microfossils as anticipated from its bathyal benthic foraminifera setting (LeRoy, 1964). Therefore, the above-mentioned scheme of planktonic foraminiferal zonation could be applied on 421 samples from outcrops and a geological map was accomplished as shown in Fig. 6 (simplified from a 1:50,000 color map by Ujiié, 1988). Areal dislocation of zone boundaries indicate a shift by fault, although its presence has not been recovered by normal field survey, except a case (Fig. 4d) that was recovered as a result of underground construction after publication of the geologic map. The map reveals development of many faults, particularly those across the NE-SW extension of the Ryukyu Island Arc. Its largest vertical throw is estimated as ~ 150 m. These faults also cut the Nakagusuku Sandstone Member (only a lithologic marker bed). It must be mentioned that all these faults ("fault a"; FA in Fig. 5) do not cut the Ryukyu Group and are discordant to faults ("fault b"; FB) developed in the Ryukyu Limestone, maximum vertical throw of which is less than ~ 50 m. Therefore, "fault a" acted before the deposition of the limestone and after that of the Shimajiri Group. A crustal movement can be presumed during a gap between ~ 1.8 Ma (latest age for the Shimajiri Group) and ~ 0.6 Ma (earliest ESR and U–Th age for the Ryukyu Limestone equivalent on Kikai Island; Omura, 1988). The movement produced an upward warping of the Ryukyu Island Arc and "fault a".

8.2. Miyako Island

On Miyako Island ca. 250 km southwest of southern Okinawa Island, outcops of the Shimajiri Group are nearly limited on its northeastern coast (Fig. 7a). Because general bedding is gently (less than a few degrees) inclined southeastwards, the older layers outcrop at the more northwestern side. The lowermost bed around the village of Shimajiri consists mainly of sandy mudstone which not contain enough amounts of planktonic fossils but of inner neritic mollusks. Even a Pliocene-type elephant, *Trilophodon* sp., was discovered from this formation (Hasegawa et al., 1973). Ujiié and Oki (1974) divided the Shimajiri Group into the Nanseien Formation (including the above inner neritic facies), Yonahama Mudstone (plentiful in planktonic microfossils), and Minehara Alternation (turbidite), in ascending order. Ujiié and Oki (1974) tried to obtain a continuous columnar section of these formations for planktonic foraminiferal zonation but failed to do it because many faults break the continuity. In the present work, I re-examined the same materials from more integrated knowledge on microbiostratigraphy, correct its earliest zone as to be the lower PL1 from N17 and recognized eight zones; i.e., lower PL1 through N22.

The majority of Miyako Island is covered with thick (< ~ 50 m) Ryukyu Limestone that dips very gently ($\sim 2°$) southwestwards and was cut by several step faults. These faults generally run in NW to SE in forming questa topography that accentuates flat surface of this island. Rain-waters easily pass through the surface composed of rather porous limestone and are reserved at the basal part of the Ryukyu Limestone above the impermeable mudstone of the Shimajiri Group. Many drilling have thus been performed to prospect the underwater throughout the island. 43 mudstone cores from these wells penetrated down to the Shimajiri were utilized for planktonic foraminiferal analysis (locations are indicated by solid triangles in Fig. 7).

Fig. 7b is a geologic sketch map based on planktonic foraminiferal zonation of these well cores and of 60 outcrop samples including those of Ujiié and Oki (1974). The figure obviously indicates that the Shimajiri Group was dislocated by many faults ("faults a") place by place. Although the precise location of these presumed faults could not be decided because of limited data from

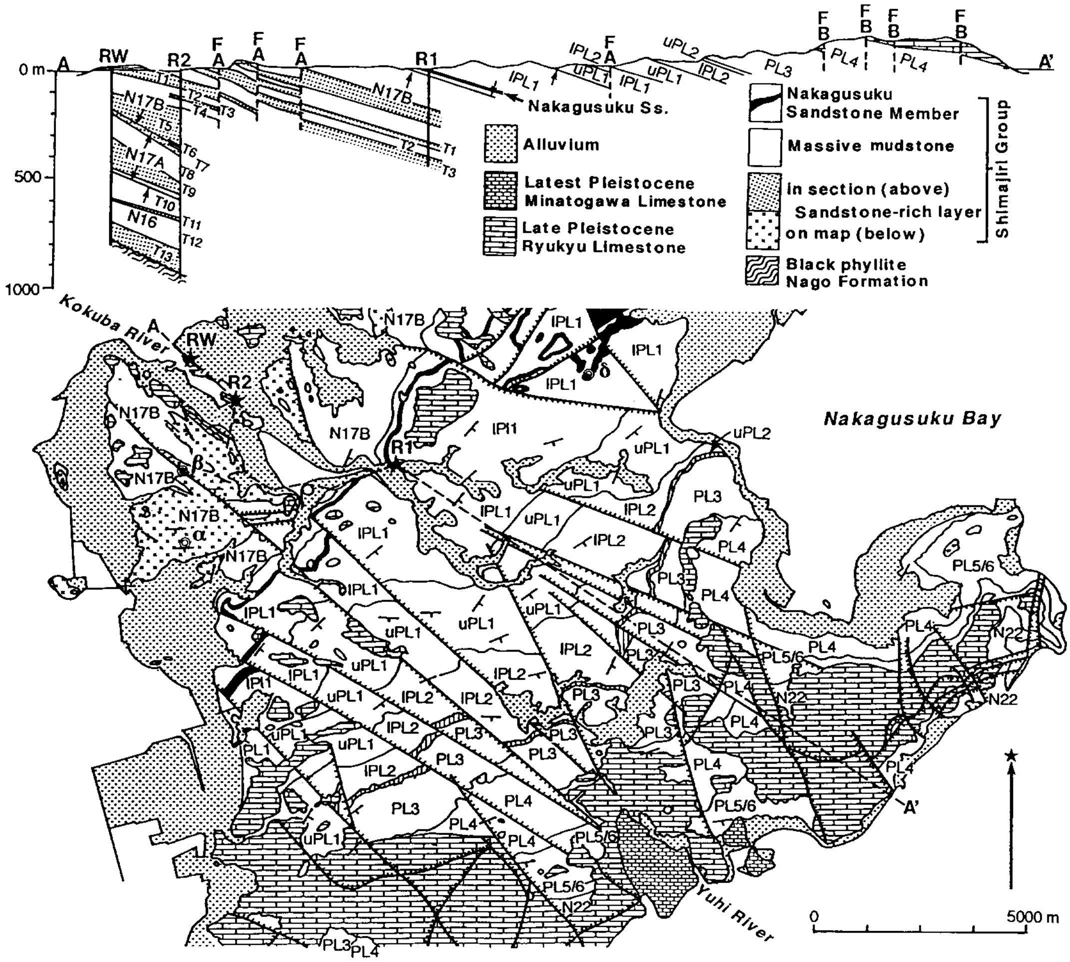

Fig. 5 Somewhat enlarged geologic map and a geologic section along *A–A'*, showing general trend of structure. Location of three outcrops in Fig. 3 are also indicated. *FA* and *FB* in the section are "fault a" and "fault b" in text, respectively.

underground, the majority of them seems to be duplicated with the location of faults ("faults b") that cut the Ryukyu Limestone as indicated in Fig. 7a. The faults a perpendicular to the arc extension are also dominant, even though four faults run in oblique or perpendicular to this major trend.

Comparing Fig. 7a with Fig. 7b, it is noteworthy that "fault b" always acted in reverse to "fault a" with much smaller throw, even if both kinds of faults are located at the same positions, as seen in two geologic sections for examples. It can be concluded, therefore, that more prominent fault-movement occurred after the deposition of the Shimajiri Group and before that of the Ryukyu Limestone also on Miyako Island similar to Okinawa Island.

An oil prospecting well was drilled at ~24 km east of Miyako Island (Lat. 24°41'N; Long. 125°44'E; water depth 286 m) and penetrated through the Yaeyama Group equivalent down to the 3711 m depth. This well recovered whole sequence of the Shimajiri Group ranging from N22 to N19 (PL1 by my re-examination) (Tsuburaya and Sato, 1985). Tsuburaya and Sato also showed a mutlichannel seismic profile cut through the well location. My re-examination of this profile (Fig. 8) indicates several faults that

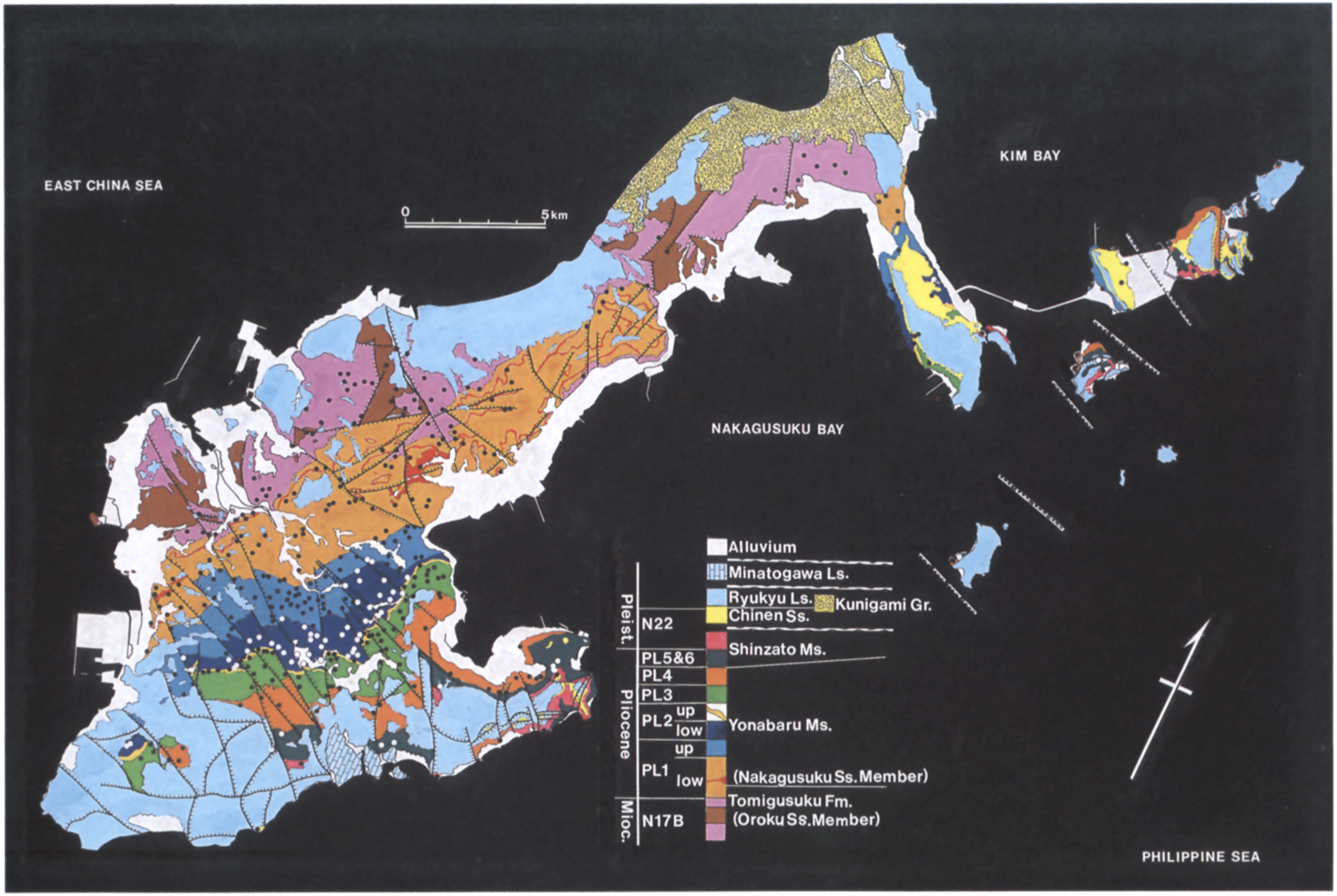

Fig. 6. Geologic sketch map of the central to southern Okinawa Island region, principally based on planktonic foraminiferal zonation of the Shimajiri Group (simplified from Ujiié, 1988). Black and white dots indicate locations of outcrop samples examined for planktonic foraminiferal zonation. *Ls* = limestone, *Gr* = gravels, *Ss* = sandstone, *Ms* = mudstone, *Fm* = formation, respectively.

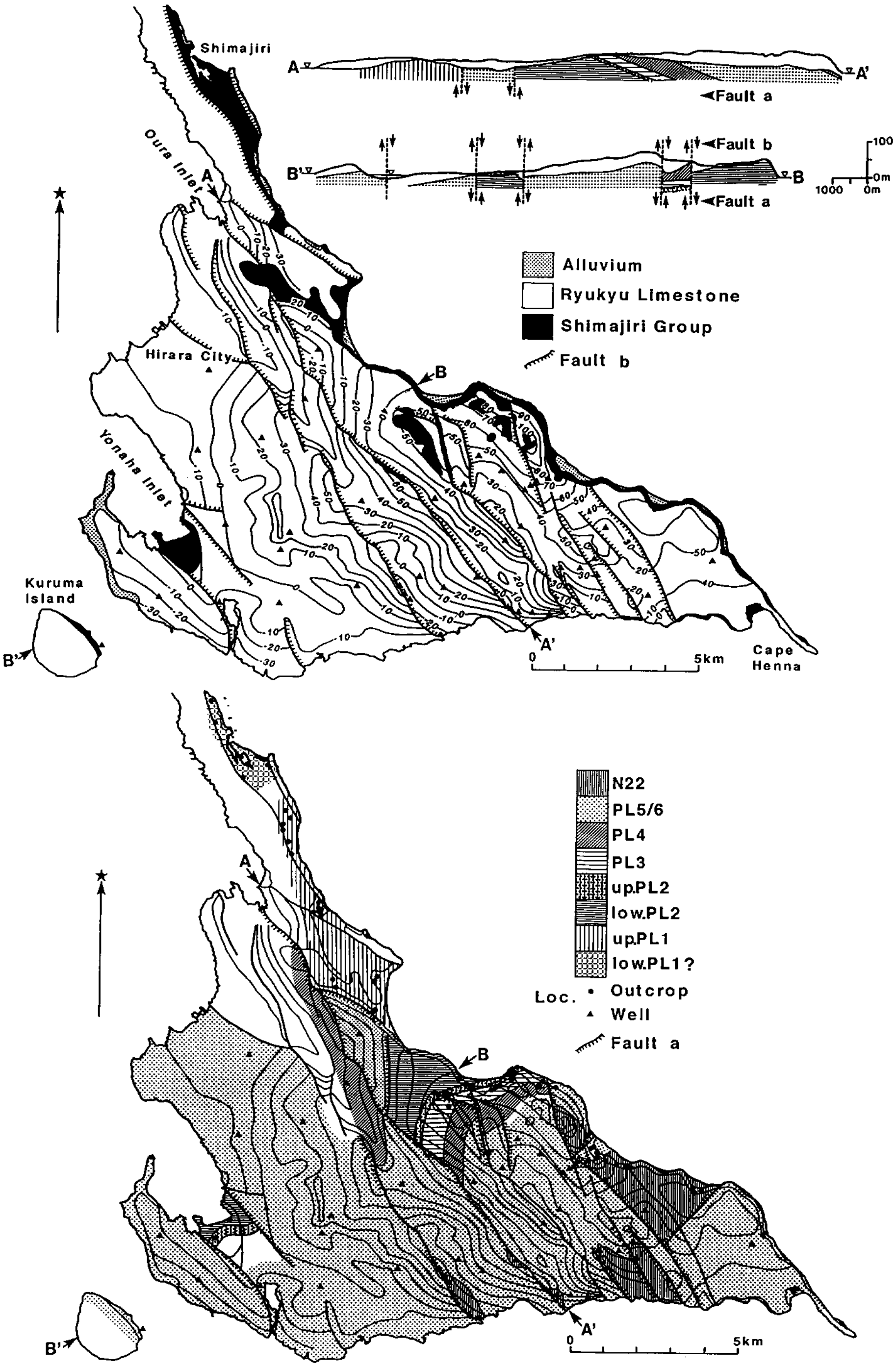

Fig. 7. (a) Distribution map of the Shimajiri Group, Ryukyu Limestone and fault b, inserted with two geologic sections, on Miyako Island. Contours (in meters) indicate the altitudes of Ryukyu Limestone base (summarized from the Geohydrologic map of Miyako Island, issued by the Okinawa Development Agency of Japan, 1982). In the sections, two kinds of faults (faults a and b) show reversal throw each other, even though they are presumed at the same location. (b) Geologic sketch map of the Shimajiri Group based on planktonic foraminiferal zonation on Miyako Island.

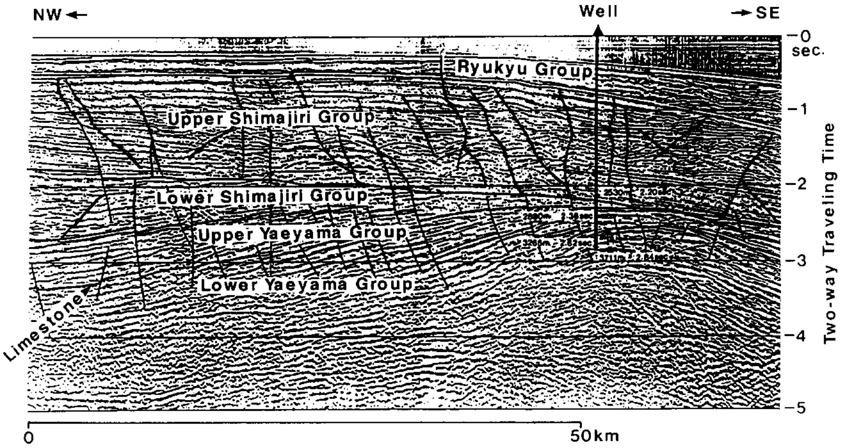

Fig. 8. A multichannel seismic profile through an oil-prospecting well at the east of Miyako Island (modified from Tsuburaya and Sato, 1985). "Faults a" are also recognized in the profile, where the Shimajiri Group is divided into the upper mudstone- and lower sandstone-rich facies. The latter unit resembles the Tomigusuku Formation of Okinawa Island but its age is of early Pliocene. A well reflected plane is composed of the late Early Miocene foraminifera-bearing limestone that divides the Yaeyama Group into two coal-bearing layers; this sequence can be correlated with a Miocene section developed on western Taiwan.

developed only in the Shimajiri Group and underlying layers but in the Ryukyu Limestone. They are compatible to "fault a" on Miyako Island. Similar faults seem to have been presented in interpretations of several single channel seismic profiles that were obtained for the publication of "Basic Map of the Sea in Coastal Waters, 1:50,000" series in Okinawa Prefecture by the Maritime Safety Agency of Japan (1985 et seq.). These maps (13 sheets already published) were made by numerous profiling, tracks of which were very closely (generally ~3 miles interval in E–W direction) settled. Unfortunately, however, only a few profiles were shown and their original records were not presented. The basis of stratigraphic correlation is unclear so that I cannot refer to those data here.

8.3. Kikai Island

Kikai Island is located at the northern end of the central Ryukyu Island Arc and underlaid with the Somachi Formation (Nakagawa, 1969) that was correlated with part of the Shimajiri Group (Fig. 9). This formation consists essentially of massive mudstone, though accompanied with sandstone or alternation bed at the apparently basal part. The Hyakunodai Limestone (~50 m thick according to Nakagawa, 1969) unconformably covers the Somachi Formation and forms a flat top plateau whose highest altitude is 204 m. While the oldest $^{230}Th/^{234}U$ age of the limestone was measured as 409 Ka, that of ESR-ages is 527 Ka (Omura, 1988). In the flank region of this plateau, the Wan Limestone is broadly distributed in having left four indistinct terraces whose $^{230}Th/^{234}U$ ages were determined as ~98–104 Ka, ~77–89 Ka, ~50–55 Ka and ~38–46 Ka in descending order of altitudes, respectively (Omura, 1988). An isolated block of limestone called the Araki Limestone is observed at the western end of this island. These three limestone formations are united into the Ryukyu Group. Semi-consolidated dune sands is distributed in the western lowland and the raised coral reef is developed particularly on the northwest coast. Both are considered to belong to the older Holocene.

Huang (1966) studied 18 planktonic foraminiferal samples collected from the Somachi Formation by Nakagawa and concluded the formation as to belong to the early Pliocene, even though he illustrated *Globorotalia truncatulinoides* at the same time. I treated 35 samples from outcrops scattered over the island and assigned its planktonic foraminiferal zonation ranging from N22 to PL4 (earliest Pleistocene to Late Pliocene).

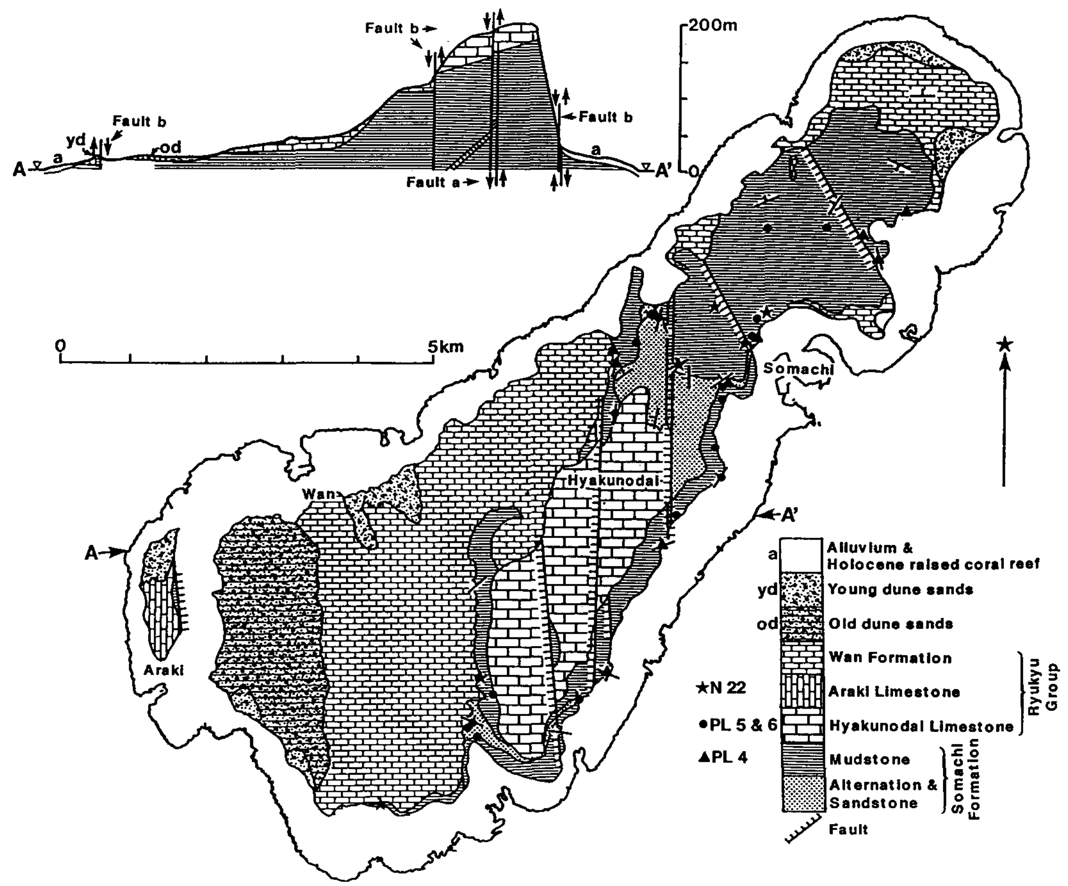

Fig. 9. Geologic sketch map and section of Kikai Island, where the planktonic foraminiferal zonation was effectively applied to reveal the stratigraphic behaviors of the Somachi Formation, equivalent to the uppermost Shimajiri Group.

The sandstone or alternation beds intercalated at the basal part and at two separated areas are of almost the same age (PL4/5) and were considered to have been dislocated by "faults a" after the deposition. Planktonic foraminiferal zonation of the Somachi Formation suggest the presence of four "faults a", among which two run in parallel to but the other two oblique to "faults b". Faults b cut only the Hyakunodai Limestone but not the Wan Limestone. Here is also presumed two kinds of fault (faults a and b) as well as on Okinawa and Miyako Islands.

9. Conclusions

The widely distributed upper Pleistocene Ryukyu Limestone suggests the presence of prototypes of the Okinawa Trough—Ryukyu Island Arc system, a backarc and forearc system at the northwestern margin of the Pacific before its deposition. In contrast, the upper Miocene to lowermost Pleistocene Shimajiri Group directly underlain by this limestone consists of muddy sediments that were supplied from the Asian continent under bathyal environment to the region of the present island arc. From this drastic change in depositional environment, Ujiié (1980) anticipated a crustal movement produced the initial subsidence in the Okinawa Trough region and the initial uplift in the Ryukyu Island Arc region. To demonstrate this hypothesis, I have tried to clarify the geologic structure of the Shimajiri Group based on planktonic foraminiferal zonation. A standard sequence at southern Okinawa Island was successfully divided into 11 zones in contrast to the rather monotonous lithology, particularly at surface exposures. Although some zones may not have global validity but are regionally valuable, the geologic structure of the Shimajiri Group was revealed as summarized in a map (Fig. 6) by zone-assignment of 421 outcrops scattered over the central to southern area of Okinawa Island.

Most striking fact is the development of faults that cut only the Shimajiri Group but not the Ryukyu Limestone and that were tentatively called "fault a". Majority of "fault a" runs in perpendicular to the island arc extension, whereas "fault b" mosaicked the Ryukyu Limestone. On Miyako Island, southern Ryukyu Arc, "fault a" was recognized by planktonic foraminiferal zonation on 43 underwater prospecting well cores and on 60 outcrop samples. Although many of "faults a" were presumed along the positions same as "faults b", their throws are reversal to and much greater than "faults b". On Kikai Island, "fault a" was also recognized in the Somachi Formation that represents the younger part of the Shimajiri Group, beside of "faults b" that cut the equivalent of the Ryukyu Limestone, Hyakunodai Limestone. Even though only an example was shown here, the development of "faults a" can be expected in many submarine seismic profiles in the adjacent seas of the Ryukyu Island Arc.

Behaviors of these "faults a" indicate that they were formed on the greatly emerged arc region after the deposition of the Shimajiri Group and before that of the Ryukyu Limestone at a certain period during the sedimentation gap from ~ 1.7 to 0.5 Ma. This upward warping must have been generated by subduction of the Philippine Sea plate and then associated with subsidence of the Okinawa Trough region.

Taking into account this crustal movement along with my experiences on the regional geology, I propose the processes concerning the geologic development of the Okinawa Trough-Ryukyu Island Arc system as follows (Fig. 10): (1) Before the Shimajiri Group deposition, this region was a peneplaned continental margin whose basement was composed essentially of such Permian through middle Eocene accretionary prisms formed under continental slope environment as represented by Iheya, Nakijin, Motobu, Nago and Kayo zones in

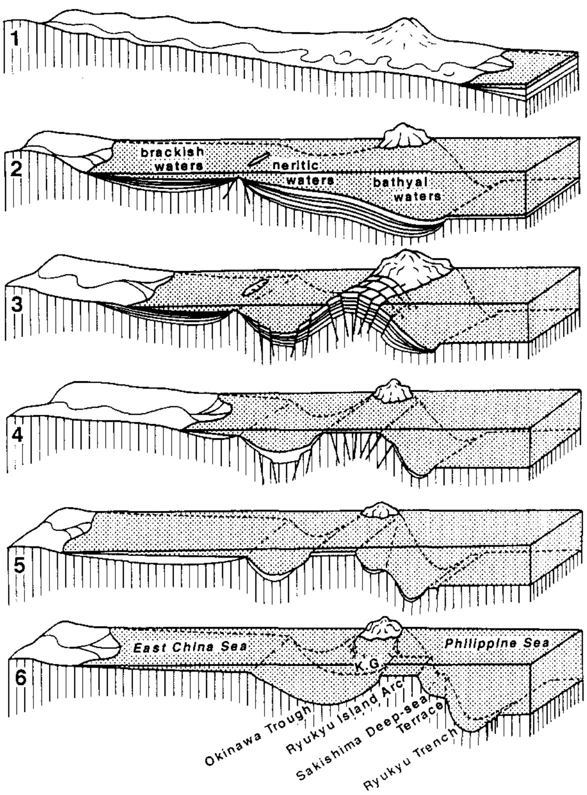

Fig. 10. Schematic block diagram explaining the development process of the Okinawa Trough and Ryukyu Island Arc since the time just before the Shimajiri Group deposition.

the northern Okinawa Island region (Fig. 10-1). After these subduction–accretion processes, however, the southern Ryukyu Island Arc was under the deposition of the Late Eocene reefal sediments (Miyara Formation) accompanied with volcanic lava and ejecta (Nosoko Formation) and under the deposition of the late Early Miocene epicontinental sediments (Yaeyama Group). (2) After ~ 6 million years hiatus, the entire region was covered by the marine Shimajiri Group, except for a land mass that existed from the southwest of Okinawa Island via nothern Okinawa to Amami-ohshima Island. Its maximum transgression reached the continental shelf in the earliest Pleistocene. During the major period of the Shimajiri Group deposition, however, the shelf area was under brackish to fresh water domain having been separated from pure marine domain by a ridge named the Shinji-Taiwan folding zone (Emery et al., 1966)

(Fig. 10-2), according to my unpublished study on oil-prospecting wells drilled in the northern East China Sea shelf. (3) A crustal movement during late Pleistocene triggered prominent subsidence of the Okinawa Trough region and upheaval of the Ryukyu Island Arc region (Fig. 10-3). "Fault a" was formed by this movement. (4) Immediately after the emergence, the still soft Shimajiri Group in the arc region was quickly eroded down to wave-base, which is adequate water depth for reef-building coral flourishing (Fig. 10-4). (5) Reefal sediments (Ryukyu Limestone) were broadly deposited over the eroded arc region where terrigenous material supply from continent was inhibited because the materials were trapped into the prototype Okinawa Trough like present (Fig. 10-5). (6) Afterwards, the Okinawa Trough spread, in having been associated with rifting, and the Ryukyu Island Arc has been uplifted associated with tilting toward the trough side until present (Fig. 10-6). Ujiié et al. (in press) indicated that such a series of movements became prominent after ~10 Ka in the southern Ryukyu Island Arc based on turbidite core analyses.

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