QUATERNARY GEOHISTORY INFERRED BY SEISMIC STRATIGRAPHY OF A CARBONATE PROVINCE IN AN ACTIVE MARGIN, OFF MIYAKO ISLAND, SOUTH RYUKYUS, JAPAN

Masayuki Obata* and Yoshihiro Tsuji

Technology Research Center
Japan National Oil Corporation
1-2-2 Hamada, Chiba 261, Japan

ABSTRACT: High resolution seismic reflection profiles acquired at western offshore of the Miyako Island in South Ryukyus have revealed the distribution, stratigraphy and structure of the Quaternary marine carbonate deposits beneath the shelf and the shelf slope. Above the Plio-Pleistocene siliciclastic basement, five seismic units, Unit 1 to Unit 5 in descending order, were identified and correlated to the Pleistocene Ryukyu Group and Holocene sediments.

A major tectonic event between ca. 1.7 Ma and 1.2 Ma deformed the Plio-Pleistocene siliciclastic basement (Unit 6). A subsequent lowstand allowed to deposit siliciclastic basal sequence (Unit 5) of the Ryukyu Group. This lowstand phase was followed by faulting which resulted in extensive erosion at the upthrownside of NE trending major normal fault on the northwestern shelf slope.

Subsequent overall transgression with fluctuation of sea level enabled to grow and deposit coral reefs and the associated carbonates (Unit 4). They are correlated to the Riukiu Limestone on land, which was deposited intermittently between ca. 1.2 Ma and 0.4 Ma. After the ample transgression represented by Unit 4, tectonic movement culminated with the progress of upheaval of the Ryukyu Arc, as evidenced with a considerable uplifting as well as faulting of the Riukiu Limestone on Miyako and Irabu Islands.

Later than 0.4 Ma, carbonate sequences younger than the Riukiu Limestone on land were deposited successively as Units 3 and 2 which represent shelf margin systems with reef developments.

Thus, sedimentation and distribution of the depositional sequences in the Pleistocene carbonates here have been largely dependent on relative sea level changes closely related to vigorous neotectonic movements, which were closely related to the evolution of the Ryukyu Arc system. The depositional style of the Quaternary carbonates in the active island arc system (Ryukyus) seems to manifest a considerable difference from that in a passive margin.

INTRODUCTION

Evolution of carbonate platforms has been well documented by seismic studies in the Caribbean region, particularly in the Bahama Platform (Hine and Neumann, 1977; Mullins and Neumann, 1979; Mullins *et al.*, 1980; Choi and Ginsburg, 1982; Eberli and Ginsburg, 1989) as well as in the Great Barrier Reef, Australia (Symonds *et al.*, 1983; Davies *et al.*, 1989). These studies have provided models for the evolution of passive margin carbonate platforms. In those areas, tectonism is a long term factor controlling the development of the platform, and has been a little influence on the Quaternary sedimentation. Quaternary carbonate platform development there is essentially controlled by sealevel changes.

This study aims to elucidate the evolution of a Quaternary carbonate platform at active margin, that is, the sedimentary framework and the influence of the neotectonism on carbonate sedimentation in the Ryukyu Island Arc system, northwest Pacific, based on the interpretation of sequences and facies by high resolution seismic profiles. It presents an example of the interactive relationship between sedimentation and dynamic tectonism on and off carbonate platform in an active island arc, where tectonic setting differs significantly from that of the passive margin.

STUDY AREA

The study area covers the western insular shelf and the upper shelf slope off Miyako and Irabu Islands in South Ryukyus (Fig. 1). The water depth of the area ranges from 60 to 800 m.

The Ryukyu Arc, which extends approximately 1,200 km from Kyusyu southwestward to Taiwan and rims the northwestern Pacific Ocean, is bounded by the Okinawa Trough to the northwest and the Ryukyu Trench to the southeast.

The bathymetrical surveys by the Hydrographic Department of the Maritime Safety Agency of Japan (hereinafter referred to as "M.S.A.") (1986) and by the present study have delineated the submarine topography in this area. The western Miyako-Irabu insular shelf is delineated by 110–130 m isobaths and is bounded by steep slopes except for the narrow area to the southwest of Irabu Island, where the shelf is bounded by a relatively gentle slope. The salient topographic

* Present address: 2-8-43-302, Iizuka, Kawaguchi, Saitama 332, Japan.

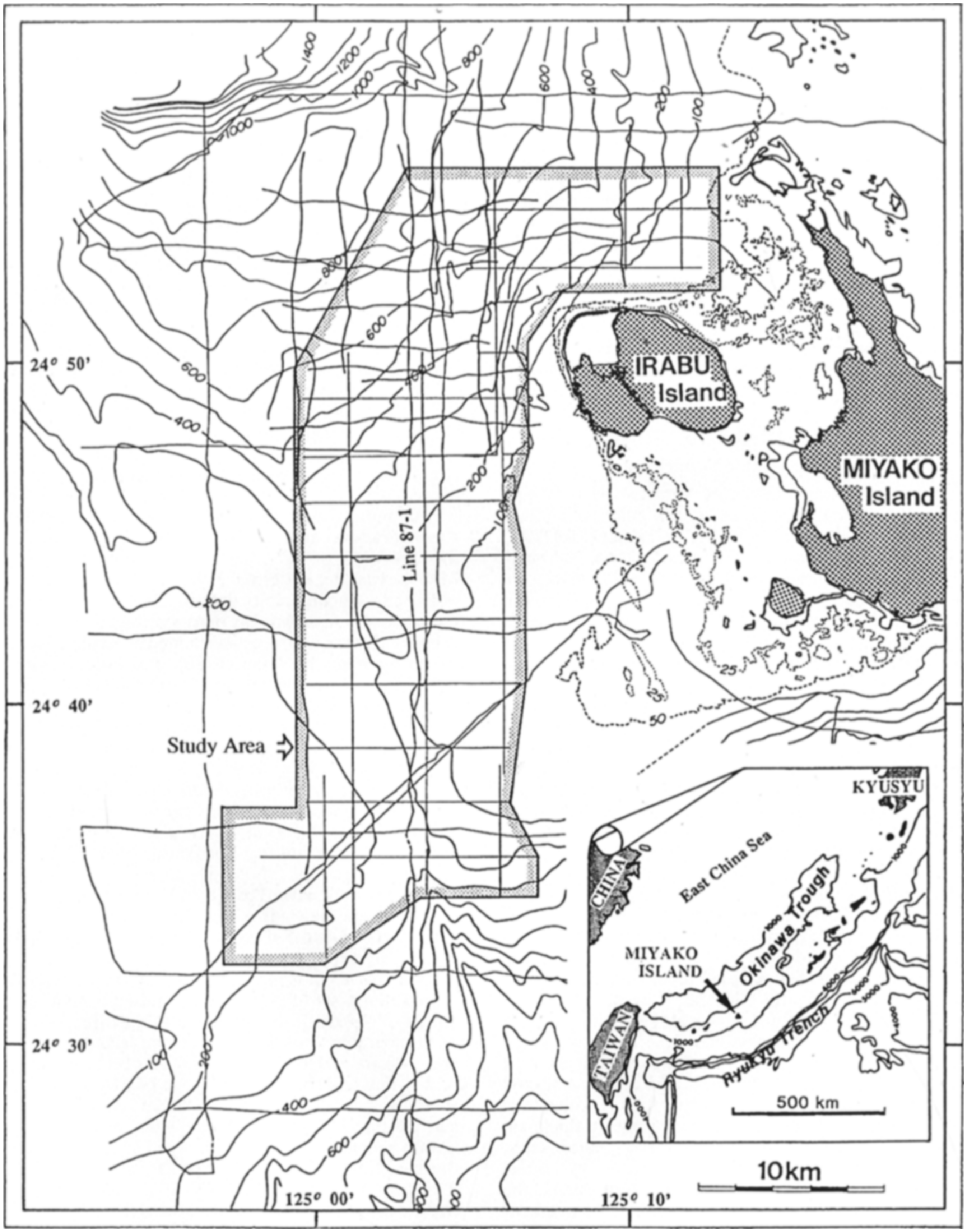

Figure 1. Index map of study area, seismic lines and bathymetry.

features of the study area are as follows: 1) Holocene coral reefs, 2) Flat plain and 3) Lineaments (Fig. 1).

Holocene coral reefs develop on the inner shelf shallower than 60 m of water depth (Tsuji *et al.*, 1989). The flat plain lies between 90 and 100 m isobaths on the outer shelf. The lineaments are recognized as alignments of coral reefs, channels and submarine valleys. The distribution of Holocene coral reefs, to the south of Irabu Island, coincides with submarine topographic highs extending in a NNW-SSE direction paralleling the trend of fault scarps recognized on Miyako Island (e.g. Ota and Nakata, 1980). Southwest of the study area, the Miyako-Irabu insular shelf is bounded westward by a NNW trending channel approximately 245 m in water depth. The submarine valleys extending in a NNW-SSE direction in water depth between approximately 200 m and 900 m are recognized on the shelf slope facing both the Okinawa Trough and the Ryukyu Trench.

GEOLOGICAL SETTING

Stratigraphic Framework

The stratigraphic succession on Miyako and Irabu Islands principally consists of the siliciclastic Plio-Pleistocene Shimajiri Group (e.g. Nakamori, 1982) and the overlying Pleistocene Riukiu Limestone (Hanzawa, 1935) which represents a calcareous part of the Ryukyu Group (Nakagawa, 1967) including non-calcareous sediments. Observations on both outcrops and borehole cores have confirmed a distinct unconformity between the two groups (e.g. Yazaki and Oyama, 1979; Yuki *et al.*, 1988).

The Shimajiri Group crops out locally on the east and south coast of Miyako Island but not on Irabu Island. This group distributes widely along the outer side of the Ryukyu Arc (Aiba and Sekiya, 1979), and crops out on some islands in central and south Ryukyus. Miyako Island is the southernmost island on which the group crops out. The lithology there is mainly characterized by sandstones, mudstones, and their alternations. Yazaki (1978) ascribed the group as a neritic-bathyal deposit. Ujiie and Oki (1974) assigned the group of Miyako Island to range from the late Miocene to early Pleistocene by planktonic foraminifers. Kuramoto and Konishi (1989) determined the age of a tuff layer in the group by K-Ar method as being ca. 3.6 Ma in the early Pliocene.

The Riukiu Limestone covers almost entire onshore Miyako and Irabu Islands. The same formation is extensively exposed in the most other part of the Ryukyu Islands (Hanzawa, 1935). Yuki *et al.* (1988) analyzed the depositional facies within the Riukiu Limestone on Irabu Island. Here, the limestone varies in thickness from 80 to 110 m and is divided into two major facies, (1) the reef/near reef facies characterized by corals, coralline algae and benthonic foraminifera, and (2) the open shelf facies represented by rhodoliths, large benthonic foraminifera and allochthonous coral fragments. Four cycles each of which indicates four a set of transgression and regression are recognized in the Riukiu Limestone. Calcareous nannoplankton data from borehole cores suggest that the Riukiu Limestone in the survey area was deposited between ca. 1.2 Ma and 0.39 Ma (Sado *et al.*, 1992).

Tectonic Framework

The Ryukyu Arc is bounded northwestward by an ENE-trending backarc basin, the Okinawa Trough, which was opened by rifting initiated in Miocene. Its major pulse of rifting occurred in Early Pleistocene (2–1.5 Ma), and the rifting still continues to the present as suggested by the black smokers at an active hydrothermal vent system (Kimura, 1990). The Ryukyu Trench where the Philippine Sea Plate is subducting to northwestward since 4 Ma bound the Ryukyu Arc southwestward. The back arc rifting associated with plate subduction created tectonism in the Ryukyu Arc in the Quaternary.

The Shimajiri Group is folded and faulted. Kizaki (1985) regarded the structure of the Shimajiri Group as an anticlinorium paralleling to the trend of Ryukyu Arc. Ujiie (1989) suggested the existence of faults which displaced Shimajiri Group on Miyako Island, and of which trend is perpendicular to that of the Ryukyu Arc. Kuramoto and Konishi (1989) pointed out that the directions of microfaults in Shimajiri Group on Miyako Island are NE and NW.

The clinounconformity defining the top of Shimajiri Group on Ryukyu Arc has been ascribed to a tectonic event. This tectonic event was named as Ryukyu Island Arc Movement by Ujiie (1980), and later renamed "Shimajiri Crustal Movement" by Kizaki (1985). The Shimajiri Crustal Movement occurred between approximately 1.7 Ma and 1.2 Ma (the early Pleistocene). These ages represent the uppermost part of the Shimajiri Group (Ujiie and Oki, 1974) and the lowest part of the Riukiu Limestone (Sado *et al.*, 1992) of the survey area, respectively. This event resulted in anticlinal uplift of the Ryukyu Arc and associated with NW-SE trending faulting (Furukawa, 1983). The compressional stress of NNW direction due to both the spreading of Okinawa Trough and subducting Ryukyu Trench made the folding with ENE axis and faulting with NW trend in Shimajiri Group before the deposition of Riukiu Limestone.

Ryukyu Group is also displaced by faults. It is observed that a set of NNW-SSE trending normal fault scarps of Riukiu Limestone creates a distinct cuesta-like topography on Miyako and Irabu Islands (e.g. Ota and Nakata, 1980). Hamamoto *et al.* (1979) interpreted that the southwestern edge of Miyako insular shelf was bounded by NW and NNW trending faults, and the minor faults parallel to them cut the Ryukyu Group beneath the northeastern insular shelf, and that the structure of the shelf slope facing the Okinawa Trough is characterized by NE, ENE, NW and NNW trending faults. M.S.A. (1986) reported that NW, NNW, NE, WNW and NNE trending faults were recognized beneath the western and southern shelf slope off Mi-

Table 1. Seismic features of the units identified and correlated to the Pleistocene Ryukyu Group and Holocene sediments.

UNIT No.	TOPOGRAPHIC HIGH / LOW	REFLECTION PARAMETERS				EXTERNAL FORMS	FACIES INTERPRETED	DEPOSITIONAL ENERGY
		CONFIGURATION	GEOMETRY AT BOUNDARY	CONTINUITY	AMPLITUDE			
Unit 1	high @beneath the shelf	parallel	concordant at top and base	very good	high	sheet drape	coarse shelf carbonate	high
	low @beneath the slope	parallel	concordant at top and base	very good	high		shelf slope carbonate	low
Unit 2	high	chaotic		poor	low	mound	reef coarse shelf carbonate	high
	high	parallel	concordant at top onlap at base	good	high	sheet drape	coarse shelf carbonate	variable
	high - low	complex sigmoid -oblique	concordant / toplap downlap at base	medium	medium-high	bank / wedge	coarse shelf carbonate	high - medium
Unit 3	high	chaotic		poor	low	mound	reef coarse shelf carbonate	high
	high	parallel	concordant at top onlap at base	good	high	sheet drape	coarse shelf carbonate	variable
	high - low	sigmoid	concordant at top downlap at base	medium	medium-high	bank / wedge	coarse shelf carbonate	medium - low
Unit 4	high @upthrown side of NE major fault	subparallel / wavy subparallel	concordant at top and base locally toplap	good	high	wedge	coarse shelf carbonate shelf slope carbonate	medium - low
	low @downthrown side of NE major fault	hammocky / cont -orted clinoform, wavy subparallel	concordant at top downlap at base	medium	medium	fan / wedge	variable	variable
Unit 5	high @adjacent to NE major fault	hammocky clino -form	concordant at top onlap at base	poor - medium	medium	slope front fill	silisiclastics turbidite?	variable
	low @away from NE major fault	wavy parallel, subparallel, divergent	concordant at top onlap at base	medium - good	high	slope front fill	silisiclastics turbidite?	variable

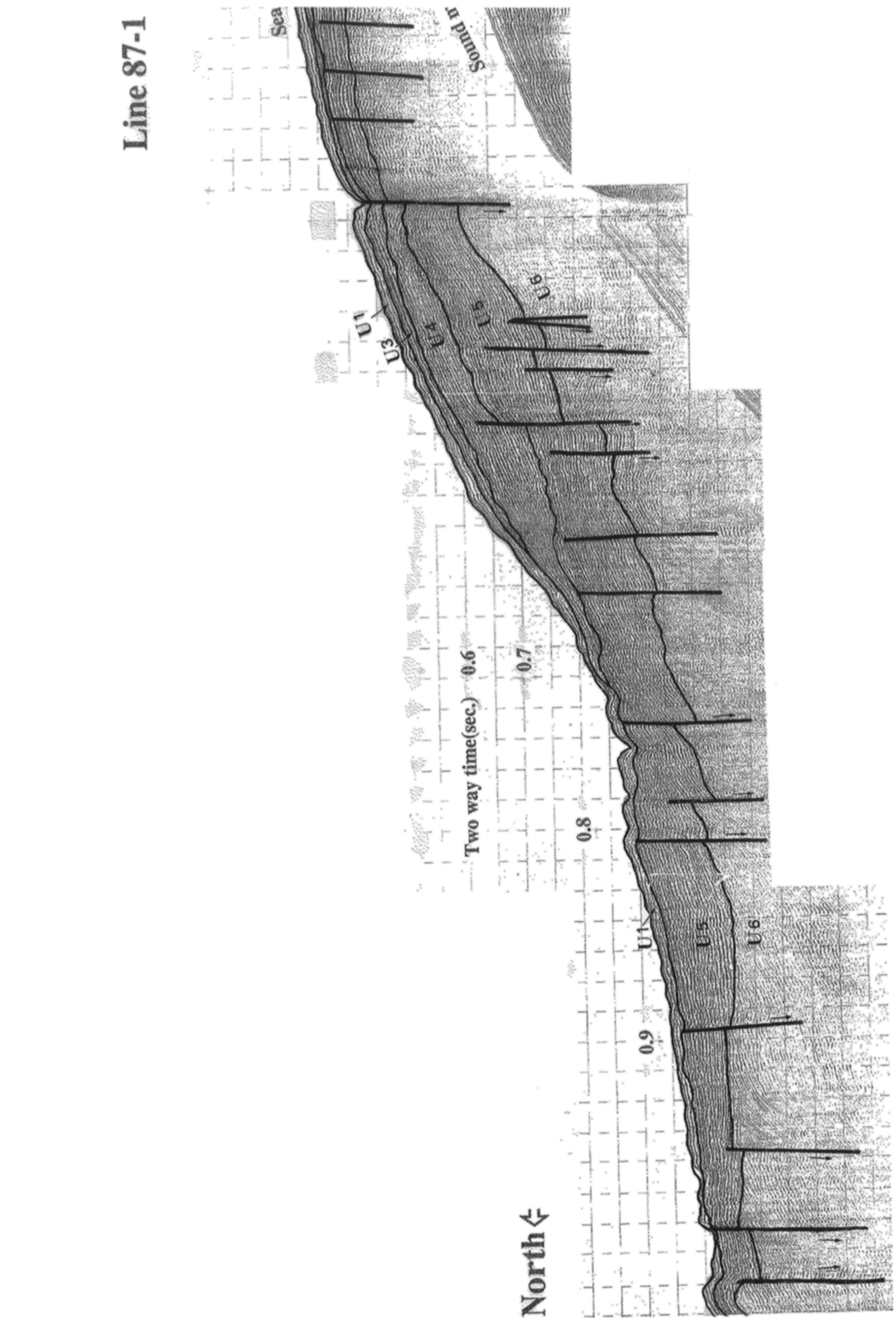

Figure 2a. Interpreted seismic section of Line 87-1 (N-S section). Northern section.

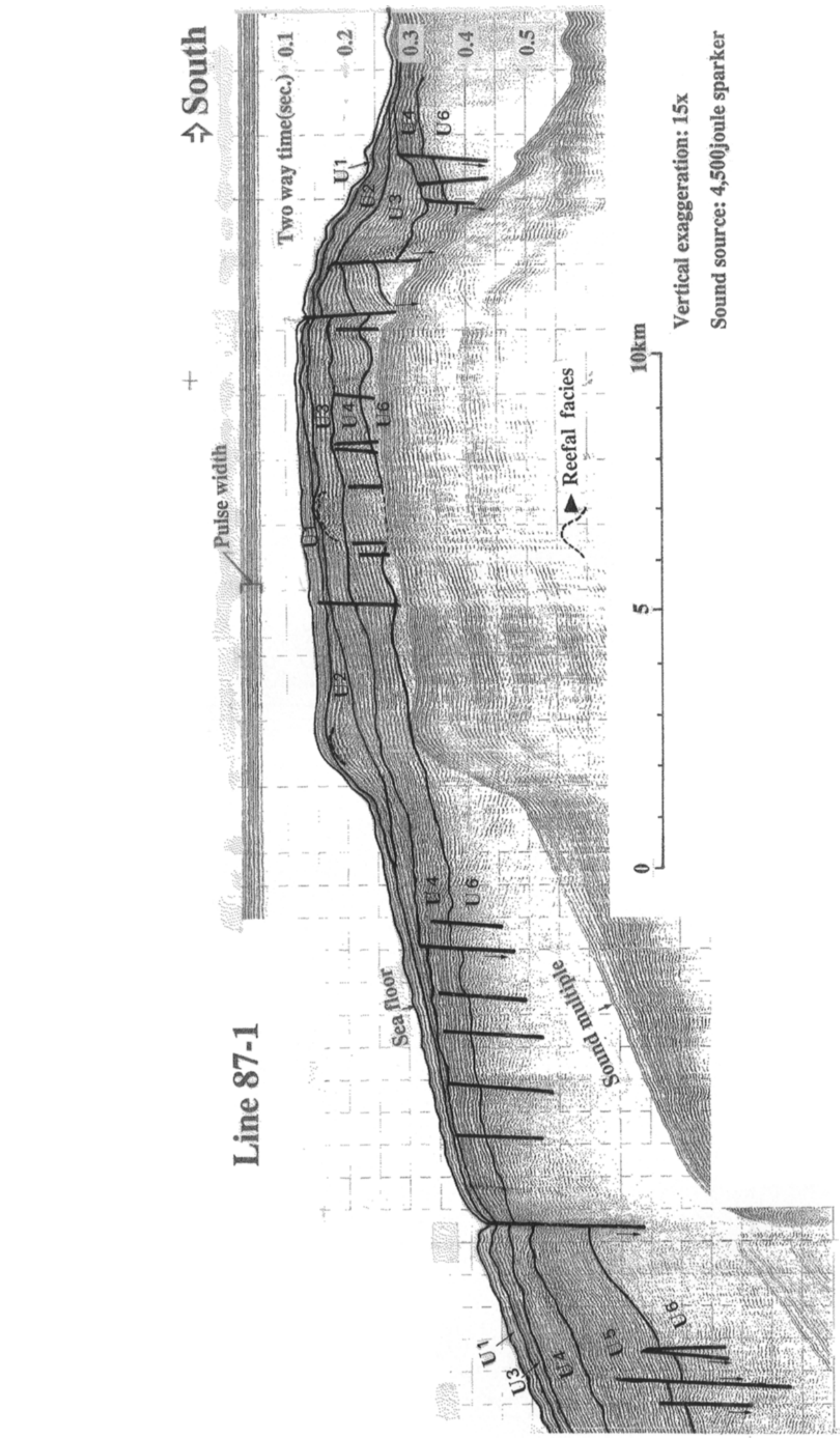

Figure 2b. Interpreted seismic section of Line 87-1 (N-S section). Southern section.

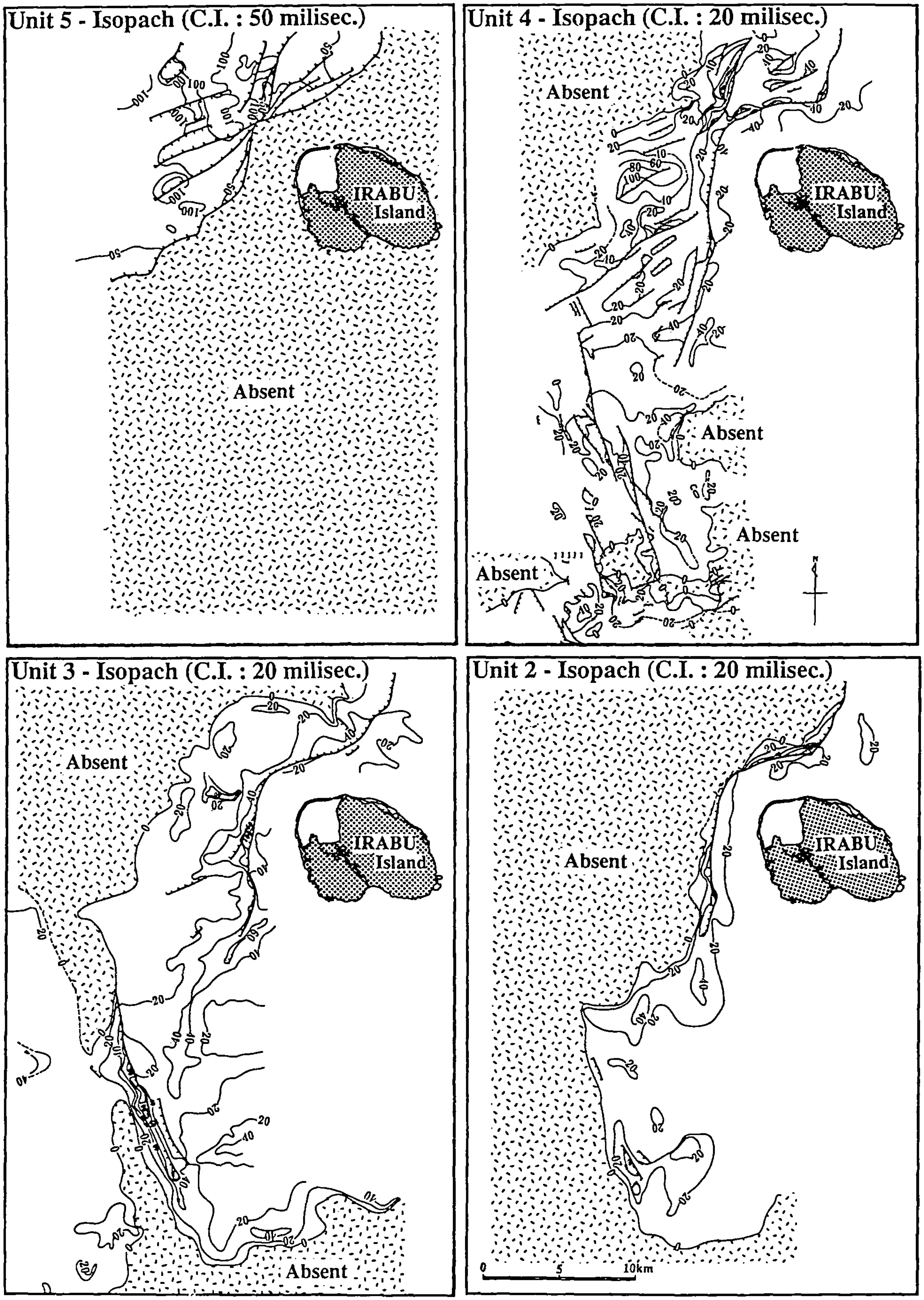

Figure 3. Isopach maps of Units 2, 3, 4 and 5.

yako Island, and that the Ryukyu Group is displaced by the NE, NNE and NW trending faults.

The normal faults of NW to NNW directions cutting the Riukiu Limestone suggest the tentional stress field parallel to the arc. Kuramoto and Konishi (1989) concluded that the Southwest ("South" of this paper) Ryukyu Arc is a westward migrating microplate (forearc sliver) and tensional stress field is held at around Miyako Island which is the eastern part of the microplate.

The tectonism caused by spreading of Okinawa Trough and subducting of the Philippine Sea Plate at Ryukyu Trench created geologic structures of NE (NNE to ENE) and NW (WNW to NNW) direction in the Quaternary in the study area.

METHOD

Data Acquisition

A total about 1,400 km of single channel data sourced by 4,500 joule sparkers of NEC and EG&G sparker systems were acquired by analog recordings (Fig. 1). The data were sampled at 1 millisecond (ms) intervals over approximately 1,000 ms of record. The received frequency ranged from 160 to 2,000 Hz. Radionavigation systems and a satellite positioning system, GPS (Global Positioning Systems) were employed for navigation and positioning during the surveys.

Seismic Sequence and Facies Analysis

This study is essentially based on the concept and procedure of the seismic sequence and facies analyses introduced by Mitchum *et al.* (1977), Sangree and Widmier (1977), and Bubb and Hatlelid (1977).

Seismic units were recognized by reflection parameters such as reflection terminations, internal reflection configurations and external forms.

The seismic sequence analysis was followed by seismic facies analysis in which the depositional facies and energy of each seismic unit were inferred by analyzing reflection configurations, continuity, amplitude and frequency (Table 1). In addition, the presence of reefal facies or carbonate buildups was carefully identified by recognizing its mounded configurations with internal chaotic reflections.

RESULTS

Depositional Sequence and Facies

As a result, six seismic units, Units 1 to 6 in descending order, were identified in the strata which are thought to be correlated to the Shimajiri Group, the Riukiu Limestone and Holocene sediments. An interpreted seismic section is presented on Figure 2. Each seismic unit was subsequently mapped to reveal its distribution and depositional configuration (Fig. 3).

Unit 6: This unit shows the widest distribution and is the lower most unit identified in the study area. Even and wavy parallel reflection configurations with poor continuity and low amplitude are common to this unit. In addition, chaotic reflection and reflection-free configurations are frequently observed. The parallel configurations usually show dipping and folding patterns.

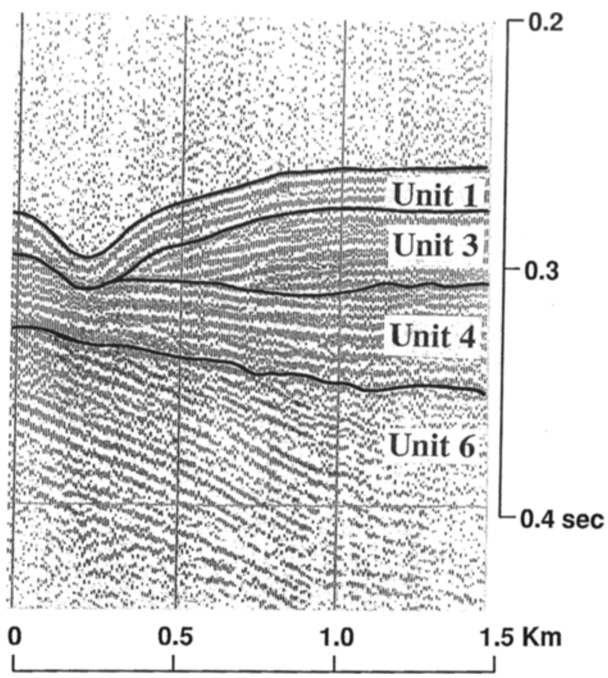

Figure 4. Toplapping reflection termination at the upper boundary of Unit 6.

Erosional truncation and toplapping terminations at the upper sequence boundary of the unit (Fig. 4) are commonly observed and imply the presence of an angular unconformity. Prominent folding patterns are frequently recognized in the unit, although the same patterns are not recognizable within the strata above the unit.

Unit 5: Unit 5 is distributed at the northwest part of the study area, and its distribution pattern is different from that of the other units (Fig. 3). Its distribution is restricted to the downthrown side of the NE trending major fault and beneath the northwestern shelf slope at water depths deeper than 300 m. Hummocky clinoforms are recognized adjacent to a major NE trending fault at its downthrown side. This fault restricts the extension of the unit landward. Along the slope into the basin, wavy parallel/subparallel configurations become more common. Divergent configurations are frequently recognized at the downthrown side of faults, where the sediments thicken greatly compared to on the other side. This unit generally shows medium to good continuity and high amplitude in its seismic reflection.

The upper boundary of the unit generally shows concave and convex patterns, whereas onlapping reflection terminations are recognized at the lower boundary.

The unit tends to thin both toward the major fault (Fig. 3) and basinward in a northwest direction. The thickness ranges from approximately 50 ms to 120 ms in two way time.

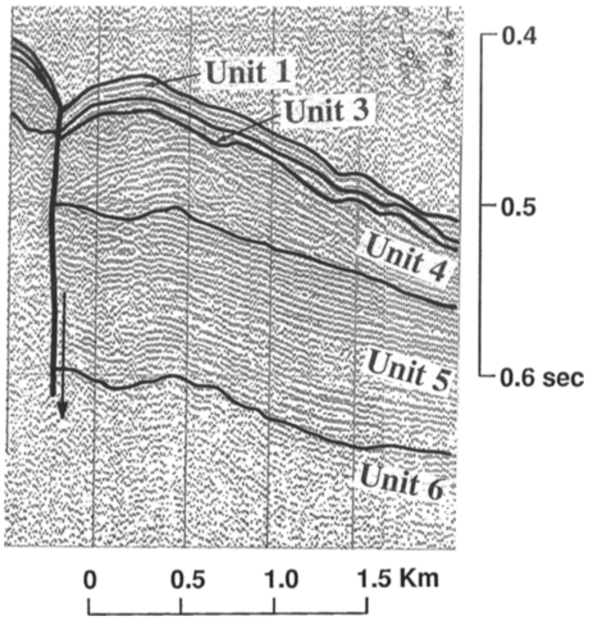

Figure 5. Hummocky/contorted clinoforms in Unit 4 at the downthrown side of the major NE trending fault (Line 9).

This unit is highly faulted by NE trending faults (Figs. 2, 3).

Unit 4: Overall reflection configuration of the unit is subparallel to wavy subparallel with good continuity and high amplitude. However, hummocky/contorted clinoforms are recognized adjacent to the NE trending major fault at its downthrown side (Fig. 5).

Toplapping terminations at the upper boundary are infrequently observed beneath the insular shelf. The unit is underlain by Unit 5 at the downthrown side of the fault and by Unit 6 at its upthrown side. The unit downlaps onto Unit 5 at the downthrown side of the fault.

The distribution of this unit is the most extensive of all units. The unit terminates basinward beneath the 500–600 m isobath to the north and west of Irabu Island, and the 300 m isobath to the south of the island. The thickest parts of the unit tend to occur along the downthrown side of NE trending faults almost paralleling the Ryukyu Arc (Figs. 2, 3). The NE trending faults are dominated on the shelf slope, although NNW trending faults extending up to the top boundary of this unit are dominantly recognized on and near the shelf (Fig. 3).

Unit 3: Sigmoid progradational reflection configurations are recognized beneath the present shelf break (Fig. 6). However, parallel to subparallel configurations are common beneath the present insular shelf. A cross sectional profile of the unit suggests that the unit acts as sheet drape, bank or wedge. The unit downlaps basinward and onlaps landward onto Unit 4 with very low angles.

Beneath the present insular shelf, mounded configurations with internal chaotic reflections are frequently recognized. This configuration could suggest the presence of a reefal facies and its distribution is restricted landward of the 110 m isobath (Fig. 7).

Sigmoid progradational and divergent configurations are recognized at the downthrown side of NNW trending extensional growth faults.

The unit tends to thick on the shelf and the thickness decrease to the margins, although the thickest parts are observed along the downthrown side of NNW and NNE trending faults (Fig. 3). Relatively thicker circular areas are delineated on the isopach map and their distribution coincides with that of reefal facies inferred from seismic profiles.

The number of faults cutting this unit is smaller than that for the Unit 4.

Unit 2: Beneath the southwestern shelf slope, Unit 2 generally shows complex sigmoid-oblique progra-

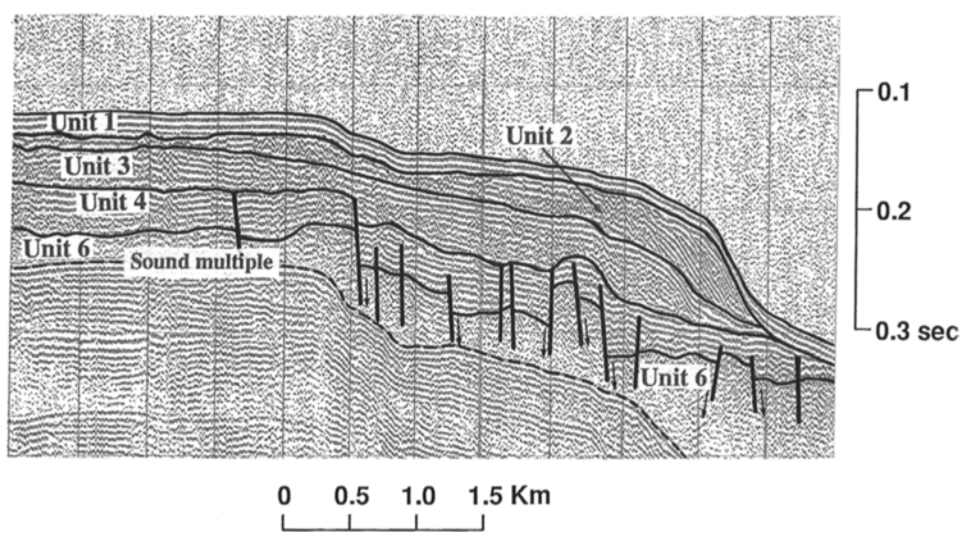

Figure 6. Sigmoid progradational reflection configuration in Unit 3. Oblique (tangential) progradational reflection configuration in Unit 2.

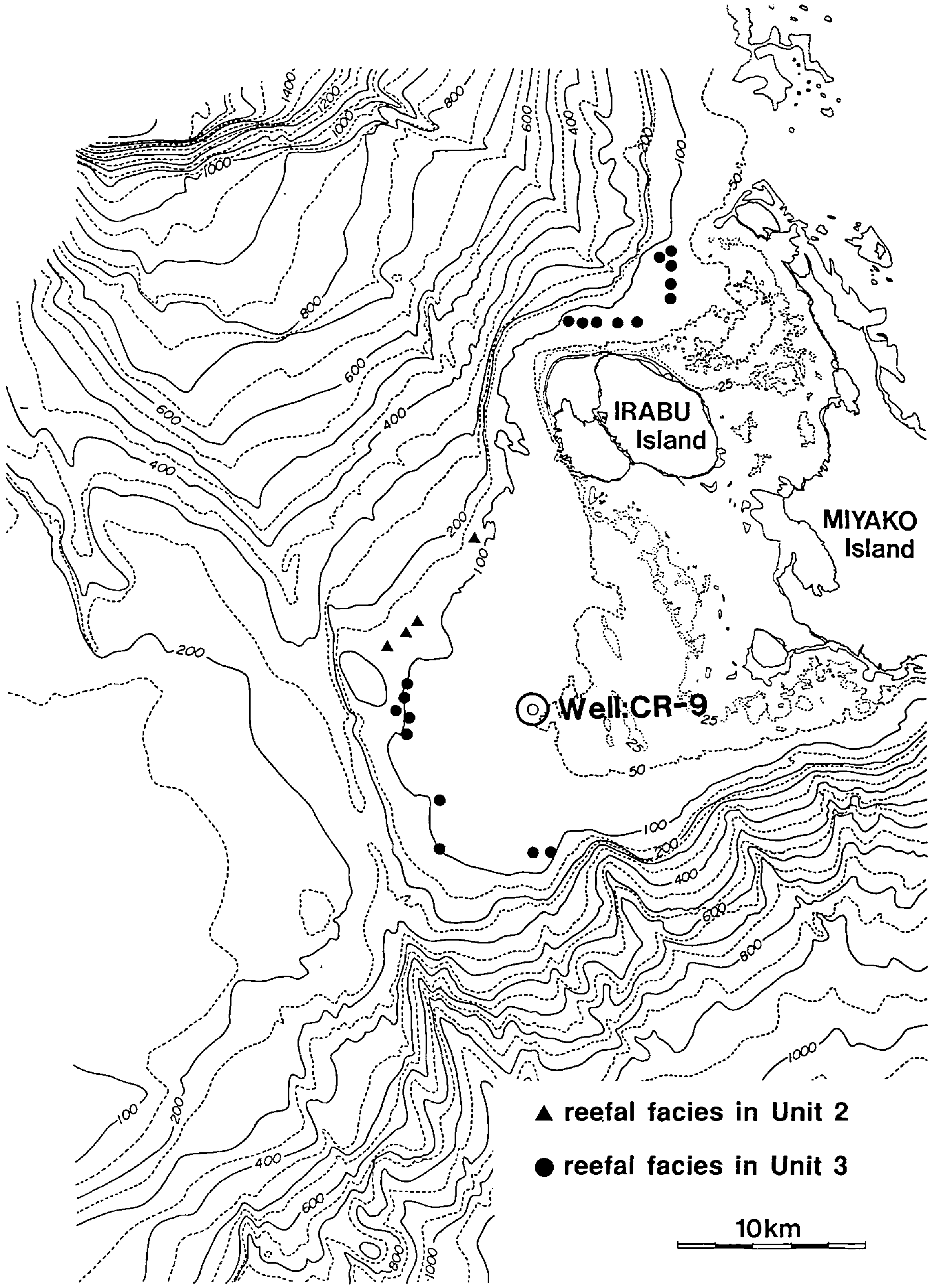

Figure 7. Distribution of reefal facies within Unit 3 and Unit 2.

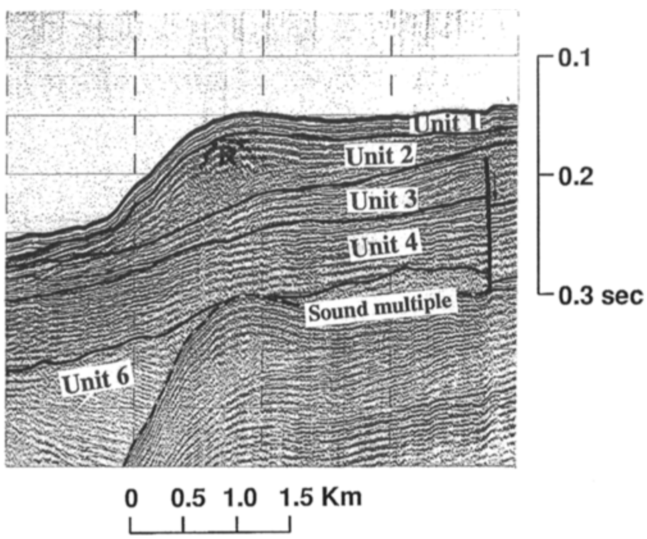

Figure 8. Mound-shaped external form with internal chaotic reflections in Unit 2, suggesting reefal facies or buildups (Line 87-1).

dational configurations (Fig. 6). Beneath the shelf break, oblique (tangential) progradational configurations are prominent (Fig. 6). Beneath the insular shelf, mound and chaotic reflection configurations are frequently recognized and suggest the presence of reefal facies (Fig. 8). The distribution of the reefal facies is restricted landward of the 125 m isobath (Fig. 7).

The unit downlaps basinward and onlaps landward onto Unit 3 with relatively high angles. The cross sectional profile is similar to that of Unit 3.

A NNE trending normal fault cuts the unit and extends into the overlying unit. This fault is thought to be a growth fault active during deposition of all units from 4 through 1. Reflection configurations on either side of the fault are totally different. Rather thicker sediments showing oblique (tangential) configurations with relatively chaotic reflections occur at the downthrown side of the fault, whereas the thinner sediments at its upthrown side show parallel configurations. Beneath the northern and western insular shelf of Irabu Island, the above depositional contrast is prominent and the shelf break is bounded by active faults. These faults formed steep scarps.

The distribution of the unit basinward terminates beneath the 250 m isobath to the northwest of Irabu Island, and the 200 m isobath to the south of the island (Fig. 3). The thickness in most areas is less than 20 ms in two way time, however, exceeds 100 ms at the downthrown side of faults.

Unit 1: This unit is characterized by parallel reflection configurations with high amplitude and good continuity (Fig. 2). The unit drapes over topographic relief in the study area, with little change in thickness. The thickness ranges from 10 ms to 20 ms in two way time. Faults cutting the unit and extending upward to the present sea-floor are recognized and interpreted as extensional growth faults.

DISCUSSION

Sedimentation and Structural Evolution

As a result of seismic sequence and facies analyses, the depositional setting and general facies of each seismic unit of the Ryukyu Group offshore correlatives (Unit 1 to Unit 5) are interpreted and summarized in Table 1, based on which regional geohistory during the Quaternary is inferred.

The structural patterns of the Unit 6 and unconformable features at its upper boundary (Fig. 4) are regarded as being identical to those of the Shimajiri Group, thus substantiating the Shimajiri Crustal Movement (Kizaki, 1985).

Unit 5 is the basal depositional sequence of the Ryukyu Group correlative and is thought to be a lowstand deposit. The Shimajiri Crustal Movement which uplifted and eroded Unit 6, caused a relative drop of sea level, removed a large amount of siliciclastic materials from the underlying unit and deposited them as a lowstand fan and wedge. During the late period of the unit, a vigorous tectonic movement could have resulted in uplift and exposure of the depositional surface landward. This tectonic movement formed major NE trending faults and surface exposure along its upthrown side. Therefore, the landward extension of the unit which was once deposited along its upthrown side may have been completely eroded. As a result, the eroded materials were transported along the fault scarp and re-deposited at its downthrown side. This process can explain the present distribution and morphology of Unit 5. Hummocky clinoforms adjacent to the faults were probably resulted from either deformation by the NE trending faulting or fan-like deposition. Extensional growth faulting could have frequently occurred and NE trending faults were most active during this erosional phase.

The depositional style of the unit is generally characterized by wavy parallel to subparallel configurations beneath the present shelf slope. This suggests that a uniform rate of deposition on a uniformly subsiding depositional surface was one of the factors related to the deposition of Unit 5. However, divergent reflection configurations are also locally found adjacent to extensional growth faults and suggest that the lateral variations in progressive tilting of the depositional surface by faulting were present. These variations of the depositional styles suggest that sedimentation of the Ryukyu Group correlative was tectonically controlled from the beginning. In addition, the upper boundary of the unit, which shows convex and concave patterns and presumably represents rapid turbiditic sedimentation may be caused by tectonic movements.

Unit 4 is correlated to the Riukiu Limestone on well CR-9 which was drilled on the Miyako insular shelf at approximately 45 m below sea level (Figs. 7, 9). Calcareous nannoplankton data from the borehole suggest that most parts of the 75 m succession of the Riukiu Limestone were deposited during the interval between

1.2 Ma and 0.39 Ma, although the uppermost part may possibly be younger than 0.39 Ma (Honda *et al.*, in prep.).

As pointed out by Ujiie (1980), the change in the depositional environment from clastic sediments of the Unit 6 (Shimajiri Group) to carbonates of the Unit 4 (Riukiu Limestone) may largely depend on the development of the Okinawa Trough, as the trough acted as a trap of the terrigenous sediments from the Asian Continent.

Deposition of Unit 4 is represented by subparallel/ wavy parallel configurations suggesting a deposition in medium to low energy environments. In addition, hummocky to contorted clinoforms locally recognized adjacent to the major NE trending fault, suggest contemporaneous down-faulting of this zone and rapid sediment supply bypassing the submarine fault scarp. During the same time as the deposition of Unit 4, reefal facies recognized in CR-9 and Riukiu Limestone on land was deposited as a landward extension of Unit 4 (Fig. 9) on the topographical high.

Cyclic vertical accumulation of four sequences (Yuki *et al.*, 1988) in the Riukiu Limestone on land suggest overall transgression between 1.2 Ma and 0.39 Ma although the oxygen isotope records of deep sea cores (Williams *et al.*, 1988) do not verify such a transgression (Fig. 10). The transgression may be due to a tectonic subsidence of the arc (Fig. 11).

Irabu and Miyako Islands were considerably faulted after the deposition of Unit 4. Faults terminating at the upper boundary of Unit 4 are most abundant among any faults cutting the Ryukyu Group correlative (Figs. 2, 9, 12). This may suggest that the most vigorous faulting occurred immediately after the deposition of Unit 4 or continued through the deposition and ceased by the beginning of the deposition of Unit 3. NNE and NNW trending faults, tended to be distributed on the Ryukyu Arc, were activated during this phase. On the contrary, the NE trending faults, tended to be found on the slope facing to the Okinawa Trough, were activated since the previous phase (Fig. 3).

The faulting and following relative sealevel drop resulted in a local erosion. Toplapping terminations of parasequences at the upper boundary of Unit 4 is locally recognized beneath the shelf.

The configuration of Unit 3 shows that the unit is a still stand deposit. The distribution of reefal facies in Unit 3 shows that the relative sea levels during deposition of Unit 3 were generally lower than those of Unit 4 (Fig. 9). The distribution of the reefal facies in Unit 3 is restricted to the area of which depth ranges from 80 to 110 m, although that of Unit 4 extends to shallower than 60 m (Fig. 7). As the oxygen isotope records of deep sea cores (Williams *et al.*, 1988) do not show any tendency of the sealevel fall after 0.4 Ma (Fig. 10), this overall relative sealevel fall can be ascribed to the tectonic uplift (Fig. 11) associated with the faulting.

Sigmoid progradational and divergent reflection configurations of Unit 3 at the downthrown side of

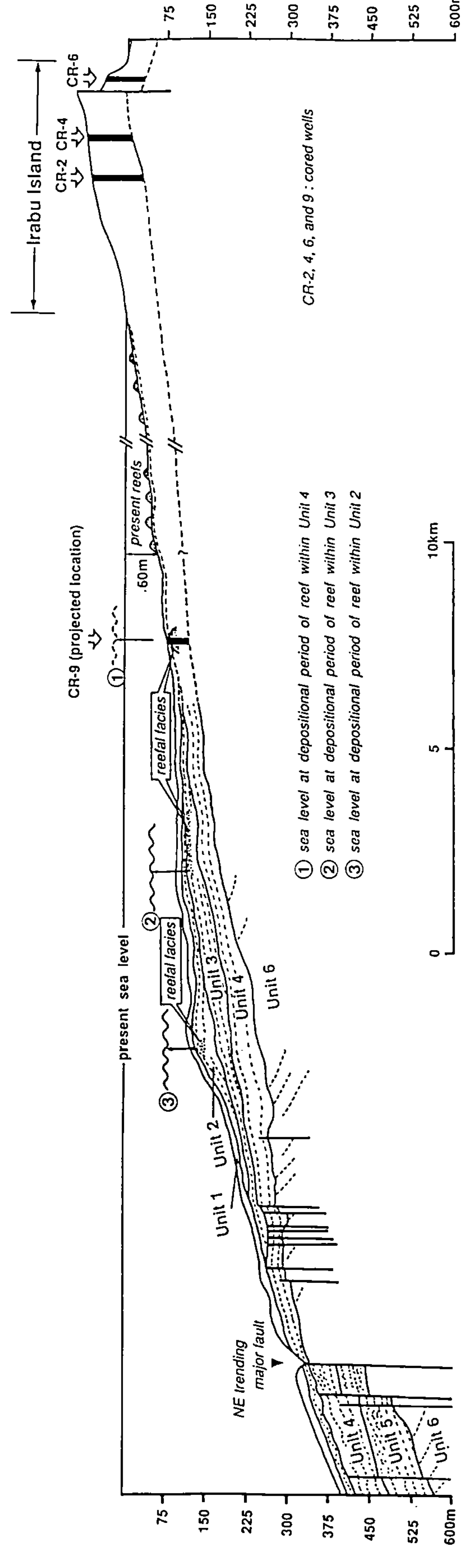

Figure 9. Schematic cross section from Irabu Island to its shelf slope. Vertical scale is shown in meter by assuming sonic velocity of 1,500 m/s in sea water.

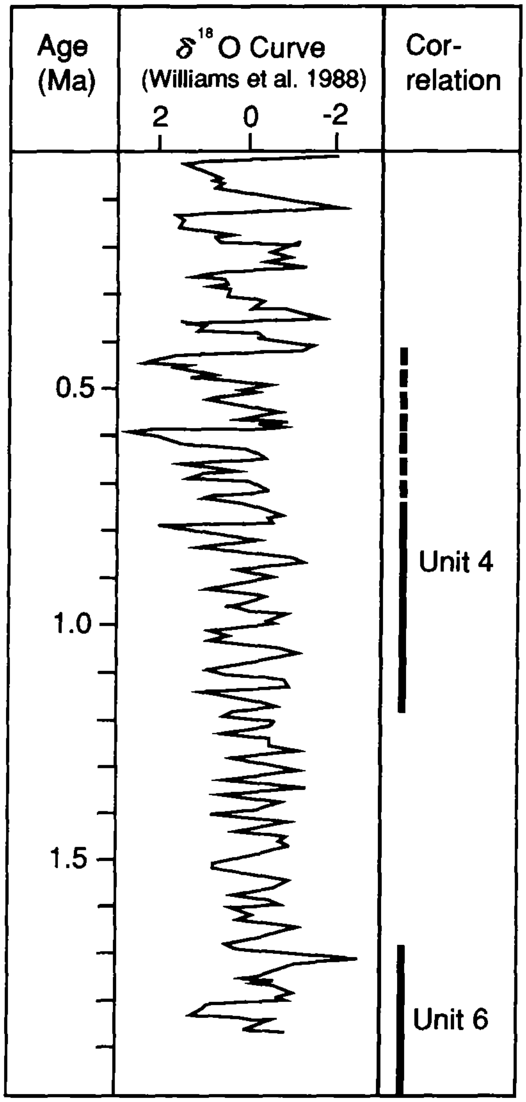

Figure 10. Oxygen isotope curve and its correlation with Units 4 and 6.

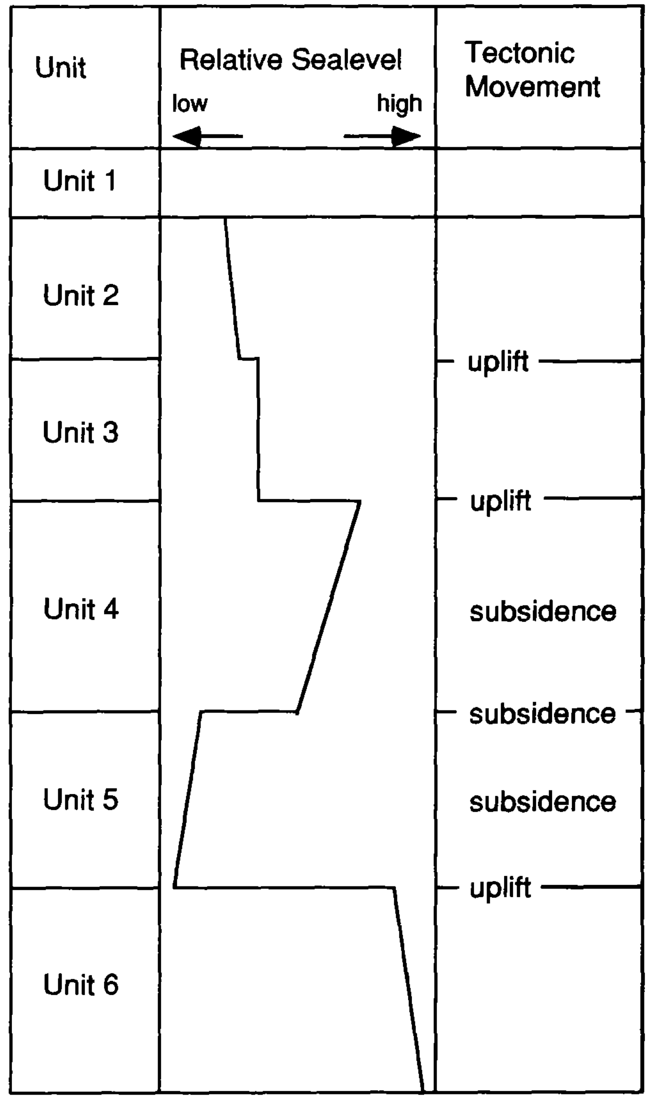

Figure 11. Relative sealevel change and tectonic movement with respect to each unit.

faults, where the thickness of the unit rapidly increases, suggest that extensional growth faulting also influenced the deposition of the unit. Consequently, faulting could have still activated and may have frequently caused depression and differential tilting at the downthrown side of faults during this phase. The distribution of these faults is concordant with the edge of the Miyako-Irabu insular shelf and suggests that the outline of the insular shelf was closely related to faulting, particularly to the west and north of Irabu Island. The deposition of the reefal facies could have been restricted to the topographic high formed by uplift along the upthrown region of these faults.

Unit 2 downlaps and onlaps onto the underlying Unit 3 basinward and landward respectively. The outer limit of reef occurrence of this unit corresponds to the present 125 m isobath (Fig. 7). As the elevation and outer limit of the reefs are compared between Unit 3 and Unit 2, those within Unit 2 tend to occur lower and more basinward (Figs. 7, 8). This suggests that further regression occurred after deposition of Unit 3 and allowed the reefal distribution to migrate more basinward. So tendency of sealevel falling cannot be seen in the oxygen isotope records (Fig. 10) that the regression also had been caused by tectonic uplift as seen in the relation between Units 4 and 3 (Fig. 11).

The distribution of Unit 2 is also controlled by extensional growth faulting. The oblique (tangential) reflection configurations with chaotic reflections recognized in the thick strata at the downthrown side of faults, suggest very rapid sedimentation, probably fan-like deposition at the downthrown side of the fault scarps. In addition, NNE and NNW trending faults crossing the Ryukyu Arc, were also activated during this phase (Fig. 3).

The depositional style of Unit 2 is characterized by complex sigmoid-oblique progradational reflection

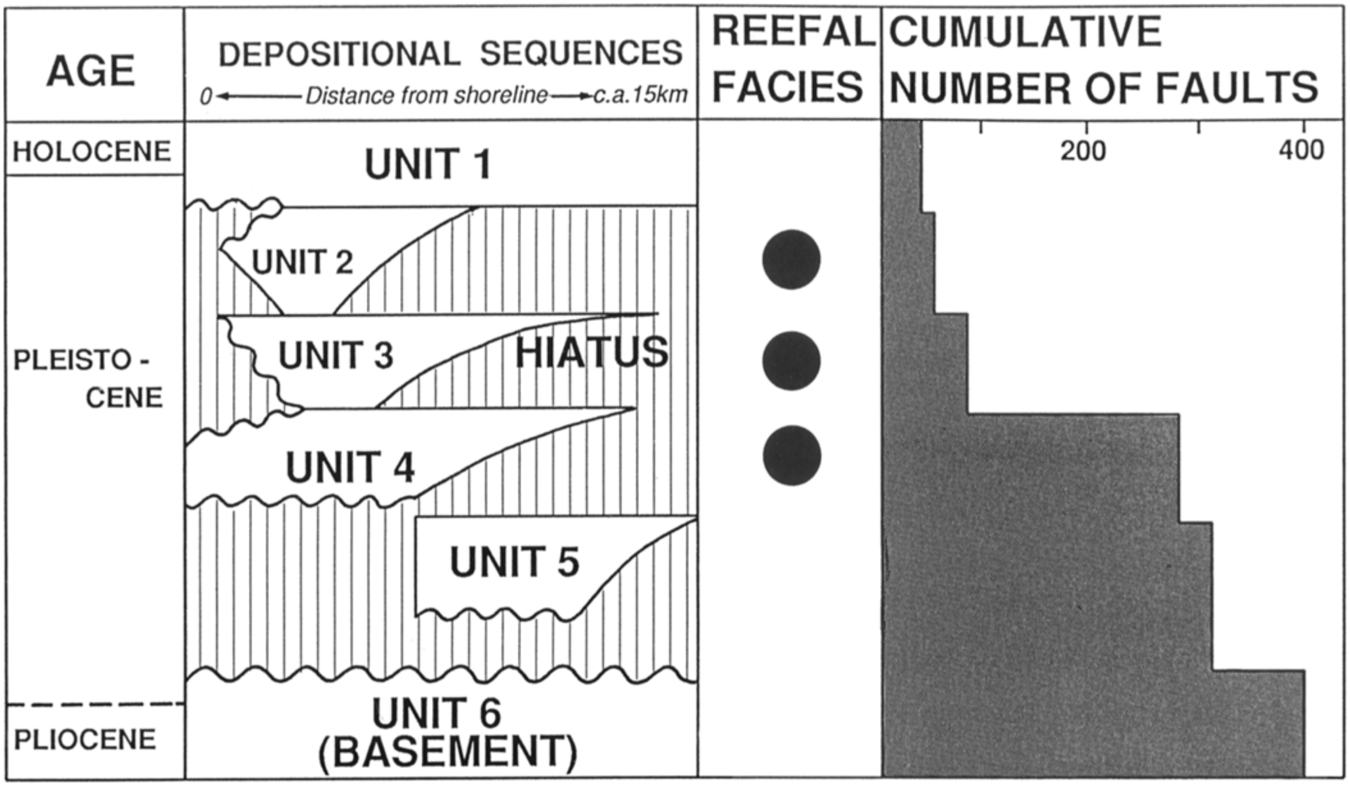

Figure 12. Seismic units and the development of reefal facies and faults in the units. The column in the right suggests that the most vigorous faulting occurred during or immediately after the deposition of Unit 4.

configurations. Relatively slow regression or stillstand of sea level could have allowed the prograding depositional style with relatively high angled stratification.

The evidence of tectonic uplift and growth faulting in Unit 2 suggests that the tectonic movement still continued during the deposition of Unit 2, although it was not as active as the previous stage. From the concordance between the distribution of Unit 2 and the isobath of present shelf break, it is inferred that the topographic outline of Miyako-Irabu insular shelf was almost completed at the end of this phase.

The lack of resolution of seismic profile has limited the accuracy of seismic facies analysis of the Unit 1. The unit is thought to contain both the youngest depositional sequence of the Pleistocene Ryukyu Group correlative as well as the Holocene sediments.

The concave and convex patterns of the sea floor frequently recognized on the present shelf slope at more than 600 m of water depth seems to suggest the presence of turbiditic facies.

Quaternary eustatic sealevel change associated with neotectonic uplift created raised marine carbonate terraces correlated to interstadials in the areas of active margin as shown on Barbados (e.g. Mesolella *et al.*, 1969), New Guinea (e.g. Bloom *et al.*, 1974), and Ryukyus (e.g. Konishi *et al.*, 1974). The resolution of the seismic study is not high enough to correlate a seismic sequence to an isotope stage (Schackleton and Opdyke, 1973) as shown by the fact that Unit 4 includes some isotopic stages between 1.2 Ma to 0.4 Ma (Fig. 10).

The deposition of the carbonates controlled by neotectonics on the Ryukyu Arc is summarized as follows:

1) The commencement of the carbonate deposition is controlled by the rifting or spreading of Okinawa Trough. The terrigenous sediments from the Asian Continent were trapped by the Okinawa Trough.

2) The distribution of the reefal facies is highly controlled by the tectonism caused by the spreading of Okinawa Trough and subduction of the Philippine Sea Plate. The reef develops on the edge of faulted upthrown side that is the topographical high. Basinward accretion of reefal deposit took place without the tendency of eustatic sealevel drop.

3) The downthrown side of the fault has the thick deposit, which is reworked sediments of the eroded sediments by uplifting and erosion and/or winnowed sediments from the shallower environment of which energy is very high.

Such a tectonically controlled Quaternary carbonate deposition is not reported from passive margin platforms of the Great Bahama Bank and the Great Barrier Reef. The framework of the basin topographies there, however, was created by tectonism with faulting in the very early stage of the basin development. The modern Great Bahama Bank was created by infilling and prograding sequences which are the result of eustatic sealevel fluctuations, although the initial topography was created in the mid-Cretaceous (Eberli and Ginsburg, 1989). The evolution of the Great Barrier Reef is primarily controlled by rifting, subsidence, plate motion (with climatic and oceanographic consequences), sealevel variation and plate collision which have acted upon the continental margin since the Cretaceous, and the post-Pliocene evolution is a function of sealevel-controlled fluvio-deltaic deposition and reef growth (Davies *et al.*, 1989).

These examples from the Great Bahama Bank and the Great Barrier Reef display that tectonism is a long term factor in the passive margin carbonate platform evolution. On the contrary, the Quaternary carbonate platform evolution off Miyako and Irabu Islands in south Ryukyus are closely related to tectonism created by back arc spreading and plate subduction. The distribution and facies development of the individual seismic units are the results of sea-level changes influenced by the tectonism.

SUMMARY

The Plio-Pleistocene and Holocene strata distributed from the insular shelf to the shelf slope of the western offshore Miyako and Irabu Islands are divided into six seismic units from Unit 1 to Unit 6 in descending order. The depositional facies and process of each seismic unit, and the influence of tectonic movements on carbonate sedimentation were analyzed, and the geohistory was summarized as follows.

Plio-Pleistocene Shimajiri Group being a siliciclastic basement, Unit 6, was folded and faulted by the Shimajiri Crustal Movement (Kizaki, 1985) which is related to the spreading of the Okinawa Trough in early Pleistocene between approximately 1.7 Ma and 1.2 Ma.

Reworked sediment from Unit 6, which is Unit 5, deposited by regression after the Shimajiri Crustal Movement. Tectonic movement allowed a NE trending major fault to be formed in the northwest of the study area and made the unit at its upthrown side to be eroded.

Unit 4, which is correlated to the Riukiu Limestone distributing on Irabu Island deposited during a part or all of the interval between approximately 1.2 Ma and 0.4 Ma, deposited with overall transgression caused by the subsidence of the arc. Reefal distribution within the unit is restricted to more landward area than approximately 60 m isobath. After the deposition of the unit, tectonic movement could have culminated and activated NE, NNE and NNW trending faults. By this movement, the crest area of the Ryukyu Arc including Miyako and Irabu Islands was uplifted and faulted mainly by NNW trending faults.

Younger strata than the Riukiu Limestone on Irabu Island, Units 3 and 2, deposited with reef development. Reefal facies within each unit is distributed more basinward than that of the unit down below, and suggest a relative sealevel drop by uplifting. The reefal facies is located at a topographic high which was formed by NE, NNE and NNW trending normal faults. These faults bounding the edge of the present insular shelf were still active during the period when those units deposited, and the thick sediments distributed at their downthrown side with the progress of extensional growth faulting.

The youngest depositional sequence, Unit 1, which comprises the top part of the Pleistocene Ryukyu Group correlative and the Holocene sediments, covered whole study area.

Carbonate sediments highly displaced and controlled its sedimentation by Quaternary tectonic movements as observed in the study area have not been documented from the passive margin context as the Great Bahama Bank and the Great Barrier Reef.

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