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Evolution of the southern Taiwan–Sinzi Folded Zone and opening of the southern Okinawa trough

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Abstract

Recent interpretation of seismic sections and free-air gravity anomalies in offshore northern Taiwan reveals that the southern Taiwan–Sinzi Folded Zone began to form in late Middle Miocene, though it was mainly constructed in the Late Pliocene with strong reverse faulting and folding. Two westward progradational sequences were deposited in the shelf basin with sediments supplied from the southern Taiwan–Sinzi Folded Zone and the southern Ryukyu Arc. These two structures are displaced by several northwest-striking dextral strike–slip faults that were active in the early Quaternary when the clockwise-rotated southern Ryukyu Arc and the folded southern Taiwan–Sinzi Folded Zone were broken. It is believed that recent extension in the southern Okinawa Trough started in the early Quaternary because uplift on the southern Taiwan–Sinzi Folded Zone continued to latest Pliocene–early Quaternary. Paleogene–Miocene sediments of the East China Sea Shelf in the western part of the southern Okinawa Trough Basin are interpreted to indicate that the East China Sea Shelf Basin extended to the east of the southern Taiwan–Sinzi Folded Zone. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

The southern Taiwan–Sinzi Folded Zone (TSFZ) separates the East China Sea Shelf Basin (referred to as “the shelf basin”) from the Okinawa Trough Basin in the East China Sea area (Fig. 1). The TSFZ is a basement high that is easily traced in satellite gravity data and runs NNE from Taiwan to about 33°N between Korea and Kyushu, Japan. It was named the Taiwan–Sinzi Folded Zone by Wageman et al. (1970), and is often called the Diaoyudao Folded Uplift Belt (Zhou et al., 1989) or Diaoyu Island Uplift (Liu, 1989) by mainland Chinese geologists.

The southern TSFZ is the roughly east–west trending southern section of the zone and extends approx. 300 km from the northern tip of Taiwan. Although the evolution and tectonic framework of the southern TSFZ have been discussed in many studies (Sun, 1985; Huang et al., 1992; Chen and Watkins, 1994; Hsiao, 1997; Hsu and Sibuet, 1995; Sibuet and Hsu, 1997), several key problems remain unsolved. First of all, while previous publications show sinistral displacements of the southern TSFZ and the southern Ryukyu Arc (Zhou et al., 1989; Yang, 1989; Wang et al., 1995), our interpretations of seismic sections, free-air gravity anomalies, and bathymetry indicate that they are offset dextrally by a series of northwest-trending strike–slip faults (Fig. 2). Second, the outline of the southern TSFZ has not heretofore or previously been well delineated. Third, the sharp termination of the thick sedimentary zone near the southern TSFZ (Fig. 3) suggests that it may have formed within the thick sedimentary zone, and that the southern Okinawa Trough Basin may have also extended within these same shelf basin deposits. While Paleogene and lower Neogene shelf basin deposits may be found in the

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southern Okinawa Trough, it appears that the major episode of extension has occurred only recently. The relationship between the northwest-trending right-lateral strike–slip faults, the opening of the southern Okinawa Trough, and the Luzon–Taiwan collision has not previously been discussed in the same context.

The timing and mechanism of extension in the southern Okinawa Trough are controversial. While some authors suggest that the southern Okinawa Trough opened as a wedge-shaped backarc basin as a result of clockwise rotation of the southern Ryukyu Arc in the Late Miocene (Miki et al., 1990; Miki, 1995; Sibuet and Hsu, 1997), others propose that it opened as a collision/lateral backarc basin in late Pliocene–early Quaternary (Letouzey and Kimura, 1986; Letouzey and Sage, 1988; Lallemand et al., 1997). Our seismic interpretation suggests that the most recent extension in the western part of the southern Okinawa Trough started in early Quaternary due to pull-apart motion of a series of NW-trending right-lateral strike–slip faults coupled to subduction of the Philippine Sea Plate.

The objective of this work is to delineate the outline of the southern TSFZ and to discuss its evolution and its relation to the opening of the southern Okinawa Trough. By interpretation of stratigraphy and deformation from seismic lines, free-air gravity anomalies, and other geological and geophysical data, we investigate the tectonic history of offshore northern Taiwan and place the southern TSFZ into that framework.

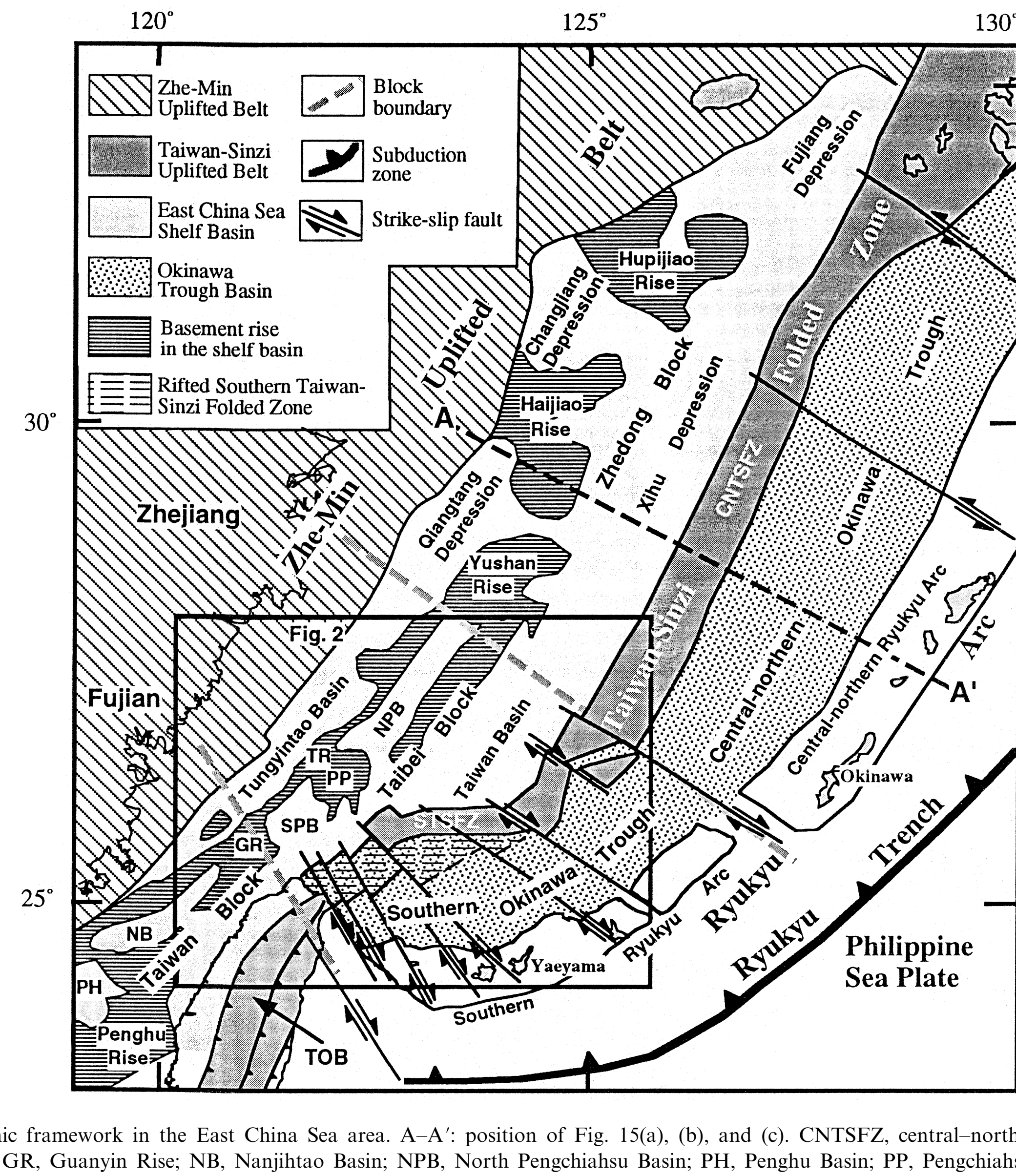

Fig. 1. Tectonic framework in the East China Sea area. A–A′: position of Fig. 15(a), (b), and (c). CNTSFZ, central–northern Taiwan–Sinzi Folded Zone; GR, Guanyin Rise; NB, Nanjihtao Basin; NPB, North Pengchiahsu Basin; PH, Penghu Basin; PP, Pengchiahsu Platform; SPB, South Pengchiahsu Basin; STSFZ, Southern Taiwan–Sinzi Folded Zone; TOB, Taiwan-Orogenic Belt; TR, Tungyintao Ridge.

Unlike previous studies, that mainly focused on seismic sequences or structures, our interpretation of seismic reflection sections combines seismic sequence and structure analyses with standard seismic interpretation procedures (Badley, 1985; Vail et al., 1977; Brown and Fisher, 1977). We then use the results of the seismic interpretation to infer tectonic deformation and basin evolution processes. In order to facilitate our discussion on the southern TSFZ, we first outline the seismic sequences and basin evolution in the southern East China Sea Basin (Kong et al., 1997a; Kong, 1998).

2. Seismic stratigraphic sequences in offshore northern Taiwan

The data set used in this study include 2-D seismic reflection sections of 49 lines of more than 5100 km, with dip sections in the southeast direction and strike sections in the northeast direction (Fig. 4). More than half of the best quality lines were provided by one of the sponsors in an industry consortium at the University of Texas Institute for Geophysics. About 17 lines of variable quality were provided by China National Offshore Oil Corp. These lines constitute a reasonably good coverage of the study area.

We defined sequence boundaries and divided seismic sequences across the basin by comparing previous work (Lee et al., 1996; Chen and Watkins, 1994; Hsiao, 1997) with our interpretation of offshore northern Taiwan. Seven regional unconformities and a few local ones are recognized, which divide the basin stratigraphy into ten or eleven sequences (Figs. 5 and 6). Only the sequences near the southern TSFZ or in the southern Okinawa Trough are outlined here. We focus here on the younger sequences, because we wish to focus on the evolution of the southern TSFZ during Miocene to Quaternary.

Sequence Z is of Upper Jurassic–Lower Cretaceous age with discontinuous and medium to high amplitude seismic facies (Fig. 5). Sequences A and B are absent in the eastern part of the shelf basin. Sequences C, D, E, and F (Fig. 7(a)) are synrift sequences deposited in the eastern part of the shelf basin in Late Paleocene–Early Oligocene. Details of their depositional characteristics are described elsewhere. Sequence F is missing in most areas. Sequence G consists of parallel to subparallel semi-continuous high amplitude facies alternat-

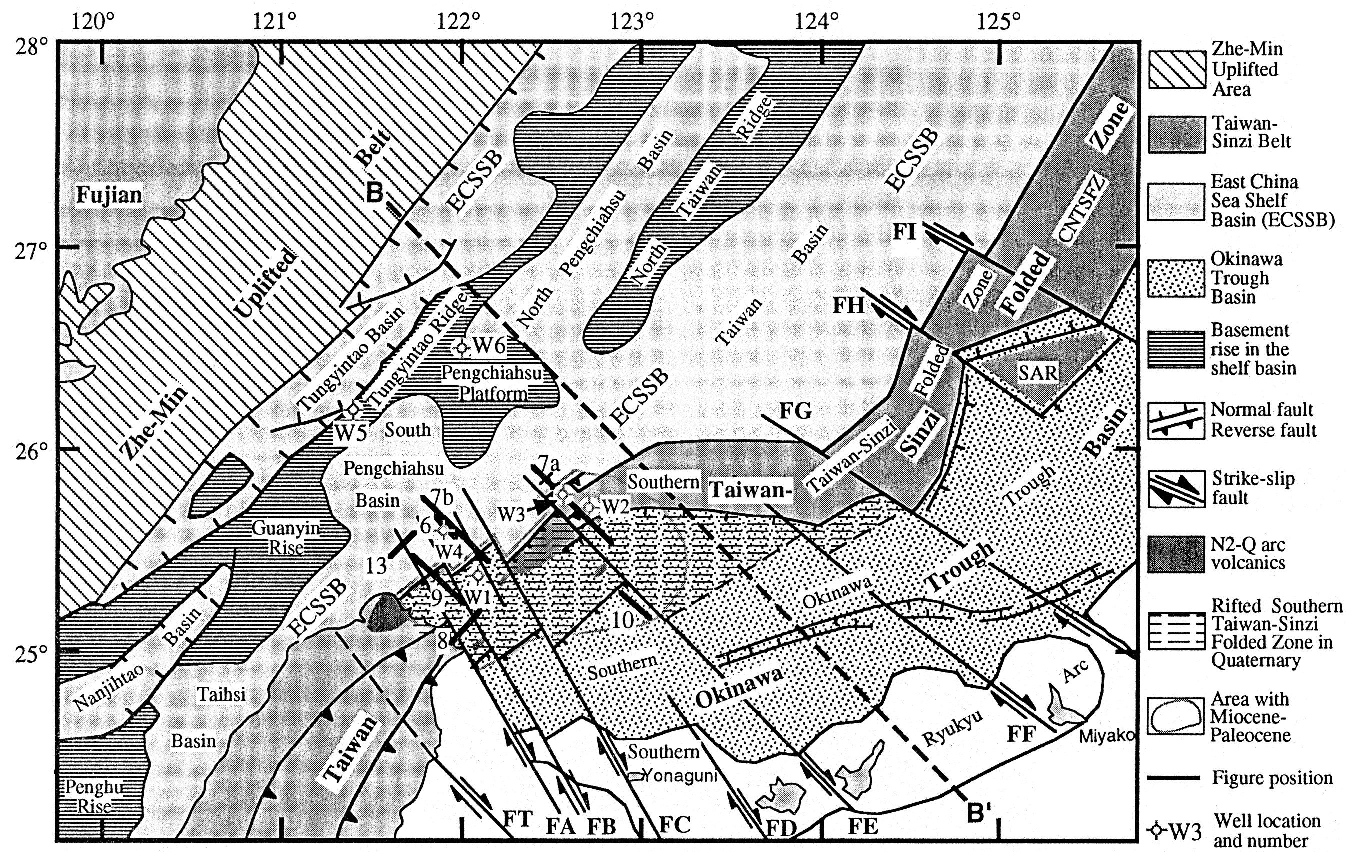

Fig. 2. Tectonic framework in the offshore northern Taiwan area affected by the Luzon–Taiwan collision. Figure positions and some well localities are shown. B–B′: position for Fig. 15(d), (e), and (f). ECSSB, East China Sea Shelf Basin; FA–FI, right-lateral strike–slip faults; FT, tear fault (Lallemand et al., 1997); SAR, stand-alone rise.

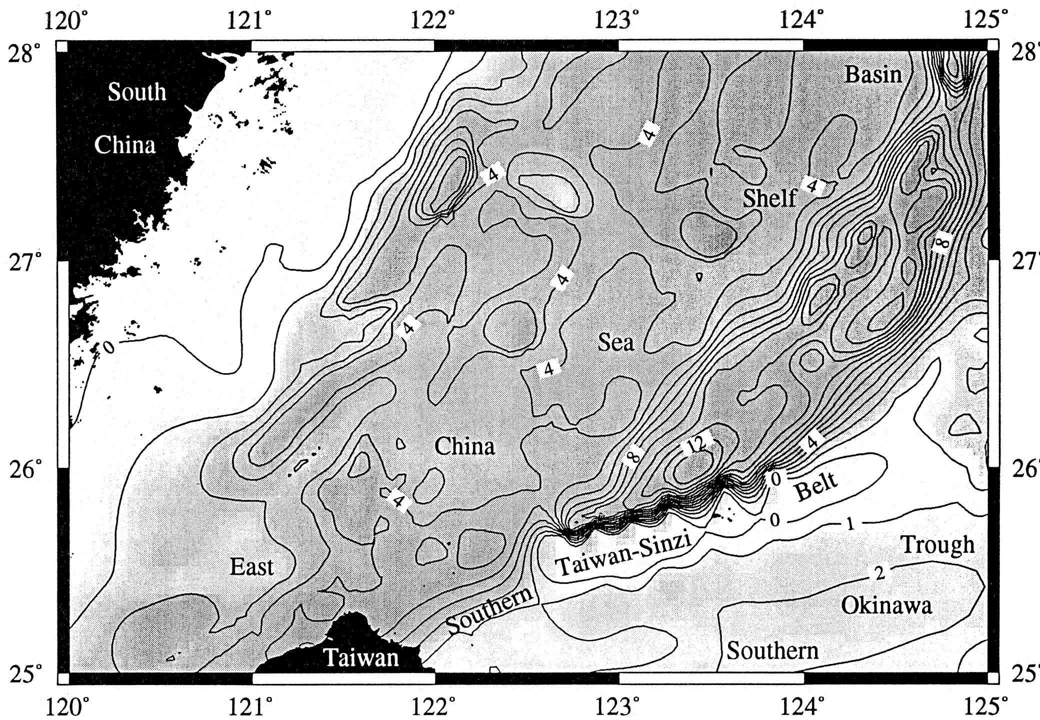

Fig. 3. Distribution of total sediment thickness (km) in Upper Cretaceous-Tertiary. Data are combined from Liu, (1992), Chen and Watkins (1994), and Huang et al. (1992). No data available along the Ryukyu Arc, in the Philippine Sea, and in the Zhejiang-Fujian coastal zone.

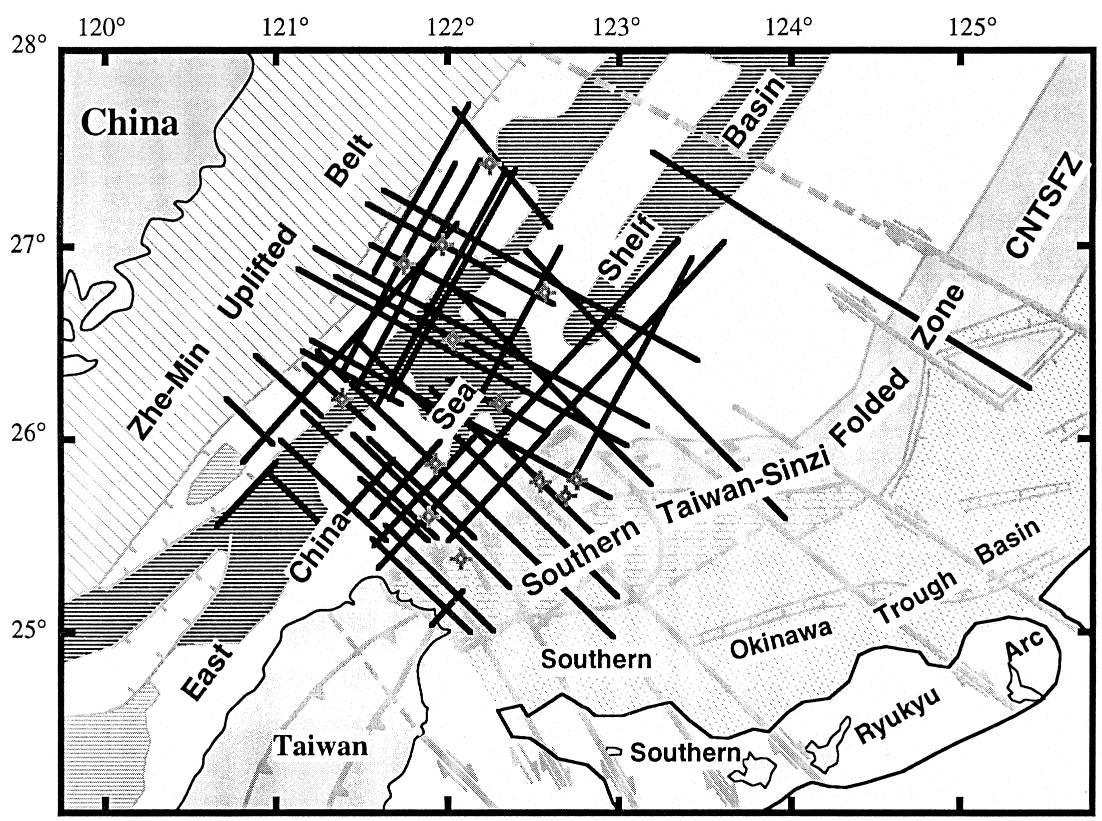

Fig. 4. Wells and 2D reflection seismic lines used in this study.

ing with low to medium amplitude facies with abundant minor truncations and numerous channels. It was probably deposited in a fluvial environment in Upper Oligocene–Lower Miocene. Westward onlaps and eastward downlaps as well as upward-coarsening in the depression in the eastern part of the shelf basin show a progradational low-stand complex, indicating a large sea-level drop at middle Oligocene (Fig. 7(b)). Sequence G is bounded at the bottom by the most significant unconformity R5 in the basin fill.

Sequence H is a thick westward progradational sequence of multiple progradational shingles in the eastern part of the shelf basin and in the central–northern part of the southern TSFZ (Figs. 2, 6, and 7), which can be interpreted from many seismic lines. Its top part was strongly eroded to form sequence boundary R7. Seismic reflections show continuous to semi-continuous low amplitude facies alternating with medium amplitude seismic facies. This westward prograding sequence indicates that sediment supply came from the east, probably from the uplifted southern Ryukyu Arc and the incipient southern TSFZ. Sequence H consists of Upper Miocene–Lower Pliocene sediments, and is separated from sequence G by sequence boundary R6.

In the eastern part of the shelf basin and the central–northern part of the southern TSFZ, sequence I1 consists of semi-continuous and discontinuous, low to high amplitude, up-coarsening, and westward prograding seismic facies with toplaps and downlaps in several westward progradational shingles (Fig. 7). It can be divided into several high frequency sequences between local erosional unconformities. Off the northeastern Taiwan coast, sequence I1 is a northward progradational sequence (Fig. 8), which indicates that a significant amount of sediment came from the Taiwan Orogenic Belt. The age of sequence I1 is latest Pliocene to early Quaternary inferred from well data. Sequence I1 is bounded from sequence H by sequence boundary R7 formed by folding and uplifting the shelf basin deposits in late Pliocene when the southern TSFZ was primarily constructed. The sedimentary source of sequence I1 is the uplifted TSFZ–southern Ryukyu Arc or the uplifted central–northern Taiwan Orogenic Belt. The multiple unconformities in sequence I1 may have formed by sea-level fluctuations or variation of sediment supply. The top of sequence I1 was truncated

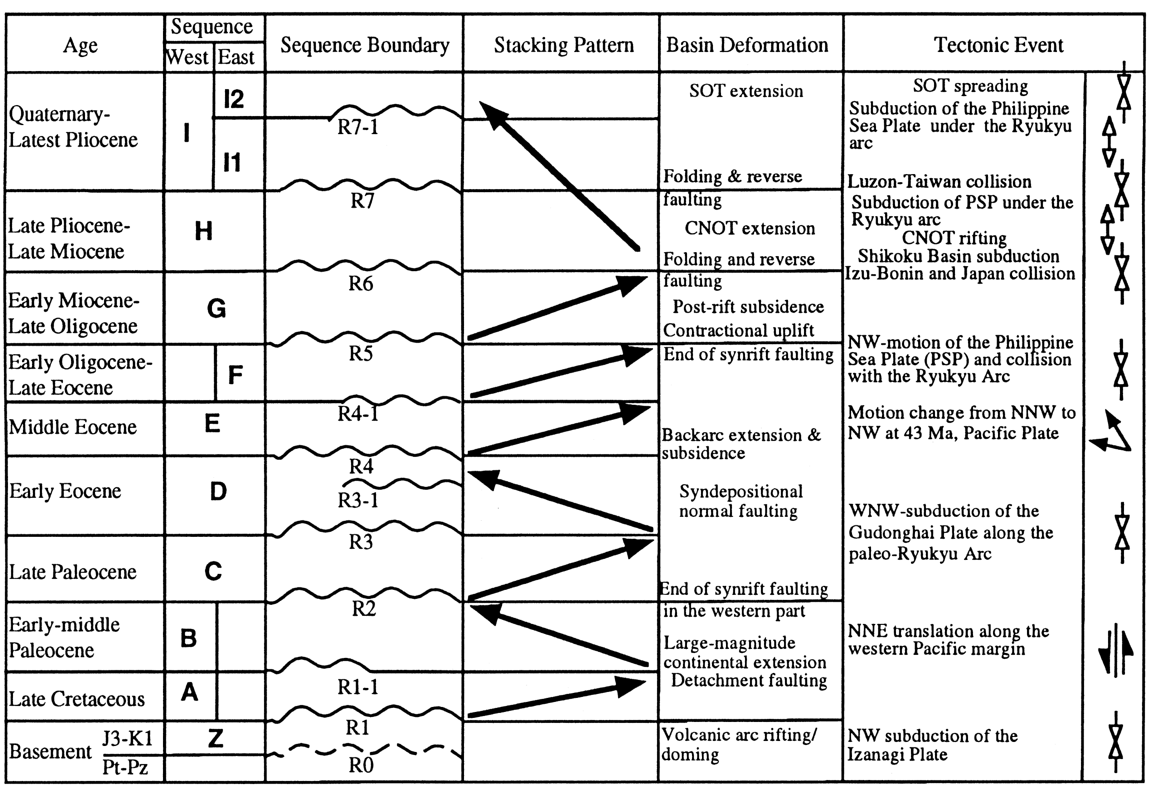

Fig. 5. Seismic stratigraphic sequences and deformation events in offshore northern Taiwan. West and East represent the western and eastern parts of the East China Sea Shelf Basin. For Sequence Boundary, the broken wavy line with R0 indicates an inferred sequence boundary. Short wavy lines represent local unconformities in the western (on left side) or eastern (on right side) part of the shelf basin. For Stacking Pattern, arrows show progradation (right) and retrogradation (left). For Basin Deformation, SOT is southern Okinawa Trough and CNOT is central–northern Okinawa Trough. For Tectonic Event, approaching arrows represent convergence, opposite arrows represent divergence, divergent arrows represent plate motion variation, and right-lateral arrows indicates translation.

and covered by sequence I2. Sequence I1 is missing in the southernmost TSFZ and the western part of the southern Okinawa Trough.

In the central–northern part of the southern TSFZ (Figs. 2 and 7(a)) and the eastern part of the shelf basin (Figs. 2 and 7(b)), sequence I2 consists of parallel, continuous, and low to medium amplitude seismic facies with a very small thickness. It is bounded from sequence I1 by local sequence boundary R7-1 marking the end of westward progradation. The age of this topmost sequence is Quaternary as revealed from well data (Hsiao, 1997). Sequence I2 in the western part of the southern Okinawa Trough and the southernmost TSFZ (Figs. 2, 7, and 9) is a synrift sequence, consist-

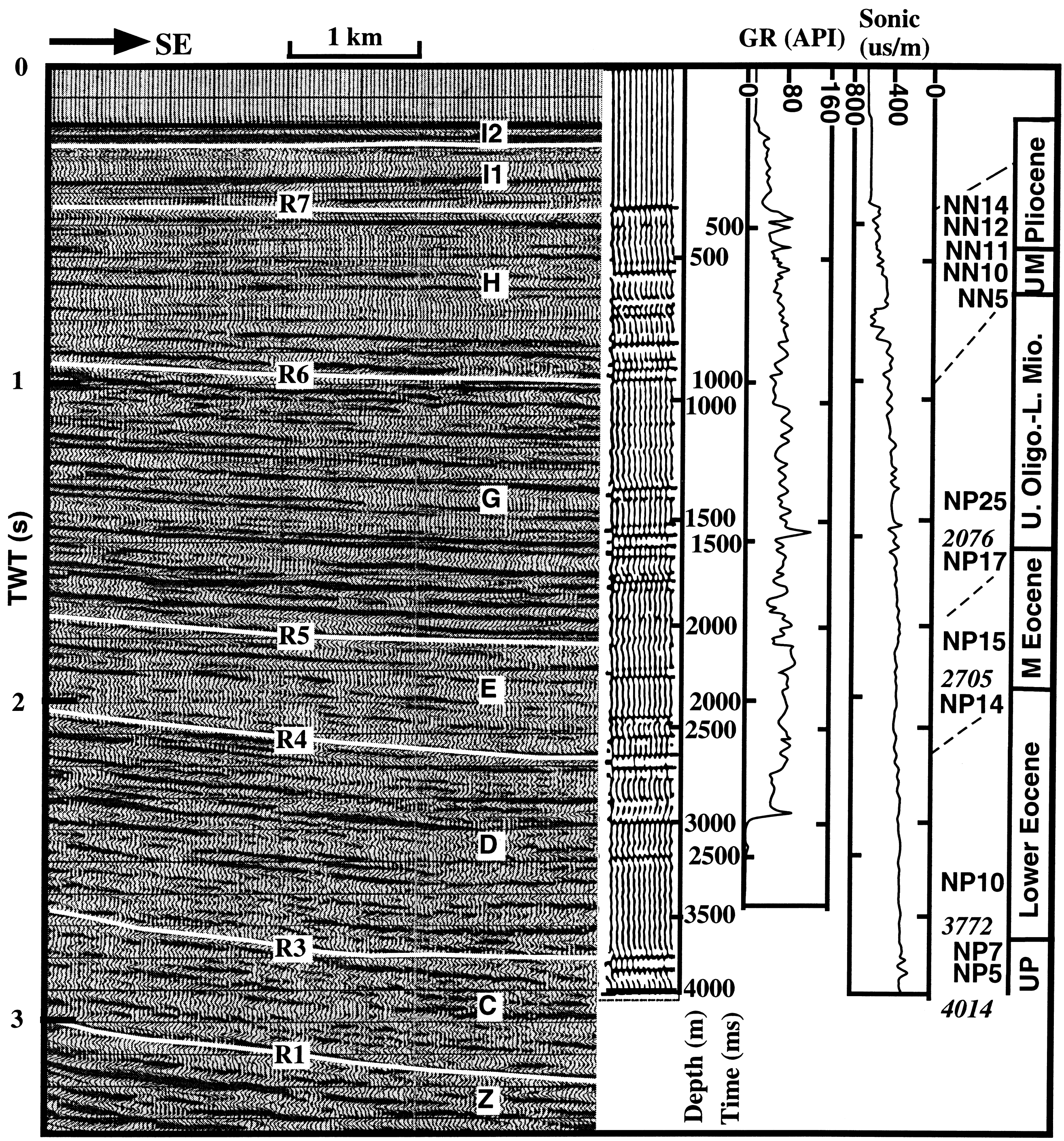

Fig. 6. Seismic sequences tied with synthetics and well logs at well W4 (YCL-1). The well log curves and synthetics are from Chen (1993). See Fig. 2 for location.

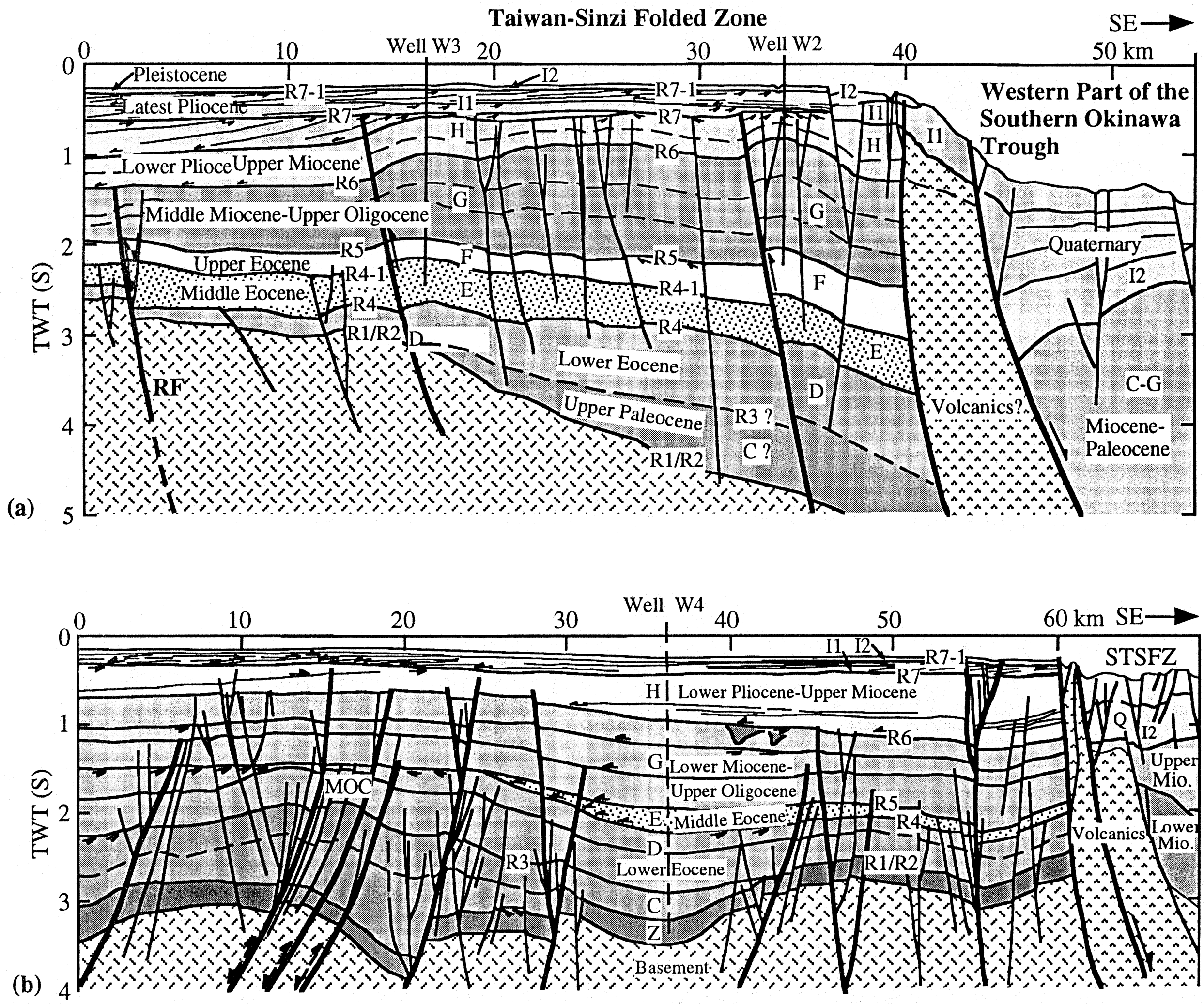

Fig. 7. (a) Seismic stratigraphy and stratigraphic deformation across the central–northern part of the southern TSFZ. RF is a minor reverse fault. (b) Seismic stratigraphy across the southern Pengchiahsu Basin and the southernmost TSFZ. Refer to Fig. 5 for symbols of sequence and sequence boundaries, and Fig. 2 for location.

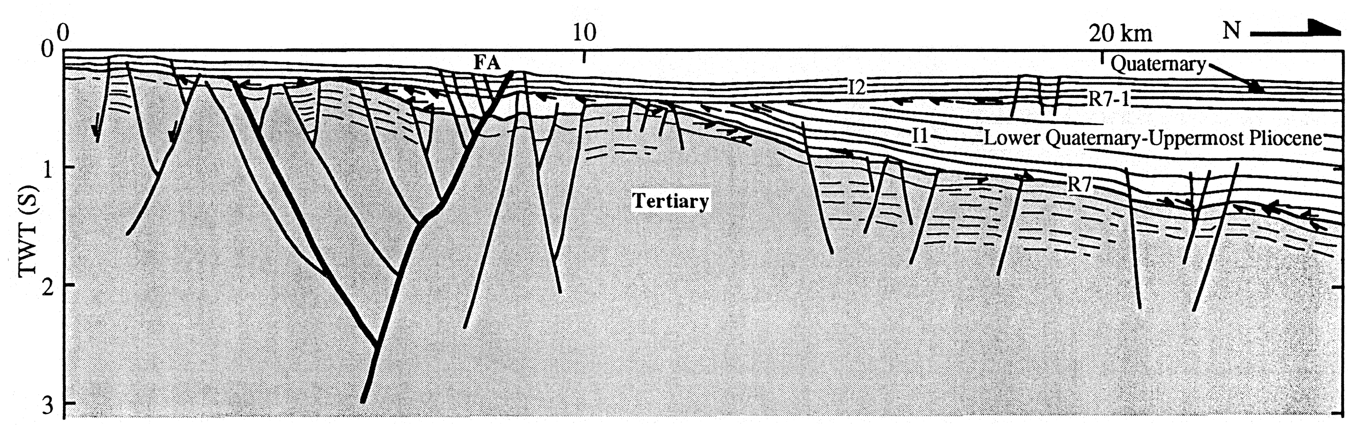

Fig. 8. Northward progradational sequence away from Taiwan and negative flower structure showing strike–slip fault FA (see Fig. 2) on strike section. The northward progradational sequence may be divided into high-frequency sequences. Two unconformities occur between sequence I2 and I1, and between I1 and Tertiary sediments. Refer to Fig. 5 for symbols of sequence and sequence boundaries, and Fig. 2 for location.

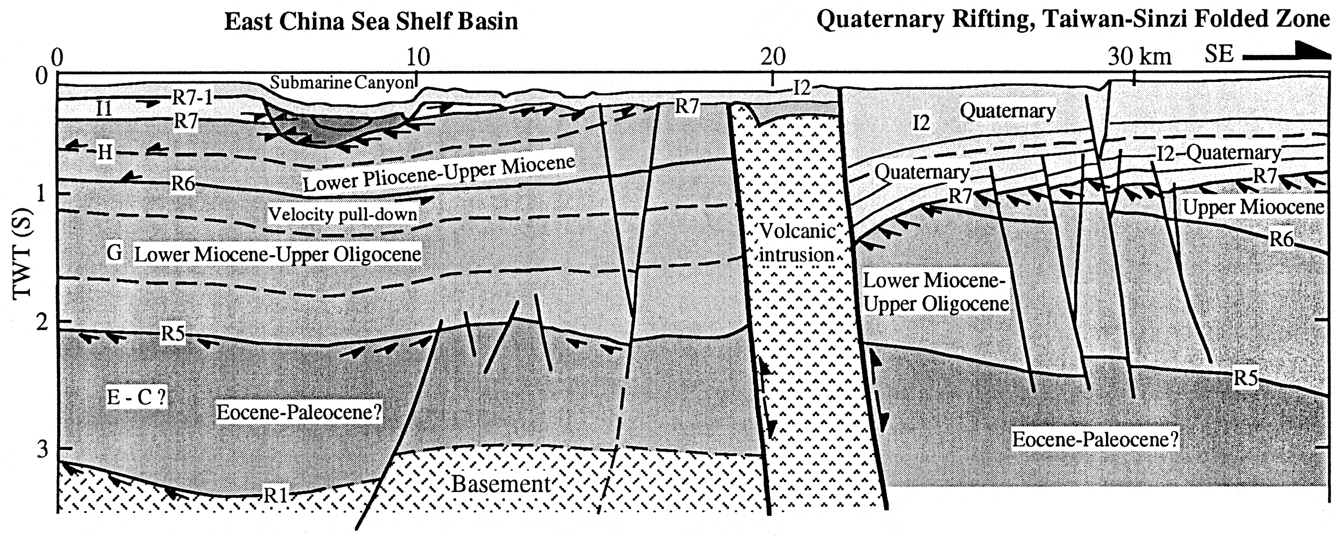

Fig. 9. Seismic stratigraphy across the southernmost TSFZ. Volcanic intrusion occurred on the western side of the collapsed southern TSFZ. Quaternary synrift sediments overlie Miocene–Paleogene sediments of shelf basin origin. Refer to Fig. 5 for symbols of sequence and sequence boundaries, and Fig. 2 for location.

ing of continuous and semi-continuous low amplitude facies interbedded with medium to high amplitude seismic facies. However, in some of the half grabens, the bottom or upper part shows high amplitude facies. The overall low amplitude of reflections implies that the recent synrift sediments came mainly from the

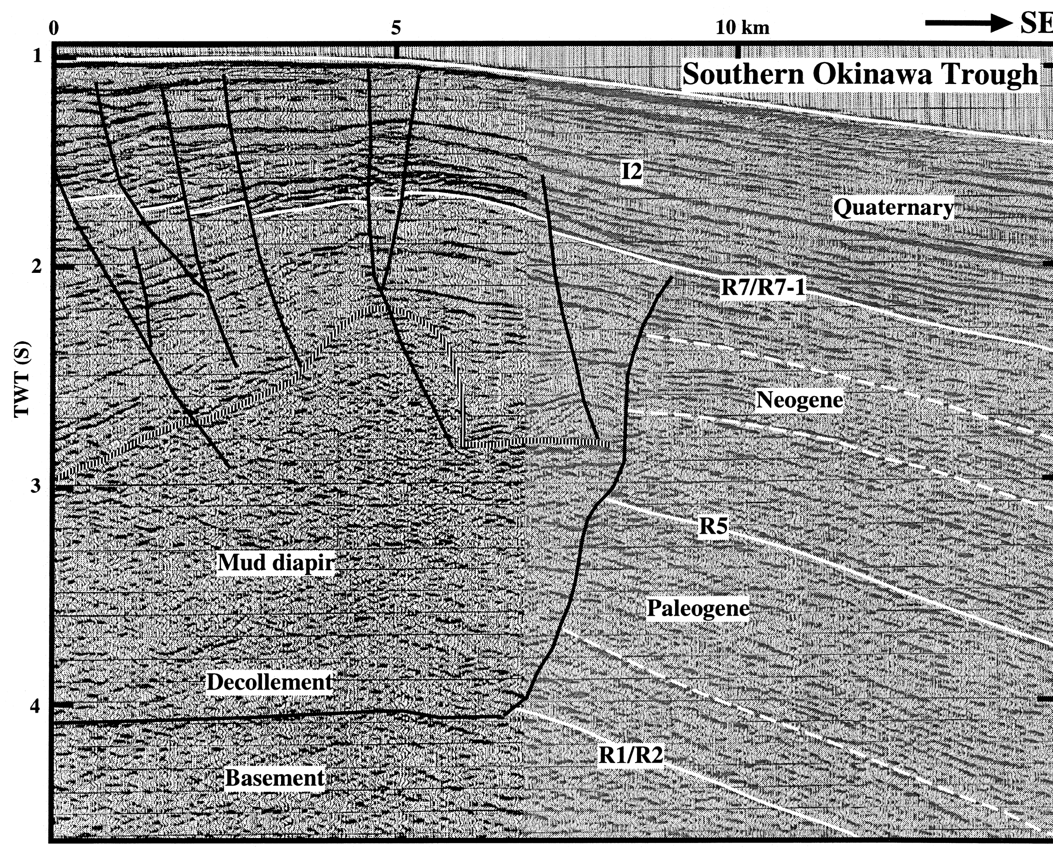

Fig. 10. Paleogene–Neogene sediments of shelf basin origin are interpreted along a dip section in the western part of the southern Okinawa Trough. A decollement may be related to mud activity. Refer to Fig. 5 for symbols of sequence and sequence boundaries, and Fig. 2 for location.

basin fill to the west. The age of this synrift sequence is Quaternary according to well data (Hsiao, 1997). In the southernmost TSFZ and the western part of the southern Okinawa Trough, sequence I2 is separated from Paleogene–Miocene sequences by the continuation of sequence boundary R7.

Along the southern TSFZ and in the western part of the southern Okinawa Trough (Fig. 2), Paleogene-Miocene sediments of the paleo-shelf basin are interpreted from their seismic reflection characteristics (Figs. 7, 9, and 10), indicating that this region was a part of the shelf basin before the opening of the southern Okinawa Trough.

3. Shelf basin evolution

Interpretation of the seismic sequences and deformation indicates that the basin-fill has been strongly deformed with multiple stages of extension and compression. In the upper part of the basement, graben structures with normal faults are recognized in basement highs, indicating an early episode of extension, probably in late Jurassic–Early Cretaceous (Kong, 1998; Kong et al., 1997a). Lower Cretaceous–Upper Jurassic sediments are revealed in wells W5 (YFK-1) and W6 (FZ 13-2-1) (Fig. 2). Such graben structures may also be seen in other parts of the shelf basin (Kong, 1998), such as the Tungyintao Basin (Tao, 1990) and the Yushan and Haijiao rises (Fig. 1). This extension was synchronous with widespread late Jurassic–Early Cretaceous extension in East China. Compression occurred in the Middle Cretaceous, resulting in the formation of sequence boundary R1 due to erosional truncation of Cretaceous or older strata. In the western part of the shelf basin, low-angle detachment faulting with upper plate normal faults, tilted blocks, roll-over strata, and horizontal displacements of up to

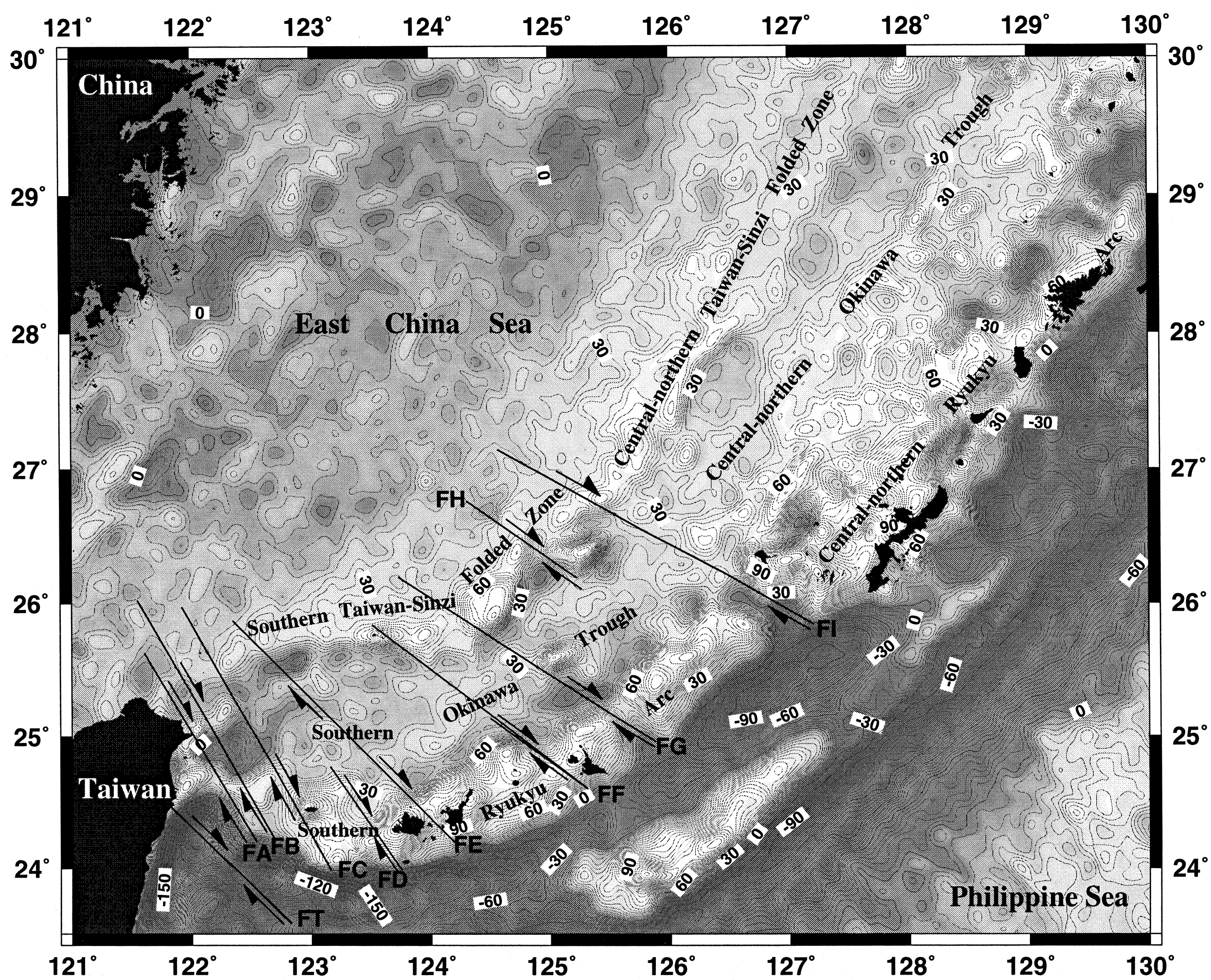

Fig. 11. Free-air gravity anomaly (mGal) map in offshore northern Taiwan (data are from Smith and Sandwell, 1995). Fault FT is called "tear fault" by Liu et al. (1996) and Lallemand et al. (1997). Faults FB, FC, and FD were also interpreted from bathymetry, earthquake, and Bouguer gravity anomaly data by Hsu et al. (1995).

5 km occurred in the late Cretaceous–Early Paleocene. Seismic reflections in the basement are chaotic, but the low-angle detachment faults are well shown with medium to high amplitude reflections. These detachment faults reflect a large-magnitude continental extension during that time (Kong, 1998; Kong et al., 1997a).

Synrifting due to detachment faulting ended at middle Paleocene with the formation of sequence boundary R2 with canyon cutting and erosional truncations. This large-magnitude extension did not occur in the eastern part of the shelf basin, where subaerial erosion occurred in late Cretaceous–early Paleocene times (Sun, 1985), indicating that the eastern part was probably a marginal plateau or a ribbon continent (Lister et al., 1986). These features are not related to the late Paleocene–Early Oligocene backarc extension in the eastern part of the East China Sea Shelf Basin (Wang and Hao, 1990; Wang et al., 1995; Zhi, 1990), which is the major basin construction event at this time, with high-angle normal faulting and strong subsidence in a narrow zone. Synrift deposition occurred in a deep rift zone in the eastern part of the shelf basin and synrift faulting ceased by late Eocene–Early Oligocene. Although the eastern part is a narrow basin at present (Fig. 3), it was much wider and located further to the east before its middle Oligocene and later inversions.

The middle Oligocene basin inversion was caused by an oblique collision between the Philippine Sea Plate and the eastern Asian margin (Kong et al., 1997b), when the Philippine Sea Plate moved north-northwestward from the equator into contact with the paleo-Ryukyu Arc. Synrift and older sediments were strongly folded and reversely faulted in middle Oligocene (Fig. 7(b)). Lower Oligocene and Upper–Middle Eocene strata, such as sequences F and E, were strongly eroded, except in deep depressions in the eastern part of the shelf basin where a low-stand complex was deposited. In the western part, even lower Eocene and some upper Paleocene strata in sequences D and C were truncated. Sequence boundary R5 was formed by this event. Although this erosional event coincided

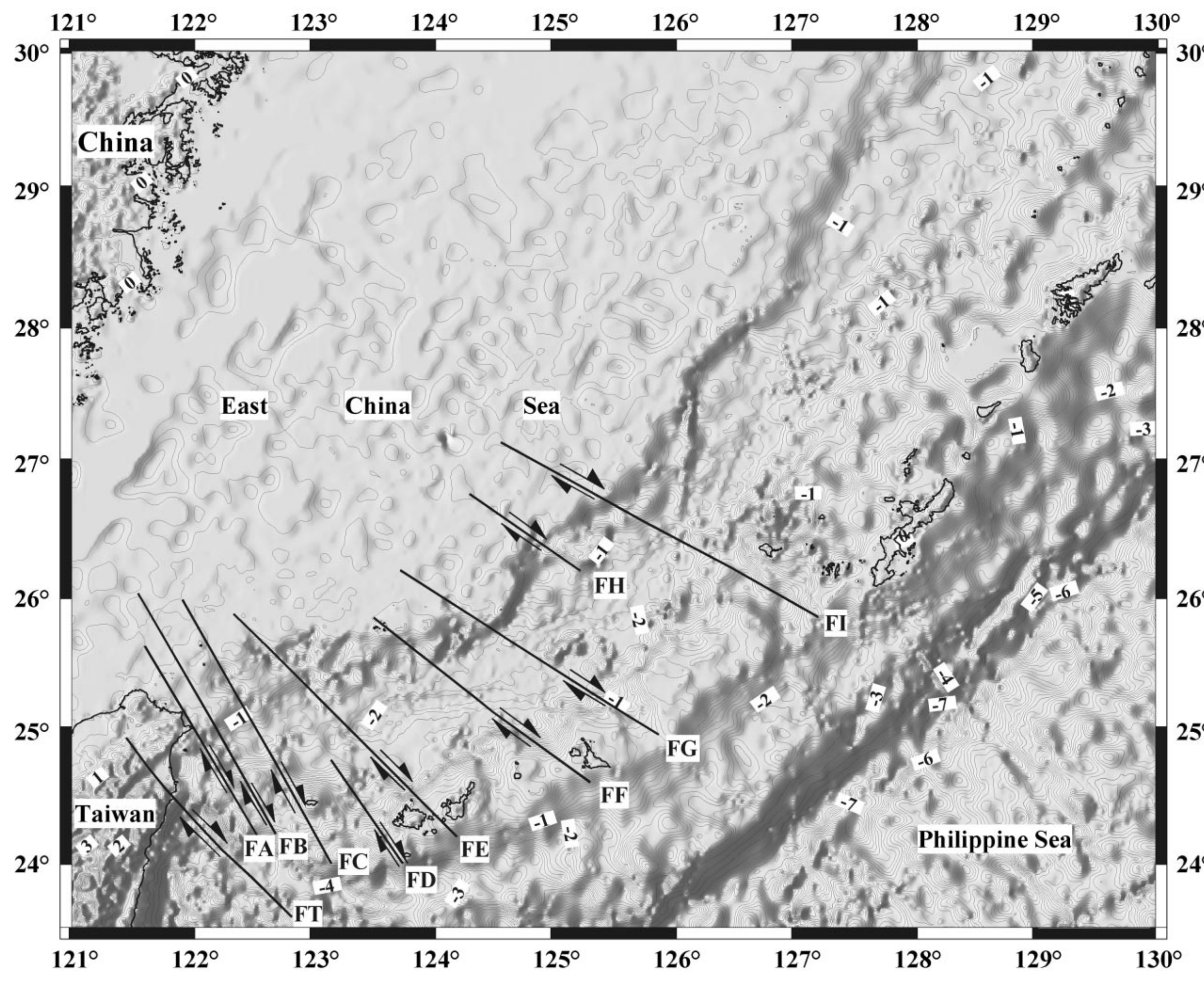

Fig. 12. Calculated bathymetry map in offshore northern Taiwan (data are from Smith and Sandwell, 1997).

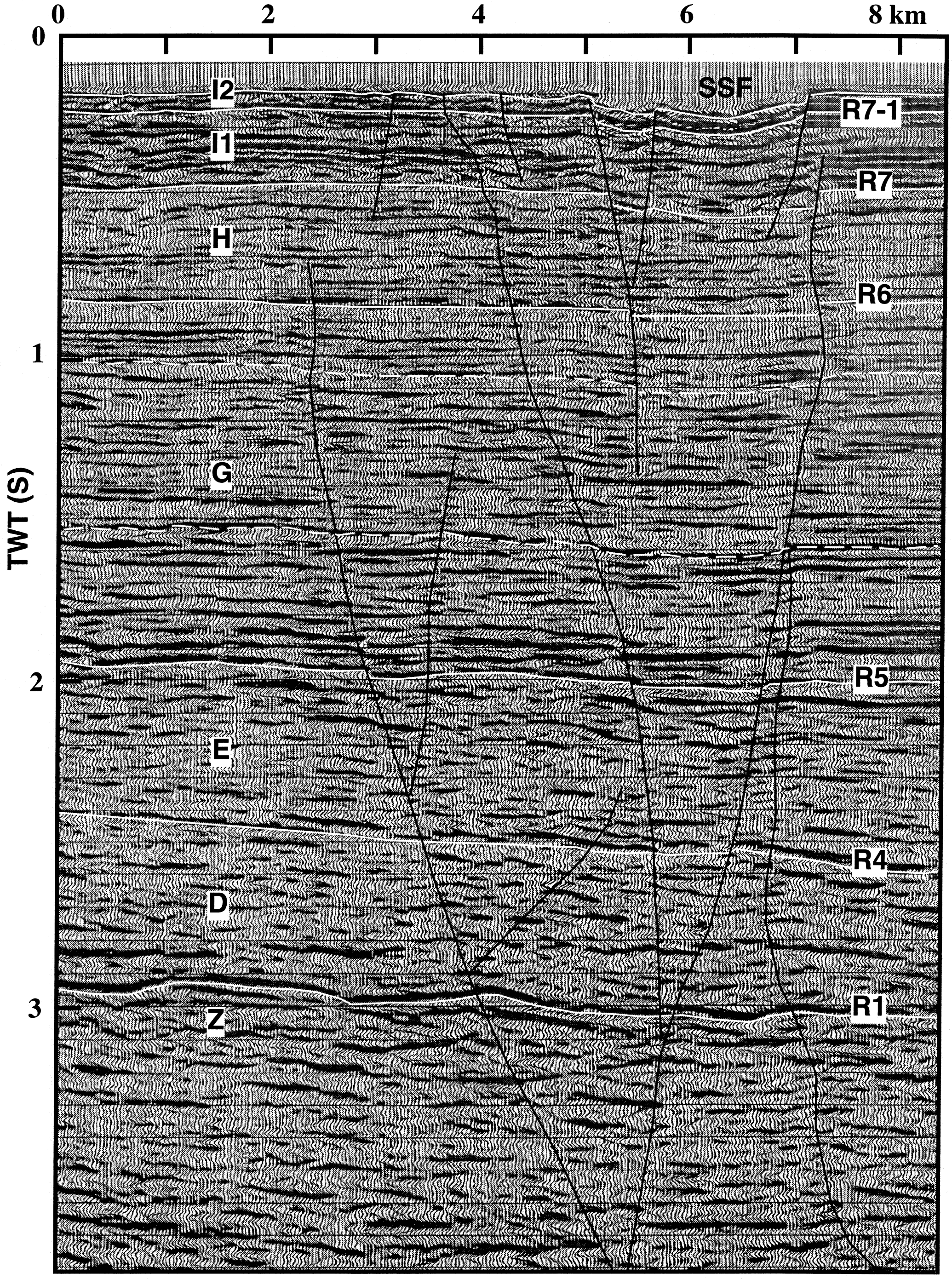

Fig. 13. Negative flower structure on strike section showing strike–slip fault FB. Refer to Fig. 5 for symbols of sequence and sequence boundaries, and Fig. 2 for location.

with a significant middle Oligocene sea level drop, it was mainly tectonically controlled, because folding and reverse faulting demonstrate that a strong compressional event took place. This event was widespread in the East China Sea area and even in the North China Basin. Nevertheless, there is no evidence for middle Oligocene construction of the present southern TSFZ.

4. Northwest-striking right-lateral strike–slip faults

The East China Sea Basin is now submerged under water. Free-air gravity anomalies (Fig. 11) and bathymetry (Fig. 12) show that the southern Ryukyu Arc is not continuous with the central–northern Ryukyu Arc, but has been rotated clockwise, displaced right-later-

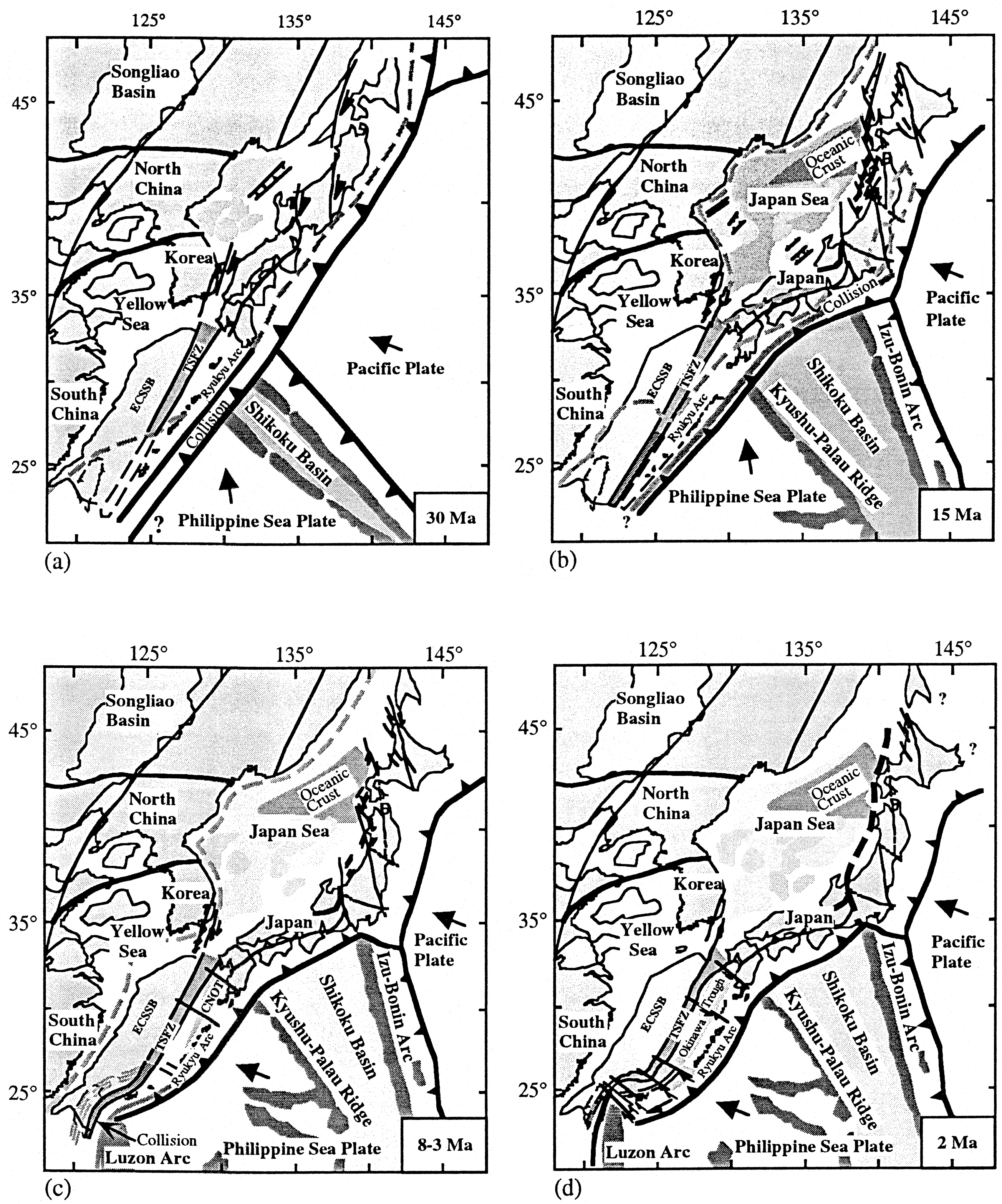
(a)
125° 135° 145°
45° 35° 25°
Songliao Basin
North China
Korea
Yellow Sea
South China
ECSSB
TSFZ
Ryukyu Arc
Collision
Shikoku Basin
Pacific Plate
Philippine Sea Plate
?
30 Ma
(b)
Songliao Basin
North China
Oceanic Crust
Japan Sea
Korea
Japan
Collision
Yellow Sea
Pacific Plate
South China
ECSSB
TSFZ
Ryukyu Arc
Shikoku Basin
Izu-Bonin Arc
Kyushu-Palau Ridge
Philippine Sea Plate
?
15 Ma
(c)
Songliao Basin
North China
Oceanic Crust
Japan Sea
Korea
Yellow Sea
Japan
Pacific Plate
CNOT
South China
ECSSB
TSFZ
Ryukyu Arc
Kyushu-Palau Ridge
Shikoku Basin
Izu-Bonin Arc
Collision
Luzon Arc
Philippine Sea Plate
8-3 Ma
(d)
Songliao Basin
?
North China
Oceanic Crust
Japan Sea
Korea
Japan
Yellow Sea
Pacific Plate
South China
ECSSB
TSFZ
Okinawa Trough
Ryukyu Arc
Kyushu-Palau Ridge
Shikoku Basin
Izu-Bonin Arc
Luzon Arc
Philippine Sea Plate
2 Ma

Fig. 14.

ally, and extended. The southern TSFZ has also been rotated clockwise and displaced right-laterally.

A series of NW-trending right-lateral strike–slip faults across the southern TSFZ and the southern Ryukyu Arc are interpreted from flower structures in seismic sections, from displaced free-air gravity anomaly zones, and from bathymetric data. These faults were presumably formed after the paleo-southern Ryukyu Arc was rotated and the southern TSFZ had been offset when tectonic disruption reached a maximum in latest Pliocene–early Quaternary. The contractional regime in Taiwan and the extensional regime in the southern Okinawa Trough–offshore northern Taiwan area are separated by NW-trending strike–slip faults FT (Fig. 2).

Fault FT is called the "tear" fault by Liu et al. (1996) and Lallemand et al. (1997) separating the westward "obducting" and northwest-subducting Philippine Sea Plate. Its existence was supported by traveltime modeling of wide-angle ocean bottom seismometer data (McIntosh et al., 1997). Its northwestern extension is expressed in low topography in northern Taiwan (Fig. 12). Its position is adopted from Liu et al. (1996), because it is consistent with the plate motion direction and separates high from low topography in northern Taiwan.

Fault FA appears as a linear gravity anomaly zone along the southernmost Ryukyu Arc (Fig. 11), and is shown by negative flower structures (Fig. 8). Its slip-sense is right-lateral, and its strike orientation may vary (Huang et al., 1992; Chen and Watkins, 1994). Faults FB and FC also appear as linear free-air gravity anomaly zones with dextrally offset features. They may also correspond to some flower structures along the strike-sections near the southern TSFZ (Fig. 13). Faults FB and FC may coincide with Hsu et al.'s (1996) faults B and A near the southern Ryukyu Arc that were interpreted from bathymetric, magnetic, gravity, and earthquake data. In addition to a clear, linear free-air gravity anomaly zone with dextrally offset features, fault FE separates the collapsed and rifted southern TSFZ (Figs. 2 and 9) in offshore northern Taiwan from the unrifted southern TSFZ (Fig. 7(a)). It may also correspond to one of the flower structures along the strike sections. The apparent sinistral offset of the southern TSFZ along fault FE (Fig. 2) may be inherited from indentation bending deformation. Faults FD, FF, FG, FH, and FI are mainly interpreted from free-air gravity anomalies (Fig. 11) and bathymetric data (Fig. 12).

Fault FI is important in separating the southern from the central TSFZ. Besides gravity, bathymetry, and seismic data, another supporting observation is that many EW- and WNW-trending right-lateral strike–slip faults exist in Yonaguni Island (Kuramoto and Konishi, 1989). The interpretation of right-lateral movement along the strike–slip fault system is also supported by work of Wageman et al. (1970), who indicated a large NW-trending right-lateral strike–slip fault across the southern Okinawa Trough near fault FI. However, focal mechanism solutions of earthquakes do not show any coherent slip patterns along these faults, probably because the strike–slip faults are on crustal scale, while most of the earthquakes used for focal mechanism solution in this area are deeper than 30 km and are near or on the subducting Philippine Sea Plate below the upper plate.

5. Evolution of the southern TSFZ

The southern TSFZ in offshore northern Taiwan is quite different from the central–northern TSFZ in its framework and evolutionary history. The northeast-trending central–northern TSFZ was formed on the western side of the central–northern paleo-Ryukyu Arc by the middle Oligocene collision (Kong, 1998) between the Philippine Sea Plate and the paleo-Ryukyu Arc (Figs. 14(a) and 15(a)). It was strongly folded and reversely faulted again (Wang et al., 1995) during a late Middle Miocene shelf basin inversion due to a collision, accompanied by strong volcanism, between

Fig. 14. Regional tectonic reconstruction. (a) Contractional folding and reverse faulting with strong erosion in the East China Sea Basin, accompanied by a large sea level drop. The central–northern TSFZ was formed by folding and reverse faulting the shelf basin strata due to a collision between the northern Philippine Sea Plate and paleo-Ryukyu Arc. The Japan Sea Basin started initial rifting due to a right-lateral pull-apart motion probably induced by this collision. Rifting also began in the Shikoku Basin in the Philippine Sea Plate. The Pacific Plate moved toward northwest. (b) The Izu-Bonin Arc and the Philippine Sea Plate began to collide with Southwest Japan and the Ryukyu Arc, enhancing clockwise rotation of the Philippine Sea Plate. Contractional reverse faulting and folding occurred again in the East China Sea Shelf Basin. Extension in the Shikoku Basin ceased by 15 Ma. Strong volcanism occurred along the Japan and central–northern Ryukyu arcs. (c) During 10–5 Ma, the Philippine Sea Plate changed motion from NNW to WNW. The Taiwan area underwent strong indentation due to the WNW-motion of the Luzon Arc, which bent the southern Ryukyu Arc. Strong thrusting and folding occurred in the Taiwan area, causing strong basin inversion in late Pliocene. Extension occurred in the central–northern Okinawa Trough and in the Shimanjiri Basin on the Ryukyu Arc. The southern Okinawa Trough area was still in a contractional regime. The present southern TSFZ was formed in the shelf basin sediments to the west of the old southern TSFZ and the southern Ryukyu Arc. (d) A series of NW-striking right-lateral strike–slip faults formed after the bent southern Ryukyu Arc and the southern TSFZ were broken. The southern Okinawa Trough rapidly rifted since about 2 Ma. CNOT, central–northern Okinawa Trough Basin; ECSSB, East China Sea Shelf Basin; TSFZ, Taiwan–Sinzi Folded Zone.

the Southwest Japan Arc–northern Ryukyu Arc and the northern Philippine Sea Plate (Figs. 14(b) and Fig. 15(b)), particularly, the Izu-Bonin Arc (Kong, 1998). Growth sequences may be identified by basal onlaps and top truncations in the upper part of the Miocene section (Wang et al., 1995). Seismic velocities indicate that the TSFZ consists of consolidated sedimentary and igneous rocks, and seismic reflections show primarily chaotic seismic facies (Chen and Watkins, 1994). Paleocene to Middle Miocene sediments may

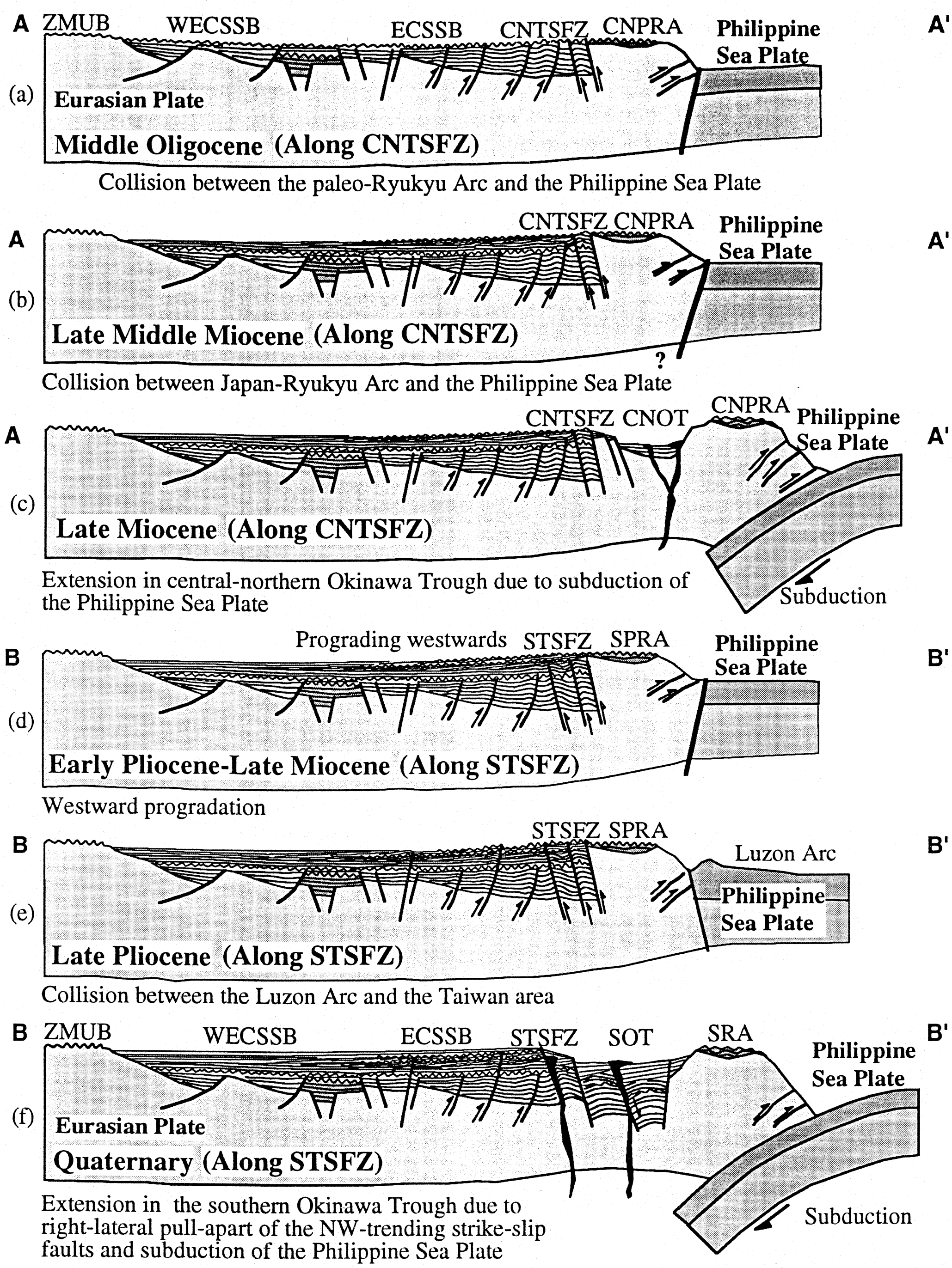

Fig. 15. Recent basin evolution model in the East China Sea area. CNPRA, central–northern paleo-Ryukyu Arc; CNOT, central–northern Okinawa Trough; CNTSFZ, central–northern Taiwan–Sinzi Folded Zone; ECSSB, eastern part of the East China Sea Shelf Basin; SOT, southern Okinawa Trough; SPRA, southern paleo-Ryukyu Arc; SRA, southern Ryukyu Arc; STSFZ, southern Taiwan–Sinzi Folded Zone; TSFZ, Taiwan–Sinzi Folded Zone; WECSSB, western part of the East China Sea Shelf Basin; ZMUB, Zhe-Min Uplifted Belt. For the position of (a), (b), and (c), see Fig. 1. For the position of (d), (e), and (f), see Fig. 2.

have been tilted, folded, and faulted on its eastern and western flanks and within the Xihu Depression (Wang et al., 1995). These deformed sediments show semi-continuous or discontinuous high amplitude with low amplitude seismic facies. Strong seismic reflections occur beneath unfolded upper Miocene strata and on top of the folded strata, which probably indicates an igneous cover on the uplifted TSFZ.

Along the rotated and dextrally displaced southern TSFZ the basement was deeply buried by thick synrift and postrift sediments, such as sequences C to H (Fig. 7). The existence of synrift and postrift sediments of the shelf basin along the southern TSFZ (Fig. 9) and in the western part of the southern Okinawa Trough (Fig. 10) indicates that the southern TSFZ was formed within the shelf basin deposits (Figs. 14(c) and 15(e)). There is no evidence that indicates a middle Oligocene paleo-fold belt existed along the present southern TSFZ or in the western part of the southern Okinawa Trough. Therefore, a middle Oligocene paleo-southern TSFZ probably did not exist or was located to the east of the present southern TSFZ if it indeed existed (Fig. 14(a)). An alternative explanation is that it simply did not form until late Middle Miocene (Fig. 14(b)). A minor reverse fault RF (Fig. 7(a)) indicates that weak contraction occurred in late Middle Miocene near the present southern TSFZ. The thick westward progradational sequence H (Fig. 7) demonstrates that uplifting occurred during late Middle Miocene along the paleo-southern Ryukyu Arc and an incipient southern TSFZ in the east (Fig. 14(b)). Thus, the southern TSFZ was probably initiated in late Middle Miocene due to the collision between the Philippine Sea Plate and the Japan–Ryukyu arcs.

The southern TSFZ was mainly constructed by the Luzon–Taiwan collision. This collision began at 5 Ma when the Philippine Sea Plate changed motion from NNW to WNW during 10–5 Ma (Seno and Maruyama, 1984). Before the Luzon–Taiwan Collision, the East China Sea Shelf Basin extended farther oceanward than it does today in the Taiwan and southern Okinawa Trough area (Fig. 14). The amount of shortening is at least 110–160 km (Kong, 1997; Suppe, 1980). Strong mountain building started at about 3 Ma in Taiwan due to fast west–northwestward indentation of the Luzon Arc (Teng, 1990). This resulted in strong contraction with intense folding and reverse faulting of the synrift and post-rift sediments within the East China Sea Shelf Basin in late Pliocene in offshore northern Taiwan (Figs. 14(c) and 15(e)). Sequence H was strongly truncated along the southern TSFZ. The westward progradational sequence I1 away from the southern TSFZ and the northward progradation away from Taiwan in the offshore northern Taiwan area (Figs. 7 and 8) are the depositional expression of this event. The multiple westward progradational shingles in sequence I1 may be due to fluctuation of sediment supply, sea-level variation, or accommodation migration. The contractional uplift along the southern TSFZ and the southern Ryukyu Arc probably continued to latest Pliocene–early Quaternary because sequence I2 is Quaternary in age. The present southern TSFZ was probably located on the western side of the paleo-southern Ryukyu Arc prior to the opening of the southern Okinawa Trough (Figs. 14(c) and 15(e)). The southern TSFZ and the southern Ryukyu Arc were rotated during the Luzon-Taiwan collision. When rotation reached a maximum, the southern TSFZ and the Ryukyu Arc were broken by a series of northwest-striking right-lateral strike–slip faults (Fig. 14).

The southern TSFZ collapsed in early Quaternary with synrift deposition (Figs. 2 and 9). Active rifting and strong synrift subsidence are still occurring in the southernmost TSFZ and the western part of the southern Okinawa Trough where strike–slip is significant (Fig. 2). The collapse of the southern TSFZ and the southern Ryukyu Arc was probably caused by a pull-apart motion of the NW-trending right-lateral strike–slip faults coupled with subduction of the Philippine Sea Plate (Figs. 14(d) and 15(f)). The total collapse of the southernmost TSFZ was probably caused by the large amount of transfer along the strike–slip faults in the immediate offshore northern Taiwan area. The western part of the southern Okinawa Trough extended within the shelf basin deposits in early Quaternary when the southern Ryukyu Arc moved southwestward from the southern TSFZ (Figs. 14(d) and 15(f)). Sediments in the southern part of the deep basin zone in the eastern part of the shelf basin (Fig. 3) were brought into the western part of the southern Okinawa Trough (Figs. 2 and 10). The stand-alone rise (SAR in Fig. 2) was isolated from the TSFZ and the Ryukyu Arc.

An early Quaternary age for the western part of the southern Okinawa Trough is supported by Letouzey and Kimura (1986), who showed that the southern Okinawa Trough opened as a collision/lateral extrusion backarc basin since 1.9 Ma. The young age of the basin is also indicated by high heat flow anomalies (Yamano et al., 1989) and by schematic stratigraphic cross-sections across the southern Okinawa Trough in Letouzey and Sage (1988). Although many people have suggested that the southern Okinawa Trough opened as a backarc basin, our interpretation shows that the NW-trending right-lateral strike–slip faults are very important in its extension. Because of the collisional aspect of the opening of the southern Okinawa Trough, it cannot be considered a simple backarc basin.

6. Conclusions

Interpretation of seismic sequences and stratigraphic characteristics in offshore northern Taiwan reveals that the stratigraphic architecture has been strongly deformed by folding and faulting due to interactions of major plates along the western Pacific margin, such as the Luzon–Taiwan collision. Formation and collapse of the southern TSFZ and opening of the southern Okinawa Trough are consequences of such plate interactions. Paleogene to Miocene sediments in the western part of the southern Okinawa Trough and along the southern TSFZ are inferred to have been part of the East China Sea Shelf Basin deposits, and indicate that the East China Sea Shelf Basin extended to the east of the present southern TSFZ before its construction and before the opening of the southern Okinawa Trough. The southern TSFZ initiated in late Middle Miocene, but it was mainly the result of folding and reverse faulting of the shelf basin sediments in late Pliocene due to a fast indentation of the Luzon Arc. Northward progradational sequences away from Taiwan and westward progradational sequences away from the TSFZ were formed after Taiwan and the southern TSFZ were uplifted. The southern TSFZ collapsed in early Quaternary as the southern Okinawa Trough opened within the shelf basin deposits. The southern Ryukyu Arc moved away from the southern TSFZ due to pull-apart movements along strike–slip faults, coupled to subduction of the Philippine Sea Plate. Motion in the southern Okinawa Trough was only the result of the Luzon–Taiwan collision as this happened at about 5 Ma, the southern Okinawa Trough must be younger.

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