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Thematic Article

Some features of the arc–continent collision zone in the Ryukyu subduction system, Taiwan Junction area

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Abstract To the northeast of Taiwan, northwestward subduction of the Philippine Sea plate is occurring beneath the Eurasian plate along the Ryukyu Trench. The Ryukyu Trench, which is well defined along the northeastern part of the Ryukyu arc, cannot be easily defined west of 123° east. This is an area where the Gagua Ridge (whose origin is controversial) enters the trench from the south. On the basis of the marine geophysical survey data the following results have been obtained. The structural elements associated with the Ryukyu subduction system deform and partially disappear west of 123° east. Among other things the Ryukyu Trench terminates close to the western slope of the Gagua Ridge. The Gagua Ridge is the result of tectonic heaping and is likely to be an uplifted sliver of oceanic crust. The interaction between the Ryukyu subduction system and the Taiwan collision zone encompasses a wide region from Taiwan to the longitude 124.5° east. The Gagua Ridge is a boundary between the active deformation zone related to the collision in Taiwan and the West Philippine Basin. It is proposed that there is a tectonic zone that can be traced from the Okinawa Trough on the north to the southern termination of the Gagua Ridge on the south.

Key words: collision, Gagua, marine geophysical survey, Ryukyu, Taiwan, tectonics.

INTRODUCTION

The South China Sea, Eurasian continent and the Philippine Sea plate are interacting with each other in the region between Taiwan and Luzon (Fig. 1). The Philippine Sea plate is subducting beneath the Eurasian plate at the Ryukyu Trench. The oceanic crust of the South China Sea subducts beneath the westward-moving Philippine Sea plate along the Manila Trench off western Luzon (Taylor & Hayes 1983; Seno & Maruyama 1984; Tsai 1986). This convergent tectonics changes to an arc–continental collision toward Taiwan (Biq 1973; Suppe 1988). Taiwan was formed as a result of the collision of the Luzon arc with the edge of the Eurasian plate since the late Neogene (Chai 1972; Chi *et al.* 1981; Teng 1990). The young orogenic belt of Taiwan consists of folded and faulted metamorphic basement rocks of Mesozoic age overlain by metamorphic and sedimentary rocks of Tertiary age. These formations occur in long narrow north-northeast-trending belts. The mountain ranges of Taiwan can be divided into two geological provinces by the Longitudinal Valley Fault, which is a geological suture between the coalesced Philippine Sea plate and the Eurasian plate. The Coastal Range to the east of the fault comprises volcanic and siliclastic sequences of the accreted Luzon arc, and the area west of the fault consists of metamorphic and sedimentary sequences of the deformed continental margin (Juan 1975; Biq 1981; Lin & Tsai 1981; Ho 1986). The North Luzon Ridge, which is the northern part of the Luzon arc, is presently undergoing deformation in response to the relative motion between the Eurasian and Philippine Sea plates. The deformation takes place through a complex pattern of strike–slip and thrust faulting. The distribution of these faults suggests that right-lateral, oblique-slip faulting occurs along northeast-trending faults, and left-lateral, oblique-slip faulting takes place on north and north-northwest-trending faults (Lewis & Hayes 1989).

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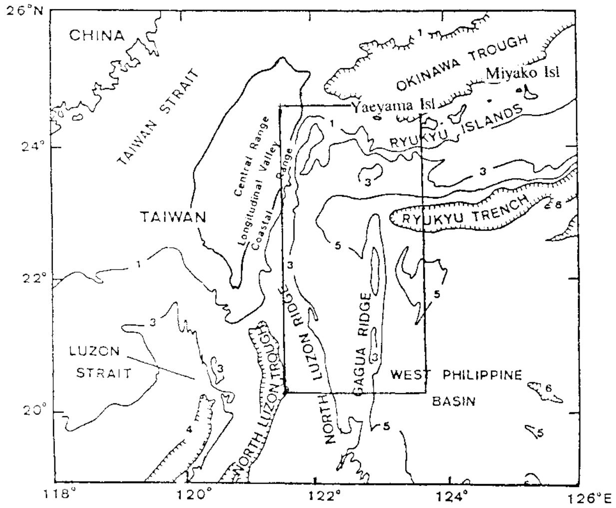

Fig. 1 Bathymetry of the Taiwan–Ryukyu region. The box outlines the study area.

In northeastern Taiwan, subduction of the Philippine Sea plate beneath the Ryukyu arc is marked by an east–west planar seismic zone located at 24° north (Tsai 1978). The Ryukyu Trench, which is well defined along the northeastern part of the arc, becomes broader and shallower as it approaches Taiwan and cannot be easily defined west of 123° east. Bowin *et al.* (1978) concluded that their free-air gravity anomaly map clearly shows the continuation of the Ryukyu Trench exactly to the continental margin of eastern Taiwan. Hagen *et al.* (1988) believe that their seismic refraction data provide further evidence for the Ryukyu Trench continuation to the east coast of Taiwan. Contrary to these interpretations Wu (1970, 1978) proposed the existence of the right-lateral trench-to-trench transform fault in the area. This transform was defined by a few right-lateral, strike–slip focal mechanisms that appeared to define a northerly striking fault plane near 123° east. In the 123° east area the submarine Gagua Ridge enters the Ryukyu Trench from the south. Bowin *et al.* (1978) tentatively identified north-trending magnetic anomalies in the Gagua Basin, which lies west of the Gagua Ridge (Fig. 2), and suggested that it was formed by a sea-floor spreading along an extinct spreading centre now represented by the Gagua Ridge. Mrozowsky *et al.* (1982) concluded that lineated sea-floor-spreading magnetic anomalies could not be mapped in the very small Gagua Basin on the basis of existing data and that the Gagua Ridge is more likely to be an upfaulted sliver of oceanic crust, perhaps similar to the ridges found bordering some fracture zones. Chemical analyses of rocks dredged from the Gagua Ridge show calc–alkaline rather than tholeiitic trends, perhaps indicating that the Gagua Ridge represents a remnant volcanic island arc (Lewis & Hayes 1989).

Previous seismic reflection surveys in the study area have consisted of single reconnaissance lines or widely spaced parallel or subparallel lines (Karig 1973; Bowin *et al.* 1978; Lee *et al.* 1980; Mrozowsky *et al.* 1982; Kimura 1985; Sibuet *et al.* 1987; Huang *et al.* 1992; Reed *et al.* 1992). Sibuet *et al.* (1995) and Hsu *et al.* (1996) have compiled new bathymetric, magnetic anomaly and gravity anomaly maps of the area east of Taiwan, the Okinawa Trough and the Philippine Sea Basin. Bathymetric, magnetic and gravity data from the National Geophysical Data Centre and data acquired east and south of Taiwan by the Institute of Oceanography, National Taiwan University have been used for preparation of maps. In the present study we utilize new marine geophysical data to investigate the nature of the interaction between the Ryukyu subduction system and the Taiwan collision zone, as well as the origin of the Gagua Ridge.

METHODS

The marine geophysical survey was conducted on board R/V *Professor Gagarinskiy* of the Russian Academy of Sciences in 1993 and 1994. For navigation the Global Positioning System (GPS) was used. The marine survey included single-channel seismic reflection, gravity, magnetic and bathymetry measurements, and it collected geophysical data along 5000-km long lines. Moreover gravity and bathymetry data were collected along two lines on board R/V *Academik Nesmeianov* in 1989. Seismic data were acquired with one airgun of 3 L volume. Gravity measurements were done by six sea highly damped spring-type gravimeters GMN-Q (made in Russia). The gravity observations were started at the pier in Keelung, Taiwan, where the base gravity station was created for converting to sea measurements in the Earth's absolute gravity field. The value of the absolute field is 978978.86 mgal (International Gravity Standard Net: IGSN-71). The international normal formulae of 1967 was used for calculation of gravity anomalies. The accuracy of the gravity data estimated by the value of discrepancies at the intersection points was 2.85 mgal, and it enabled us to construct a free-air gravity anomaly map with contour intervals of 10 mgal. The magnetic total

Fig.2

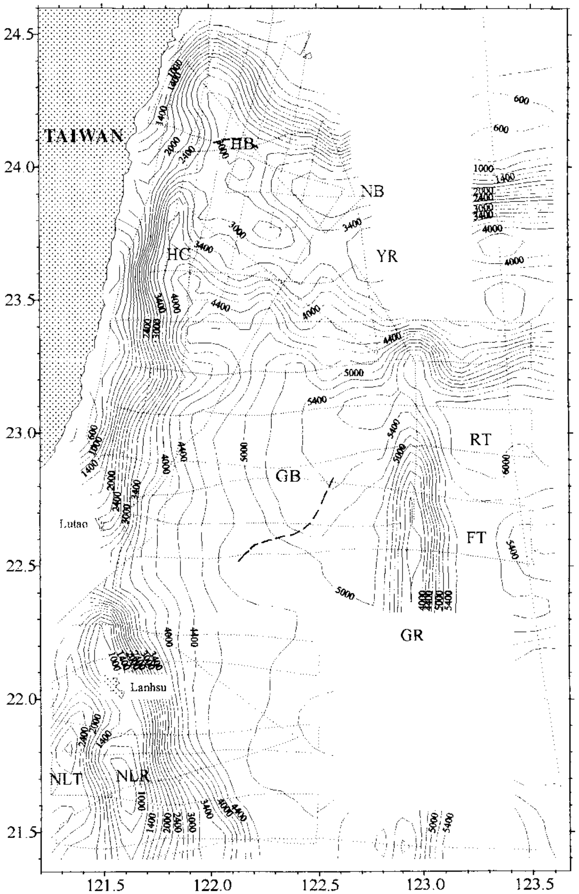

Fig.3

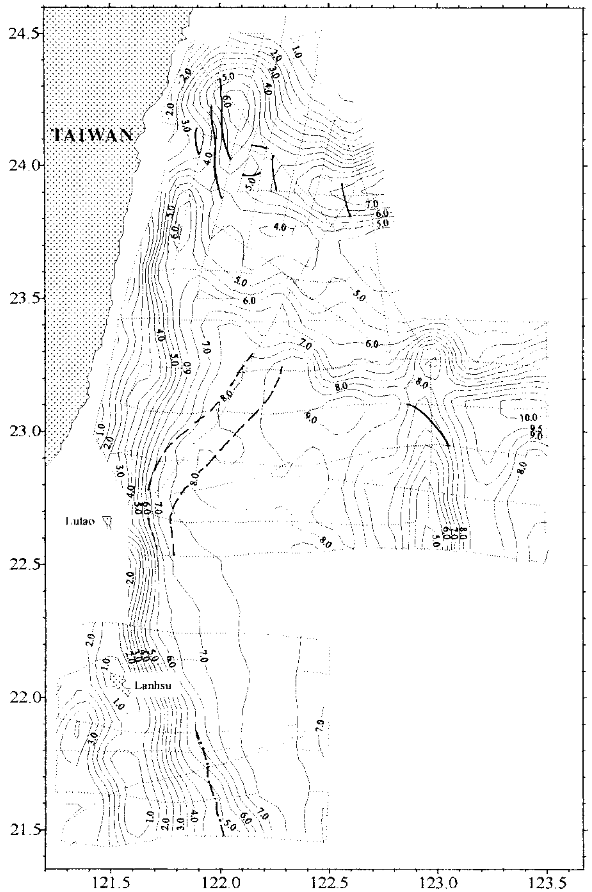

Fig.4

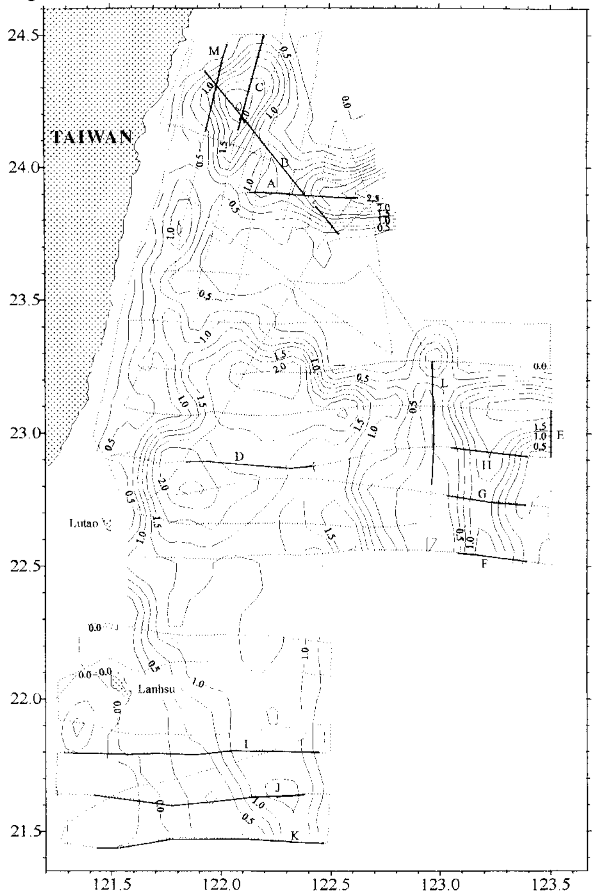

Fig. 2 Bathymetric map of the study area. Contours every 200 m. Dotted lines are ship tracks, broken lines are the axis of submarine channels. NB, Nanao Basin; HB, Hualien Basin; GB, Gagua Basin; RT, Ryukyu Trench; NLT, North Luzon Trough; FT, Foot Trough; HC, Hualien Canyon; GR, Gagua Ridge; NLR, North Luzon Ridge; YR, Yaeyama Ridge.

Fig. 3 Acoustic basement map of the study area. Contours every 0.5 s. Heavy lines are normal faults, two broken lines outline the deformation zone, the broken line with dots is the axis of an intra-arc basin. See explanation in the text.

Fig. 4 Isopach map of the study area. The contour interval is 0.25 s. Dotted lines are ship tracks. Heavy lines show sections of profiles illustrated in the present study.

intensity measurements were performed by the proton magnetometer MBM-1 (made in Russia). The magnetic results are reported as an anomaly by subtracting the International Geomagnetic Reference Field (IGRF-88) and the diurnal variations from each data point. Bathymetry data were acquired by a wide-beam echo-sounder.

OBSERVATIONS AND RESULTS

BATHYMETRY

The westernmost portion of the Ryukyu Trench, the Nanao forearc basin, the Yaeyama, North Luzon and Gagua Ridges, North Luzon Trough and Gagua Basin are prominent bathymetric features of the eastern Taiwan offshore area (Fig. 2). Bathymetric data acquired in our cruises were gridded and contoured using the commercial SURFER software. The other geophysical maps given in the present study were contoured in the same manner. In the study area the Ryukyu Trench is ~5800–6000 m deep and has an east–west strike. It bends to the north at ~123° east. The Nanao Basin with its northwest-north–southeast-south strike extends along the continental slope of the southern Ryukyu islands. The basin floor deepens gently eastward from a depth of 3600 m to 4200 m. The Nanao Basin bends sharply to the north at ~122.3° east where its strike becomes ~northwest–southeast. On the basis of geophysical data which will be presented below we separated this westernmost part of the Nanao Basin and called it the Hualien Basin. The southern flank of the Nanao Basin is formed by the Yaeyama Ridge, which rises above the Nanao Basin floor up to 1200 m.

The Gagua Ridge, a prominent north–south-trending ridge, continues from ~20.75° north to its intersection with the Ryukyu Trench at ~23° north (Mammerickx *et al.* 1976). The crest of the Gauge Ridge fluctuates between 3600 and 4200 m below the sea surface in the study area. A narrow trough which is linked to the Ryukyu trench occurs along the eastern foot of the ridge. The North Luzon Ridge trends roughly north–south and extends from northern Luzon to the east of Taiwan. The volcanic province of the Coastal Range of Taiwan, together with the small volcanic islands of Lutao and Lanshu south of Taiwan represent the northward continuation of the North Luzon Ridge. The ridge runs into the Coastal Range near 23° north (Huang *et al.* 1992). A narrow bathymetry passage with a northeast–southwest strike is seen between the Lutao and Lanshu volcanic islands. This passage is connected to the northern portion of the North Luzon Trough (Huang *et al.* 1992). A submarine channel with an east-northeast strike (broken line in Fig. 2) represents the eastward continuation of the passage. The northernmost part of the North Luzon Trough, a roughly north–south-trending basin, is positioned west of the North Luzon Ridge. The trough is ~2000–2800 m deep in the study area (Fig. 2). The Gagua Basin lies between the North Luzon Ridge to the west and the Gagua Ridge to the east. In the study area the Gagua Basin is ~4000–5000 m deep.

SEISMIC MEASUREMENTS

The acoustic basement map constructed from seismic reflection data is given in Fig. 3. Acoustic basement depressions correspond to the Ryukyu Trench and the Nanao, Hualien and Gagua Basins, respectively. The Gagua, North Luzon and Yaeyama Ridges are expressed by basement highs. The Ryukyu Trench probably bends at ~123° east to the north. It is marked by a 9.0 s contour on the north and on the east. The east–west trending of the Nanao Basin and the ~north–south trending of the Hualien Basin are marked by 5.5 s contours. They are separated by a small-amplitude basement high. The Gagua Basin is approximately marked by a 7.0 s contour. On the northwest it connects to the north–south-trending basement low which coincides with the Hualien canyon (Fig. 2; Sibuet *et al.* 1987). The crest of the Gagua Ridge is outlined by a 5.0 s contour. The cross-section of the ridge is asymmetric. The western ridge slope dips gently while its eastern slope dips steeply. The ridge subsides gradually in the northward direction. There is a trough along the eastern base of the ridge.

The major part of the study area is blanketed by sediments (Fig. 4). The distribution of sediments follows the structural features. The main depocenters include the Nanao, Hualien and Gagua Basins, the Ryukyu Trench and the trough along the eastern foot of the Gagua Ridge. The sedimentary thickness exceeds 3.5 s in the Nanao Basin, is up to 2.5 s in the topographic low of the Gagua Basin and exceeds 2.0 s in the Ryukyu Trench and in the Hualien Basin. Acoustic basement is exposed in the most part of the North Luzon, Gagua and Yaeyama Ridges. There are two major sedimentary bodies in the Gagua Basin, one lies near the Hualien canyon mouth and the other near the mouth of the large submarine canyon which cuts between the volcanic islands of Lutao and Lanshu (Reed *et al.* 1992). These canyons are carrying much of the orogenic detritus from eastern Taiwan which deposits in the northern region of the basin, resulting in the formation of the thick sedimentary layer.

STRATIGRAPHY OF THE SEDIMENTARY LAYER

The sediment fill of the Nanao Basin is comprised of two major seismic sequences. The upper seismic sequence is characterized by low-frequency stratified reflectors (Fig. 5). The high continuity/variable amplitude reflectors from within the sequence indicate turbidite deposition alternating with pelagic and/or hemipelagic deposition. The lower seismic sequence is acoustically transparent. Both seismic sequences onlap to the Ryukyu arc continental slope and the Yaeyama Ridge. These seismic sequences are separated by an unconformity (Fig. 5). Letouzey and Kimura (1986) reported that there is a prominent unconformity from within the sedimentary sequence on multichannel seismic reflection profiles that cross the forearc area of the Ryukyu Trench. This unconformity corresponds to a strong erosional event that affected the whole arc–forearc region before the late Miocene. It seems plausible that the age of the Nanao Basin unconformity separating the stratified and transparent sequences is the late Miocene.

The sediment fill of the Hualien Basin is intensely deformed. The Hualien Basin is divided into the southern and northern parts by a submarine channel with an east–west strike (Fig. 2). The northern part with thick sediments is more severely faulted and/or folded than the southern part with thin accumulations of sediment (Fig. 5b). The sedimentary layer is mainly comprised of stratified units alternating with transparent ones. The reflectors onlap to the eastern and western basin slope (Fig. 5b). On the contrary, the sedimentary sequences are continuously traced on its northern slope up to a shelf break (Fig. 6). There is the prominent unconformity from within the sedimentary sequence in the northern part of the Hualien Basin. The reflectors onlap the unconformity. The divergent and subparallel reflection configurations can be recognized above the unconformity (Fig. 6). The same seismic image of depositional sequences is typical of the rapid fall of the relative sea level (Vail *et al.* 1977). Sibuet *et al.* (1987) suggested that a general uplift affected the Ryukyu arc after a change in the motion of the Philippine Sea plate with respect to Eurasia during the early Miocene. The uplift ended in the middle or late Miocene (Letouzey & Kimura 1986). Consequently the age of the unconformity is the late Miocene or early Pliocene.

Sedimentation in the Gagua Basin occurs mainly as turbidite deposition of detritus transported

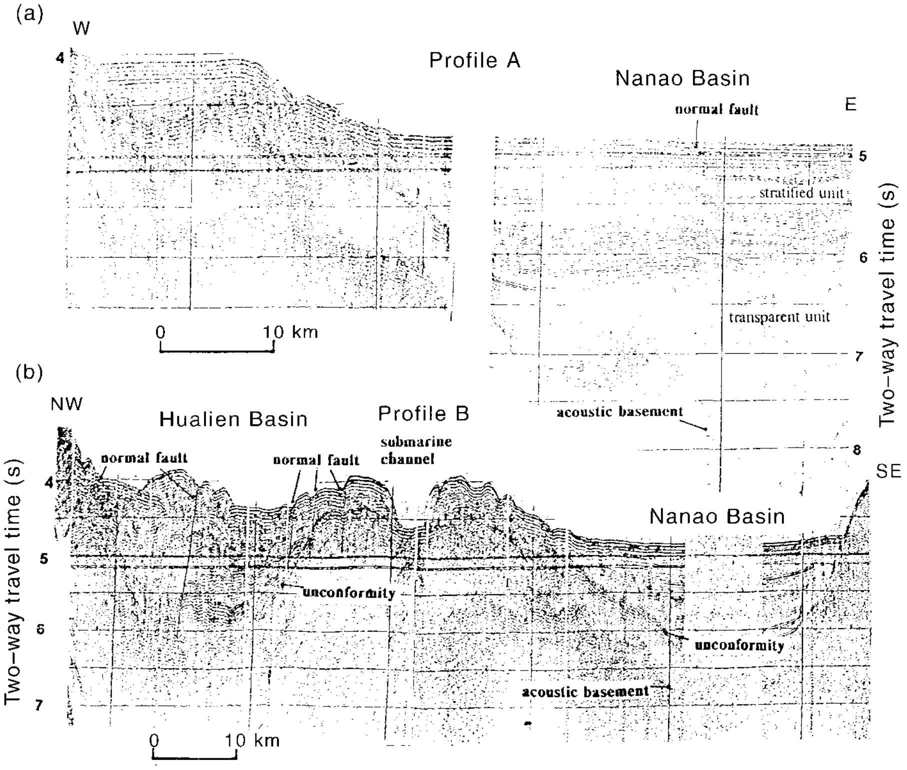

Fig. 5 Single-channel reflection profiles A and B across (a) the Nanao Basin and across (b) the Nanao and Hualien Basins. The locations of profiles are shown in Fig. 4.

along canyons and channels, and as background sedimentation of hemipelagic mud out of suspension between turbidite events in the basin. The high-amplitude, laterally continuous reflectors within the basin indicate deposition of turbidites (Fig. 7). We can recognize two major turbidite events in the Gagua Basin. The turbidite events correspond to periods of increased sediment supply to the Gagua Basin. Possible mechanisms for major variations of sediment supply to the basin include eustatic sea level change (Vail *et al.* 1977) and a rapid uplift of a source terrain on land. The effect of sea level lowstands on a deep-water sedimentary basin is the rapid formation of submarine fans fed by clastic detritus that bypasses the exposed continental shelf (Vail *et al.* 1977). According to Vail *et al.* (1977) the two youngest major global sea level lowstands were dated as Late Pliocene–early Pleistocene (2.4 Ma) and Late Miocene (6.8 Ma) ages. We suggest that two prominent turbidite depositional cycles in the Gagua Basin are correlated with the Late Pliocene–early Pleistocene and the Late Miocene global sea level lowstands.

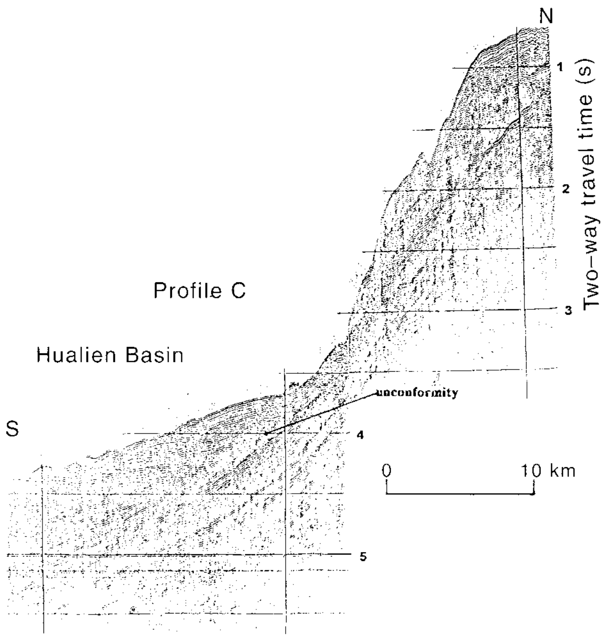

Fig. 6 Single-channel reflection profile C along the Hualien Basin. The seismic reflectors are continuously traced on the northern slope of the basin. The location is shown in Fig. 4.

The sedimentation fill of the Ryukyu Trench includes two acoustic units. The upper one is characterized by stratified reflections and the lower unit is acoustically transparent (Fig. 8). The transparent unit probably represents pelagic and/or hemipelagic sediment overlying oceanic crust, and the stratified unit is representative of turbidite deposition. The age of the sediment is unknown. The period of increased sediment supply to the Ryukyu Trench and to an adjacent part of the West Philippine Basin probably coincides with general uplift of the Ryukyu arc; if so, the bottom of the stratified unit can be dated as early Middle Miocene.

Sedimentation in the trough along the Gagua Ridge foot occurs as pelagic and/or hemipelagic deposition (upper transparent unit) and as turbidite deposition (lower stratified unit). The thickness of the turbidite sediments in the trough decreases northward from its southern end (Fig. 9). These observations suggest northward transport of clastic sediments along the trough in this region. The seismic tracks that cross the trough to the south at ~ 21.5° north show the reverse order of the transparent and stratified units (Karig & Wageman 1975; Fig. 2; Mrozowsky *et al.* 1982; Fig. 9). Karig and Wageman (1975)

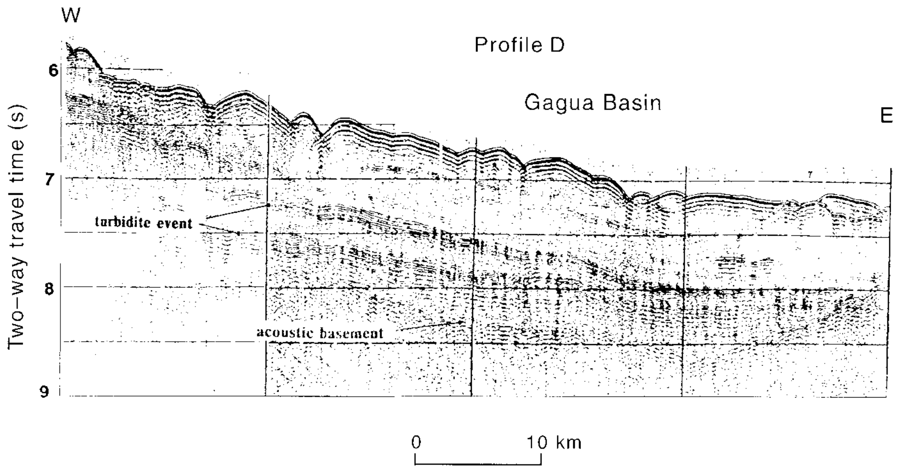

Fig. 7 Single-channel reflection profile D across the Gagua Basin. Two major turbidite events are seen. The location is shown in Fig. 4.

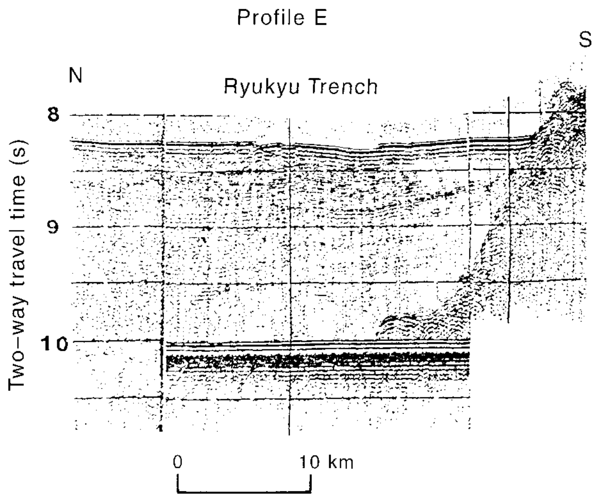

Fig. 8 Single-channel reflection profile E across the Ryukyu Trench. The location is shown in Fig. 4.

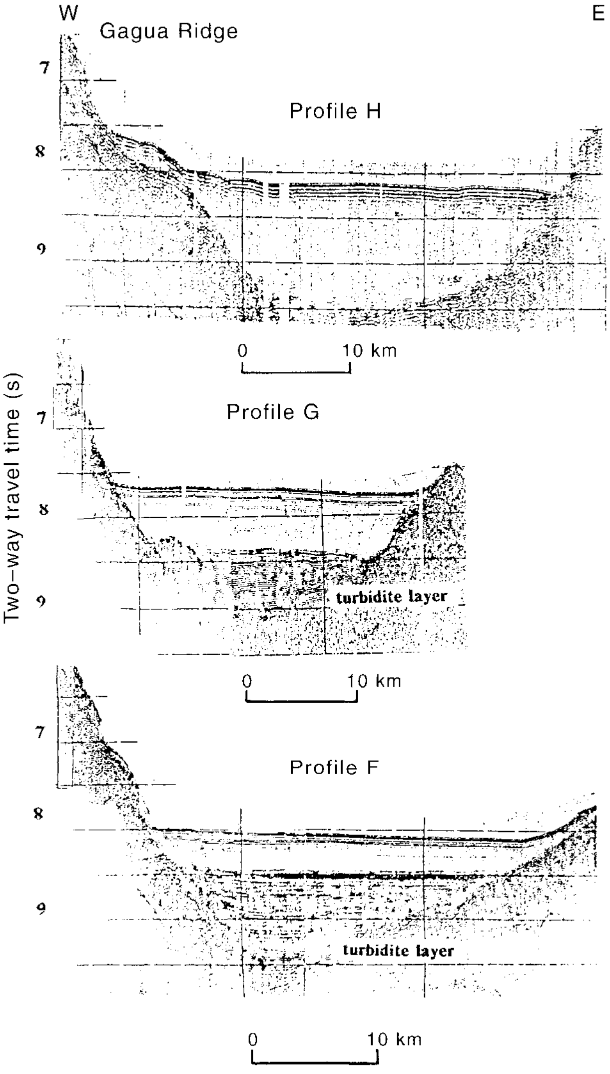

Fig. 9 Single-channel reflection profiles H–F over the trough along the Gagua Ridge foot showing the northward decrease of the turbidite thickness. The locations are shown in Fig. 4.

revealed the existence of a large sediment apron that extends into the West Philippine Basin from northeastern Luzon. The apron is fed by the Cagayan submarine canyon system which supplies material from northern Luzon. They concluded that the upper stratified unit is due to the rapid collection of coarse material caused by the Late Pliocene uplift of Luzon. We believe that the orogenic detritus that formed the lower stratified unit into the trough to the north of 21.5 north was transported to the trough from the Gagua Basin through the bathymetric passage between two summits of the Gagua Ridge, located at ~ 21.5° north. If so, the top of the stratified unit is probably correlated with the Late Pliocene–early Pleistocene global sea level lowstand.

RECENT DEFORMATION

A series of single-channel seismic reflection profiles reveals deformation of sedimentary strata in the Hualien, Nanao and Gagua Basins and on the eastern slope of the North Luzon Ridge. Very well-developed structures characteristic of active subsidence are present in the Hualien and Nanao Basins. The western slope of the Hualien Basin is cut by numerous normal faults that offset much of the entire sediment section overlying acoustic basement (Fig. 10). Track spacing is small in the basin and we were able to determine along-strike continuity of several individual faults. The faults

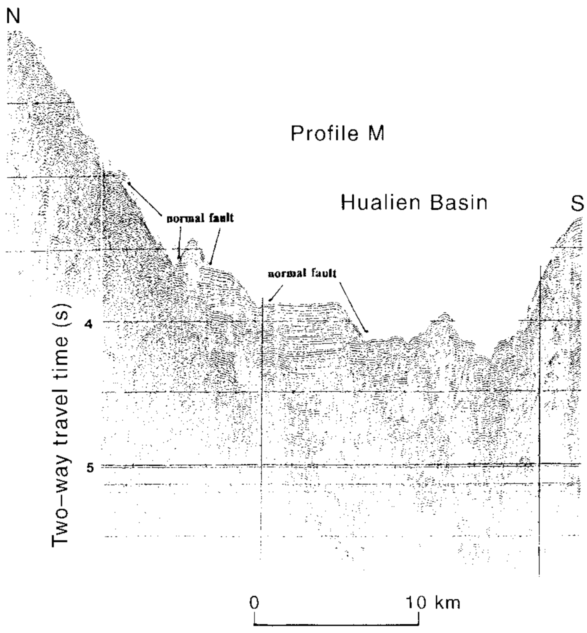

Fig. 10 Single-channel reflection profile M along the Hualien Basin. There are numerous faults that cut the western slope of the basin. The location is shown in Fig. 4.

trend north–south and extend along the western basin slope (Fig. 3). The eastern slope of the southern part of the basin is disrupted by a normal fault. Within the Hualien Basin, seismic reflections are curved downward indicating a rapid subsidence of the basin axis during sedimentation (Fig. 5b).

Several normal faults cut the western closure of the Nanao Basin. The main fault disrupts and offsets the entire sedimentary sequence and probably the acoustic basement (Fig. 5a). The major structural features of the Nanao Basin are landward tilting at the depth of once-horizontal sedimentary horizons, caused by the relative uplift of the Yaeyama Ridge, and the downward warping of reflections, caused by subsidence of the basin axis (Fig. 5b).

Much of the sedimentary section is involved in recent faulting and folding along the western margin of the Gagua Basin. On lines that show recent deformation, folds and thrust faults can be recognized. Track spacing is too large to determine the degree of along-strike continuity of individual folds or faults, but the zone of the deformation appears to be continuous over ~ 100 km along the strike (Fig. 3).

Huang *et al.* (1995) suggested that a small narrow trough-like basin that lies along the eastern slope of the North Luzon Ridge is an intra-arc basin (Fig. 11). The intra-arc basin is the result of strike–slip fault development in the eastern part of the ridge which forms pull-apart basins. Seismic tracks that cross the Ryukyu Trench–Gagua Ridge junction area show a series of faults that disrupt sediments and acoustic basement near the Gagua Ridge tip (Fig. 12).

The zone of extension-related deformation is located in the Taiwan–Ryukyu arc junction area. This zone includes the Hualien Basin and the western closure of the Nanao Basin. The seismicity between 24° north and 24.5° north is characterized by mainly normal fault-type focal mechanism solutions, with some mechanisms indicative of strike–slip faulting (Yeh *et al.* 1991). Thus, earthquake seismicity studies and seismic reflection data indicate that the westernmost portion of the Taiwan–Ryukyu junction area is under an extension regime.

The zone of deformation along the western margin of the Gagua Basin and strike–slip faults on the eastern slope of the North Luzon Ridge clearly demonstrate that this area is presently undergoing active compression. Notice that south of 24° north the high level of shallow seismic activity and focal mechanism solutions (Yeh *et al.* 1991) indicate that the western margin of the Gagua Basin and the North Luzon Ridge is presently under a compression regime. The Hualien area which lies near 24° north is charac-

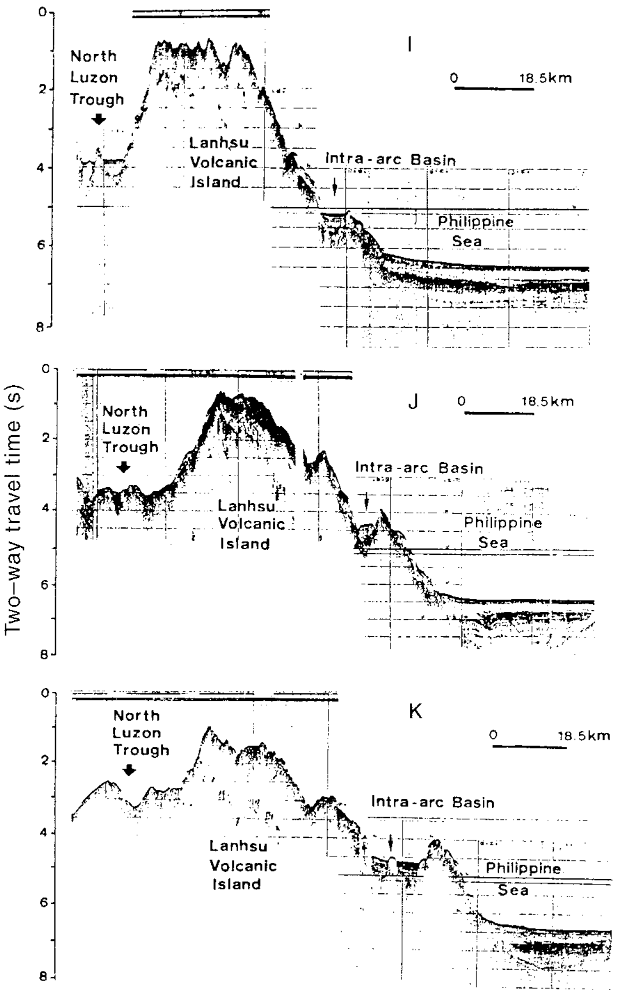

Fig. 11 Single-channel reflection profiles I–K over the eastern slope of the North Luzon Ridge showing a trough-like intra-arc basin. The locations are shown in Fig. 4.

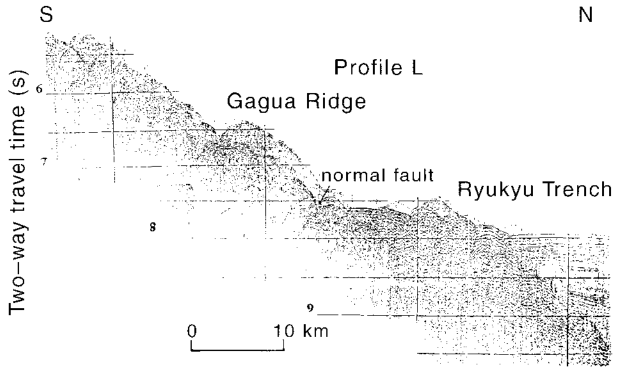

Fig. 12 Single-channel reflection profile L along the crest of the Gagua Ridge illustrating the Gagua Ridge subduction beneath the Ryukyu ARC. The location is shown in Fig. 4.

terized by a very complex stress pattern incorporating compression and tensional stresses (Yeh *et al.* 1991). It is felt that the Hualien area is the transitional region between the extension zone to the north and the compression zone to the south.

GRAVITY

The negative free-air anomaly prevails in the study area (Fig. 13). The correlation between the free-air gravity anomaly patterns and the bathymetry is discernible here. The Ryukyu Trench is associated with a gravity low of –100 to –150 gal. Free-air anomalies over the Nanao Basin are –150 to –200 gal. The Hualien Basin is characterized by a very negative free-air anomaly of up to –230 gal. The free-air anomalies over the Yaeyama Ridge are ~ –70 to –90 mgal and anomalies over the Gagua Basin are of –10 to –40 mgal. The North Luzon Ridge and its extension to the north is marked by a +10 mgal contour. Free-air anomalies over the ridge are up to +130 mgal. The free-air anomaly over the Gagua Ridge does not exceed +40 mgal and the relative anomaly maximums do not coincide with the ridge crest but are dislocated to the western ridge slope.

MAGNETIC ANOMALY

Figure 14 shows the total field magnetic anomaly of the study area. Positive and negative subparallel pairs of relatively high magnetic anomalies (~ 125 nT) with broad east–west trending cover the topographic lows of the Gagua Basin. The northwest-north–southeast-south-trending high magnetic anomalies up to +200 nT are centred over the North Luzon Ridge. In contrast, the Gagua Ridge, the Nanao and Hualien Basins and the Ryukyu Trench are characterized by a broad relatively low-amplitude (25–50 nT) magnetic anomaly. The east–west-trending high magnetic anomaly (up to +175 nT) is centred over the deep bathymetric passage between the Lutao and Lanshu Islands.

DISCUSSION

The Nanao Basin is situated between the volcanic Ryukyu arc and the Ryukyu Trench. The basin is expressed in the bathymetry, the acoustic basement relief and the free-air gravity field (Figs 2, 3, 13). In general, the sediment fill of the Nanao

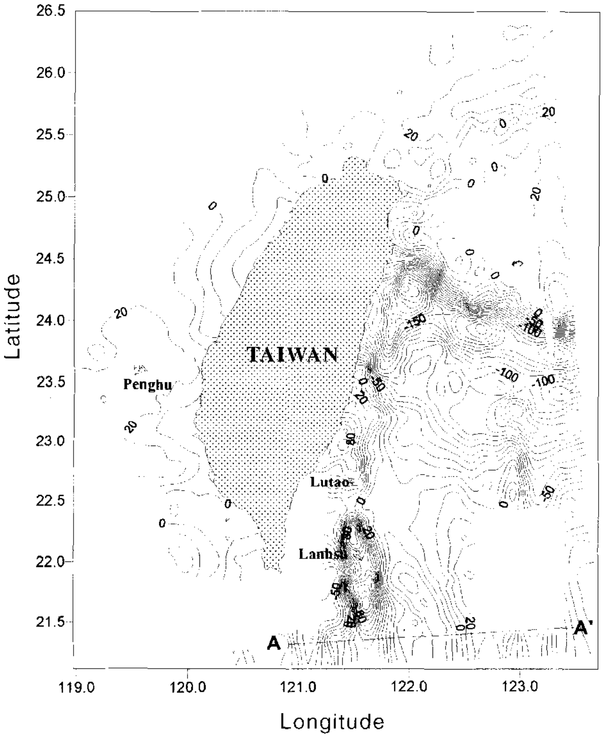

Fig. 13 Free-air gravity anomaly map of the Taiwan area. Contours every 10 mgal. Heavy line is the location of the density model profile shown in Fig. 15. Ship tracks are shown in Fig. 14.

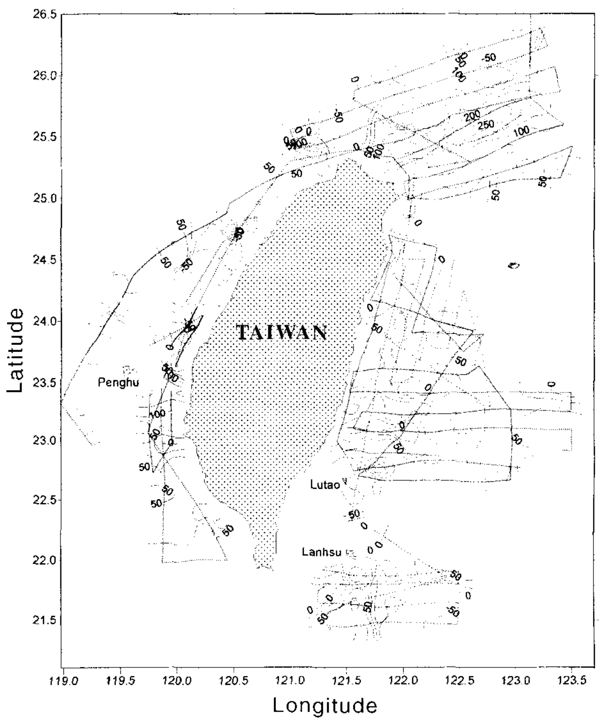

Fig. 14 Contours of total magnetic intensity anomalies in the Taiwan area. The contour interval is 25 nT. Dotted lines are ship tracks. Broken contour lines are negative anomaly.

Basin is not intensely deformed. The Nanao Basin is associated with a negative free-air anomaly (–140 to –190 mgal). This anomaly runs parallel to both the topographic trench and a negative free-air anomaly (–100 to –140 mgal) associated with it. The occurrence of the axis of the minimum free-air anomaly at the landward side of the topographic trench axis is a common feature of the free-air gravity anomalies in the northwest Pacific. Unlike the Nanao Basin, the Hualien Basin has an approximately north–south strike that is subparallel to the Taiwan shoreline and is clearly defined in the acoustic basement relief and the free-air gravity field only. The Hualien Basin sedimentary layer is intensely deformed. The Hualien Basin is associated with a very negative free-air anomaly (up to –230 mgal) which runs parallel to the Taiwan shoreline. The Nanao and Hualien Basins are separated by small-amplitude relative highs of the acoustic basement and free-air anomaly. These geophysical distinctions between the Nanao and Hualien Basins provided the basis for their separation.

The structural elements associated with the Ryukyu Trench subduction zone can be recognized in the study area to the east of ~ 123° east. These structural elements include the Ryukyu Trench, the forearc Yaeyama Ridge and the Nanao Basin and are clearly defined by the geophysical data. In contrast, we cannot recognize the usual structural elements associated with a subduction zone to the west 123° east. The topographic Ryukyu Trench disappears to the west at ~ 123° east (Fig. 2), and the free-air gravity anomaly associated with the Ryukyu Trench closes near 123° east (Fig. 13). On the acoustic basement map (Fig. 3) the 9.0 s contour corresponding to the trench is interrupted by the Gagua Ridge and is likely to be the depression relating to the Gagua Basin to the west of the Gagua Ridge.

The distribution of hypocenters along numerous north–south-striking cross-sections clearly demonstrates that, offshore of northeastern Taiwan, the Philippine Sea plate is subducting northward under the Eurasian plate, with the northwestern tip of the seismic slab under the Pleistocene volcanoes of northern Taiwan (Wu *et al.* 1991). Based on the focal mechanism solutions, Wu *et al.* (1991) proposed that the subduction near Taiwan (to the west of longitude 122.06–123° east) is moving faster than the subduction associated with the southwestern part of the Ryukyu arc.

From paleomagnetic constraints coming from the southwestern Ryukyu Islands, Miki (1995) explained the motion of these islands (Yaeyama Islands) with respect to Eurasia by a clockwise rotation of 25° around a pole located in northern Taiwan between 10 Ma and 6 Ma. He also noted that the Miyako Islands, which are located 90 km east of the Yaeyama Islands, appear to have undergone little tectonic rotation. A possible explanation for these paleomagnetic results is that the Yaeyama Islands and Miyako Island belong to different tectonic blocks and that only the Yaeyama block has rotated. Sibuet *et al.* (1995) suggest that the southwestern portion of the Okinawa platelet, west of the longitude 123.5° or 124.5° east, was rotated during the collision in Taiwan (i.e. during the last 4 million years), while the curved shape of the rest of the Okinawa Trough was acquired since the onset of the back-arc basin extension (i.e. during the Middle Miocene to Recent). From this discussion it is clear that the interaction between the Ryukyu subduction system and the Taiwan collision zone encompasses a wide region that extends up to the Okinawa Trough on the north and to a longitude of ~ 124.5° east on the east.

The Gagua Ridge enters the Ryukyu Trench from the south. The northern Gagua Ridge toe that is situated close to the trench axis is dissected into two halves by a normal fault subparallel to the trend of the trench (Figs 3, 12). The difference in water depths of the crests of the southern and northern halves of the ridge is ~ 1500 m. Seamounts entering a trench will be either subducted or accreted to the landward trench slope (Kobayashi 1985). According to our geophysical data there is no evidence of accretion of excessive amounts of the Philippine plate material onto the Ryukyu forearc in the area of the Ryukyu Trench and the Gagua Ridge intersection. No compressional deformation such as folding and thrusting is observed on the Gagua Ridge. The above-mentioned observations and seismic reflection records indicate that the northern half of the ridge appears to be subducting at the Ryukyu Trench beneath the Ryukyu arc (Fig. 12). Tomoda and Fujimoto (1983) proposed, on the basis of gravity data, that seamounts which are supported by the buoyancy of their crust cannot be subducted beneath island arcs, however, seamounts whose load is supported by the buoyancy of the asthenosphere can be subducted. Because the Gagua Ridge is subducted beneath the Ryukyu arc it is thought that the Gagua Ridge is characterized by relatively 'heavy' crust and hence is relatively thin crust.

The gravity data were used to develop a density model along the latitude of ~ 21.5° north (profile A, Fig. 13). The profile A crosses the North Luzon

Ridge, the Gagua Basin and the Gagua Ridge (Fig. 15). The geometry of near-surface layers is constrained by seismic reflection data. Densities were assigned to the crustal layers on the basis of refraction velocities (Louden 1980; Hagen *et al.* 1988) using the Nafe–Drake curve (Nafe & Drake 1963) as a guide. The model gravity field was calculated using the two-dimensional method. Because the crustal structure is a primary object of the present study we have assumed that the upper mantle density is constant and equals 3.35 gcm^{-3}.

According to the density model the North Luzon Ridge crustal thickness is ~ 19 km. The North Luzon Ridge is characterized by the positive free-air gravity anomaly of up to 120 mgal. The ridge is composed typically of volcanic islands of andesitic breccia, basalt and tuff (Huang *et al.* 1992). Our density model does not contain some high-density bodies also (Fig. 15). It is known that this petrologic sequence cannot be a source of a large-amplitude positive free-air anomaly that is associated with the North Luzon Ridge. In the study area the North Luzon Ridge width is ~ 50 km. As a rule positive morphostructures of the same size are not compensated for by an underlying lithosphere. Therefore the North Luzon Ridge is probably a mostly uncompensated structure (Watts *et al.* 1980). Thus the analysis of the ridge gravity and topography suggests that the large-amplitude positive gravity anomaly is explained not only by the partial topographic load compensation, but the ridge is supported dynamically by other forces such as the driving force of a plate convergence. This conclusion is supported by the above-mentioned observations that the western margin of the Gagua Basin and the North Luzon Ridge is presently under a compression regime.

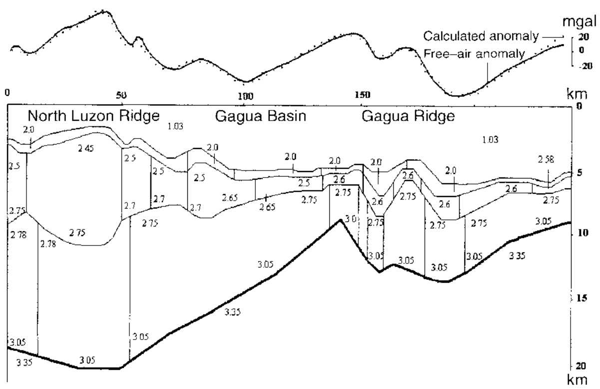

Fig. 15 Gravity model density distribution across the North Luzon Ridge, the Gagua Basin and the Gagua Ridge. The profile location is shown in Fig. 13 (line AA′).

According to the density model the Gagua Ridge crustal thickness is ~ 8 km (Fig. 15). This value approximates the Northwest Pacific Basin crustal thickness (Bee & Bibee 1989) and differs from a typical aseismic oceanic ridge crustal thickness. The ridge crustal layers are conformably deformed in two asymmetric westward overturned folds that are accompanied by a narrow high of the Moho discontinuity beneath the western slope of the Gagua Ridge. In general the Gagua Ridge is formed by the uplifting of a mafic and ultramafic strata of the lower crust and upper mantle. This is supported by the above-mentioned observation about the relatively low-amplitude magnetic anomaly over the ridge. The Gagua Ridge differs greatly from the volcanic North Luzon Ridge. The essential distinctions are the crustal thickness and the magnetic anomaly amplitude. The above-listed observations let us suggest that the Gagua Ridge is the result of tectonic heaping and support the suggestion of Mrozowsky *et al.* (1982) that the Gagua Ridge is an upfaulted sliver of oceanic crust. Moreover the Gagua Ridge is the boundary between a region of thin oceanic crust of the West Philippine Basin on the east and a region of thicker crust of the Gagua Basin on the west. The epicentral distribution around Taiwan shows that far more events are located between eastern Taiwan and the Gagua Ridge than to the east of the Gagua Ridge (Hamburger *et al.* 1983; Cheng *et al.* 1992).

CONCLUSION

The major conclusions concerning the structural features of the arc–continental collision in the Ryukyu subduction system–Taiwan junction area are the following.

The structural elements associated with the Ryukyu subduction system deform and partially disappear west approximately of 123° east. Among other things the Ryukyu Trench does not extend to the east coast of Taiwan and terminates close to the western slope of the Gagua Ridge.

No geophysical characteristics typically associated with an aseismic oceanic ridge such as relatively thicker crust is observed on the Gagua Ridge. Its crustal thickness is ~ 8 km. We suggest that the Gagua Ridge is the result of tectonic heaping and is more likely to be an uplifted sliver of oceanic crust.

The North Luzon Ridge is probably a mostly uncompensated structure and is supported dynamically by the driving force of a plate convergence.

The interaction between the Ryukyu subduction system and the Taiwan collision zone encompasses a wide region that extends up to the Okinawa Trough on the north and is bounded by the longitude ~ 124.5° east on the east.

Gagua Ridge is the boundary between the active deformation zone related to the collision in Taiwan to the west and the West Philippine Basin to the east. We believe that the ridge is the southward prolongation of the area bounding the above-mentioned region of interaction. We propose that there is a wide tectonic zone that can be traced from the Okinawa Trough near the longitude 124.5° east to at least the south termination of the Gagua Ridge.

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REFERENCES

BEE M. & BIBEE L. D. 1989. A seismic refraction study of Cretaceous oceanic lithosphere in the Northwest Pacific Basin. *Marine Geophysical Research* **11**, 239–61.

BIQ C. C. 1973. Kinematics pattern of Taiwan as an example of actual continent–arc collision. *Report of the Seminar on Seismology, US-ROC Cooperative Science Program*, pp. 21–26.

BIQ C. C. 1981. Collision, Taiwan style. *Memoir of the Geological Society of China* **4**, 91–102.

BOWIN C., LU R. S., LEE C. S. & SHOUTEN H. 1978. Plate convergence and accretion in Taiwan–Luzon region. *American Association of Petroleum Geologists Bulletin* **62**, 1645–72.

CHAI B. H. T. 1972. Structure and tectonic evolution of Taiwan. *American Journal of Science* **272**, 389–442.

CHENG S. N., LEE C. T. & YEH Y. T. 1992. Seismotectonics of the Ryukyu arc. *In* Wang J. H ed. *Proceedings of the Fourth Taiwan Symposium on Geophysics*, pp. 507–16. Taiwan.

CHI W. R., NAMSON J. & SUPPE J. 1981. Stratigraphic record of plate interactions in the Coastal Range of eastern Taiwan. *Memoir of the Geological Society of China* **4**, 155–94.

HAGEN R. A., DUENNEBIER F. K. & HSU V. 1988. A seismic refraction study of the crustal structure in the active seismic zone east of Taiwan. *Journal of Geophysical Research* **93**, 4785–96.

HAMBURGER M. W., CARTWHEEL R. K. & ISAACS B. L. 1983. Seismotectonics of the Northern Philippine Island Arc. *In* Hayes D. E. ed. The Tectonic and Geological Evolution of Southeast Asian Seas and Islands, Part 2. *Geophysical Monograph* **27**, 1–22. American Geophysical Union, Washington DC.

HO C. S. 1986. A synthesis of the geological evolution of Taiwan. *Tectonophysics* **125**, 1–16.

HSU S-K., SIBUET J-C., MONTI S., SHYU C-T. & LIU C-S. 1996. Transition between the Okinawa Trough backarc extension and the Taiwan collision: New insight on the southernmost Ryukyu subduction zone. *Marine Geophysical Research* **18**, 163–87.

HUANG C. Y., SHYU C. T., LIN S. B., LEE T. Q. & SHEU D. D. 1992. Marine geology in the arc–continent collision zone off southeastern Taiwan: Implications for late Neogene evolution of the Coastal Range. *Marine Geology* **107**, 183–212.

HUANG C. Y., YANG P. B., SONG S. R. *et al.* 1995. Tectonics of short-lived intra-arc basins in the arc–continent collision terrain of the Coastal Range, eastern Taiwan. *Tectonics* **14**, 19–38.

JUAN V. C. 1975. Tectonic evolution of Taiwan. *Tectonophysics* **26**, 197–212.

KARIG D. E. 1973. Plate convergence between the Philippines and the Ryukyu Islands. *Marine Geology* **14**, 153–68.

KARIG D. E. & WAGEMAN J. M. 1975. Structure and sediment distribution in the northwest corner of the West Philippine Basin. *In* Karig D. E., Ingle J. C., Jr Bouma A. H. *et al.* eds. *Initial Report of the Deep Sea Drilling Project* **31**, pp. 615–620. US Government Printing Office, Washington DC.

KIMURA M. 1985. Formation of the Okinawa Trough. *In* Nasu N., Kobayashi K., Uyeda S., Kushiro I. & Kagami H. eds. *Formation of Active Ocean Margins*, pp. 567–91. Terra Publishing, Tokyo.

KOBAYASHI K. 1985. The fate of seamounts and oceanic plateaus encountering a deep-sea trench and their effects on the continental margins. *In* Nasu N., Kobayashi K., Uyeda S., Kushiro I. & Kagami H. eds. *Formation of Active Ocean Margins*, pp. 625–37. Terra Publishing, Tokyo.

LEE C., SHOR G. JR, BIBEE L. D., LU R. S. & HILDE T. W. C. 1980. Okinawa Trough: Origin of a back-arc basin. *Marine Geology* **35**, 219–41.

LEWIS S. D. & HAYES D. E. 1989. Plate convergence and deformation, North Luzon Ridge, Philippines. *Tectonophysics* **168**, 221–37.

LETOUZEY J. & KIMURA M. 1986. The Okinawa Trough: Genesis of a back-arc basin developing along a continental margin. *Tectonophysics* **125**, 209–30.

LIN M. T. & TSAI Y. B. 1981. Seismotectonics in Taiwan-Luzon area. *Bulletin of the Institute of Earth Sciences, Academy Sinica* **1**, 51–82.

LOUDEN K. E. 1980. The crustal and lithospheric thickness of the Philippine Sea as compared to the Pacific. *Earth and Planetary Science Letters* **50**, 275–88.

MAMMERICKX J., FISHER R. L., EMMEL F. J. & SMITH S. M. 1976. Bathymetry of the East and Southeast Asian seas. *Geological Society of America, Map Chart Series* MC–17.

MIKI H. 1995. Two-phase opening model for the Okinawa Trough inferred from paleomagnetic study of the Ryukyu arc. *Journal of Geophysical Research* **100**, 8169–84.

MROZOWSKY C. L., LEWIS S. D. & HAYES D. E. 1982. Complexities in the tectonic evolution of the West Philippine Basin. *Tectonophysics* **82**, 1–24.

NAFE J. E. & DRAKE C. C. 1963. Physical properties of marine sediments. *In* Hill M. N. ed. *The Sea*, vol. 3, pp. 794–815. Wiley Interscience, New York.

REED D. L., LUNDBERG N., LIU C. S. & KUO B. Y. 1992. Structural relations along the margins of the offshore Taiwan accretionary wedge: Implications for accretion and crustal kinematics. *Acta Geologica Taiwanica*, **30**, 105–22.

SENO R. & MRUYAMA S. 1984. Paleogeographic reconstruction and origin of the Philippine Sea. *Tectonophysics* **102**, 53–84.

SIBUET J-C., HSU S-K., SHYU C-T. & LIN C-S. 1995. Structural and kinematic evolution of the Okinawa Trough backarc basin. *In* Taylor B. ed. *Backarc Basin: Tectonics and Magnetism*, pp. 343–379. Plenum Press, New York.

SIBUET J. S., LETOUZEY J., BARRIER F. *et al.* 1987. Back arc extension in the Okinawa Trough. *Journal of Geophysical Research* **92**, 14401–63.

SUPPE J. 1988. Tectonic of arc–continental collision on both sides of the South China Sea: Taiwan and Mindoro. *Acta Geologica Taiwanica* **26**, 1–18.

TAYLOR B. & HAYES D. E. 1983. Origin and history of the South China Basin. *In* Hayes D. E. ed. The Tectonic and Geological Evolution of Southeast Asian Seas and Islands, Part 2. *Geophysical Monograph Series* **27**, pp. 23–56. American Geophysical Union, Washington DC.

TENG L. S. 1990. Geotectonic evolution of late Cenozoic arc–continent collision in Taiwan. *Tectonophysics* **183**, 57–76.

TOMODA Y. & FUJIMOTO H. 1983. Roles of seamount, rise and ridge in lithosphere subduction. *In* Hashimoto & Uyeda S. eds. *Accretion Tectonics in the Circum-Pacific Regions*, pp. 319–31. Terra Scientific Publishing Co., Tokyo.

TSAI Y. B. 1978. Plate subduction and the Plio-Pleistocene orogeny in Taiwan. *Petroleum Geology of Taiwan* **15**, 1–10.

TSAI Y. B. 1986. Seismotectonics of Taiwan. *Tectonophysics* **125**, 17–38.

VAIL P. R., MITCHUM R. H. JR, TODD R. G. *et al.* 1977. Seismic stratigraphy and global changes of sea level. *Memoir of the American Association of Petroleum Geologists* **26**, 49–50.

WATTS A. B., BODINE J. H. & RIBE N. M. 1980. Observation of flexture and geological evolution of the Pacific ocean basin. *Nature* **283**, 532–7.

WU F. T. 1970. Focal mechanisms and tectonics in the vicinity of Taiwan. *Bulletin of the Seismological Society of America* **60**, 2045–56.

WU F. T. 1978. Recent tectonics of Taiwan. *Journal of Physics of the Earth* **26** (Suppl.), S265–99.

WU F. T., SALZBERG D. & RU R. J. 1991. The modern orogeny of Taiwan. *In Taicrust Workshop Proceedings*, pp. 49–62. Taipei, Taiwan, Republic of China.

YEH Y-H., BARRIER E., LIN C-H. & AGELIER J. 1991. Stress tensor analysis in the Taiwan arc from focal mechanisms of earthquakes. *Tectonophysics* **201**, 267–80.