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A detailed study of the Gagua Ridge: A fracture zone uplifted during a plate reorganisation in the Mid-Eocene

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Abstract

Recent multibeam bathymetric and geophysical data recorded in the West Philippine Basin, east of Taiwan, reveal new information on the structure and the tectonic origin of the oceanic Gagua Ridge. This linear, 300 km-long, 4 km-high, north-south-trending ridge, is being subducted beneath the Ryukyu Trench along 123° E. This basement high separates two basins of different ages. Its summit is marked by two crests and an axial valley. A map of the basement top shows the region of the ridge to be composed of a set of linear and parallel ridges and troughs. All these elements suggest that the development of the ridge, and its surroundings, has been influenced by strike-slip deformation. Nevertheless, the height of the ridge indicates also an important compressive component in the deformation. Gravity models across the ridge show local compensation with a crustal root, indicating that an overthickening of the crust occurred when it was young and thus more easily deformable. This idea is strengthened with flexural modeling of the lithosphere that bends under the load of the ridge, indeed it indicates that the high probably formed when the underlying lithosphere was young. We interpret the Gagua Ridge as a fracture zone transverse ridge uplifted during a transpressive episode along a north-south -trending fracture zone in the middle Eocene time, if we accept Hilde and Lee's (1984) model of magnetic lineations. This tectonic event could be contemporaneous with a change of the pole of rotation of the West Philippine Basin which occurred about 43/45 Ma ago.

Introduction

Topography of the world's seafloor is becoming increasingly investigated, using satellites, side-scan sonar and multi-beam echo sounder. Many seafloor topographic features can now be recognized with good resolution, especially the oceanic spreading centers and subduction trenches. However, the largest areas of the bottom of oceans consist of sedimented abyssal plains, in which we can observe submarine plateaus, volcanoes, and aseismic ridges. One unusual feature of the oceanic seafloor is the Gagua Ridge, which lies in the northwestern edge of the Philippine Sea Plate near Taiwan (Figure 1).

The Gagua Ridge is a major narrow, linear high which separates two oceanic basins of the Philippine Sea Plate. This N–S trending ridge deepens and seems to vanish northward in the Ryukyu subduction zone. The origin of this prominent ridge has remained enigmatic. It has been interpreted as a trench-slope break of an inactive subduction zone (Karig and Wageman, 1975), an extinct spreading center (Bowin et al., 1978), an uplifted sliver of oceanic crust, perhaps similar to ridges bounding fracture zones (Mrozowski et al., 1982), and as a 'feature related to an early Tertiary subduction zone which existed to the eastern margin of Luzon' (Evans and Lewis, 1984). In addition, Sibuet and Hsu (1997) have proposed that north of 23° N, the Gagua Ridge could have been a plate boundary between the Philippine Sea and Huatung plates.

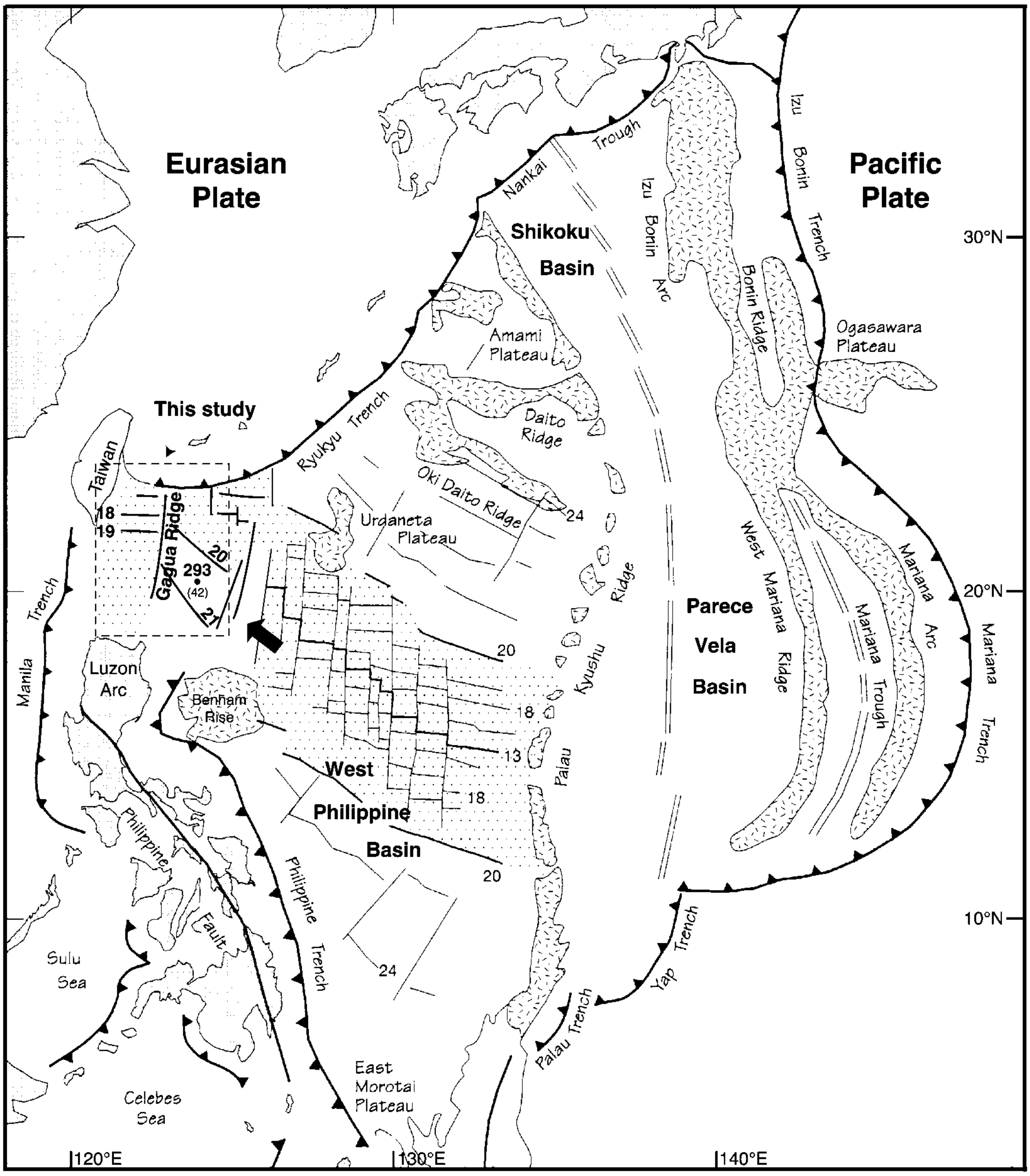

Figure 1. Geodynamic setting of the Philippine Sea Plate modified after Hall et al. (1995). Magnetic lineations and transform faults are from Hilde and Lee (1984) in the West Philippine Basin. The dotted area of the West Philippine Basin is the area produced by spreading after anomaly 20 (≈45 Ma). The study area east of Taiwan is indicated by a small box. The thick solid arrow represents the convergence of the PSP relative to the fixed Eurasia Plate after Seno et al. (1993). DSDP (Deep Sea Drilling Project) site number 293 is located in the Philippine Sea with absolute crustal age in brackets.

New data were collected over the western part of the Philippine Sea Plate during the ACT (Active Collision in Taiwan) cruise onboard the French R/V *L'Atalante* in 1996. These data comprise swath bathymetry, side-scan sonar imagery, six-channel reflection seismics, gravity, and magnetics (Lallemand et al., 1997). The new geophysical data allow a detailed study of the ridge and the adjacent basins, and reveal insights regarding its tectonic origin and mechanisms of formation.

Neither the origin of the western and southern parts of the Philippine Sea Plate nor the kinematics of the whole plate are well understood. In order to know the geodynamic evolution of the entire plate, it is important to understand the deformation it was subjected to. As the Gagua Ridge is a major tectonic feature, it appears that solving the problem of its origin could help in understanding the Cenozoic history of the Philippine Sea Plate.

Geodynamic background

The Philippine Sea Plate

The Philippine Sea Plate is a small plate sandwiched between the converging Eurasian and Pacific Plates. It is surrounded on all sides by subduction zones (e.g., Nankai, Ryukyu, Philippine trenches to the west, and Izu-Bonin, Mariana, Yap and Palau trenches to the east) (Figure 1). The plate consists of three oceanic basins which have been tectonically inactive since at least the middle Miocene time, and possibly since the early Oligocene time: the West Philippine Basin, the Shikoku Basin and the Parece Vela Basin (Rangin and Pubellier, 1990). These basins are respectively dated from 56 to 33 Ma, from 25 to 15 Ma, and from 30 to 17 Ma. Currently, the small Mariana Basin has been opening for 6 Ma (Hussong and Uyeda, 1981).

The Philippine Sea Plate is converging towards the Eurasian Plate at a rate of 7.1 cm/yr in a direction of N308° near Taiwan (Seno et al., 1993). In this region, the Eocene oceanic crust of the West Philippine Basin is subducting along the Ryukyu Trench. The oceanic nature of the crust was attested by seismic-refraction data (Murauchi et al., 1968) and deep sea drilling at site 293 (20°21.25′ N; 124°05.65′ E) (DSDP 31). The site 293 was drilled immediately west of the old spreading center (Figure 1). The bottom of the stratigraphic column consists of brown mudstone with reworked late-mid Eocene fossils, overlying a Miocene basaltic breccia probably associated with the mid-plate faulting within the West Philippine Basin between late Eocene (?) and mid Miocene (Karig et al., 1975). An age of 42 Ma was determined from a gabbro sample, but this age is considered unreliable (Ozima et al., 1977).

The Ryukyu Trench constitutes the northwestern boundary of the Philippine Sea Plate. This trench extends over 1200 km between Kyushu (Japan) and Taiwan, and subduction has been active since late Cretaceous at least near Japan (Le Pichon et al., 1985; Sibuet and Hsu, 1997). At its southwestern extremity, the Ryukyu subduction zone merges into the Taiwan collision zone. The present boundary between Eurasia and the Philippine Sea Plate follows the Manila Trench (south of Taiwan), Taiwan Island and the Ryukyu Trench (east of Taiwan). South of Taiwan, the Eurasian Plate subducts eastward beneath the Luzon Arc while east of Taiwan, the Philippine Sea Plate subducts northwestward beneath the Ryukyu Arc.

The geodynamic setting of the Gagua Ridge

The Gagua Ridge belongs to the Philippine Sea Plate. This north-south trending ridge is linear, continuous for over 300 km, 20 to 30 km wide and rises 2 to 4 km above the adjacent sea floor (Figure 2). North of 23° N, the ridge deepens and seems to die out. A segment of the Gagua Ridge may have already subducted beneath the Ryukyu margin, being responsible for the reentrant of 18.5 km (20 km wide) into the accretionary wedge (Schnürle et al., 1998a; Sibuet et al., 1998). Nevertheless, Dominguez et al. (this issue), based on forearc basin and accretionary wedge deformation find only evidences for a short segment of the Gagua Ridge being already subducted. The ridge isolates the Huatung Basin to the west from the main West Philippine Basin to the east. The Huatung Basin contains sediments derived from the Taiwan mountain belt. As sediments transported from the west are dammed by the ridge, they accumulate into the Huatung Basin, which therefore lies 500 m higher than the West Philippine Basin. The only passage for sediments to reach the open abyssal plain to the east is the Ryukyu Trench.

The magnetic lineations of the two basins adjacent to the ridge were determined by Hilde and Lee (1984). Although the age of the lineations is not entirely reliable in the Huatung Basin (Lee, personal com.), their orientation is well determined (Hsu et al., 1998). Then, on both sides of the ridge, the magnetic lineations trend differently, and according to Hilde and Lee (1984), they are possibly offset left-laterally along the Gagua Ridge.

Previous studies

As previously mentioned, the Gagua Ridge has been variously interpreted. Lee and Hilde (1971), based on the magnetic lineations, concluded that the Central Basin Spreading Center (CBSC) (which crosses the whole basin from the inactive Palau-Kyushu Ridge to the vicinity of Luzon (Mammerickx et al., 1976)) is an inactive spreading center offset by several fracture zones. The ridge consists of a succession of smaller en échelon ridges and troughs, trending N105°, and regularly offset along N–S segments (Lewis and Hayes, 1980) (Figure 1). On both sides of the Gagua Ridge,

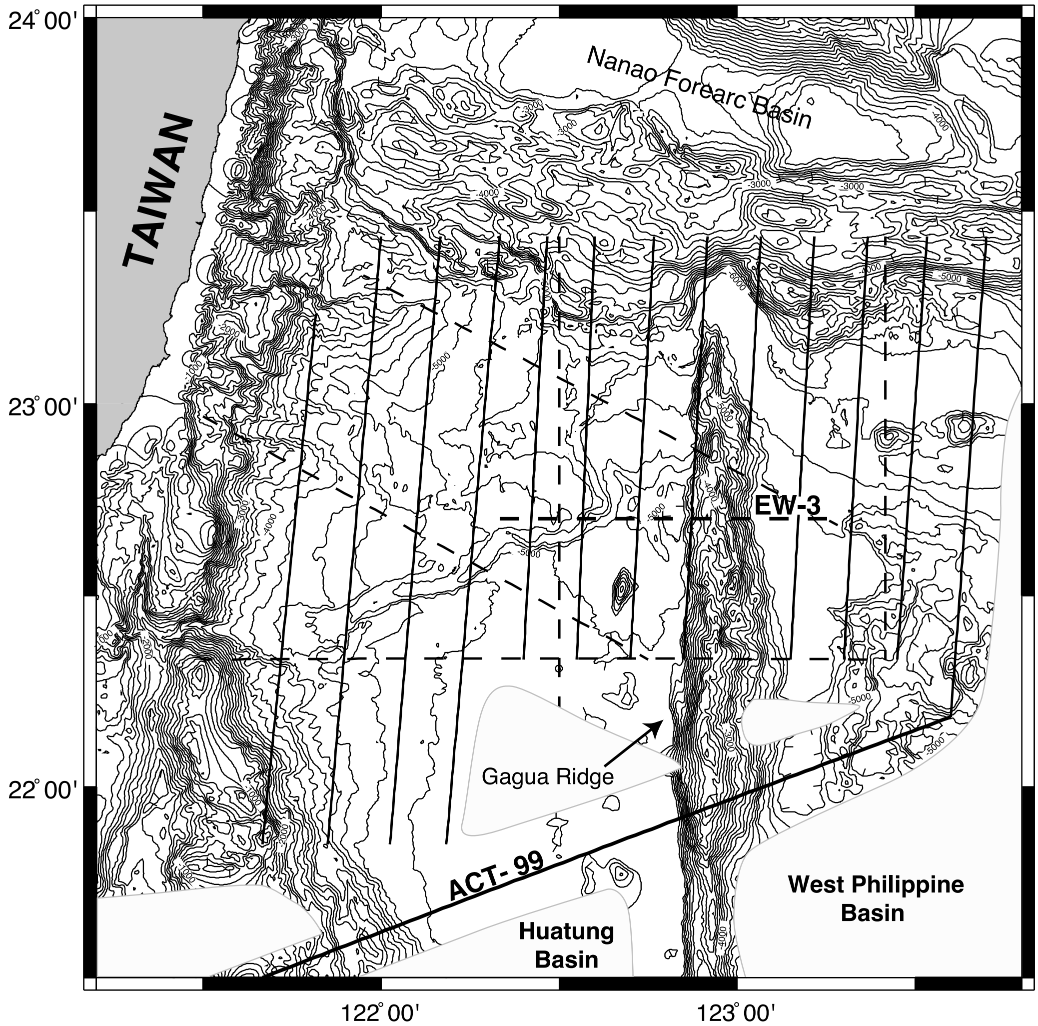

Figure 2. Multibeam bathymetry of the Gagua Ridge and its surroundings, at 200 m contour interval. Location of the 14 6-channel seismic lines of the R/V L'Atalante during the ACT cruise (solid lines) and location of the 5 TAICRUST multi-channel seimic profiles EW9509 (dashed lines), all used in this study. Only lines ACT-99 and EW-3 are shown in this paper. Gray areas are without data.

the magnetic lineations show a different trend (Hsu et al., 1998). Thus, oceanic crust on either side of the Gagua Ridge probably formed at different periods in time and in a different kinematic setting. According to Hilde and Lee (1984), west of the ridge, in the Huatung Basin, anomalies 16 to 19 (39 to 44 Ma) trend E–W, as do magnetic anomalies 19 to 13 in the central part of the West Philippine Basin. Although the precise age of the lineations in the Huatung Basin is not well constrained, we will use it in this study as an hypothesis. Immediately east of the Gagua Ridge, anomalies 20 to 21 (46 to 50 Ma) trend N120° similar to those determined in the northern and southern parts of the West Philippine Basin. In this basin, the age suggested by the magnetic anomalies is confirmed by the deep sea drilling at site 293. As a result, magnetic anomalies across the ridge appear to be offset left-laterally by about 150 km, corresponding to an age difference of 4 ± 2 Ma. This age difference across the ridge is not totally reliable because of the lack of accurate data in the Huatung Basin. Besides, using the age versus depth of oceanic basement curve for slow spreading ridge (Le Pichon et al., 1973; Sclater et al., 1971), Sibuet et al. (1998) concluded that the oceanic crust of the Huatung Basin could be 8–16 m.y. older than the Philippine Sea Basin crust, east of the ridge.

According to Hilde and Lee (1984), the magnetic pattern in the West Philippine Basin results from two stages of opening of the basin at the CBSC. Prior to 45 Ma, the West Philippine Basin crust was formed by NE-SW spreading from the CBSC at a half-rate of 44 mm yr^{-1}. This episode is identified by lineations 20–26 (45–60 Ma) in the northern and southern parts of the basin and in a small area east of the Gagua Ridge. At about 45 Ma (anomaly 20), the spreading slowed down (18 mm yr^{-1}), and its direction changed to a more N–S direction, perhaps because of a plate reorganisation in the Pacific, and a major rotation of $\sim$50° of the Philippine Sea Plate which occurred between 50 and 40 Ma (Hall et al., 1995). The CBSC was reorganized into numerous, short E–W segments offset by N–S transform faults. The Huatung Basin crust perhaps formed during this second spreading phase. Spreading on the CBSC ceased at 35 Ma (anomaly 13) (Hilde and Lee, 1984).

The Gagua Ridge is located south of the West Philippine Basin fossil spreading center. Indeed, west of 126° E, all the magnetic lineations belong to the southern part of the basin (Figure 1). Lewis and Hayes (1980) pointed out the lack of CBSC morphology west of 126° E. At this longitude, the CBSC is offset to the north by a large right-lateral offset, and it has already subducted beneath the Ryukyu Trench.

Some dredges were made during R/V Vema cruise V3609 at a site on the Gagua Ridge between 20° N and 21°30′ N. A large assortment of both altered and unaltered igneous rocks was recovered, including coarse-grained gabbros, layered gabbros, amphibolites, serpentinized amphibolites and basalts. Some basalt samples display slickensides (Mrozowski, 1982). Thus Mrozowski et al. (1982) and Hilde and Lee (1984) concluded that the Gagua Ridge was an up-faulted sliver of oceanic crust, perhaps similar to the ridges observed bounding fracture zones. Evans and Lewis (1984) analyzed rocks recovered during this Vema cruise, and they affirmed that these rocks are amphibolitic gneisses, siltstones, basalts, andesites and cumulate gabbros. These rocks were sheared and recrystallized at high temperatures (550–600 °C). They concluded that the ridge might be the result of an early Tertiary subduction zone which existed to the east of Luzon. However, these rocks were recovered at a site where the Luzon Volcanic Arc and the Gagua Ridge merge (20°24′ N). Therefore, these rocks seem to belong rather to the Luzon Volcanic Arc, except for the gabbro samples which may come from the Gagua Ridge. Another dredge, which was made on the west flank of the ridge (at 21°29′ N, far from the Luzon Arc), reveals gabbros, and no other rocks like andesites or gneisses. Thus, the dredged rocks show the ridge to be formed of deformed oceanic crust, rather than having a volcanic origin. This is confirmed by the magnetics over the ridge zone (Hsu et al., 1998). Indeed, the magnetic signature of the ridge consists in the same signature than the adjacent crust, but with a little higher amplitude, suggesting that it is formed of oceanic crust. Finally, dredges and magnetics suggest a crustal composition rather than an arc origin.

Gagua Ridge: an old fracture zone?

Because the magnetic lineations trend differently on both sides of the Gagua Ridge, and because this linear ridge, composed of igneous rocks, trends parallel to the N–S fracture zones of the West Philippine Basin, we made the assumption that the Gagua Ridge could be associated with a fracture zone. The new data collected during the ACT cruise allow us to present a detailed analysis of the ridge and to test this possibility (Figure 2).

Bathymetry of the basins adjacent to the ridge

The West Philippine Basin is about 500 m deeper than the Huatung Basin. The bathymetry of the former is about 5500 m while the depth of the latter shallows towards Taiwan (Figure 3). There is a bathymetric difference between the two basins because of the influx of terrigenous sediments coming from the Taiwan island, through several submarine canyons, and also because the eastern part of the subducting plate is plunging to the north (6300 m in the Ryukyu Trench) whereas the western part of the plate, although also subducting, rises near the collision zone of Taiwan (5700 m maximum depth in the trench).

A N120° structural trend appears in the West Philippine Basin. This morphologic pattern corresponds to the original grain of the sea-floor acquired near the spreading axis during the first spreading episode. In the Huatung Basin, no E–W structures are observable because they are likely buried beneath the great amount of sediments supplied from Taiwan.

Map of the top of the basement

In order to assess the true size and shape of the Gagua Ridge, we have generated a basement map (Figure 4) by stripping sediment layers from 19 seismic reflection lines (Figure 2). On each seismic line, sediment-thicknesses in seconds were converted into

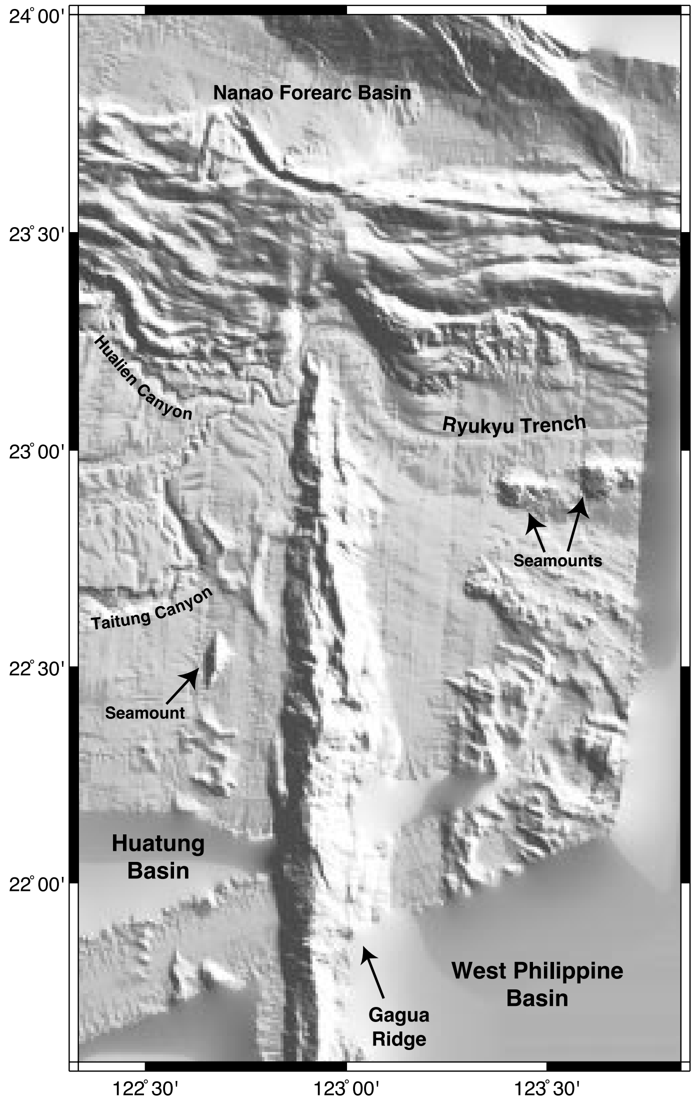

Figure 3. Shaded view of the northern segment of the Gagua Ridge, obtained from swath bathymetry acquired during the ACT cruise, using GMT (Generic Mapping Tool) software (Wessel and Smith, 1991, 1993). Note the 120° trending grain of the seafloor and the perpendicular structures, which are probably old transform faults, east of the ridge.

meters, using a depth-dependent interval velocities scale in sediments. These velocities were obtained using the Hamilton curve (Hamilton, 1980) and using split spread seismic refraction profiles near the Nankai Trench (Stoffa, 1992). Then, we calculated the basement depth along each seismic line, and the basement map of the study area was constructed (Figure 4).

The basement map shows that the northward dip of the Philippine Sea Plate is steeper in the east (about 9000 m in the trench) than in the west (7000 m) because the western part of the plate is influenced by the collision in Taiwan. In addition, a deep (up to 7500 m), narrow (10 to 20 km wide) linear trough bounds the eastern flank of the Gagua Ridge. The ridge crest (1520 m at 22°05′ N) rises 5200 m above the basement of this trough. West of the ridge, a second trough parallels the ridge, but it is shallower (6750 m), narrower and less regular than the eastern trough. The summit of the ridge lies about 4950 m above the bottom of the western trough. This trough is adjacent to the ridge only south of 22°15′ N whereas to the north, it is offset by 30 km towards the west. In general, the highest point of the ridge lies adjacent to the deepest parts of both troughs. The depth of the basement of

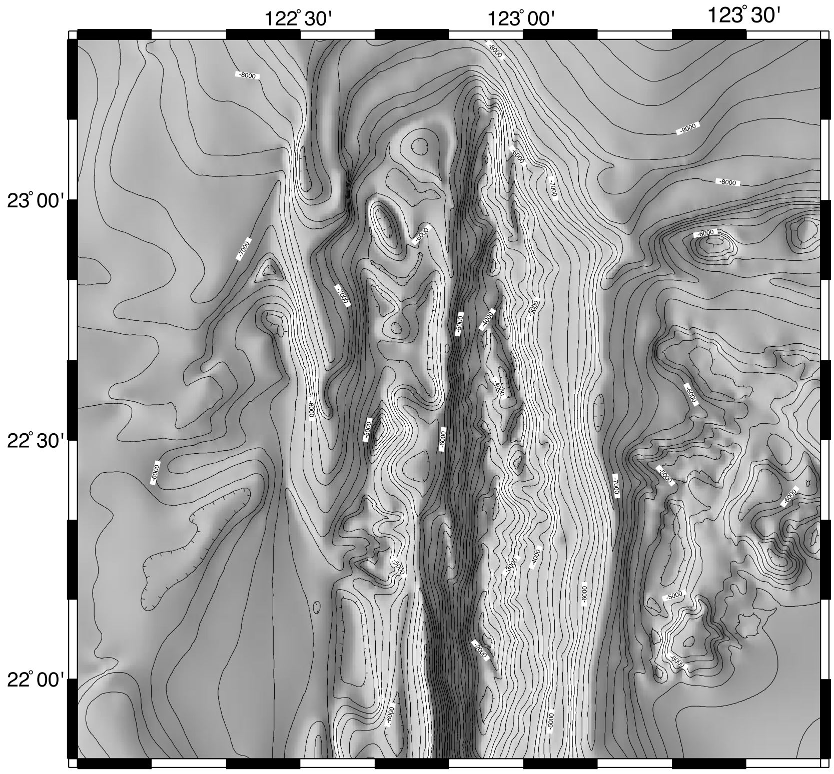

Figure 4. Shaded view of the map of the top of the basement, in the study area, obtained from 19 seismic profiles (see location on Figure 2). Contours are every 250 m. Note the two linear, deep, narrow troughs which parallel the ridge. The highest point of the ridge is 5.2 km above the basement of these troughs. This linear set of ridges and troughs is typical of a Fracture Zone.

both basins averages 5500–6000 m, but the Huatung Basin contains more sediments than the West Philippine basin. Now, in basins with thick sediments, the basement of the basin will rebound isostatically if the sedimentary cover is removed from the basin. As a result, a sediment loading correction is necessary for the calculation of the basement depth (Tamaki, 1986). Crough (1983) presented a simple formula for the sediment loading correction for an oceanic basin. The correction formula is:

$$Db = Dw + 600T,$$

where Db is basement depth after sediment loading correction (m), Dw is water depth (m), and T is the two-way travel time in the sediment (s). According to this formula, the estimated subsidence of the oceanic basement of the Huatung Basin caused by this load is about 500 m, suggesting that prior to sediment deposition, the Huatung Basin was approximately 500 m above the West Philippine Basin.

In conclusion, the Gagua Ridge probably formed along a fracture zone, in part because the high relief of the ridge and its associated set of linear and parallel troughs are characteristic of the fracture zones of oceanic seafloor. Indeed, topography of many fracture zones often consist of similar scars produced by transform faulting (Menard and Atwater, 1969).

Seismic reflection lines

Most seismic reflection lines (Figure 2) across the Gagua Ridge show the same seismic pattern as revealed by ENE–WSW trending line ACT-99 (Figure 5). This line shows a lack of layered reflections in the ridge. The ridge appears to be composed of the same material as the surrounding oceanic crust, and to be devoid of sediments. Layered sediments in both the western and eastern troughs onlap the ridge and adjacent oceanic basement, and show no evidence of tectonic deformation. This lack of deformation in the troughs can be a valid indication of the age of the last deformation episode at the origin of the Gagua Ridge. Indeed, this absence of tectonic deformation together with the respective ages of the basins adjacent to the ridge (middle late Eocene) suggest that the troughs have been tectonically inactive since the middle late

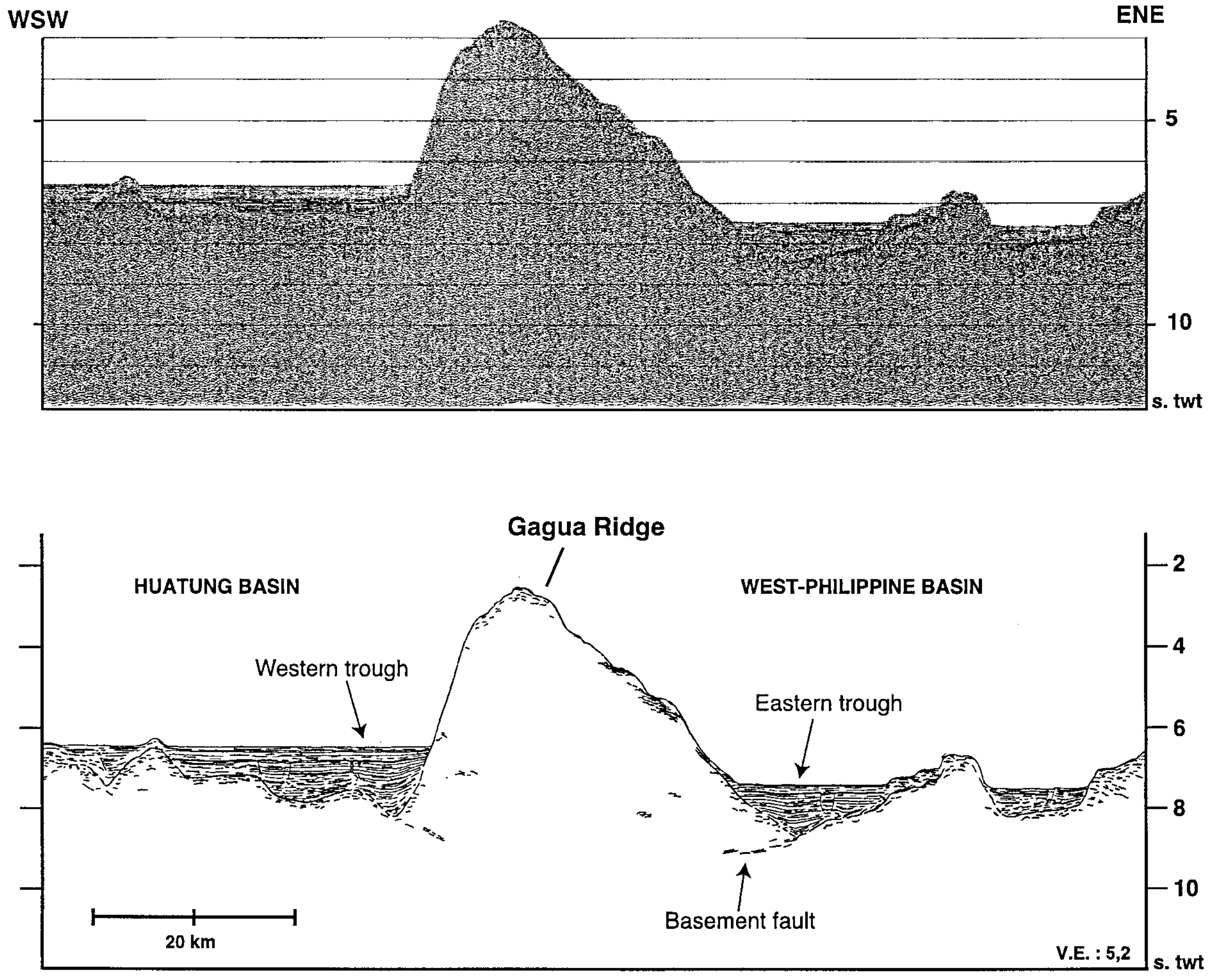

Figure 5. Portion of WSW-ENE time migrated 6-channel seismic line ACT-99 across the asymmetric Gagua Ridge, West Philippine and Huatung Basins. Note the depth difference of 500 m between the basin floors adjacent to the ridge, and the lack of deformation in sediments in the two Eocene basins. V.E. ≈5.2 at seafloor. See location in Figure 2.

Eocene at least. Therefore, we suppose that the Gagua Ridge formed before the late Eocene.

Surface structure of the Gagua Ridge

Swath bathymetry and side-scan sonar imagery provide the basis for a detailed analysis of the Gagua Ridge structure. From the bathymetric map (Figure 6), the northern part of the ridge seems to be buried beneath the trench fill sediments in the Ryukyu Trench. North of 23°10′ N, the maximum depth of the summit of the ridge is 6000 m, whereas to the south, the highest point of the ridge reaches 1520 m in bathymetric map. The basement map shows that, to the north, the ridge is only about 500 m above the basement of the adjacent basins. Thus the ridge is interrupted, at least partially, north of 23°15′ N. The morphostructural map (Figure 7) shows the ridge to be cut by several lineaments. One of them trends NE–SW and offsets sinistrally the northern part of the ridge at 22°57′ N. Another one offsets the northern part of the ridge at 22°51′ N in a dextral sense. These may be faults (they offset parts of the ridge) which are not continuous across the high, probably because they are old and inactive. Indeed there is no earthquake activity associated with the Gagua Ridge except one quake which is perhaps related to several NNW–SSW strike-slip faults deforming the Huatung Basin (Schnurle et al., 1998b). Therefore, there is probably no active fault deforming the ridge at present.

The summit of the Gagua Ridge is marked by two linear, gently sinuous, north-south trending crests of

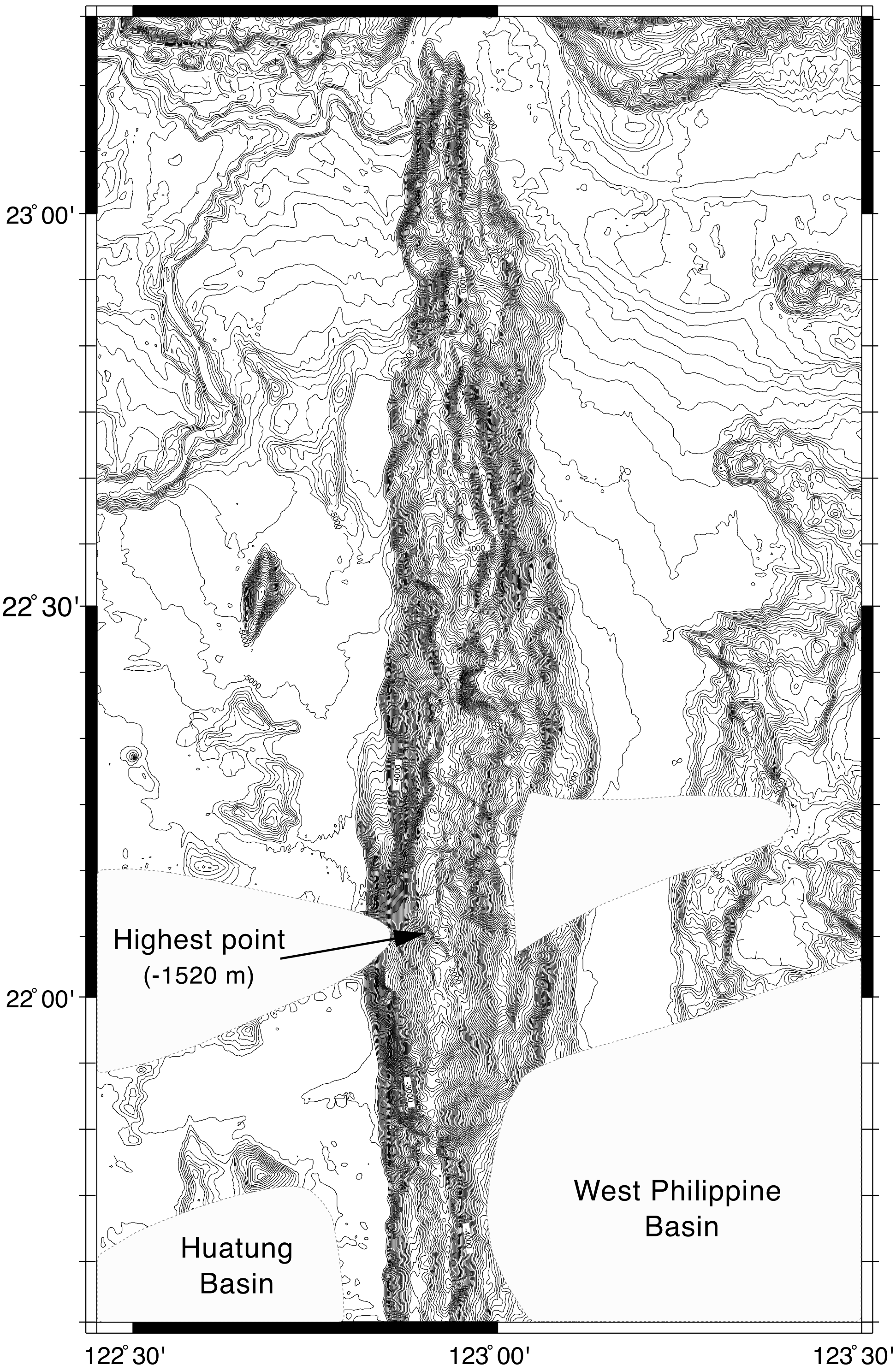

Figure 6. Bathymetric map, close-up of the Gagua Ridge, obtained during the ACT cruise. Isobaths every 50 m. The summit of the ridge is marked by one or two crests separated by an axial valley. This may indicate that the ridge development was influenced by axial strike-slip motion. Note the lack of trace of volcanism. Structural interpretation is shown at the same scale on Figure 7.

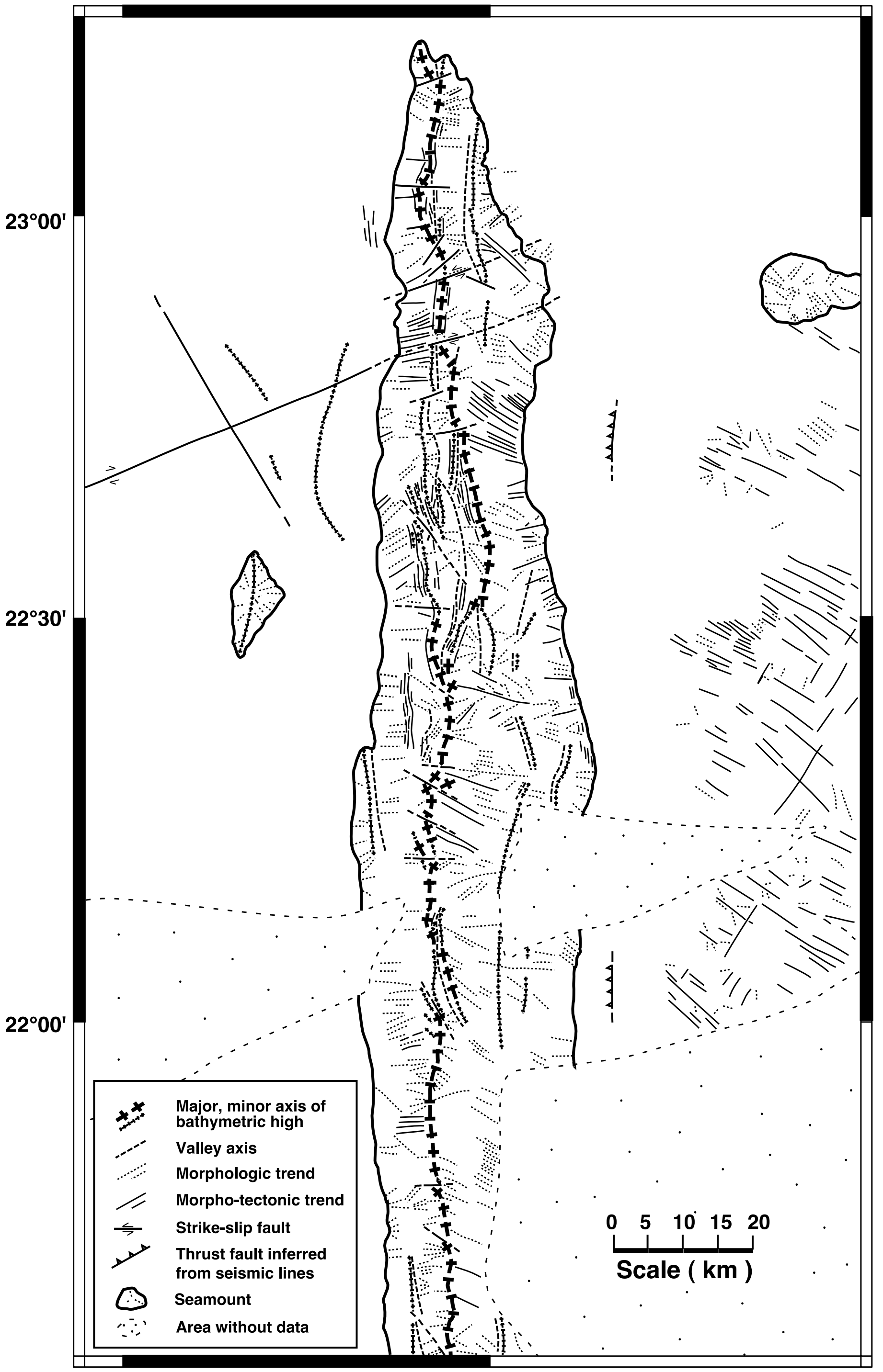

Figure 7. Interpretative structural map, obtained after analysis of the bathymetric map (Figure 6) and of the side-scan sonar imagery acquired during the ACT cruise (not shown in this paper).

different height. They are separated by an axial valley, which reaches 800 m in depth with respect to the adjacent crests. Crests and valleys could be related to an old strike-slip deformation along the whole ridge. The position of the highest crest (essentially undisrupted) varies with latitude and defines an asymmetric shape of the ridge in cross-section. North of 22°50′ N and south of 22°30′ N, the highest crest is located in the western part of the ridge. The steepest flank (17°) therefore faces west. Between 22°50′ N and 22°30′ N, the highest crest stands in the eastern part of the ridge and the steepest flank (15°) faces east. Otherwise, three kinds of lineaments are obvious along the ridge (Figures 6 and 7). Some morphological lineaments roughly trend ENE–WSW on the western flank of the ridge and WNW–ESE on its eastern flank. Some N–S gently sinuous structural trends are visible (Figures 3 and 7) not only in the summit of the ridge but also along its flanks. Finally, there are several NNW–SSE troughs on the summit. The latter two structural trends (N–S and NNW–SSE) may be related to an old north-south sinistral strike-slip deformation episode with NNW–SSE Riedel fractures or Riedel shears. We note that no circular features indicating volcanism have been recognized.

Gravimetry

Free air anomaly signature of the ridge

The free air anomaly (FAA) map (Figure 8A) results from a new compilation of all available gravity data by Hsu et al. (1998), including the data coming from the ACT cruise. North of 23° N, very low values (−120 mgal) indicate a mass deficit at the Ryukyu Trench where water and sediments replace the plunging lithosphere, as the Philippine Sea Plate subducts toward the northwest. Southeast of Taiwan, the Luzon volcanic arc is marked by a gravimetric high (up to +150 mgal). The Gagua Ridge is characterized between latitudes 20°30′ N and 23° N by a FAA high (up to +90 mgal). The positive anomaly over the ridge is bounded on its east side by a strong low (−70 mgal) related to the deep and narrow trough which parallels the eastern flank of the ridge (see Figure 4). The shallower western trough shown on the basement map, is not clearly expressed on the gravity map. Indeed, it appears locally as a low anomaly (−10 mgal). The positive anomaly which characterizes the ridge totally disappears north of 23° N and south of 20°30′ N, and locally near latitude 21°40′ N, whereas the negative anomaly which bounds the eastern flank of the ridge is continuous and still prominent as far south as the East Luzon Trench.

The gravity anomaly observed over the ridge is probably the result of the topography effect, but the high cannot be completely explained by this effect. Indeed, the Bouguer anomaly map (Hsu et al., 1998) shows a low value at the location of the ridge, with respect to its surrounding. In general, such a low Bouguer anomaly is interpreted as indicating a crustal thickening. Therefore, in the case of the Gagua Ridge, this low anomaly could reflect a crustal thickening, or the existence of a body of unusual density at depth. Gravity models across the Gagua Ridge therefore offer a useful tool to constrain its subsurface structure.

Gravity modeling

Most E–W gravity profiles across the Gagua Ridge between 21°50′ N and 22°40′ N show a similar gravity pattern. Gravity models were constructed along several profiles in order to investigate the crustal structure of the ridge. The models shown in this study (Figure 9) are two dimensional because the linear high presents a nearly cylindrical structure. In particular, gravity anomaly was modeled along seismic line ACT-99 (Figure 8B) because this line was recorded continuously across the ridge during the ACT cruise, and provided a good constraint on the bathymetry, and on the basin structure adjacent to the ridge. Moreover, it is representative of all the E–W models constructed between 21°50′ N and 22°40′ N, except that it is located at the area of maximum amplitude of the FAA (22°05′ N). The gravity profile along line ACT-99 shows a paired positive and negative anomaly with a maximum peak-to-trough amplitude of 150 mgal. This indicates a mass excess (+90 mgal anomaly) over the ridge and a mass deficit (−60 mgal anomaly) over the eastern trough. A slight negative anomaly is observed over the western trough (−10 mgal). Gravity models were made with Hypermag software (Saltus and Blakely, 1993). Hypermag is an interactive, 2D and 2.5D modeling program for gravity and magnetic data, written in Fortran 77. The 2D gravity equations are from Grant and West (Grant and West, 1965). The program allows the user to calculate the gravity field produced by a 2D subsurface distribution of density, assuming that the studied object is in isostatic equilibrium. The 2D density is represented by 2D polygons of arbitrary shape, each with a specified density. In the strictly 2D case, the polygons represent the cross section of bodies that extend infinitely in both directions perpendicular to the plane of the

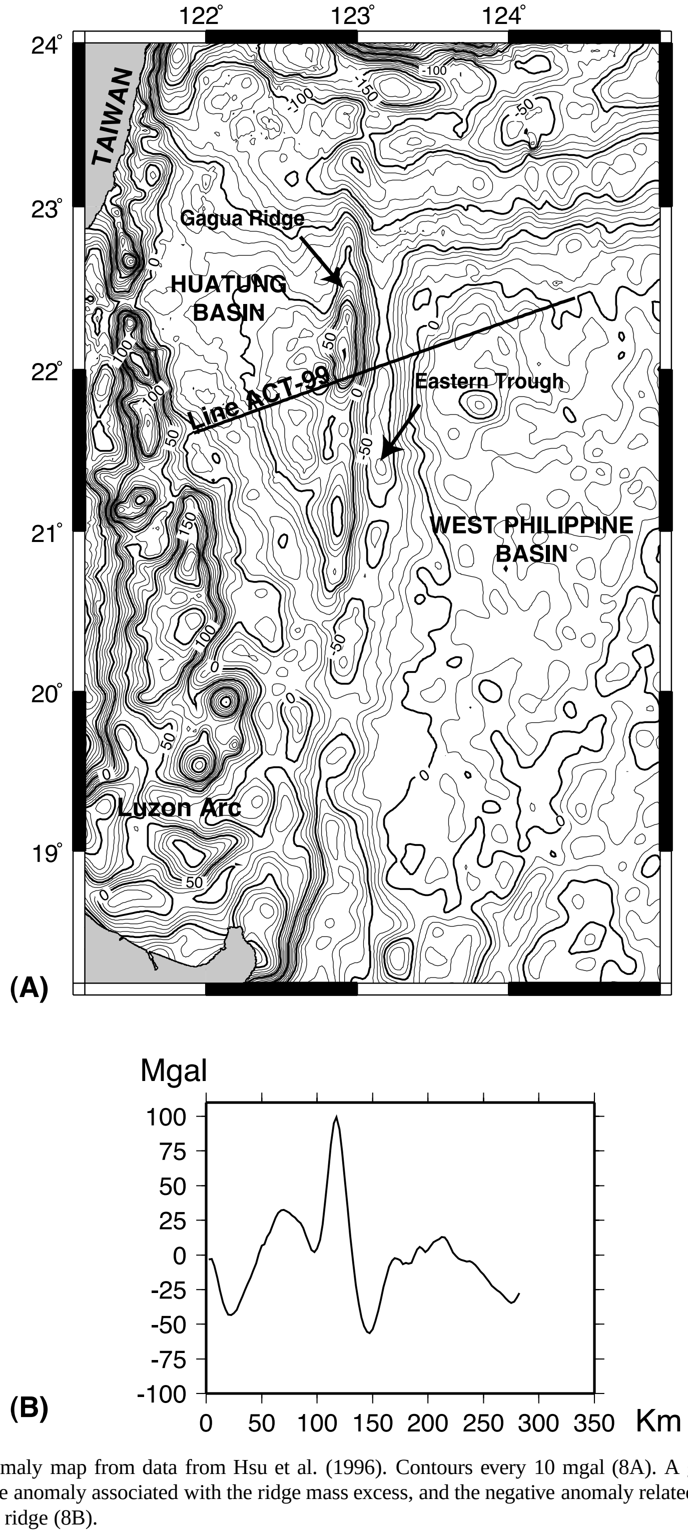

Figure 8. Free-air gravity anomaly map from data from Hsu et al. (1996). Contours every 10 mgal (8A). A gravimetric transect along line ACT-99 shows the high positive anomaly associated with the ridge mass excess, and the negative anomaly related to the basement trough which bounds the eastern flank of the ridge (8B).

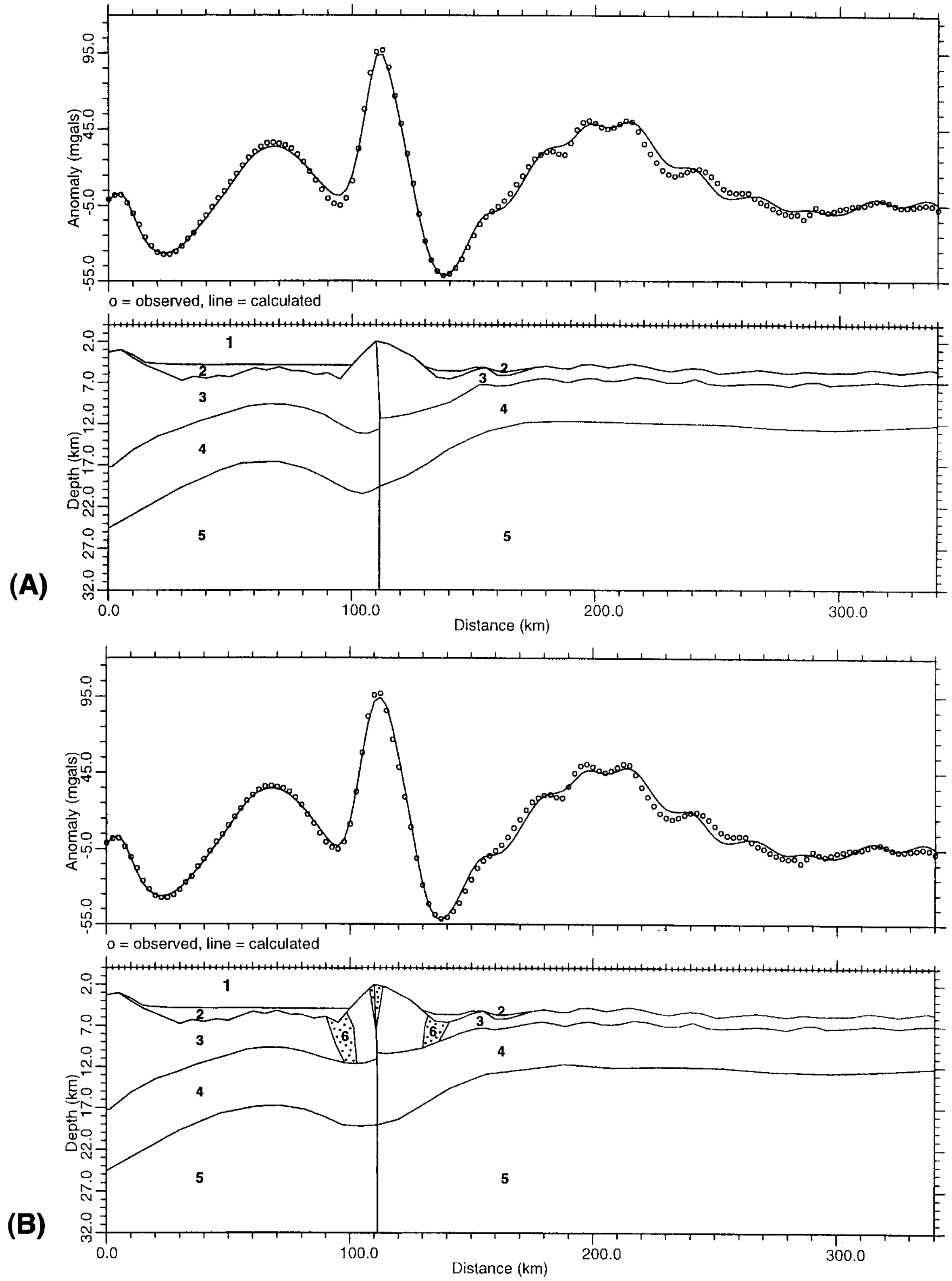

Figure 9. Gravity models along line ACT-99, (A) Simple model showing the presence of a localized root beneath the ridge. (B) Model including bodies of low density (dashed areas) at the location of the main presumed faults, where the upper crust is likely altered. Density values used in the gravity models are listed in Table 1.

Table 1. Density values in the 2D polygons, i.e., bodies which are involved in the gravity models (Figure 9). (a) Density values used to calculate the gravity anomaly in the Huatung Basin, provided by recent seismic refraction data (OBS) (Yang et al., 1998; Liu et al., 1998). (b) Values used in the West Philippine Basin, coming from seismic refraction data of Murauchi et al. (1968). The density values are not the same in the two basins because these basins formed during two kinematic settings (see previous studies section). The conversion of the P-wave velocities into densities was made by applying the Birch's law.

Bodies nature	Bodies number	Thickness (km)	Velocity (km/s)	Density (g/cm^3)
(a)				
Water	1	1.55–6.5	1.5	1.03
Sediment	2	0–3	2.0	2.15
Basalt	3	4	5.5	2.60
Gabbro	4	7	7.2	3.00
Mantle	5	>22	8.0	3.26
Altered basalt	6	variable	4.8	2.5
(b)				
Water	1	1.55–6.5	1.5	1.03
Sediment	2	0–3	2.0	2.15
Basalt	3	1.7	5.5	2.60
Gabbro	4	5.2	7.0	2.93
Mantle	5	>22	8.1	3.31
Altered basalt	6	variable	4.8	2.5

polygons. The performance of gravity models requires knowledge of the density of the bodies involved, or at least the P-wave velocity in these bodies. East of the ridge, seismic refraction data of Murauchi et al. (1968) were available in the West Philippine Basin for a crust similar in age to that of the basin adjacent to the eastern flank of the ridge. For the Huatung Basin west of the ridge, recent seismic refraction data (OBS) from the TAICRUST survey onboard the R/V Maurice Ewing (cruise EW 9509) (Yang et al., 1998, Liu et al., 1998) provide P-wave velocities, and by applying velocity-density relationships (Birch's law), one can obtain estimated density values (Table 1). Based on these data, the crust of the Huatung Basin appears to be 11 to 12 km thick. This thick crust might be the result of an excess of volcanism, as observed on other parts of the West Philippine Basin, near the Benham Rise or the Urdaneta plateaus. In any case, this unusual thickness is well constrained with the OBS data, and this allowed us to use well-known thickness and density in the gravity model. On the other hand, the thickness of the West Philippine Basin crust east of the ridge appears to be normal. This difference of crustal thickness on both sides of the ridge could reflect different periods in time and a different kinematic setting for the formation of the two basins. The ACT-99 gravity model (Figure 9A) shows the Gagua Ridge to be locally compensated by an overthickened crust as deep as 20 km depth, i.e., a total crustal thickness of about 18 km at the ridge location. We completed a second gravity model (Figure 9B) along the same line, using bodies of low density at the location of the presumed faults. Indeed, it has been shown that the crust within several fracture zones is intensely fractured and hydrothermaly altered, and characterized by low compressional wave velocities (and consequently by low density) (Detrick et al., 1993; Begnaud et al., 1997). Therefore, modeling several bodies of low density (see Table 1) at the location of the presumed main faults results in a more realistic model. This second-generation model also shows thickening of the crust beneath the ridge to as deep as 19 km (i.e., a total crustal thickness of about 17 km).

The gravity models were calculated at 22°05′ N and they remain valid only between 21°50′N and 22°30′ N. Indeed, north of 22°05′ N, the height of the ridge diminishes continuously until disappearing north of 22°30′ N. Similarly, the positive FAA vanishes. South of 22°05′ N, the FAA gradient decreases abruptly until 21°35′ N. At this point, the ridge is marked by a FAA which reaches only +10 mgal, because of the reduced height of the ridge at this location. Far to the south, the ridge is again characterized by greater topographic high and consequently by an higher FAA. Gravity models (not presented here) which were calculated north of 22°30′ N and near 21°30′ N present only a small root beneath the ridge, because the FAA is modest at these locations. As a matter of fact, Karp et al. (1997) developed a density model across the ridge along the latitude of 21°30′ N. As the FAA reaches only +10 mgal, they found a crustal thickness of the ridge of only 8 km. At the locations where the ridge is not very well prominent and consequently where the FAA is modest, it appears that the thickening shown on the ACT-99 gravity model, was less pronounced. The height of the ridge at these locations is minor. Later, we will discuss the possible reasons for the thickening of the crust at the location of the ridge.

Flexural modeling of the lithosphere under the load of the ridge

Flexural modeling of the lithosphere under the load of the Gagua Ridge allows an estimation of the age of formation of the ridge. We assume that the ridge formation corresponds to the loading of a semi-infinite plate (because of the existence of a presumed fault at the fracture zone) with a volume of rocks equivalent to the estimated volume of the Gagua Ridge. Indeed, the top of the basement observed along the seismic reflection line ACT-99 (Figure 5) appears to bend towards the ridge. This implies a crustal deflection under the load of the ridge. The lithosphere bends under surface load and the amplitude of the flexural bulge relates to the effective elastic thickness (related to the rigidity) of the lithosphere at the time of loading. As the rigidity of the plate (increasing with its age) increases, the amplitude of the deflection and hence of the resulting bathymetry and bending of the lithosphere dramatically decrease, and deflection wavelength increases. In this study, we modeled the flexural shape of the crust that bends under the load of the ridge by a thin elastic semi-infinite plate with an effective elastic thickness (Te) of 5 to 20 km (0 km corresponds to the local type-Airy compensation) (Figure 10).

In a general way, there is a best fit between the shape of the crust inferred from the seismic reflection line ACT-99, and the flexural shape of the crust calculated here in the model which implies the flexure of the West Philippine Basin under the load of the ridge (Figure 10B). Indeed, for the case in which the Gagua Ridge is loading the Huatung Basin (Figure 10A), we never obtained a good fit, however thin or thick the plate was. Therefore, we will consider only the model which implies the deflection of the West Philippine Basin under the load of the ridge (i.e., a sliver of the Huatung Basin is loading the West Philippine Basin). In this case, the best fit between the shapes of the crust observed and calculated, was obtained with an elastic thickness Te of about 5 to 8 km (Figure 10B). Because $Te \approx 3.6 \times \sqrt{\text{age}}$ (Watts et al., 1980), we conclude that the loading occurred when the plate was about 2 to 5 Ma old. We notice that considering the shape of the crust observed on the gravity models (Figure 9) instead of considering the shape of the crust inferred from the top of the basement (see line ACT-99, Figure 5), we obtained the same result: the best fit indicates that the plate was 2 to 5 Ma old at the time of loading (Figure 10B). As at the location of the line ACT-99, the plate is 46 m.y. old in the West Philippine Basin according to Hilde and Lee (1984). Thus the loading – i.e., the Gagua Ridge formation – probably occurred 41 to 44 m.y. ago. As the Huatung Basin is 39 to 44 Ma old according to the same authors, it loaded the West Philippine Basin nearly while it was being formed. This is consistent with observations which were made on transverse ridges bounding fracture zones: transverses ridges appear often to have formed as younger-side lithosphere overthrust older-side lithosphere (McCarthy et al., 1996). Moreover, the ridge formation usually occurs along the transform fault, and later also along the fracture zone, few millions years after the passage at the ridge-transform intersection (Sandwell, 1984), that is to say when the plates are very young.

The Gagua Ridge origin and formation mechanisms

All the elements of our study suggest that the Gagua Ridge is a transverse ridge which was built up on a fracture zone. Usually, the formation of transverses ridges bounding fracture zones can be explained by several mechanisms. In the next part, we will discuss possible mechanisms of the ridge formation, as well as the age and the reason for its uplift.

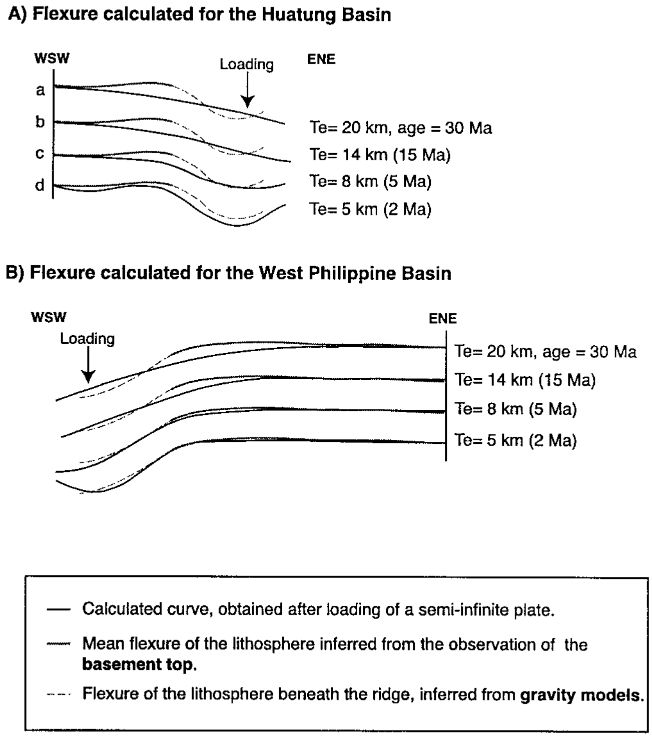

Figure 10. Model of bending of the lithosphere under the load of the ridge. We obtained different flexural shapes of the crust for different elastic thicknesses (Te), i.e., different ages of the crust at the time of loading. The best fit to the shape of the crust observed in the seismic line ACT-99 is obtained for $Te = 8$ km, i.e., for an age = 5 Ma, when the loading occurs on the eastern plate. We conclude that the oceanic plate was about 5 Ma years old when the Gagua Ridge formed.

Origin of the transverse ridges bounding fracture zones

Some fracture zone transverse ridges show characteristics that are quiet similar to those of the Gagua Ridge. For example, the Central Pacific fracture zone morphology is a scarp with a simple transverse ridge, the horizontal offset is about 150 km and the age difference across this fracture zone is less than 5 m.y. (Nakanishi, 1993). But the maximum height of the Central Pacific fracture zone ridges above seafloor is 1 km whereas the maximum height of the Gagua Ridge above the seafloor reaches 4 km.

Processes which usually produce uplift of ridges associated with transform fault zones are numerous. As transform faults represent a mechanical contact between lithospheres of different ages and thermal structures, a flexure grows across the fault, caused by thermal bending stresses, differential subsidence, and lateral heat flow across the transform fault. Therefore, a single fault scarp separating younger and older lithosphere develops and the younger lithosphere flexes upward at the fault, while the older flexes down, producing a characteristic high/low pair in bathymetry and gravity (Sandwell, 1984; Wessel and Haxby, 1990; Christenson and McNutt, 1992). Other mechanisms which can contribute to the development of transform fault topography are hot spot intrusion in the faults which act as preferential conduits for flow of magma (McNutt et al., 1989; Kruse and Kightlinger, 1992), diapiric intrusion of serpentinites (Bonatti., 1978), or a change in spreading direction which can induce a component of tension or compression across transform faults. Many ridges bounding fracture zones – especially those located in the Pacific – are due to a kinematic reorganisation (even slight) of the plates (e.g. Menard and Atwater, 1969; Kruse et al., 1996).

In the case of the Gagua Ridge, only a small flexure (less than 1 km) due to different cooling and subsidence rates could have contributed to the formation of the high, because of the small age difference between the two basins adjacent to the ridge. This age difference is indeed supposed to be only about 4 m.y (Hilde and Lee, 1984) to 8–16 m.y. (Sibuet et al., 1998). There is no evidence of magmatic or diapiric intrusion. The ridge is linear, and the two north-south gently sinuous crests separated by an axial valley show that the development of the ridge has probably been largely influenced by axial strike-slip faulting along the transform fault (in a dextral sense), and later the fracture zone (in a sinistral sense). The sinistral sense of the last strike-slip deformation was shown by the NNW–SSE Riedel shears on the summit of the ridge (Figure 3). Finally, the Gagua Ridge seems to be rather the result of a tectonic event. Given the age of the ridge formation, the tectonic episode on the origin of the high might be related to a kinematic change which occurred in the Philippine Sea Plate in Tertiary time. This hypothesis will be discussed below.

Tertiary kinematics of the West Philippine Basin

The major question is: since the Gagua Ridge can only be partially the result of a flexure across the fracture zone, which tectonic episode ultimately led to its formation?

The Gagua Ridge is supposed to have formed 41 to 44 Ma ago (see Gagua Ridge: an old fracture zone section) when the West Philippine Basin opened in a back-arc setting, behind the active arc in the Halmahera region (Hall et al., 1995). During this back-arc spreading episode, the Philippine Sea Plate (which consisted solely of the West Philippine Basin at this time) underwent a major clockwise rotation between 50 Ma and 40 Ma, about a pole located at 10° N, 150° E (Hall, 1996). The middle Eocene time (around 43–45 Ma) is characterized by a major change in the Pacific Plate motion producing the well known bend in the Emperor-Hawaiian seamount chain (Clague and Jarrard, 1973). This probably produced a change in the behaviour of the Philippine Sea Plate around 43 Ma (Hilde and Lee, 1984) or 45 Ma (Hall et al., 1995), as the pole of rotation of the plate migrated. Finally, the 45–34 Ma period represents the dying phase of spreading in the West Philippine Basin (Hilde and Lee, 1984; Hall, 1996). Thus, the uplift of the Gagua Ridge appears to be contemporaneous of the change of spreading direction in the West Philippine Basin, because of the change of the pole of rotation of the Philippine Sea Plate, at about 43–45 m.y. Next, the precise mechanisms of the ridge formation will be discussed.

Gagua Ridge formation mechanisms

The transform fault and later the fracture zone at the location of the Gagua Ridge formed during the second spreading episode in the West Philippine Basin as shown by its north-south orientation (see Figure 1). The Gagua Ridge was built up along this fracture zone probably at the beginning of the second spreading episode, because it is supposed to have formed at 41 to 44 Ma as the second episode started around 44 Ma. Then, at the time of the formation of the ridge, west of the north-south fault, the crust of the Huatung Basin was being formed, and to the east, the West Philippine Basin crust adjacent to the ridge was very young (Figure 11A). As the clockwise rotation of the West Philippine Basin, which occurred between 50 Ma and 40 Ma, was not accomplished between 44 and 41 Ma, compressive stresses were probably applied to the fracture zone which may have presented a zone of weakness (Figure 11B). At this time, the oceanic crust was so young, hot and easily deformable (especialy the crust of the Huatung Basin), so that deformation was localized along this weakness zone. The former north-south fracture zone therefore may have behaved as a transpressive plate boundary during an episode of oblique compression, during a plate reorganization.

Compressive deformation could explain the height of the ridge, and the thickening observed on the gravity model (Figure 9). Based on the data presented here, we propose that the uplift of the high and the thickening in depth could be related to a major west-dipping thrust for three reasons. First, a continuous trough bounding the eastern flank of the high, suggests an emergence of a major fault. Indeed, this trough seems to be a major feature as it is well expressed on the map of the top of the basement (Figure 4) and the FAA map (Figure 8). Secondly, flexural modeling (Figure 10) showed a best fit for the model implying the flexure of the West Philippine Basin under the load of the ridge, that is to say for the case in which a sliver of the Huatung Basin loaded the West Philippine Basin, suggesting a west-dipping thrust. Thirdly, evidences of the west-dipping thrust are perceptible on the EW-3 seismic reflection line (see location Figure 2) perpendicular to the ridge. Here, several west-dipping reflectors are well expressed in the basement of the West Philippine Basin and they extend beneath the high (Figure 12). Finally, because of the compressive stresses, a west-dipping thrust was probably created and a sliver of the Huatung Basin overthrusted the West Philippine Basin towards the east (Figure 11C). The trough which bounds the western flank of the ridge may indicate a minor east-dipping thrust, antithetic to the major west-dipping thrust.

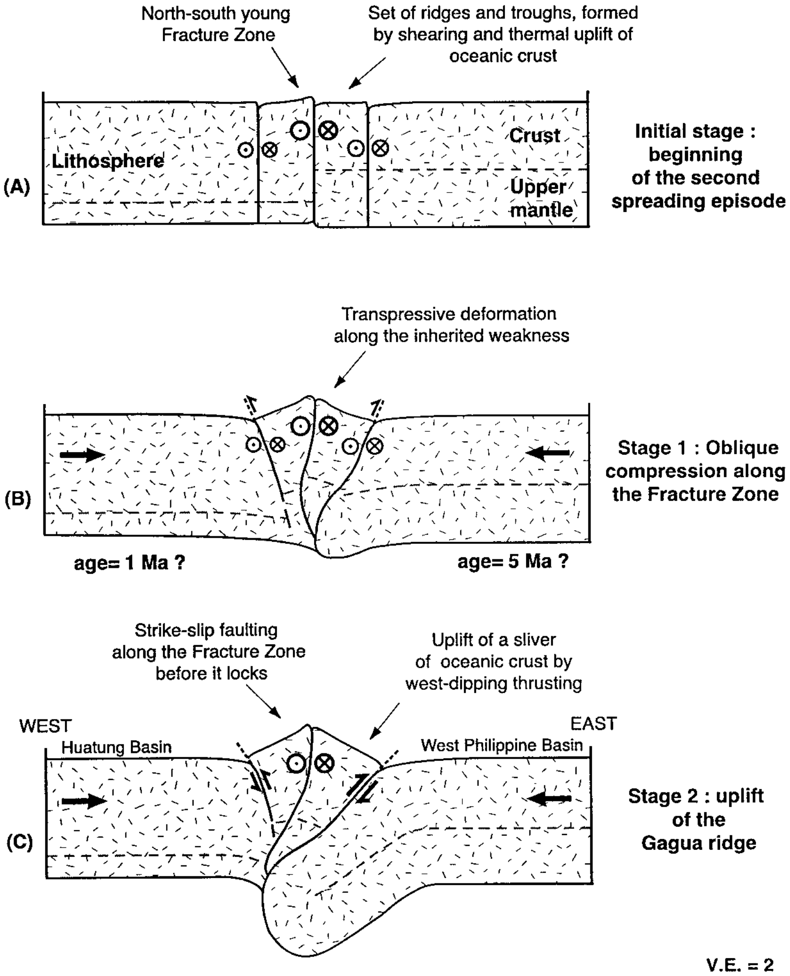

Figure 11. Model of formation of the Gagua Ridge. (A) Initial stage: formation of a north-south fault, i.e., a north-south zone of weakness. (B) Formation of the high because of a transpressive episode along an inherited weakness, because of oblique convergence. (C) The compressive component of the transpressive episode along the pre-existing old transform fault induces a major west-dipping thrust, whose emergence is marked by the trough bounding the eastern flank of the ridge. Pure strike-slip deformation is localized at the summit of the ridge.

Moreover, at the time of formation of the ridge, a strike-slip deformation probably took place along the transform fault and later along the fracture zone during a few millions years. This deformation could explain the crests and the axial valley observed on the summit of the ridge. This is in a good agreement with observations which show that fracture zones may undergo vertical and horizontal slip for a few million years before they lock, after the passage at the ridge-transform intersection (Sandwell, 1984). Finally, owing to the extreme youth of the crust, the zone of deformation appears narrow (30 to 40 km wide), and the structure due to both the strike-slip and compressive deformations are well expressed.

A modern analogue: The Macquarie Ridge Complex

The Gagua Ridge is probably the result of an transpressive episode due to a change of motion of the Philippine Sea Plate. A modern analogue of the Gagua Ridge could be the Macquarie Ridge Complex, south of New Zeland. This is a 1500 km long, complex bathymetric ridge in the Southern Ocean, lying along the Pacific-Australian plate boundary. It is composed of three linear, 4 to 5 km high segments, each roughly similar in size to the Gagua Ridge. One of them, the Puysegur Ridge, is bounded throughout much of its length by trenches and troughs (Delteil et al., 1995). This 400 km long ridge has steep slopes on both sides and a summit composed of twin ridges. Elongated

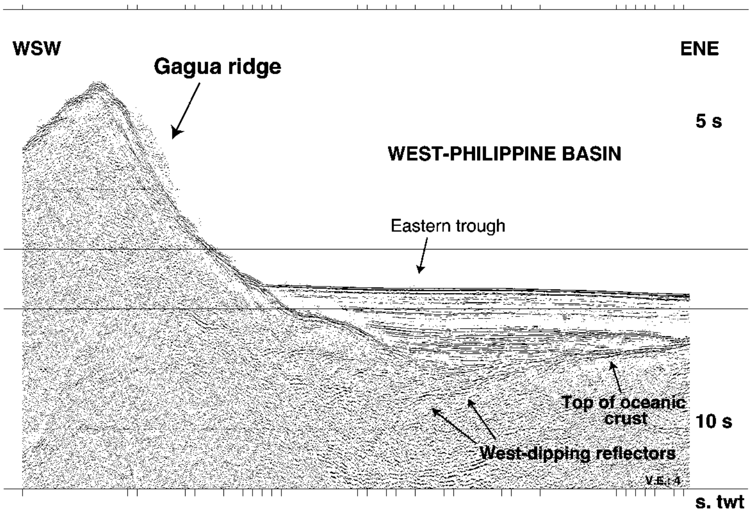

Figure 12. Portion of E-W time migrated 6-channel seismic line EW-3 across the eastern flank of the Gagua Ridge, and the West Philippine (see location in Figure 2). Note the presence of several west-dipping reflectors beneath the eastern flank of the high. These reflectors could mark the presence of a west-dipping thrust. Professor C.-S. Liu is greatly acknowledged for providing this new seismic reflection line.

lense-shaped crests and troughs over a width of 15 km strongly suggest a major strike-slip zone. The ridge constitutes an active zone of deformation a few ten kilometers wide, and strike-slip deformation is exclusively localized at the ridge summit. The ridge consists of oceanic basalts, serpentinites, peridotites, and gabbros (Mortimer, 1995). Collot et al. (1995) interpreted it as a transform plate boundary that has been subjected to oblique convergence, caused by the migration of the Pacific-Australian pole of rotation. Indeed, the Puysegur Ridge is characterized by both compressional and strike-slip focal mechanisms (Ruff et al., 1989; Anderson, 1990). This transpressional strike-slip fault is evolving into a nascent subduction zone further north (Collot et al., 1995). The Gagua Ridge presents similar characteristics as the Puysegur Ridge. It probably formed during a nearly similar event but it never reached the oblique subduction stage.

Conclusion

The detailed analysis of the bathymetric and geophysical data acquired during the ACT cruise, combined with other regional data, allowed us to gain a better understanding of the nature of the Gagua Ridge. The ridge is composed of deformed and sheared oceanic crust, and did not result from an episode of volcanism. We suggest that this linear high probably formed about 41 to 44 Ma, during the middle Eocene time. It is likely the result of a kinematic reorganisation in the Pacific which produced a migration of the pole of rotation of the Philippine Sea Plate, around 43–45 Ma. During this tectonic episode, the oblique compressive stresses applied along the young fracture zone were easily concentrated because the oceanic crust was still hot and easily deformable. Thus, the young age of the crust explains the narrow zone of deformation localized along the north-south fracture zone. The strike-slip deformation which took place along the fault before it locked, is attested by the linear crests and the axial valley which run along the summit of the ridge. Compressive deformation can explain the height of the ridge. It is recorded by the trough which bounds the eastern flank of the ridge, indeed this trough marks the emergence of a west-dipping thrust which led to the uplift of the basement high. The idea whereby numerous anomalous high transverse ridges observed in the oceans are produced by a change in spreading direction (McCarthy, 1996) has been confirmed by the study of the Gagua Ridge.

Several open questions, however, remain. For instance, it is unclear how far Gagua Ridge has subducted beneath the Ryukyu margin. Sibuet et al. (1998) suggest it extends beneath the Okinawa Trough based on anomalous volcanism in the trough, but Dominguez et al. (1999) can only trace the Gagua Ridge beneath the forearc basin. A second question regards the relative difference in lithospheric ages on opposite sides of the ridge. If it is on the order of 4 m.y. (Hilde and Lee, 1984) to 8–16 m.y. (Sibuet et al., 1998), this would suggest that Gagua Ridge is an intraoceanic fracture zone. However, if it is much greater, then Gagua Ridge may have served as a plate boundary. Therefore, further studies, e.g., magnetic anomaly and/or isotopic dating studies on samples collected on both sides of the Gagua Ridge are necessary to better constrain kinematic evolutionary models.

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