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Morphology and tectonics of the Yap Trench

Toshiya Fujiwara¹, Chiori Tamura², Azusa Nishizawa³, Kantaro Fujioka¹, Kazuo Kobayashi¹ & Yo Iwabuchi³

¹Japan Marine Science and Technology Center, Yokosuka 237-0061, Japan; ²Ocean Research Institute, University of Tokyo, Tokyo 164-8639, Japan; ³Hydrographic Department of Japan, Tokyo 104-0045, Japan

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Abstract

We conducted swath bathymetry and gravity surveys the whole-length of the Yap Trench, lying on the southeastern boundary of the Philippine Sea Plate. These surveys provided a detailed morphology and substantial insight into the tectonics of this area subsequent the Caroline Ridge colliding with this trench. Horst and graben structures and other indications of normal faulting were observed in the sea-ward trench seafloor, suggesting bending of the subducting oceanic plate. Major two slope breaks were commonly observed in the arc-ward trench slope. The origin of these slope breaks is thought to be thrust faults and lithological boundaries. No flat lying layered sediments were found in the trench axis. These morphological characteristics suggest that the trench is tectonically active and that subduction is presently occurring. Negative peaks of Bouguer anomalies were observed over the arc-ward trench slope. This indicates that the crust is thickest beneath the arc-ward trench slope because the crustal layers on the convergent two plates overlap. Bouguer gravity anomalies over the northern portion of the Yap Arc are positive. These gravity signals show that the Yap Arc is uplifted by dynamic force, even though dense crustal layers underlie the arc. This overlying high density arc possibly forces the trench to have great water depths of nearly 9000 m. We propose a tectonic evolution of the trench. Subduction along the Yap Trench has continued with very slow rates of convergence, although the cessation of volcanism at the Yap Arc was contemporaneous with collision of the Caroline Ridge. The Yap Trench migrated westward with respect to the Philippine Sea Plate after collision, then consumption of the volcanic arc crust occurred, caused by tectonic erosion, and the distance between the arc and the trench consequently narrowed. Lower crustal sections of the Philippine Sea Plate were exposed on the arc-ward trench slope by overthrusting. Intense shearing caused deformation of the accumulated rocks, resulting in their metamorphism in the Yap Arc.

Introduction

The Yap Trench lies on the southeastern boundary of the Philippine Sea Plate in the western Pacific (Figure 1). The Yap Trench is one section of a continuous system of arcuate trenches. These include the Izu-Bonin, Mariana, Yap, and Palau trenches, framing the eastern boundary of the Philippine Sea Plate. The Yap Trench is in a complex tectonic region of convergence between the Philippine Sea, the Pacific, and the Caroline plates. The Yap, Palau trenches, and the Ayu Trough, which is located in the southwest of the Palau Trench, form a plate boundary between the Philippine Sea and the Caroline plates. The Yap and Palau trenches are considered to be convergent boundaries,

while the Ayu Trough is thought to be a divergent boundary (Weissel and Anderson, 1978; Fujiwara et al., 1995). Models of Philippine Sea Plate motion (Ranken et al., 1984; Seno et al., 1993) indicate that the rotation pole of the Philippine Sea-Caroline plates is at the junction of the Palau Trench and Ayu Trough, near 6° N, 134° E. The rate of relative plate motion is estimated to be 0.7°/m.y., that is, 0–6 mm/yr along the Yap and Palau trenches (Seno et al., 1993). The age of the subducting West Caroline Basin of the Caroline Plate is estimated to be 35–30 Ma (Bracey, 1975; Hegarty and Weissel, 1988; Yamazaki et al., 1994), and the age of the overlying Parece Vela Basin of the Philippine Sea Plate is estimated to be 30–25 Ma (Mrozowski and Hayes, 1979).

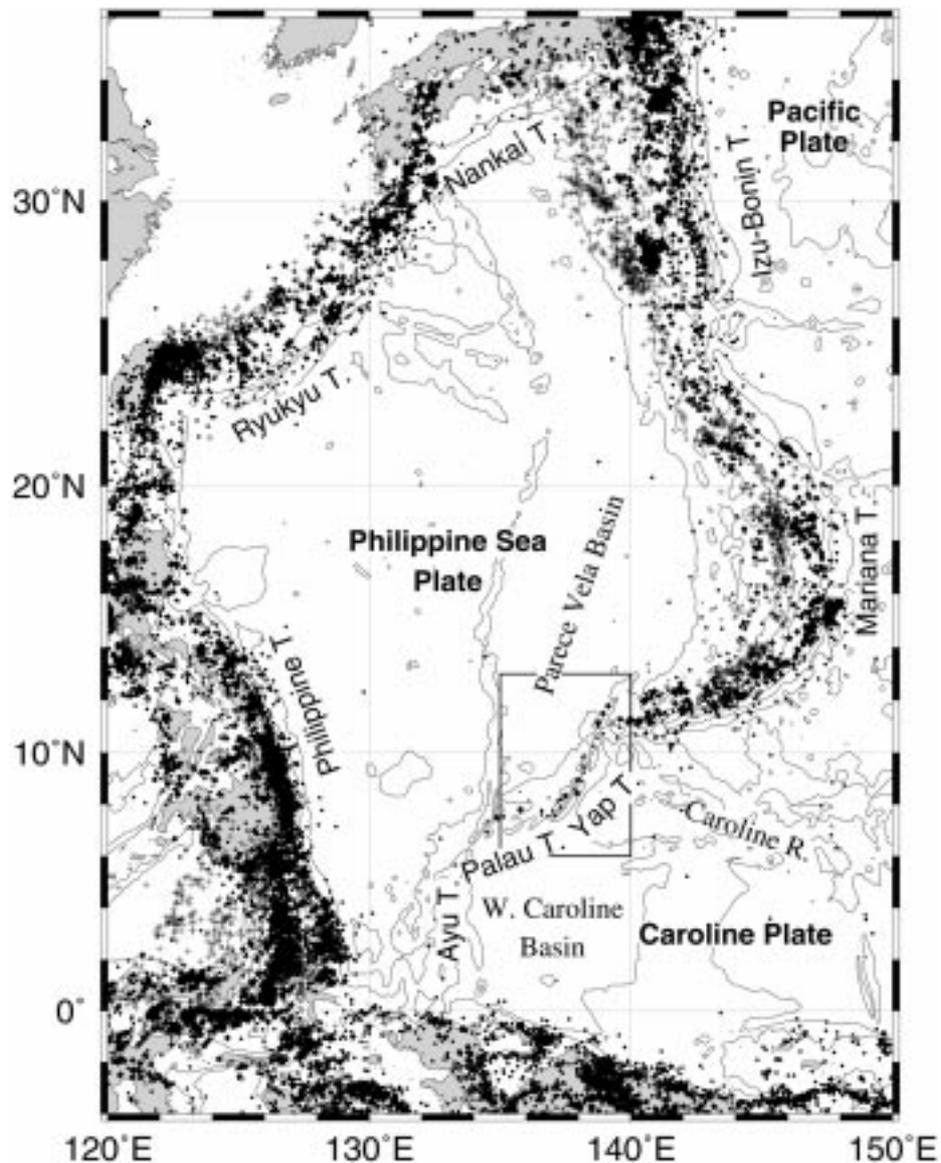


Figure 1. Location map of the Yap Trench. The contour interval is 2000 m. The box shows the survey area as shown in Figure 3. The distribution of earthquake hypocenters are represented by solid black symbols: Circles = source depth shallower than 50 km, Diamonds = 50–100 km, Crosses = deeper than 100 km. Global hypocentral data from ISC since 1980.

The length of the Yap Trench is about 700 km (Figure 2). The trench axis elongates in a convex shape toward the southeast. An arc involving the Yap Island on the Philippine Sea Plate side forms a trench-arc system. This arc consists primarily of metamorphic rocks and lacks active volcanism (Shiraki, 1971; Hawkins and Batiza, 1977). The arc-type rocks found on the islands are no younger than Late Oligocene or Miocene. The distance between the island-arc and the trench axis is about 50 km, which is much less

than that of other trench-arc systems. The Caroline Ridge, oriented in an ESE-WNW direction, intersects the trench from the east. This ridge consists of a chain of seamounts thought to be of hotspot origin (Keating et al., 1984) of less than 40 m.y. (Hegarty and Weissel, 1988). Seismicity along the trench is low. Earthquakes occur at a depth of less than 50 km, and no deep-focus earthquakes are apparent along the trench. A Wadati–Benioff zone, demonstrated by a plane of deep-focus earthquakes reflecting dynamic

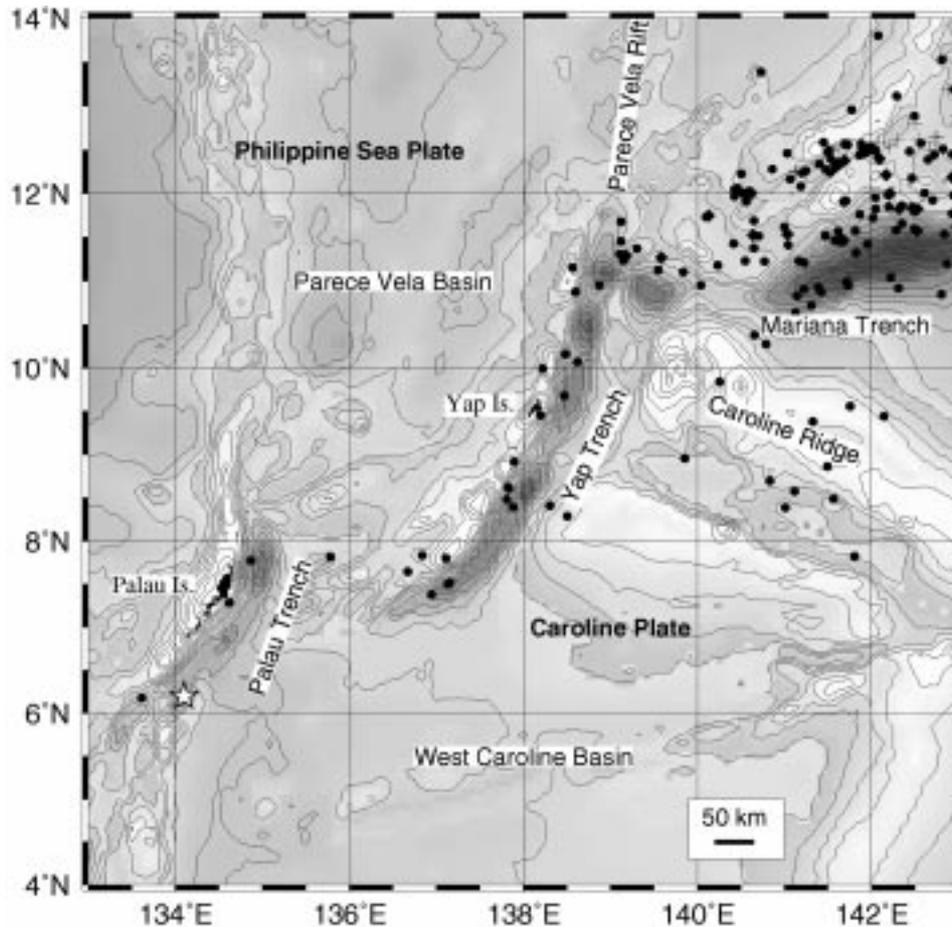


Figure 2. Bathymetric map of the circumambient regions of the Yap Trench. The contour interval is 500 m. The bathymetric data are based on the global bathymetry of ETOPO5 (NGDC, 1988). The star symbol shows the pole position of Philippine Sea - Caroline plates estimated by Seno et al. (1993). The solid black symbols show hypocentral distribution. See Figure 1 caption.

interaction between a subducting and an overriding plates, is thus not defined. Considering the above geological and geophysical features, the Yap Trench is controversial regarding the activity of plate subduction at present. Hawkins and Batiza (1977) and McCabe and Uyeda (1983) suggested that subduction at the Yap Trench may have suspended by collision of the Caroline Ridge. McCabe and Uyeda (1983) suggested that the Caroline Ridge collided with the Yap Trench in early Miocene, and that this collision made the volcanic activity in the Yap Arc stop, and narrowing the distance between arc and trench. In contrast, some petrological and geophysical studies suggested that subduction at the trench may still be active. Fresh volcanic rock fragments and hydrothermally affected rocks, dredged in the back-arc region, may suggest in-situ or nearby hydrothermal activity in relation to

Quaternary volcanic activity (Fujioka et al., 1986). High heat flow values were observed in the back-arc region and appreciably large values of negative free-air gravity anomalies were observed along the trench axis (Nagihara et al., 1989). Large negative gravity anomaly is indicative of dynamic force exerted on crust under the trench associated with ongoing subduction of the oceanic lithosphere. Observation of micro-seismic activity in the trench area suggested that tectonic force, found in active subduction zones, acted on the crust of the trench (Sato et al., 1997).

Prior to our study, there were insufficient data for understanding the tectonics and geodynamics of the Yap Trench. We conducted swath bathymetry and gravity surveys of the Yap Trench aboard the R/V Yokosuka in 1993, 1994 and 1996, in combination with dive surveys of the research submersible Shinkai

6500 (Fujioka et al., 1994, 1996). We hope that our study stimulates further geological and geophysical studies in this region, focused on morphotectonic characteristics, by providing a high quality base map, and that it will provide insight into the tectonics of the Yap Trench, the Philippine Sea Plate and the circum-plates.

Data acquisition

The majority of swath bathymetric data was collected on the Y93-03, Y95-06 and Y96-12 cruises of the R/V Yokosuka using a Furuno HS-10 multibeam echosounder (Nishizawa et al., 1994; Fujiwara et al., 1996b, 1997a, b). The HS-10 has 45 beams and a swath width of 90°, which covers double the water depth. The ship was navigated using a Global Positioning System (GPS), and the geographic coordinate WGS-84 was used throughout the surveys. Sound velocity profiles for the calculation of water depth were based on an expendable bathothermograph (XBT); salinity, temperature, and depth (STD) observations measured by the Shinkai 6500 during these surveys. Underway surveys were conducted in transit and on submersible maintenance days. Survey ship tracks were aligned unsystematically because they were restricted by dive sites (Figure 3). 95 track crossings used in estimating cross-over errors were obtained during the cruises. Cross-over errors have standard deviation of 21.4 m. A full coverage swath of the multibeam was achieved over the area deeper than 5000 m in water depth. Other multibeam data was previously collected aboard the S/V Takuyo in 1989 and 1990 in the northernmost part of the trench at the junction with the Mariana Trench (Iwabuchi et al., 1990). Two tracks of multibeam data across the trench were obtained during the KH92-1 cruise of the R/V Hakuho-maru in 1992 (Fujiwara et al., 1996a). Inclusion of these data provides bathymetry coverage of the whole Yap Trench length, from the northern terminal to the southern end at the junction with the Palau Trench from 12° N to 7° N. A total of 52,000 km² areal coverage was obtained, the tracks reaching 20–40 km from the off-axis on both sides.

Shipboard gravity data were collected using a LaCoste & Romberg shipboard gravimeter S-63 during the Y95-06 cruise (Fujiwara and Tamura, 1996). Shipboard gravity data were tied to absolute gravity values at reference points in the port of Palau, measured using a LaCoste & Romberg gravimeter G-1093. Free-air gravity anomaly was calculated after subtracting the

standard gravity formula IAG 1967 (IAG, 1967) from observed data. A total of 44 track crossings used in estimating cross-over errors were obtained during this cruise. Cross-over errors have a standard deviation of 3.24 mgal after a drift correction.

Bathymetry

Along-axis variations in morphology

Bathymetry of the whole-length Yap Trench is shown in Figure 4. Several isolated deeps are found at 11°07' N, 10°30' N, 9°38' N, and 8°26' N. The strike direction of the trench axis bends at these deeps. The strike directions are N25° E (11°07' N–10°30' N), N10° E (10°30' N–9°38' N), and N30° E (9°38' N–8°26' N), respectively. Morphological characteristics divide this trench into two parts, with 8°26' N as the boundary between these parts. South of 8°26' N there is no prominent deep, and the strike direction of the axis changes continuously from N30° E to N110° E at 7°20' N, 136°00' E.

The water depth along the trench axis varies from 6000 to 9000 m (Figure 5). The deepest point, 8946 m, was determined at 10°29.957' N, 138°40.987' E. This makes the Yap Trench one of the deepest trenches in the world (Fujiwara et al., 1997a). Local shallow depths on the sea-ward trench slope, at 10°50' N, 10°10' N, and 9°00' N, are regarded as seamounts encountering the trench. Shallow depths on the arc-ward trench slope are correlative with the shallow depths on the opposite sea-ward trench slope, suggesting that they are influenced by the seamounts on the sea-ward trench slope. The axial depths and depths of the arc-ward trench slope decrease monotonically from 8°26' N toward the south. The depths of the sea-ward trench slope south of 8°26' N are relatively constant and have no correlation with those of the axis and the arc-ward trench slope. The trench deep, which is deeper than 6000 m, is interrupted by the topographic high at 136°00' E elongating to about N30° E (Figures 4 and 5). There is no trench type morphology between 136°00' E and the northern end of the Palau Trench situated at 7°55' N, 135°00' E (Kato et al., 1986).

Across-axis variations in morphology

The Yap and Mariana trenches intersect at a near perpendicular at 11°07' N, 139°00' E (Figure 6). A topographic high is located at 11°18' N, 138°55' E north of

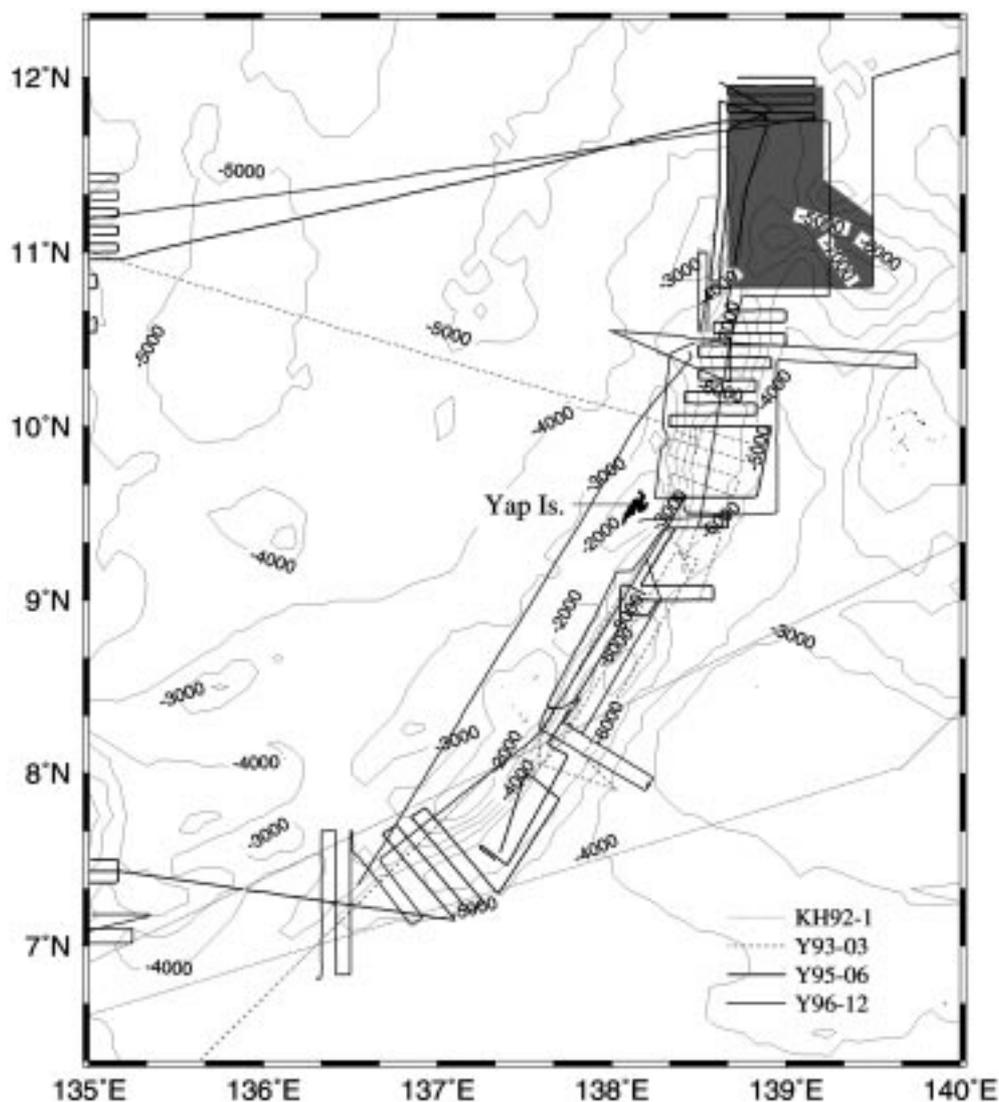


Figure 3. Survey ship tracks in the region of the Yap Trench. The solid, gray and dashed lines show the tracks from the Y95-06, Y96-12, and Y93-03 cruises of the R/V Yokosuka, respectively. The dotted lines show the tracks of the KH92-1 cruise of the R/V Hakuho-maru. The area surveyed by Iwabuchi et al. (1990) aboard the S/V Takuyo is stippled.

the junction. A deep valley with a steep escarpment is elongated toward the north from $11^{\circ}30'N$, $138^{\circ}50'E$ to $12^{\circ}00'N$, $139^{\circ}00'E$. The escarpment steeply dips west; the relative height is about 1500 m. The escarpment has a strike direction of $N20^{\circ}E$ in almost the same direction as that of the northern portion of the Yap Trench.

Horst and graben structures, roughly 5 km in width and 500 m in relative height, are apparent on the sea-ward trench slope (Figure 6). This structure indicates a normal fault due to bending of the subducting oceanic plate. Strikes of the horst and graben structures have

bimodal strike orientations, parallel to the trench axis and oblique to the trench axis, of about $N30^{\circ}E$. Hill-sides of bathymetric highs on the sea-ward trench slope, which face the trench and are considered to be seamounts encountering the trench, have step-like escarpments with strikes parallel to the trench axis. This suggests that the mountains are dissected by normal faults before subduction (e.g., Mogi and Nishizawa, 1980). Lineated structures parallel to the trench axis are also apparent on the sea-ward seafloor.

South of $8^{\circ}26'N$ the trench axis is curved toward the south. The morphology is monotonous in

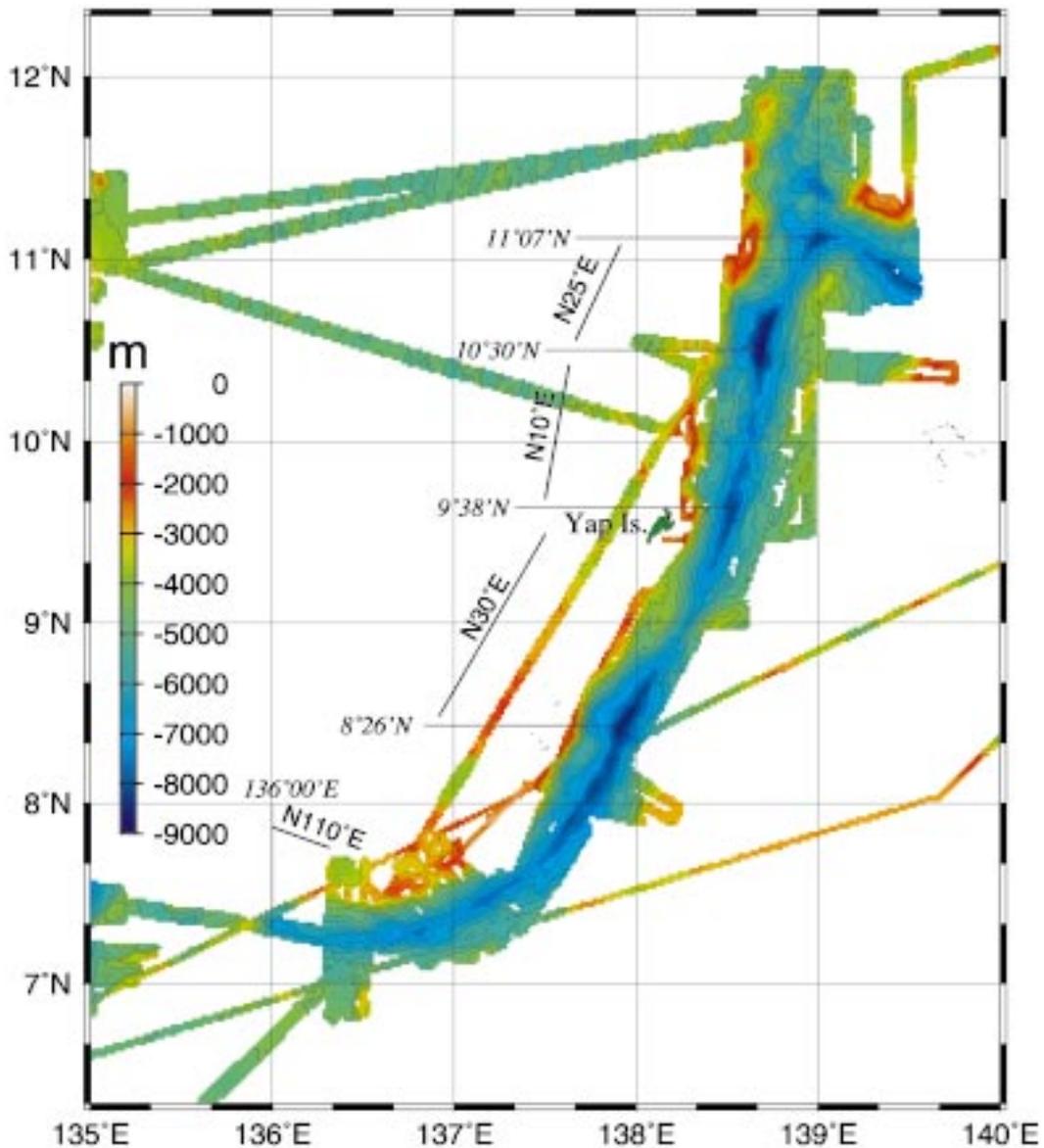


Figure 4. Bathymetric map of the whole-length of the Yap Trench. The dark color indicates deeper water depth. The contour interval is 500 m.

contrast to that of the northern part of the trench (Figure 7). Identical morphological structures with strikes of about N30° E are apparent in the southern part of the trench, in addition to the predominant trench parallel structure.

There is no indication of thick of flat lying layered sediment accumulations in the trench axis (See cross sections of a fold-out chart). The slope angles of the sea-ward trench slopes indicate 4–6°, except for the places of seamounts encountering. These slope angles are much higher than those of typical

trench 1–3° slopes. Major two slope breaks are common over the entire arc-ward trench slope at around 4000–5000 m and 6000–7000 m depths. There are three types of slope break morphology: Two slope breaks look like fault notches in shape (Profile 19 in Figure 8). A mid-slope basement high is formed at 4000–5000 m (Profile 26 in Figure 8). The other type, a mid-slope basement high, is formed at 6000–7000 m (Profile 11 in Figure 8). It is not acceptable to consider that the origin of this basement high is sedimentary accretion since sedimentation is not

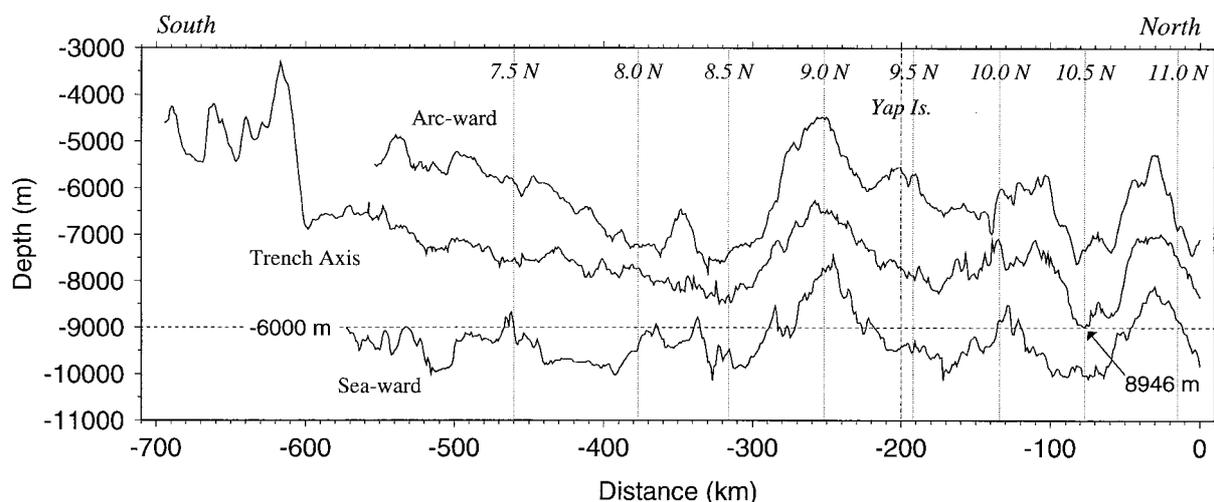


Figure 5. Bathymetric cross sections along the trench axis. Zero km corresponds to $11^{\circ}07' N$, $139^{\circ}00' E$, and -694 km corresponds to $7^{\circ}28' N$, $135^{\circ}10' E$ in the axial profile. The tick marks on the vertical axes are 500 m apart. The dashed line corresponds to 6000 m depth for the profile of the sea-ward trench slope. Profiles on the arc-ward and sea-ward trench slopes extend parallel to, and are 10 km apart from the axial profile, respectively.

found in this trench axis. The origin of the arc-ward trench slope break is thought to be a fault. The mid-slope basement high tends to be associated with the seamounts, sitting on the sea-ward trench slope. The basement high is thought to be formed by crustal deformation caused by collisional stress of the presumed subducting seamounts. Subducted seamounts successively cause force which uplifts the overlying crustal layer at the fault.

Gravity anomaly

Figure 9 shows a free-air gravity anomaly field in the circumambient regions of the Yap Trench. The free-air gravity data are merged with gravity anomaly data derived from satellite altimetry (Sandwell and Smith, 1997) in order to cover the unsurveyed area. The Caroline Ridge has positive anomalies associated with the distribution of seamounts. The Parece Vela Basin and the West Caroline Basin show near-zero free-air anomaly for the whole of the basin, except for small scale bathymetric reliefs; therefore, the basin is considered to be under isostatic condition. Free-air gravity anomaly of the Parece Vela Basin gradually increases, up to $+100$ mgal toward the trench. Such long-wavelength variation of free-air anomaly can be maintained due to the basin being uplifted by a tectonic force. Negative free-air gravity anomalies reach below -200 mgal along the trench axis (Nagihara et al., 1989; Fujiwara

and Tamura, 1996). Large negative anomaly is commonly found along subduction zones; the observed gravity anomaly therefore indicates that the crustal layers at the trench are dragged downward and are not in isostatic equilibrium (e.g., Morgan, 1965a, b). The negative anomaly belt disappears at $136^{\circ}00' E$ to the west, harmonized with the trench bathymetry. Prominent positive anomalies of about $+200$ mgal are found along the Yap Arc. There is a zone of near-zero free-air gravity anomaly, with a width of 50 km, in the intersection of the Yap Trench and the Caroline Ridge between $8^{\circ}40' N$ and $10^{\circ}40' N$. In this zone, no conspicuous bathymetric high is observed, in contrast to the edifice to the east (Figure 2).

Bouguer gravity anomaly was calculated by subtracting Bouguer gravity correction from the free-air anomaly. The Bouguer gravity correction was based on a three-dimensional terrain correction with an assumed crustal density of 2670 kg/m^3 and a seawater density of 1030 kg/m^3 . The calculation was conducted using the method of Parker (1972). The global bathymetric data of ETOPO5 (NGDC, 1988) were employed to fill the unsurveyed area. Large negative anomalies are observed over the Caroline Ridge (Figure 10). Bouguer gravity anomaly is primarily attributed to a depth variation of Moho discontinuity showing crustal thickness. Negative anomaly indicates that a thicker crust overlies a high density upper mantle. Our results indicate that the ridge has the roots of a low density crust which is thus uplifted by

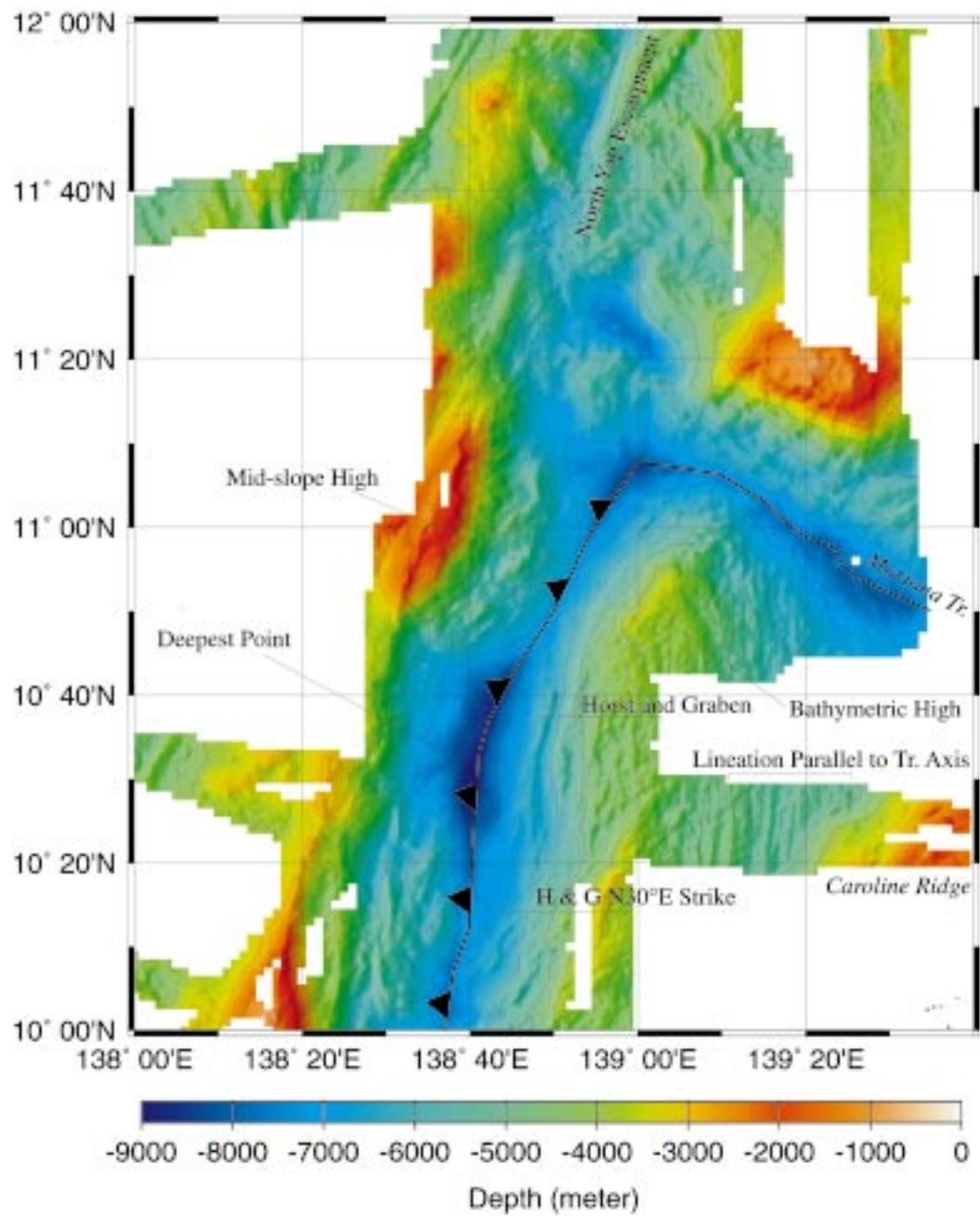


Figure 6. Bathymetric map with interpreted structural morphology of the northern Yap Trench, illuminated from the northwest. The contour interval is 1000 m.

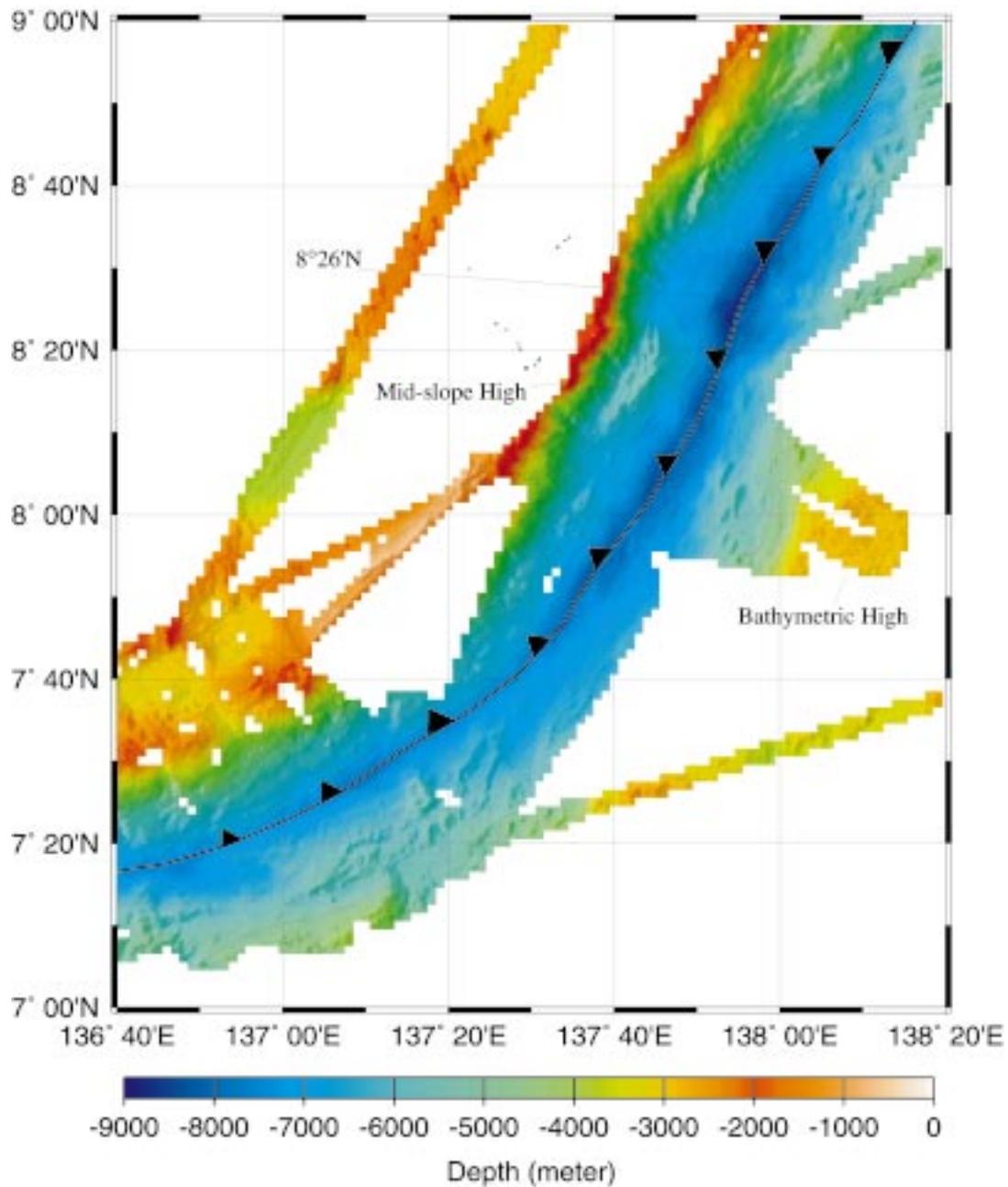


Figure 7. Bathymetric map with interpreted structural morphology of the southern Yap Trench, illuminated from the northwest. The contour interval is 1000 m.

buoyancy. The northern Yap escarpment, as shown in Figure 6, is no longer a remarkable feature in Bouguer gravity anomaly, although the free-air anomaly shows negative values at the escarpment and the structure is not isostatically compensated. Our results indicate that this escarpment is a relic of past tectonism, that this es-

carpment originates from a normal fault, as argued by Iwabuchi et al. (1990). The negative peaks of Bouguer anomalies along the Yap Trench are apparent over the arc-ward trench slope. Our results show that the thickest crust is probably beneath the arc-ward trench slope because of overlap of the crustal layers of the conver-

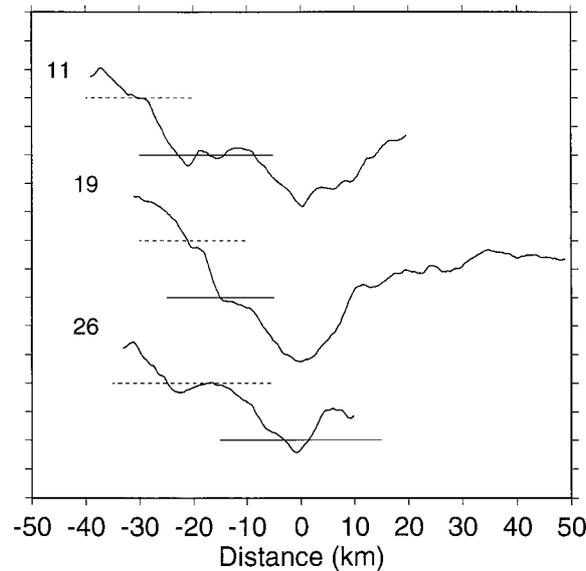


Figure 8. Bathymetric cross sections. See fold-out chart for location of profiles. Zero km corresponds to the trench axis. The left side shows arc-ward trench slopes, and the right side shows sea-ward trench slopes. The solid and dashed horizontal lines indicate 6000 m and 4000 m in depth, respectively. The tick marks on the vertical axes are 1000 m apart.

gent two plates. In most trenches, a negative peak of Bouguer anomaly appears over the arc (e.g., Fujimoto and Tomoda, 1985; Yang et al., 1992), reflecting thick growth of the crust beneath the arc. However, positive anomalies are apparent over the Yap Arc between $9^{\circ}20'N$ and the northern end of the trench. These positive anomalies suggest that high density material underlies the arc and that low density volcanic arc crust does not grow beneath the arc. Dynamic force is therefore perhaps exerted on the arc in order to maintain the uplifted arc, although the arc does not exhibit buoyancy. Negative anomalies are apparent over the island arc, indicating the existence of a thick arc crust to the south of $8^{\circ}20'N$, although negative peaks are still situated over the arc-ward trench slope. The Bouguer gravity anomalies show near zero or slightly lower in the trench and Caroline Ridge intersection, between $8^{\circ}40'N$ and $10^{\circ}40'N$. This indicates that an abnormally thick crust is absent, in contrast to the crust beneath the Caroline Ridge to the east.

Discussion

Structural model of the Yap Trench

Our swath bathymetric data show that there appears to be little or no sediment cover along the axis of the Yap Trench (Figure 8). A sedimentation rate of 4–37

m/m.y. since Oligocene has been determined at the nearest Deep Sea Drilling Project (DSDP) Site 55–58 on the Caroline Ridge, at around $10^{\circ}N$, $145^{\circ}E$ (Bukry et al., 1969). The seismic reflection survey, conducted in the KH84-1 cruise aboard the R/V Hakuho-maru, revealed a sedimentary layer about 400 m in thickness on the West Caroline Basin (Tokuyama et al., 1985). Therefore, if subduction has ceased in the past, the trench deep must have been covered with thick sediment from the Caroline Ridge or the West Caroline Basin. Sedimentary basins are actually found at the junction areas with the Palau Trench (Kato et al., 1986), areas regarded as tectonically inactive. Sediments in the trench axis are thought to be subducted.

The observed morphological characteristics suggest that the Yap Trench is still tectonically active and that subduction of the oceanic plate ensues at this trench. The geomorphological trend of about $N30^{\circ}E$ in the sea-ward trench slope, oblique to the trench axis, corresponds to the normal direction of the Caroline Ridge elongation. This suggests that the seafloor structure is deformed by compressional stress due to the collision of the seamounts of the Caroline Ridge. The lineated structure, observed on the seafloor in the intersection of the trench and ridge, suggests fractures, presumably caused by bending of the oceanic plate prior to subduction beneath the arc. The seamount

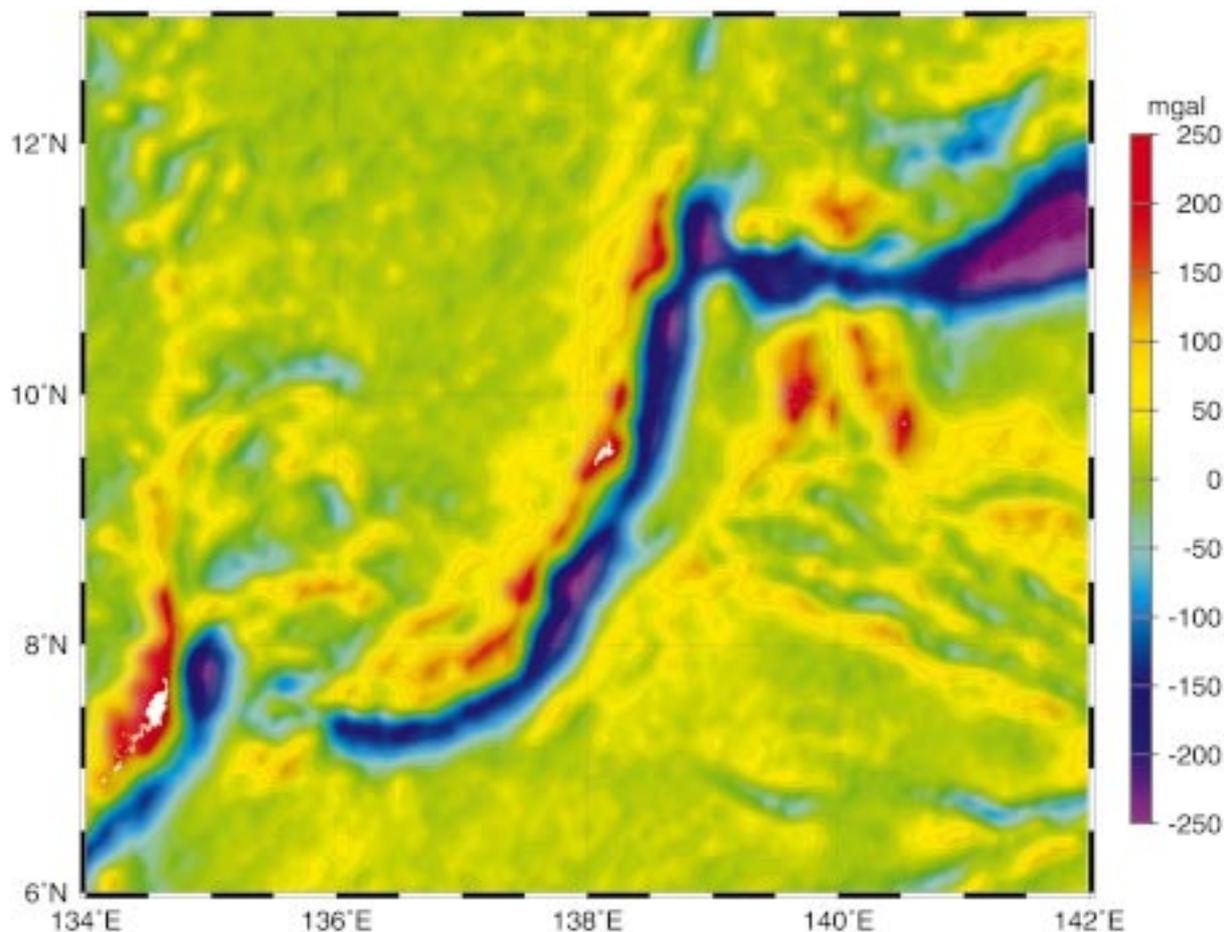


Figure 9. Free-air gravity anomaly field of the circumambient region of the Yap Trench, illuminated from the northwest. The contour interval is 20 mgal.

chains abutting the trench are influenced by fracture prior to subduction. Seamounts are dissected by normal faulting due to oceanic plate bending (Figure 11). Crustal thinning occurs because crustal blocks, which are dissected by the faulting, slide, and tilt of the trench slope. The relatively flat seafloor and near-zero gravity anomalies were formed in consequence. The still less dense subducting crust increases the compressional force, making the abnormally high $4\text{--}6^\circ$ angle of the sea-ward trench slope. This also causes vertical tectonic movement on the Yap Trench. Subducted seamounts elevate the trench axis by nearly 3 km, as compared to the maximum depth of the axis.

The trench slope breaks of the arc-ward trench slope were already noted by Fujioka et al. (1989) from the seismic reflection surveys of the KH84-1 and KH86-1 cruises. They argued that these slope breaks indicate lithological boundaries. Gabbroic rocks were

exposed on the trench slope shallower than the 6000 m slope break, whereas ultramafic rocks were found on the trench slope deeper than this break (Fujioka et al., 1996). Therefore the boundary suggested is the Moho discontinuity, the arc-ward trench slope consisting of the exhumed oceanic lower crust and the upper mantle of the overriding plate (Figure 11). The results of these geological investigations are consistent with gravity analysis. Bouguer gravity analysis shows that dense crustal layers underlie beneath the northern part of the Yap Arc instead of of less dense volcanic arc crust accumulation.

Even though the Yap Trench is an active trench, a question has arisen regarding the mechanism determining the water depths of the trench. The Yap Trench is of great depth even though the young and relatively less dense Caroline Plate is subducting at a very slow rate. Deep trenches can not be maintained

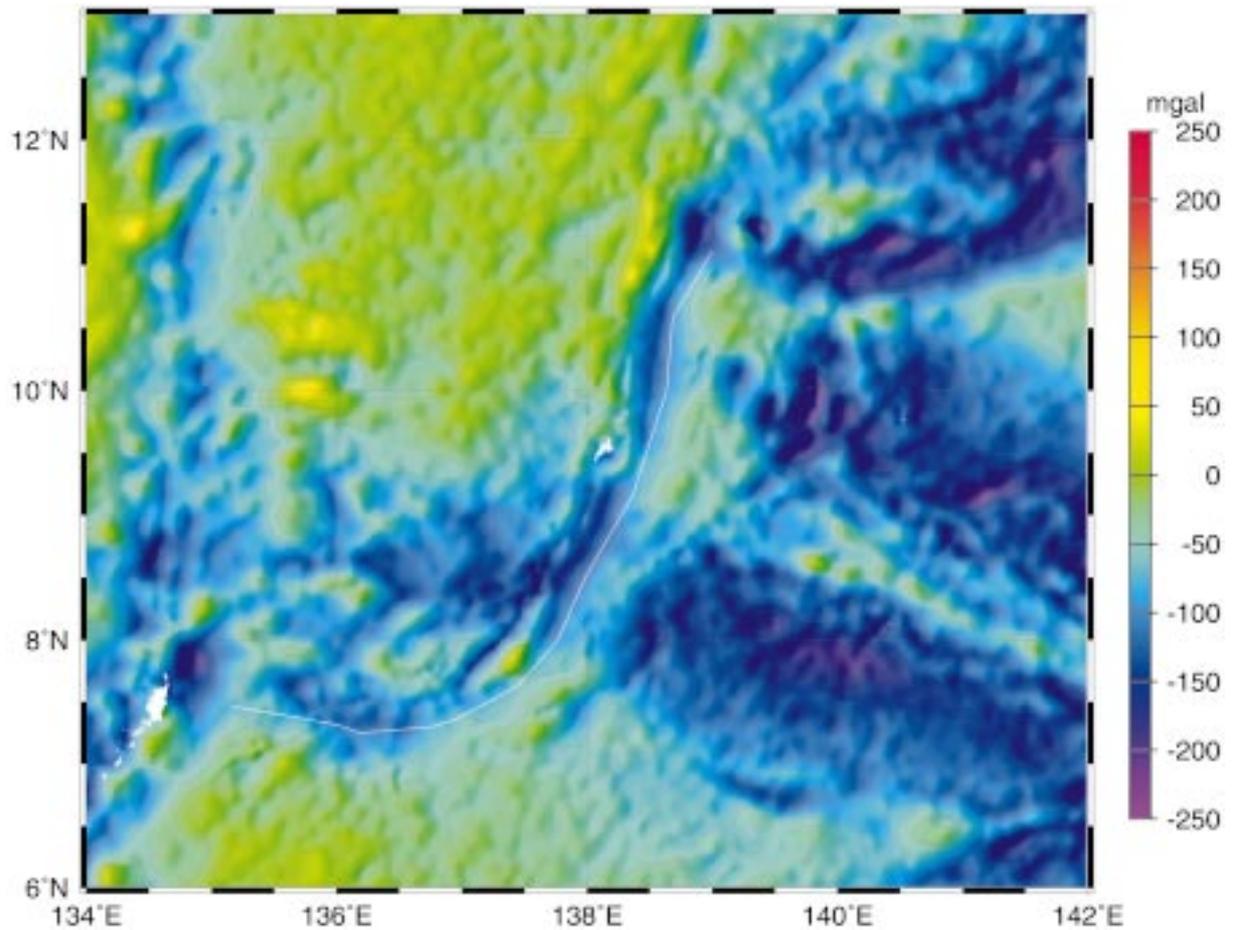


Figure 10. Bouguer gravity anomaly field of the circumambient region of the Yap Trench, illuminated from the northwest. The contour interval is 20 mgal.

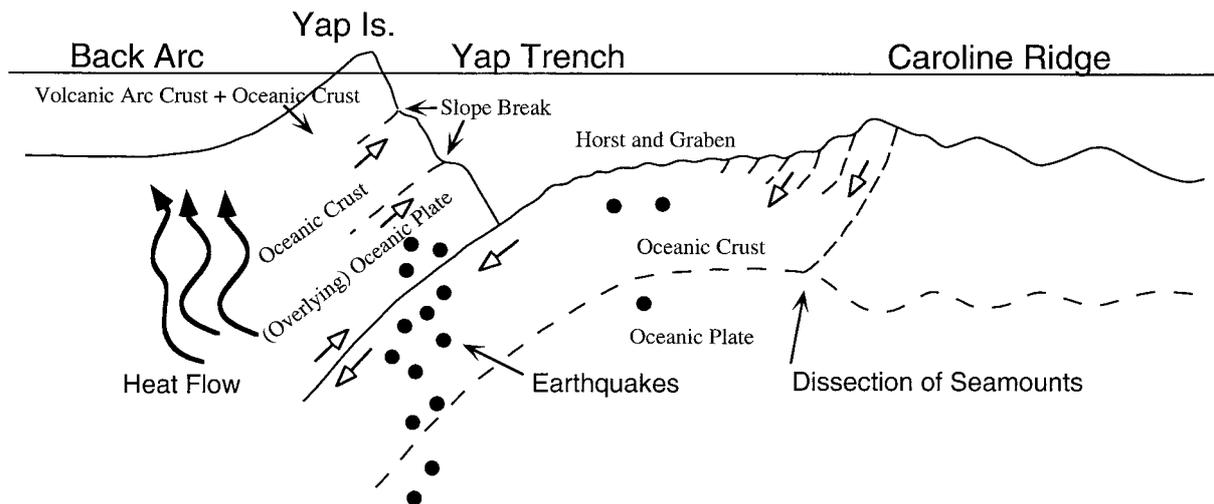


Figure 11. Schematic across the axis cross section of the northern part of the Yap Trench and its tectonic interpretation.

without any driving mechanisms. Subducting force exerted on the oceanic crust likely depends on the subduction rate and the age of the oceanic plate, that is, on the thickness of dense lithosphere, reflecting negative buoyancy, although deep trenches found elsewhere in the world are not really accompanied by these parameters. One possible explanation is that the overlying high density arc forces the crust downward to the great trench depths of nearly 9000 m.

Earthquakes indicate current tectonic activity. Seismicity in the northern part of the Yap Trench was observed by four ocean bottom seismometers with hydrophones (OBSHs) during the KH86-1 cruise and by a small array of seismometers on the Yap Island (Sato et al., 1997). More than 100 events were detected for the approximately 10 days of OBSHs deployment (Figure 12). The pattern of hypocentral distribution is similar to a typical pattern found in other active subduction zones (e.g., Hirata et al., 1983, 1989). Many earthquakes occurred in the arc-ward side. This seismicity is probably caused mainly by thrusting between the overriding and the subducting plates. No seismicity was observed in the region along the trench axis because the coupling between two plates seems to be weak. A few earthquakes, occurring on the sea-ward side, appear to be due to normal faulting caused by bending of the subducting plate. The earthquakes were particularly concentrated along a line of 20 km apart from the trench axis. (Figure 12 and 13c). It is interesting that this location nearly corresponds to the position of the negative peak of the Bouguer gravity anomaly (Figure 13d). This suggests that stress concentrates in the accumulated crust beneath the arc-ward trench slope. It should be noted that no earthquakes occurred further than 60 km from the trench axis in the back-arc regions or deeper than 40 km in depth, even in the event-detectable area with a radius of 100 km (Figures 12 and 13c). Although the distance from the axis is much shorter and the depth is much shallower than those in other active trenches, a brittle-ductile transition probably occurs at these places.

Heat flow observation suggests a pattern similar to that of other trench-arc systems (Figure 13a). Low heat flow in the sea-ward ocean basin and high heat flow in the arc and the back-arc region were observed (Nagihara et al., 1989; Kinoshita and Kasumi, 1989). The peak values are 20–80 mW/m² higher than a mean value of 88±21 mW/m² in the Parece Vela Basin (Mrozowski and Hayes, 1979). A plausible explanation for this high heat flow in the back-arc is the reflection of recent thermal activity induced by

subduction. This high heat flow occurs within a distance of 70 km from the trench axis. This distance is much shorter than that found in other active trench-arc systems. The appearance of high heat flow near the trench is possibly correlative with the subduction of the young aged Caroline Plate, consisting of the West Caroline Basin and the Caroline Ridge. The existence of this hot region is consistent with the results of the limit of seismicity within 60 km from the trench axis and the hydrothermally altered rocks dredged from the back-arc (Fujioka et al., 1986). Subduction at the trench still has continued, however, active arc volcanism is not found in this trench-arc system and no indication of a newly grown thick crustal layer is identified in the gravity signal. The active arc volcanism may not occur in bulk at present because the plate convergent rate is very slow (e.g., Iwamori, 1996).

The Yap Trench is now located in the southern extension of the Parece Vela Rift, which is an extinct spreading center of the Parece Vela Basin (Figure 2). Okino et al. (1998) showed large sinuous fracture zones starting from the Parece Vela Rift in the central part of the Parece Vela Basin. They argued that these fracture zones were created during 19–15 Ma by seafloor spreading. These fracture zones have a trend similar to the Yap Trench; it thus seems probable that the Yap Trench originated from one of these fracture zones. This idea is, however, inconsistent with the geology of the Yap Island. Hawkins and Batiza (1977) proposed that the Yap Arc originally formed as a volcanic arc in Eocene or Oligocene, which is older than 19–15 Ma. The lithology is different from the island-arc because the fracture zone probably consists of only oceanic crust. Therefore, we postulate that the trench evolved from the proto-Mariana-Yap Trench. A study of the evolution of the southernmost part of the Parece Vela Basin, not yet clearly understood, will make constructing a more precise evolutionary model of the Yap Trench possible.

Implications for the tectonic evolution of the Yap Trench

We propose a model for the evolution of the Yap Trench after the collision of the Caroline Ridge, a model attempting to explain several facts concerning the geology and the geophysical data of the area. The Yap Arc was formed as a volcanic arc (Figure 14a). The Caroline Ridge came in contact with the Yap Trench (Figure 14b). McCabe and Uyeda (1983) proposed that this ridge collided in Eocene-Oligocene.

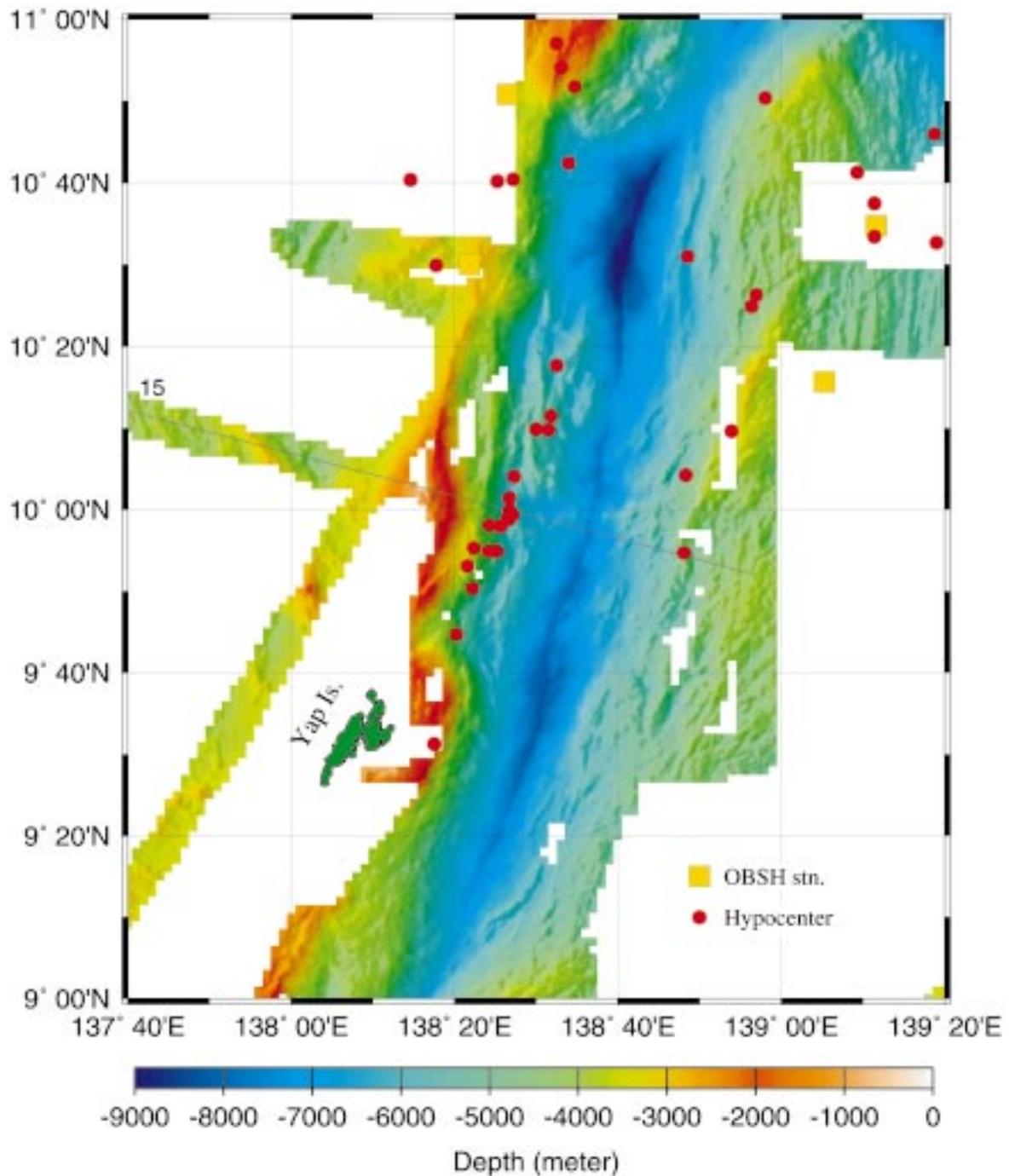


Figure 12. Hypocentral distribution of earthquakes superposed on swath bathymetry. The hypocentral data are from Sato et al. (1997). The red circles show hypocentral distribution. The yellow squares show locations of the deployed OBSHs. The solid lines show locations of the profile of geophysical cross section across the trench axis as shown in Figure 13.

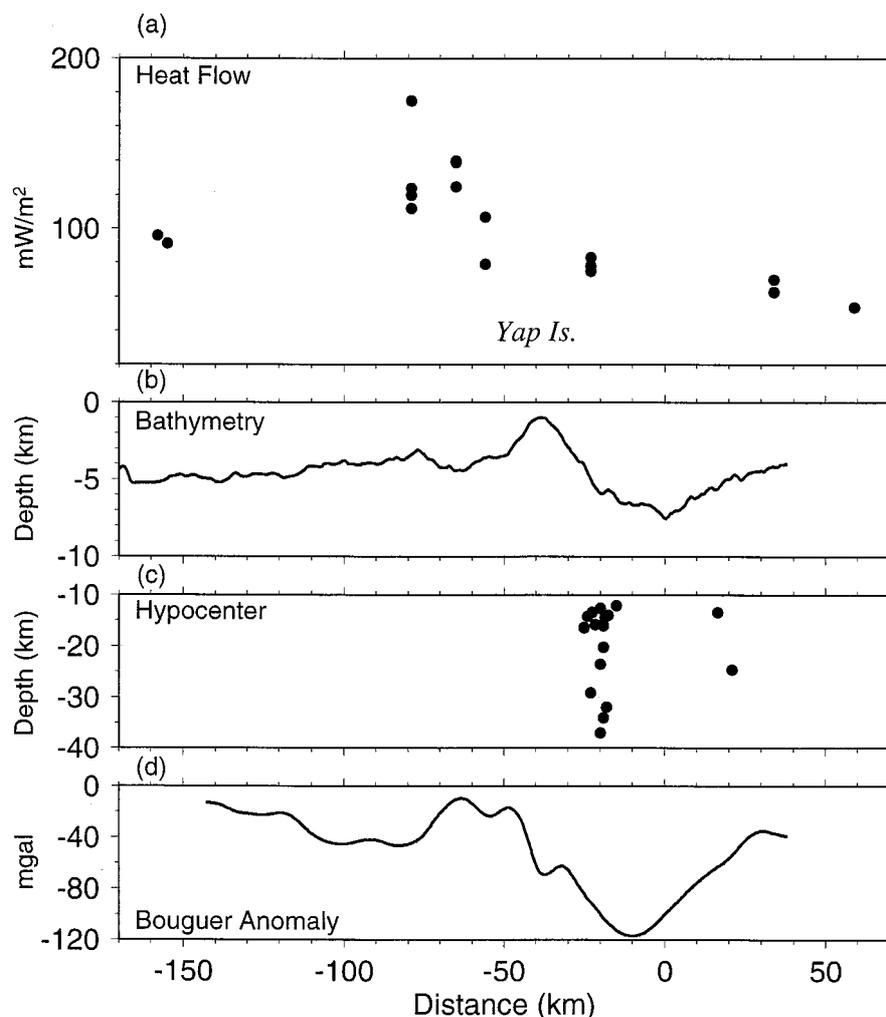


Figure 13. Geophysical cross sections across the northern Yap trench-arc system. See Figure 12 for location of the profile. Zero km corresponds to the trench axis. (a) Heat flow profile. The solid circles show heat flow observation. Heat flow data are from Nagihara et al. (1989) and Kinoshita and Kasumi (1989). (b) Bathymetry (c) Hypocentral distribution of earthquakes. The solid circles show hypocenters within a bin of 10 km in width. (d) Bouguer gravity anomaly.

This collision caused change in the mode of back-arc spreading found in the Parece Vela Basin. Mrozowski and Hayes (1979) assumed a much slower spreading rate at about 25 Ma. Okino et al. (1998) suggested that another spreading stage occurred from about this time. A new configuration of the plate boundary between the Caroline and the Philippine Sea plates was established (Figure 14b). The pole of plate rotation has subsequently been situated at the junction between the Palau Trench and the Ayu Trough. Seafloor spreading along the Ayu Trough started (Weissel and Anderson, 1978; Fujiwara et al., 1995), while subduction along the Yap and Palau trenches continued at very slow rates of convergence, 0–6 mm/yr (Seno et al., 1993).

Back-arc spreading in the southernmost of the Parece Vela Basin would have ceased. The cessation of volcanism at the Yap Arc was contemporaneous with the collision of the Caroline Ridge (Hawkins and Batiza, 1977). This collision resulted in westward drift of the Yap Trench with respect to the Philippine Sea Plate. On the other hand, the Mariana Trench moved eastward with respect to the Philippine Sea Plate, caused by seafloor spreading of the Parece Vela Basin accompanied with eastward migration of the spreading center (Okino et al., 1998) and by opening of the Mariana Trough since 5 Ma (Hussong and Uyeda, 1982) in the back-arc of the Mariana Trench.

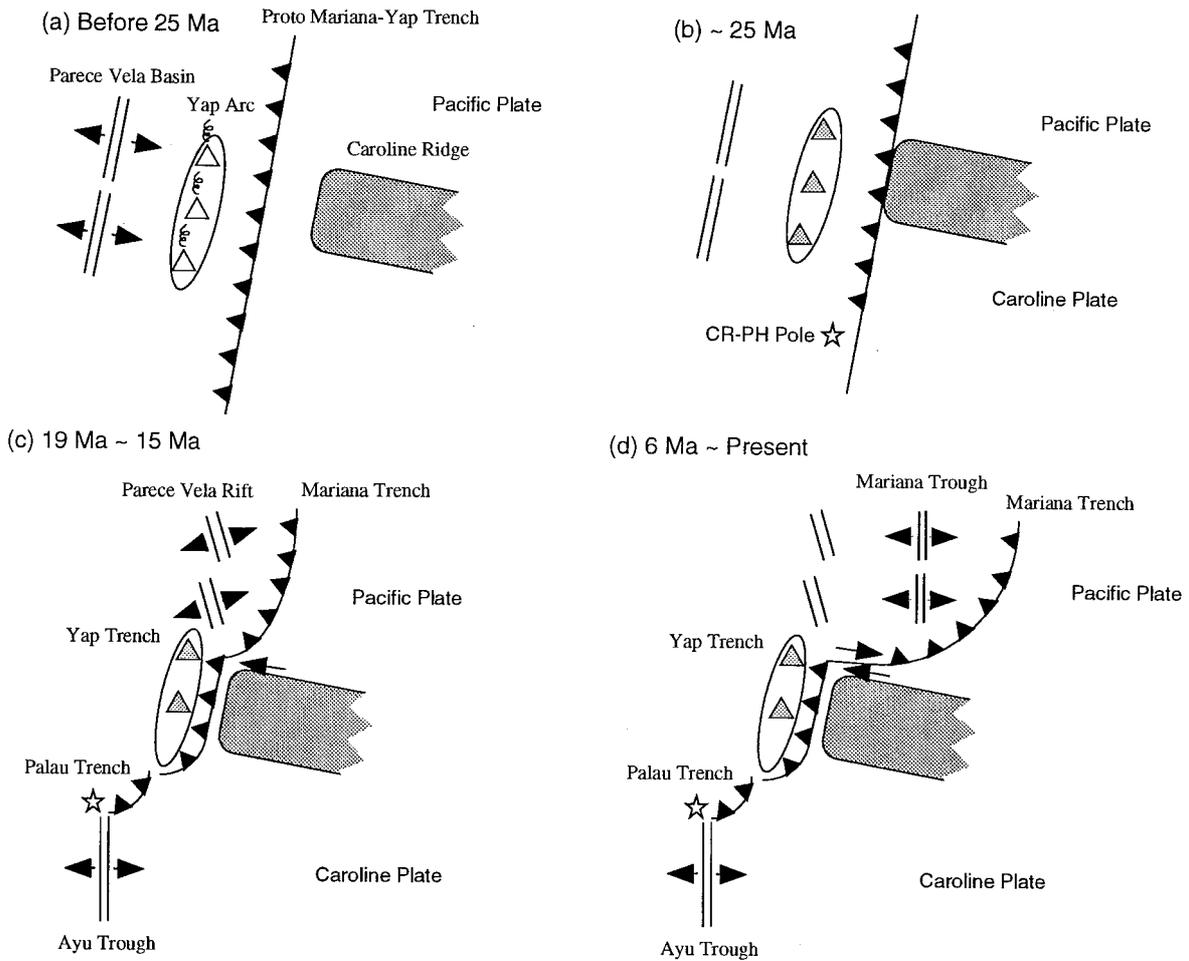


Figure 14. Proposed scenario of the evolution of the Yap Trench.

The former island arc crust of the Yap Arc eroded. Lower crustal sections of the overriding Yap Arc were exposed on the arc-ward trench slope by thrusting. Intense shearing caused deformation of the accumulated rocks, resulting in their metamorphism in the Yap Arc (Hawkins and Batiza, 1977). The distance of trench migration in the northern part of the trench is supposed to be about 100 km, considering the convergence rate and duration. This estimate is consistent with the distance remaining between the trench and the arc, which is about 100 km narrower than that of a typical trench-arc system (Figures 14c and 14d). A smaller volume of crustal erosion in the southern part of the trench compared to the northern part is suggested by the negative Bouguer gravity anomaly beneath the arc. This is probably due to the migration distance of the southern part of the trench, a distance shorter than that of the northern part.

Conclusions

Swath bathymetry and gravity surveys of the whole Yap Trench length (7°00'–12°00' N, 136°30'–139°00' E) were conducted aboard the R/V Yokosuka and the supplementary R/V Hakuho-maru and the S/V Takuyo cruises. Full multinarrow beam areal coverage was obtained where the water depth was deeper than 5000 m. These surveys provided a detailed description of trench morphology to clarify the tectonics of the Yap Trench.

(1) The morphology along trench axis shows a great difference between the northern and the southern part of the Yap Trench. There is large variation in the axial depth in the north of 8°26' N. In contrast, the axial depths monotonically decrease from 8°26' N toward the south.

(2) Horst and graben structures in the sea-ward trench slope and lineated structures parallel to the trench axis in the sea-ward seafloor were observed. These structures indicate normal faulting caused by bending of the subducting oceanic plate. Geomorphological trending of about N30° E oblique to the trench axis possibly reflects toward the normal direction of the Caroline Ridge elongation, suggesting that the collision of the ridge significantly effects the tectonics of the trench. The dip angles of the sea-ward trench slope indicate 4–6°, which are much higher than those of a typical 1–3° trench slope. There is no indication of thick flat lying layered sediment accumulations in the trench axis.

(3) Major two slope breaks were commonly observed all over the arc-ward trench slope at depths of around 4000–5000 m and 6000–7000 m. The origin of the slope breaks is thought to be thrust faults and to indicate lithological boundaries. The arc-ward trench slope consists of the oceanic lower crust and the upper mantle of the Philippine Sea Plate overriding the Caroline Plate. Bouguer gravity analysis shows that high density crustal layers underlie the northern part of the Yap Arc.

(4) Negative peaks of Bouguer anomalies were observed over the arc-ward trench slope. This suggests that the thickest crust is beneath the arc-ward trench slope because of the overlap of the oceanic crustal layers of the convergent two plates. Bouguer anomalies are positive over the Yap Arc between the northern end and 9°20' N. These positive anomalies suggest that the arc has no buoyant crust. Nevertheless, dynamic force exerts on the crust to maintain the arc uplifted.

(5) A scenario of tectonic evolution is proposed. The Caroline Ridge collided with the Yap Trench at about 25 Ma. However, subduction along the Yap Trench still continued, but with very slow rates of convergence, 0–6 mm/yr. The cessation of volcanism at the Yap Arc was contemporaneous with collision of the ridge. The frontal part of the Yap Trench was removed by subduction erosion after the collision, and the distance between arc and trench then narrowed due to the westward migration of the trench with respect to the Philippine Sea Plate. Lower crustal sections became exposed on the arc-ward trench slope by overthrusting. Intense shearing caused deformation of the accumulated rocks, resulting in their metamorphism in the Yap Arc.

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