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Genetic relations between the central and southern Philippine Trench and the Sangihe Trench

Serge E. Lallemand,¹ Michel Popoff,² Jean-Paul Cadet,³ Anne-Gaelle Bader,⁴
Manuel Pubellier,⁴ Claude Rangin,⁴ and Benoît Deffontaines³

Abstract. We surveyed the junction between the central and southern Philippine Trench and the Sangihe Trench near 6°N using swath bathymetry, gravity, and magnetics. These data, along with seismicity, allow us to discuss the genetic relations between these trenches and the forces acting on converging plates. Our final model favors the northern extension of the Halmahera Arc up to 8°N, with three segments offset left-laterally along NW-SE transform faults. Accretion of the northern segment to Mindanao Island 4 to 5 m.y. ago resulted in the failure within the Philippine Sea Plate east of the arc. Initiation of the Philippine Trench between 7°N and 10°N agrees with the maximum recorded depth of the Philippine Trench floor (10,000 m below sea-level) and Philippine Sea slab (200 km). South of 6°N (trench junction), another segment of the arc is being subducted beneath the Sangihe margin, while south of 3°N, the southern segment of the Halmahera Arc is still active. The rapid southward shallowing of the trench floor along the southern Philippine Trench, the type of faulting affecting both sides of the trench, the lack of significant interplate seismicity, and the concentration of the seismicity beneath the Miangas-Talud Ridge are interpreted as a slowing down of the subduction along this branch of the Philippine Trench compared with the rest of the subduction zone. The Sangihe deformation front has been recognized up to 7°N but seems active only south of 6°N.

1. Introduction

In May 1994, the R/V *L'Atalante* surveyed the area south of 7°N during the MODEC cruise (see location on Figures 1 and 2). Swath bathymetry, sonar imagery, six-channel reflection seismics, gravity, and magnetic anomalies were recorded in the northern part of the Molucca Sea and along the Philippine Trench up to 11°N off Leyte (Figure 2).

The Philippine Sea Plate (PSP) is mostly surrounded by trenches (Figure 1), except along a short segment in the south where the Ayu spreading center forms the boundary between the PSP and the Caroline Plate [Fujiwara *et al.*, 1995]. Furthermore, the convergence is partitioned along its western boundary, so that slip vectors cannot be simply used for constraining its motion [McCaffrey, 1996]. Consequently, the exact azimuth and magnitude of plate motion along its rim remain controversial [Seno, 1977; Karig and Cardwell, 1986; Huchon, 1986; Ranken *et al.*, 1984; Seno *et al.*, 1993; McCaffrey, 1996]. The numerous subduction zones fringing the western boundary of the PSP on each side of the Philippine Islands render the southwestern plate boundary particularly complex. This problem is especially true south of Mindanao

in the Molucca Sea (Figure 2), where it is impossible, on the basis of global plate kinematics, to estimate the relative plate convergence individually along each subduction zone. Preliminary results from Geodynamics of the South and South East Asia (GEODYSSSEA) Global Positioning System (GPS) measurements indicate that the "Sundaland block" is rotating clockwise with respect to Eurasia around a pole located south of Australia [Chamot-Rooke *et al.*, 1997]. The convergence between Sundaland and PSP is distributed over a 600 km wide zone from Sulawesi to Luzon islands. Only 45% of the convergence, i.e., ≈ 3 cm/yr, is accommodated along the Philippine Trench in the southern Philippines and probably even less along the southern branch of the Philippine Trench according to Rangin *et al.* [1997] (no definite constraints).

The convergence across the Philippine Trench may decrease in magnitude south of 6°N, as indicated by shallowing bathymetry and the disappearance of the accretionary wedge from 4° to 2°N [Nichols *et al.*, 1990]; symmetrically, the same situation occurs north of 15°N as shown by the scarce earthquake hypocenters and diminution of converging character of the inner wall as seen on reflection seismics [Lewis and Hayes, 1983]. South of Mindanao, the bathymetric trough in the prolongation of the Philippine Trench deviates toward the southeast by about 30° (Figures 1 and 2). The trench fringes the Snellius Ridge to the east [Rangin *et al.*, 1996] and shallows from 9500 m at 6°N (junction between central and southern Philippine Trench) to 5000 m at 3°N, where the last seismic evidence of thrusting is observed [Nichols *et al.*, 1990]. Immediately south of 3°N, the East Morotai Plateau clogs the bathymetric trench. Part of the 1994 survey, discussed here, was devoted to the tectonic significance of the junction near 6°N between the central and southern branches of the Philippine Trench and the possible relations with the northern termination of the Sangihe Trench. In fact, the

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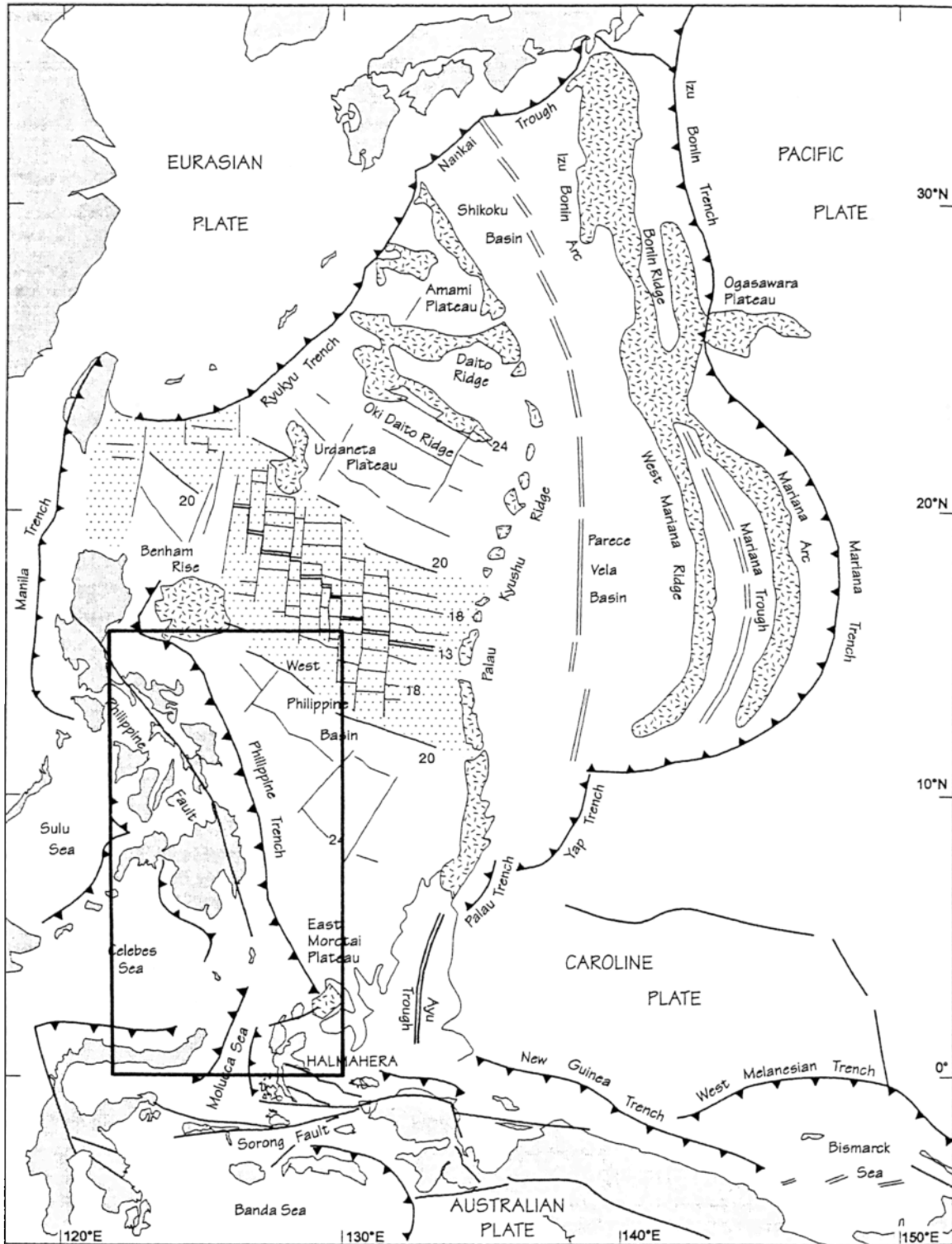


Figure 1. Tectonic setting of the Philippine Sea Plate modified after Hall et al. [1995]. The stippled area of the West Philippine Basin is the area produced by spreading after anomaly 20 (≈ 45 Ma); anomaly identifications in the West Philippine Basin are from Hilde and Lee [1984]. The box outlines the location of Figure 2.

deformation front of the Sangihe subduction zone has been traced during the MODEC cruise [Rangin et al., 1996] up to the junction between the central and southern Philippine Trench. The deformation is thus distributed in the northern Molucca Sea over the Cotobato, Sangihe, and Philippine subduction zones, the latter two joining near 6°N.

2. Geodynamic Background

2.1. Converging Plates

The Molucca Plate, between Halmahera and Sulawesi/Sangihe island arcs on Figure 2, has no surface

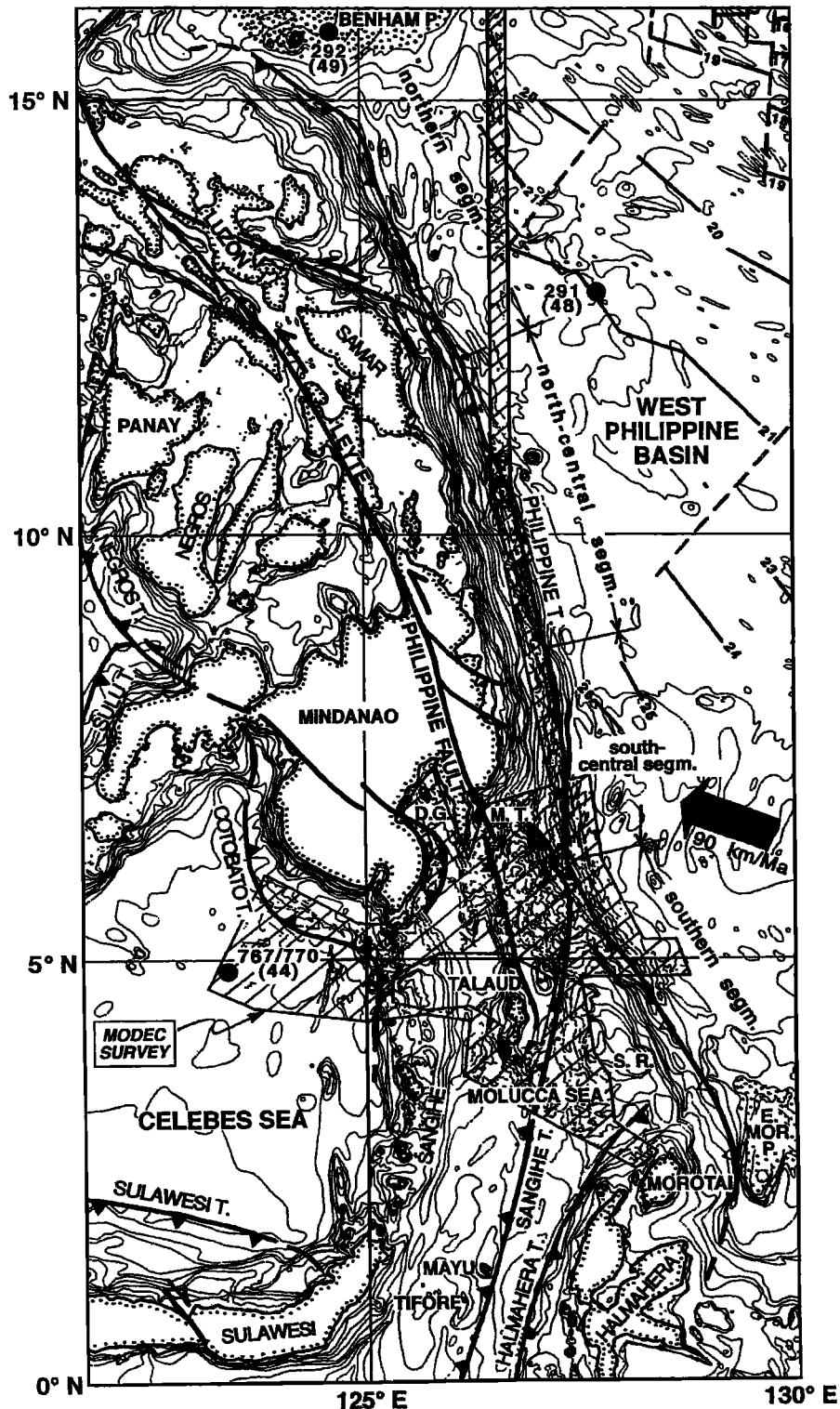


Figure 2. Map showing the main structural features in the vicinity of the Philippine Trench. Bathymetry from General Bathymetric Chart of the Oceans (GEBCO) database except in the area surveyed during MODEC and DAVAPUS oceanographic cruises (dashed domain). Isobaths every 500 m. The thick solid arrow represents the convergence of the PSP relative to the fixed Eurasia plate after *Seno et al.* [1993]. The length of the arrow exactly represents 90 km, i.e., 1 m.y. of convergence. Magnetic lineations (16 to 26) and transform faults (dashed lines) are from *Hilde and Lee* [1984]. The Philippine Trench has been cut into four segments (segm.) (see text for details). T, trench; P, plateau; E MOR P, East Morotai Plateau; S R, Snellius Ridge, M T, Mati Fault, D G, Davao Gulf. Solid dots are deep-sea drilling sites, numbered Deep Sea Drilling Project (DSDP) or Ocean Drilling Project (ODP) sites and the absolute age (Ma) of the oceanic crust, e.g., 292 (49).

expression except a collisional complex pinched between these two active volcanic arcs [Silver and Moore, 1978]. Three major lithospheric plates interact in the Molucca Sea south of Mindanao, in the vicinity of the southern branch of the Philippine Trench (Figure 1). The Eurasia plate to the west, composed of marginal basins (Celebes, Sulu, or South China Sea) separated by continental fragments drifted from the Eurasia continent, converges obliquely with the PSP to the east, along the so-called Philippine mobile belt. The mobile belt consists of sliver arc terranes fringed by N-S subduction zones and laterally displaced between the former Eurasia Plate and PSP [Rangin and Pubellier, 1990; Pubellier et al., 1992]. To the south, the Australian plate moves northward relative to Eurasia and interacts complexly with the NW-SE convergence between the Eurasian Plate and the PSP.

2.2. Philippine Fault

The Philippine Trench and fault system south of Luzon is often cited as a case study for strain partitioning [e.g., Fitch, 1972; Pinet, 1990; Aurelio, 1992; Quebral, 1994; McCaffrey, 1992]. The central part of the sinistral Philippine Fault, south of Luzon, formed in Plio-Pleistocene times [Aurelio, 1992; Quebral, 1994]. On the basis of field observations, Quebral et al. [1996] show that the fault reactivates preexisting collisional features. Its southward propagation is related to the completion of the collision. Motion along the fault diminishes progressively in Mindanao in a WNW-ESE trending horse-tail system (Figure 2). Detailed seafloor imagery allowed us to map the southernmost offshore trace of the Philippine Fault, i.e., the Mati Fault near 6°30'N (Figure 2) [Rangin et al., 1996]. The fault does not extend in the Davao Gulf south of Mindanao (Figure 2), as previously supposed [Quebral et al., 1996]. The N-S trending Miangas-Talud Ridge lies in the southern prolongation of the Philippine Fault and has been interpreted as the emerged backstop of the west-vergent Sangihe subduction zone [Rangin et al., 1996]. Both N-S trending thrusts and NW-SE strike-slip faults characterize this seismically active ridge [Quebral, 1994; Quebral et al., 1996; A.-G. Bader et al., Active slivering of oceanic crust along the Molucca Ridge (Indonesia-Philippine): Geodynamic implication, submitted to *Tectonics*, 1997, here in after referred to as Bader et al., submitted manuscript, 1997].

2.3. Philippine Trench

The origin of the Philippine Trench has been related to the flip of subduction from west to east of the Philippine Islands after the locking of convergence to the west caused by the collision of the Palawan and Zamboanga continental blocks [Barrier et al., 1991]. The collision of the Palawan block with Mindoro is dated 8 to 9 Ma [Rangin et al., 1989; Marchadier and Rangin, 1990] and a large amount of shortening (50%) could thereafter have been accommodated by intra-arc deformation. In this hypothesis, the Philippine Trench is thus younger than 8 to 9 Ma. The oldest recorded age for the volcanic activity related to the subduction of the PSP is 2.5 Ma in Leyte [Sajona et al., 1994], which means that subduction along the Philippine Trench probably started before 4 Ma (taking into account the minimum time required between initiation of subduction and volcanism).

The obliquity (defined as the angle between the plate convergence vector and the direction orthogonal to the trench) of plate convergence across the Philippine Trench, from a

pole of rotation based on best fit to slip vectors at trench, varies from about 30° to 35° in the northern and southern segments of the trench, to 20° near 10°N and, locally, 0° between 6°N and 7°N, according to McCaffrey [1996] (about 20° more using the pole of Seno et al. [1993]).

3. Gravity, Magnetism, and Seismicity of the Study Area

3.1. Gravity

A free-air gravity anomaly map was produced after the cruise [Rangin et al., 1996]. Because of the large width of the swath, ship tracks were spaced every 10 nautical miles on average, so that geophysical measurements such as gravity, magnetism, or reflection seismics were not optimum for generating a homogeneous grid. However, we observe a remarkable correspondence between our data and the satellite-derived free-air gravity database of Smith and Sandwell [1995] (Figure 3). This comparison gives more confidence in the gravity values, taken from the global database, along the trench axis. Equidistant bathymetric and gravimetric transects (every 150 km), normal to the trench, are plotted on Figure 4.

The first observation is that the minimum free-air anomaly (FAA = -260 mGal) occurs where the trench is deepest (-10100 m) near 10°N (transects 4 and 5 on Figure 4) but also over a broad area west of the junction near 6°N, where the lower trench slope is 6500 ± 3000 m deep (transect 7 on Figure 4). There the width of the gravity low (less than -200 mGal) is 100 km, yet it is only 30 km near 10°N. The minimum (-260 mGal) is shifted westward by about 25 km with respect to the morphological trench (-220 mGal). This has been interpreted as (1) low-density material belonging either to the Sangihe accretionary wedge or to a subducting basin of the northern Halmahera arc [Rangin et al., 1996]; (2) the result of N-S extension due to a horsetail termination of the Philippine Fault (M. Pubellier et al., Upper plate deformation induced by subduction of large asperities: Molucca Sea and Mindanao (Philippines-Indonesia) submitted to *Tectonophysics*, 1997, here in after referred to as Pubellier et al., submitted manuscript, 1997); or (3) caused by the vertical offset of the subducting PSP along a N-S trending west dipping intraplate thrust located beneath the eastern flank of the Miangas Ridge (Bader et al., submitted manuscript, 1997).

Second, the FAA associated with the outer rise (bending) of the Philippine Sea Plate before entering the subduction zone increases both in magnitude and width when approaching the junction near 6°N. This probably reflects the flexural response of the PSP at a convex trench junction [Deplus and Dubois, 1989].

Third, the Philippine Trench gravity low diverges southward of the junction (Figure 3) into two branches. The western branch extends southward along 127°±20'E (across a steep ESE-WNW gradient near 5°N) throughout the Molucca Sea, reaching -180 mGal between the Halmahera and Sulawesi volcanic arcs. This low has been attributed to the expression of the Sangihe and/or Halmahera Trenches [Moore and Silver, 1983]. The eastern branch extends southeastward at an angle with the N-S central Philippine Trench. It corresponds to the morphological southern branch of the Philippine Trench. This low decreases significantly southward reaching 0 mGal at 3°30'N, where the water depth is still 6000 m. The flexure of the PSP, when approaching the Philippine Trench, is

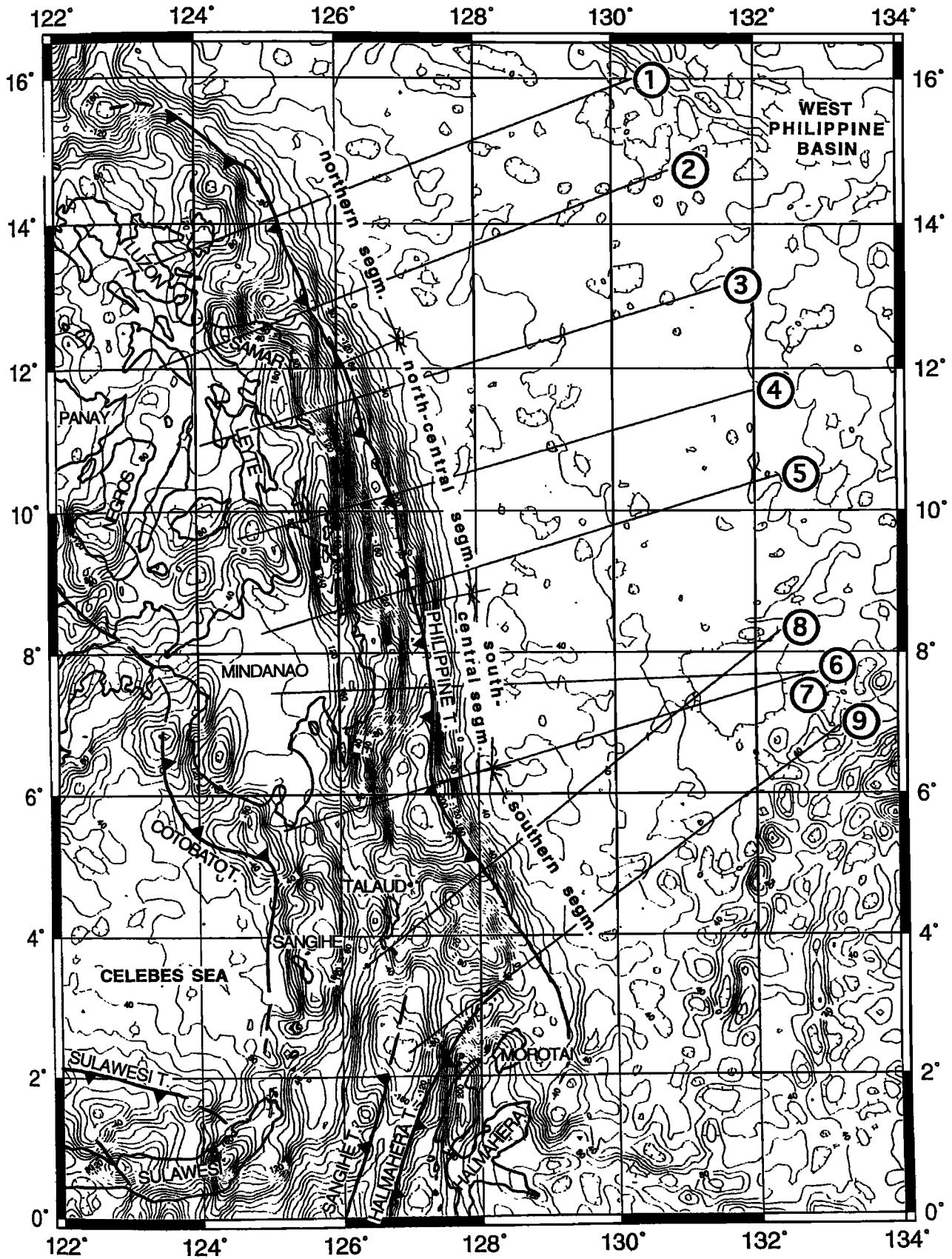


Figure 3. Free-air gravity anomaly map from *Smith and Sandwell [1995]*, contours every 20 mGal. Bathymetric and gravimetric transects (1 to 9) of Figure 4 shown. T, trench.

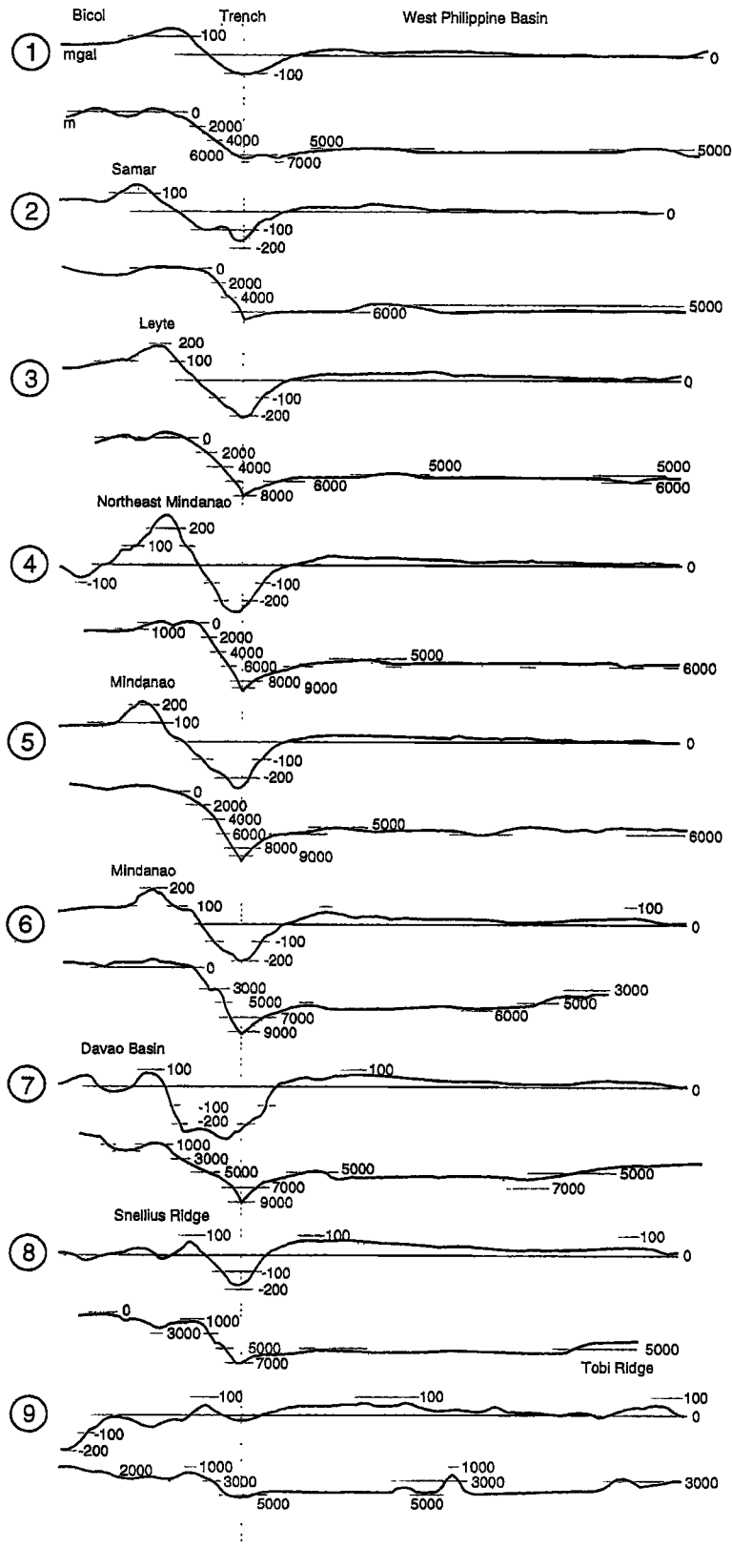


Figure 4. Superimposed (bottom) bathymetric and (top) gravimetric transects normal to the Philippine Trench. See Figure 3 for location. VE = 10 (bathymetry in meters extrapolated from *Mammerickx et al.* [1976] and MODEC survey). Gravity anomalies are expressed in milliGals. The morphological trench is always at a distance of 250 km from the beginning of the transect. The first 250 km to the west of the transects correspond to the overriding plate, and the 600 km to the right are the unsubducted Philippine Sea Plate.

expressed both in bathymetry and gravity at, and to the north of, the junction (transects 1 to 7, Figure 4), but it is mainly expressed in the gravity 150 km south of the junction (transect 8, Figure 4) and disappears south of 3°30'N (transect 9, Figure 4). Consequently, the Philippine Trench loses its gravity/morphology subduction character south of 3°30'N, except the local low of - 50 mGal observed immediately east of Halmahera island between 1 and 2°N.

3.2. Magnetics

Very low amplitude magnetic anomalies were recorded on the outer wall of the Philippine Trench during the MODEC cruise. *Mrozowski et al.* [1982] suggested that the subducting Philippine Sea crust, south of Luzon, was not typical oceanic crust but rather a thickened crust as indicated by slightly higher gravity anomalies and the lack of clear magnetic lineations. They distinguished the "main Philippine Basin" from the "southern subbasin" along latitudes $7 \pm 1^\circ$ N. This southern sub-basin is \approx 100-200 m shallower than the main basin. This is due both to a slightly greater sediment cover in the subbasin and to a shallower depth of the top of its acoustic basement. Reconstructions of the PSP generally take the southern subbasin to be older than 50 Ma [e.g., *Hall et al.*, 1995]. NW-SE trending anomaly 21 has been drilled at Deep Sea Drilling Project (DSDP) site 291 giving an Eocene age of 48 Ma (Figure 2). South of there, the crust is older and of uncertain origin [*Hall*, 1996]. Anomaly 26 (60 Ma) has been tentatively identified by *Hilde and Lee* [1984] between latitudes 7 and 8°N just off the trench, as shown on Figure 2. Using extrapolations from their magnetic map, the structural grain of the crust, parallel to the magnetic lineations, should strike $N130^\circ \pm 20^\circ$ depending on the latitude, while fracture zones should trend $N35^\circ \pm 5^\circ$.

3.3. Seismicity

The Benioff zone of the west dipping Philippine Sea slab is well defined beneath the Philippines Islands from 15°N (at the latitude of south Luzon) to 7°N (the latitude of South Mindanao) reaching 200 km in depth from 7°N to 10°N. South of 7°N, seismicity is inadequate to see the slab geometry [*Cardwell et al.*, 1980] because the Philippine Sea slab is too short and the contorted Molucca slab interferes. *Cardwell et al.* [1980] defined a trace for the Philippine Sea slab as far south as 3°N off Morotai. Cross sections of seismicity between latitudes 1°N and 10°N (Figure 5) illustrate the complexity of earthquake distribution, especially between 4°N and 7°N. Earthquake hypocenters reflect the mechanical identity of the PSP lithosphere under compression, west of Halmahera Trench, down to 1°N (Figure 5), but interplate seismicity is scarce, as indicated by a plot of focal mechanisms of shallow earthquakes extracted from the Harvard centroid moment tensor (CMT) data set (Figure 6).

The PSP is undergoing trench-perpendicular bending north of 6°N, along or immediately east of the trench axis, whereas no bending related extension is observed in the south within the same plate. This could reflect the existence of E-W compressive tectonic forces acting on the subducting PSP along the southern branch of the trench which inhibits any shallow extension within the plate.

It is clear from seismicity records (Figure 6) that the main interplate seismogenic zone, south of 6°N, corresponds to the N-S Miangas-Talaud Ridge which is interpreted by *Rangin et*

al. [1996] as the emergence of the Sangihe backstop. Earthquake distribution suggests that much more convergence is accommodated beneath the Miangas-Talaud Ridge (Sangihe subduction) than beneath the inner wall of the southern branch of the Philippine Trench.

4. Morphology Revealed by Swath Bathymetric Survey

We divide the 1800 km long Philippine Trench into four segments, mostly based on depth and the azimuth of the trench axis (Figures 2 and 7).

4.1. Northern segment

The northern segment of the trench, between 15°30'N and 12°N, has a mean depth of 6500 m (see Figure 2). The Benham Plateau clogs the trench to the north so that the trench axis locally trends N60°W, whereas it trends N25°W south of the plateau. The obliquity of the convergence between the forearc sliver and the PSP could be less than 30° according to the high level of slip partitioning at these latitudes [*McCaffrey*, 1996].

4.2. North-Central Segment

This segment of the trench, between 12°N and 8°40'N, trends roughly N18°W. Figure 8 gives a sample of the bathymetric map obtained along the ship's route, on which the depth of the trench floor is often 10000 m; 10100 m was reached at 9°22'N, which ranks the Philippine Trench among the deepest in the world. The slab reaches 200 km depth in the southern part of this segment (Figure 5).

The mean dip of the PSP, just before entering the subduction zone, is 6°. Normal faulting is observed near the trench with maximum vertical scarp offsets reaching 1500 m at 10°30'N. Mean vertical offsets generally range between 250 and 500 m. Scarps trend between N30°W and N-S (see rose diagram, Figure 8) slightly oblique to the N30° to N50°W oceanic crust fabric (see magnetic lineations, Figure 2). It thus seems that most of the faults were formed recently as a consequence of the strong bending of the PSP. They mostly face the trench, but some face eastward. The trench axis appears as a succession of en échelon narrow basins, each 30 to 60 km long, trending N25°W, regularly offset along N-S segments 10 km long.

The lowermost inner slope dips about 20° all in the survey area (between 8°50'N and 10°40'N) and is deeper than 8000 m. Such a high taper (20° of surface frontal slope + 6° of subducting plate slope) necessarily implies inner slope instabilities and gravitational collapse of material down into the trench, using reasonable parameters of friction and pore fluid pressures in, and at the base of, the margin [*Lallemand et al.*, 1994]. As no filling of the trench is observed (V-shaped cross section), we conclude that the entire volume of slumped material is continuously underthrust beneath the inner trench wall. The steepness of the lower part of the inner wall may result from the high interplate macrofriction generated by the seafloor roughness (scarps) but also to the subcrustal removal of the margin near the toe.

4.3. South-Central Segment

In Figures 9 and 10, we did not separate the south-central (between 8°40'N and 6°10'N) and southern segments (between

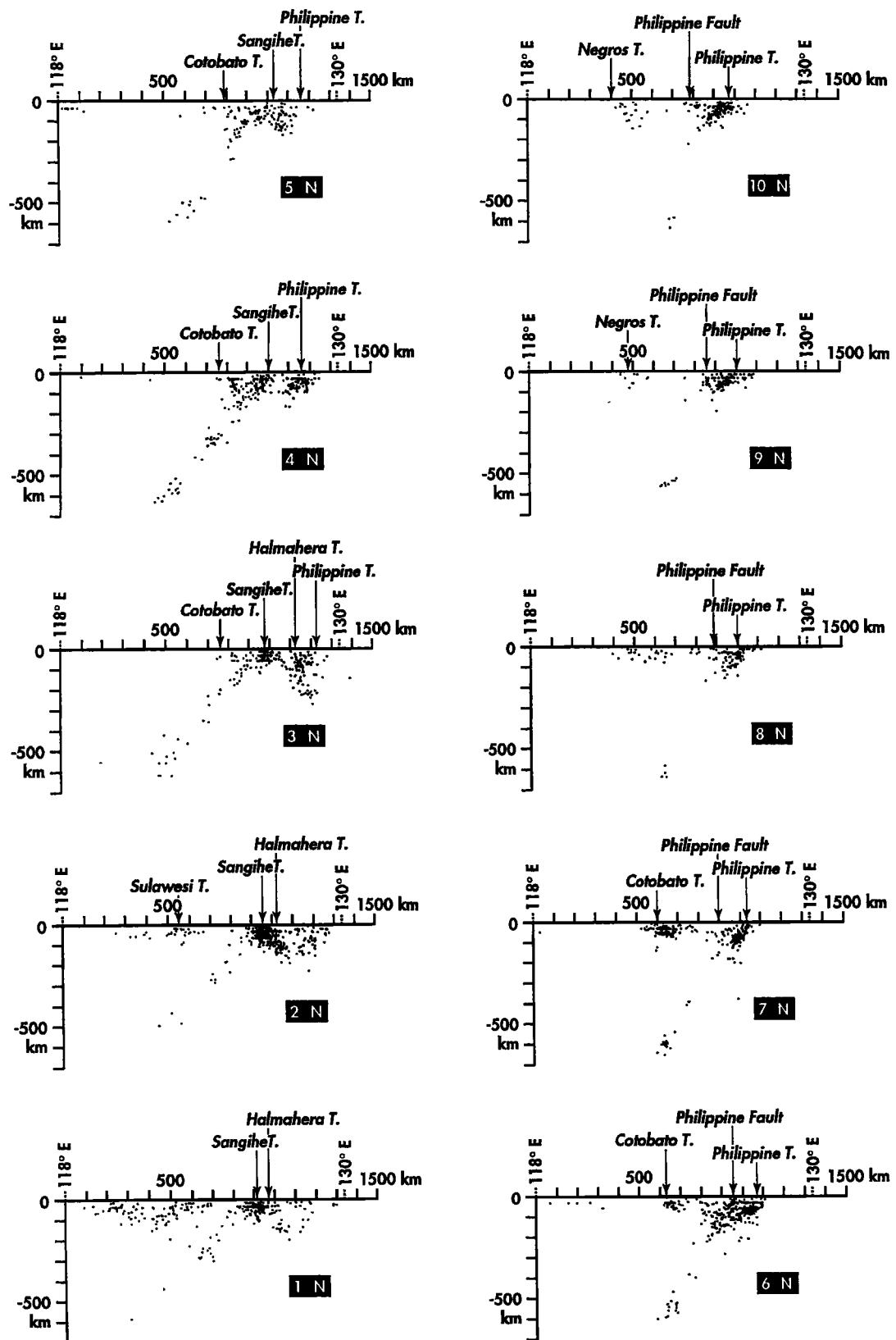


Figure 5. Cross sections, down to 700 km depth, with earthquake hypocenters projected along vertical planes at latitudes 1°N to 10°N, with a width of 1° of latitude, between longitudes 118°E (0 km) and 130°E (1332 km). Data sources come from (1) the Council of the National Seismic System which use data from the Northern California Earthquake Data Center from 1964 to 1977 (magnitudes $M_w = 4$ to 7.9) and (2) Harvard Centroid Moment Tensor (CMT) hypocenters from 1977 to 1994 (magnitudes $M_w = 4.9$ to 7.7). T, trench.

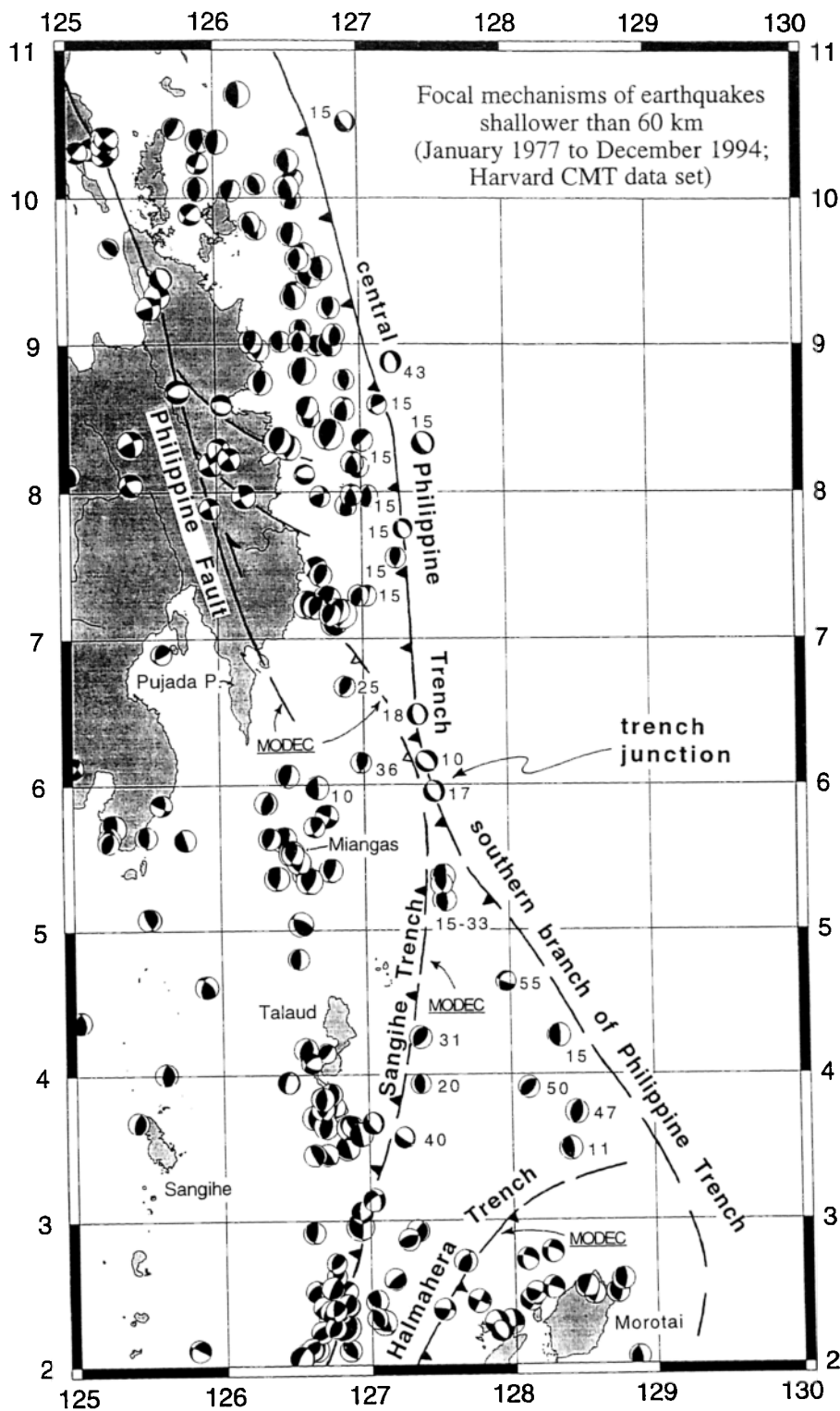


Figure 6. Harvard CMT solutions for shallow earthquakes (0-60 km) along the Philippine Trench (1977 to 1994). Size of beachballs is a function of earthquake moment. MODEC label indicates sections of plate boundary studied during MODEC cruise [Rangin *et al.*, 1996]. Numbers are centroid depth of earthquakes (km) given for some events. Note the frequent shallow seismicity beneath the Philippine margin north of 6°N and beneath the Pujada-Talaud Ridge south of 6°N. There are very few shallow earthquakes on the west side of the southern branch of the Philippine Trench, indicating that seismic coupling is very low compared to the north. Most earthquakes are deeper than 100 km and probably correspond to the Molucca Sea Benioff zone dipping in the opposite direction. P, peninsula.

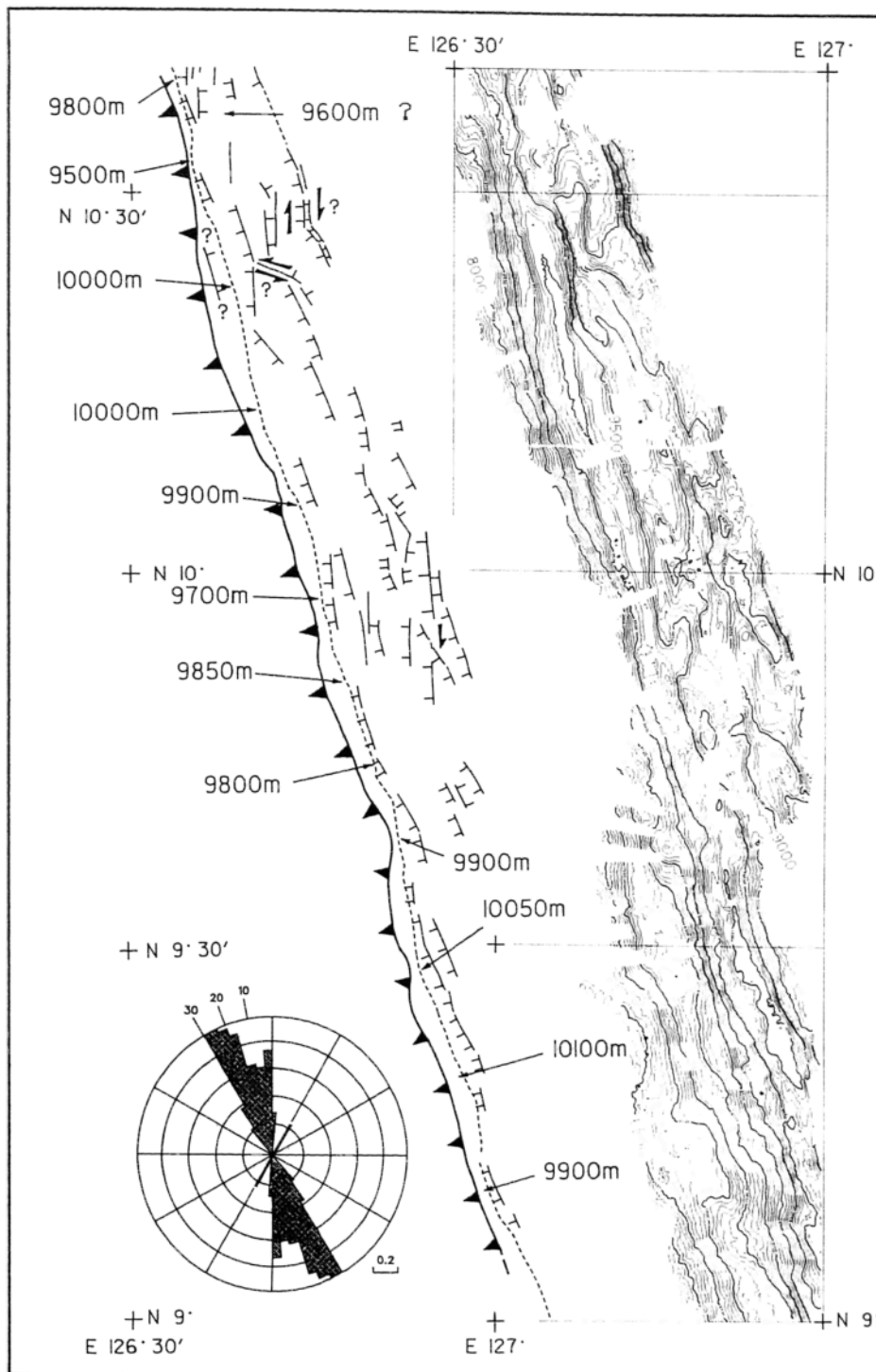


Figure 8. Bathymetric map obtained using a single track along the Philippine Trench axis after the MODEC cruise (DAVAPUS cruise). Isobaths every 100 m. Structural interpretation is shown at the same scale on the left, with dashed line for the axis of the trench, solid line for the deformation front, and triangles on the overriding plate side. Barbs are on the downfaulted side along the normal faults of the subducting plate. Diagram of oceanic faults direction is also shown (azimuth/cumulate fault lengths).

5. Structural Synthesis and Discussion

5.1. Philippine Trench From North to South

The geometry of the Philippine Sea slab seems rather symmetrical both north and south of 9°N. The slab is longest where the trench is deepest and where arc magmatism is the

oldest. One can thus imagine that subduction first initiated near 9°N and then propagated to both north and south at some point, at least 4 m.y. ago according to the oldest age of the volcanic arc. To the north, the convergence between the Eurasia plate and the PSP is transferred from the west dipping Philippine Trench to the east dipping Manila Trench (Figure

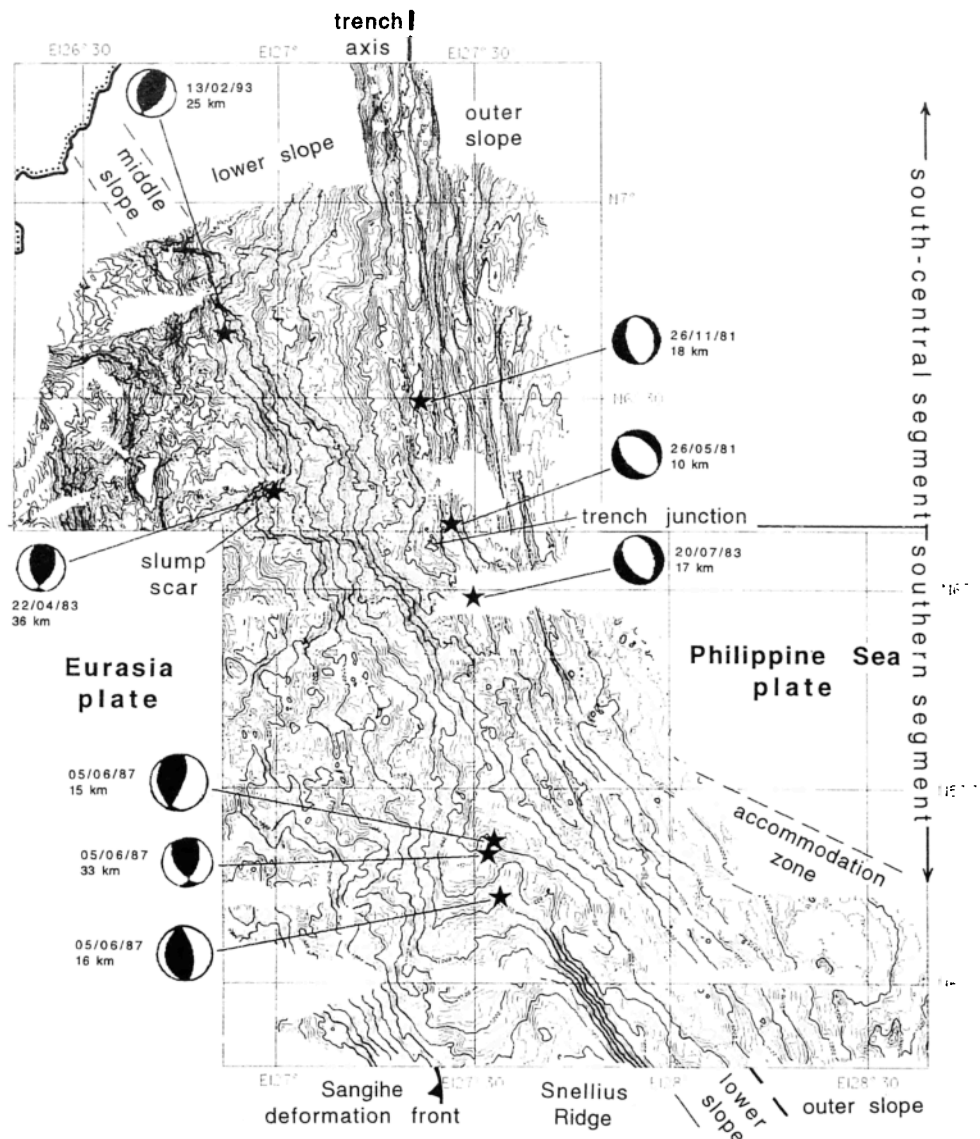


Figure 9. Bathymetric map obtained during the MODEC cruise in the vicinity of the trench junction southeast of Mindanao. Isobaths every 100 m. Stars represents epicenters of shallow earthquakes for which focal mechanisms are available (see Figure 6). Date and depth of events are indicated near the beachballs.

1). Both subduction zones overlap between 13°N and 16°N. To the south, the convergence is transferred from the Philippine Trench mainly to the Sangihe Trench as attested by the regional seismicity (Figure 6).

5.2. Molucca Sea and Philippine Sea Slabs

We have used closely spaced latitudinal cross-sections of seismicity (Figure 5) to propose an isopach map of the Benioff zones of the Molucca Sea and Philippine Sea slabs in the study area (Figure 13). The doubly verging Molucca slab, described near Mayu and Tifore Islands (see location on Figure 2) by *McCaffrey et al.* [1980] is recognized up to 4°N with a NNE-SSW trending hinge. The west dipping slab reaches almost 700 km beneath the Celebes Basin (see the cross section at 7°N on Figure 5) and 200 km east of Halmahera island (between 1°N and 3°N on Figure 5). The contour lines differ slightly from the geometry proposed by *Cardwell et al.* [1980], especially between 4°N and 8°N, where it seems pointless to choose between the various slab combinations.

The important point is that seismicity occurs down to 200 km over a broad area between latitudes 4°N to 8°N and between 125°E and 128°E. This is the area of the junction between the central and southern Philippine Trench and the Sangihe Trench. Interpretative E-W cross sections will be further given (Figure 14), based on the detailed bathymetry from the MODEC cruise and onland geology, in agreement with seismicity and gravity data.

5.3. The 20 to 30 m.y. Long-Lived Sangihe Trench

The west dipping Molucca Sea slab reaches the mantle discontinuity beneath the Celebes Basin, attesting that at least 1000 km of plate convergence has been accommodated across the Sangihe Trench. This is clearly the deepest slab known along the Philippine mobile belt. Late Miocene volcanics attributed to the Sangihe subduction were found in southwestern Mindanao [*Pubellier et al.*, 1991]. Tholeiitic and calc-alkaline magmatism of early Miocene (19 and 22 Ma) and

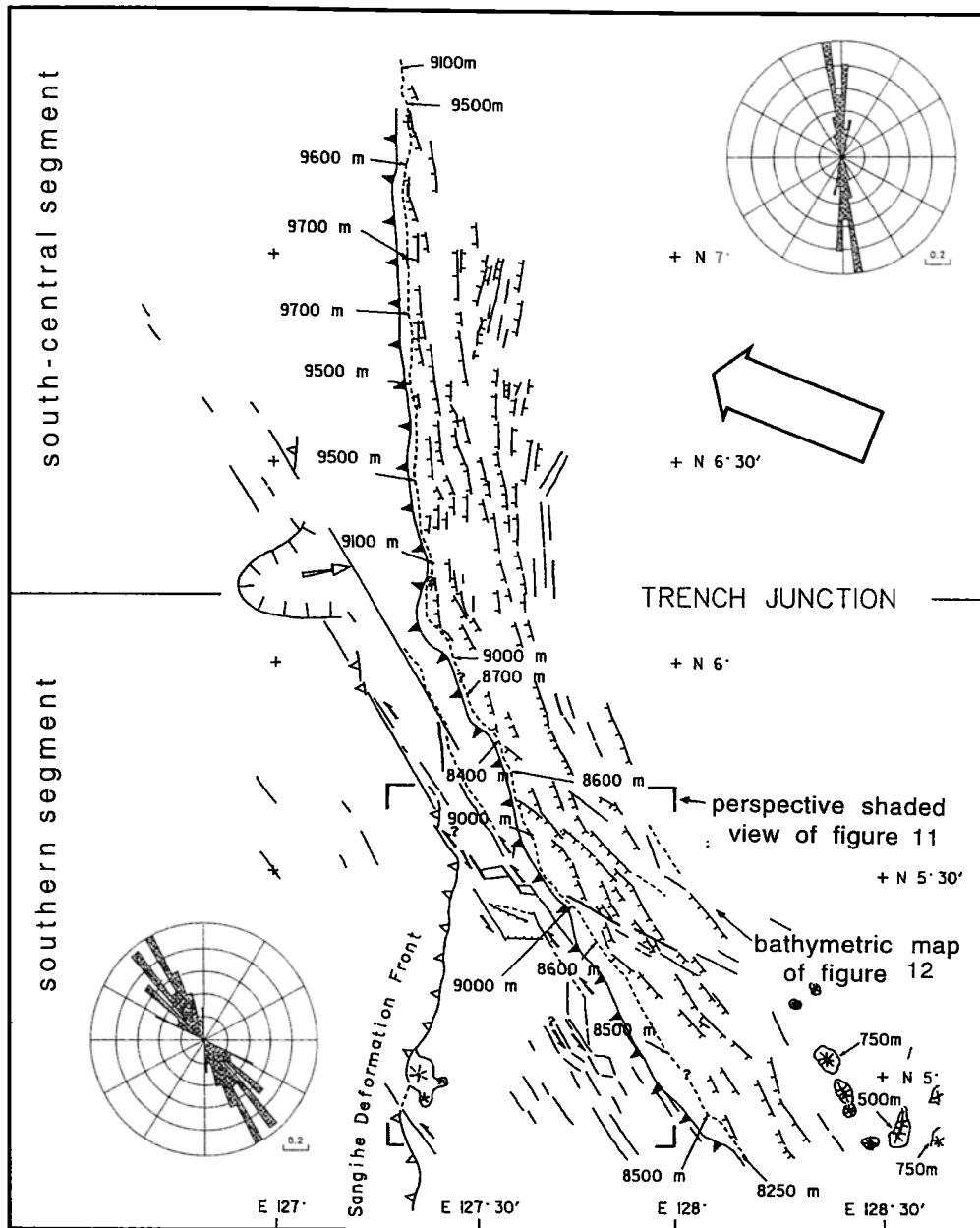


Figure 10. Structural interpretation of bathymetric map (Figure 9) with dashed line for the axis of the trench, solid line for the deformation front, and triangles on the overriding plate side. Barbs are on the downfaulted side along the normal faults of the subducting plate. Diagrams of fault directions are also shown for both south-central and southern segments. The four corners delineate the location of the area used for the shaded perspective view of Figure 11. Thin dots outline the rectangular area of Figure 12.

even Oligocene (28 Ma) have also been reported in the northern arm of Sulawesi by *Priadi* [1993]. Present volcanic activity along the Sangihe volcanic arc and the high level of seismicity beneath the Sangihe forearc attest to convergence being still active along this subduction zone. The 1000 km of convergence during 25 m.y. gives a mean convergence rate of 4 cm/yr, which is reasonable. This is a minimum estimate because we ignore the possibility of the slab passing through the "670 km" mantle discontinuity. The Sangihe Trench has been traced east of the Talaud Ridge by the MODEC team [*Rangin et al.*, 1996] and might extend up to 7°N following the base of the steep middle slope (Figures 2 and 9).

5.4. The 10 m.y. Long-Lived Halmahera Subduction Zone and Its Supposed Northern Extension

The east dipping Molucca Sea slab reaches 200 km depth between latitudes 1 and 3°N (Figures 5 and 13). The volcanic arc, related to eastward subduction of the Molucca Sea plate at the Halmahera Trench, was initiated at the beginning of the late Miocene [*Sufni Hakim and Hall*, 1991], with a brief cessation of volcanism during the Pleistocene [*Hall*, 1987]. The 300 km long, at maximum, east dipping slab obtained during 10 m.y. years gives a maximum mean rate of 3 cm/yr

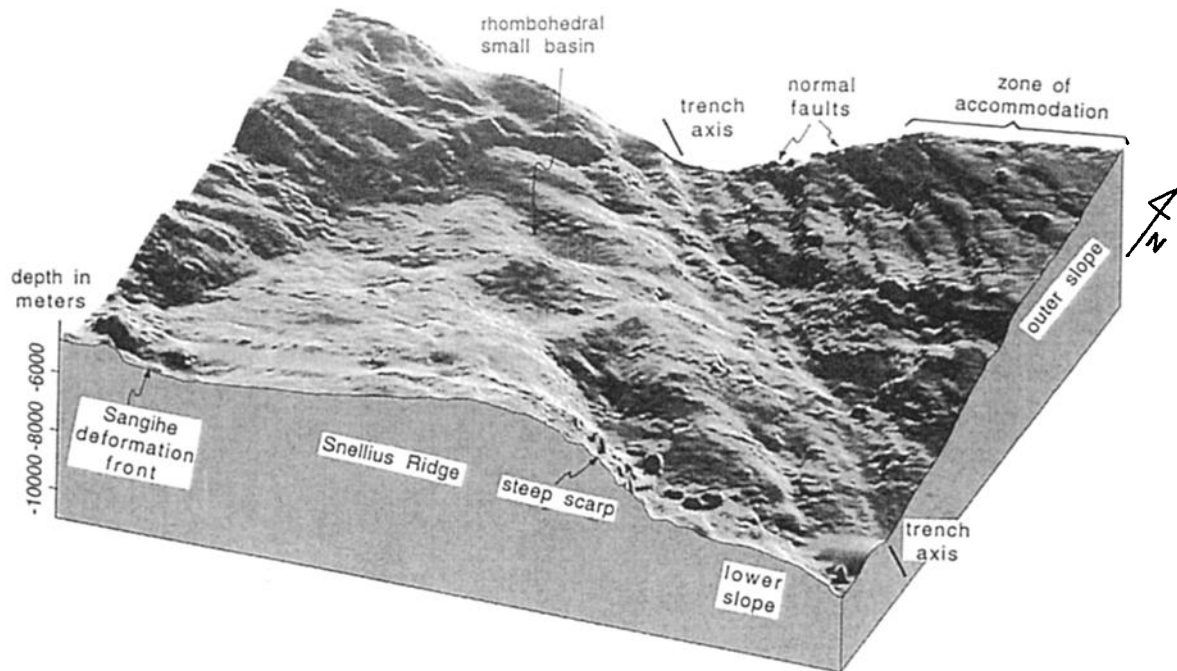


Figure 11. Perspective shaded view of part of the southern Philippine Trench. View looking toward the NW. The frontal section crosses the Sangihe deformation front, the Snellius Ridge, and the lower slope of the Philippine Trench. West facing scarps of normal faults are clearly observed on the outer wall. The steep (20°) eastward flank (scarp) of the Snellius Ridge is observable in cross section. Small rhombohedral basins are detected on the lower slope just north of this scarp. The N-S trending Sangihe deformation front can be followed on the west side of the diagram. Vertical exaggeration $\approx \times 5$.

for convergence across the Halmahera Trench. The present deformation front turns eastward just north of Morotai island (Figure 2) as revealed during the MODEC cruise [Rangin *et al.*, 1996]. However, two possible lines of evidences are present, pertaining to a northern extension of the Halmahera arc: (1) based on stratigraphic correlations, Hall [1987] considered that the basement of East Mindanao and the Halmahera basement complex were part of a single arc and forearc of Late Cretaceous - Early Tertiary age; (2) according to morphological and gravimetric data recorded during the MODEC cruise, the Snellius Plateau, which is pinched between the Sangihe and the southern Philippine Trenches, might represent a relict of the northern Halmahera Arc between Morotai and Mindanao. In this hypothesis, the former Halmahera Trench, north of 3°N , should have been subducted beneath the Sangihe deformation front.

5.5. Fate of the Molucca Sea Slab

We have tentatively interpreted three latitudinal cross sections of seismicity in the junction area between the Philippine, Sangihe, and former Halmahera Trenches (Figure 14). We did not cut the Molucca Sea slab (west dipping high-angle reverse fault) along its hinge as proposed by Cardwell *et al.* [1980] and McCaffrey *et al.* [1980] for the southern part of the Molucca Sea and by Bader *et al.* (submitted manuscript, 1997) for the northern part, because it was not necessarily required to fit the seismicity or gravity data. Inasmuch as the Miangas-Talaud Ridge could represent the basement of the Sangihe forearc of oceanic origin [Rangin *et al.*, 1996] (Bader *et al.*, submitted manuscript, 1997), we think that it is simpler to relate the high-angle reverse faulting mechanisms to the

deformation of the forearc basement rather than to the deeper Molucca Sea plate. The question of whether or not the Molucca plate is faulted at its hinge is not critical for the present model. According to Hall's [1996] Cenozoic reconstruction model of Southeast Asia, the Molucca Sea was a very wide area formed by trapping of Indian Ocean lithosphere at 25 Ma. Its age should thus be pre-Tertiary. Such an old, and dense, oceanic lithosphere should sink into the mantle after arc-arc collision rather than be accreted, in agreement with the deepening of the slab northwestward (Figure 13). Depending on the upper mantle viscosity, the inverted U-shaped slab will sink vertically (low viscosity) or will sink toward the WNW in the direction of the longest slab (high viscosity plus slab pull) requiring the unbending of the opposite-verging slab.

5.6. Progressive Subduction and Accretion of the Northern Extension of the Halmahera Arc

From south to north, we observe (1) the active Halmahera volcanic arc associated with a clear deformation front (Halmahera Trench) for which, probably recent, northern termination has been traced during the MODEC cruise until 3°N ; (2) a remnant of the Halmahera Arc (Snellius Ridge) entering the Sangihe subduction zone; and (3) an exotic terrane, which should represent the northern extension of the Halmahera Arc, accreted east of the Philippine Fault in Mindanao. Intense deformation and stacking of lithospheres are evidenced from seismicity distribution between 4°N and 8°N (Figure 5). The three interpretative cross sections attempt to reconcile the various data in this complex area.

5.6.1. The 5°N section. At this latitude, the Molucca Sea slab is sufficiently shallow to be responsible for

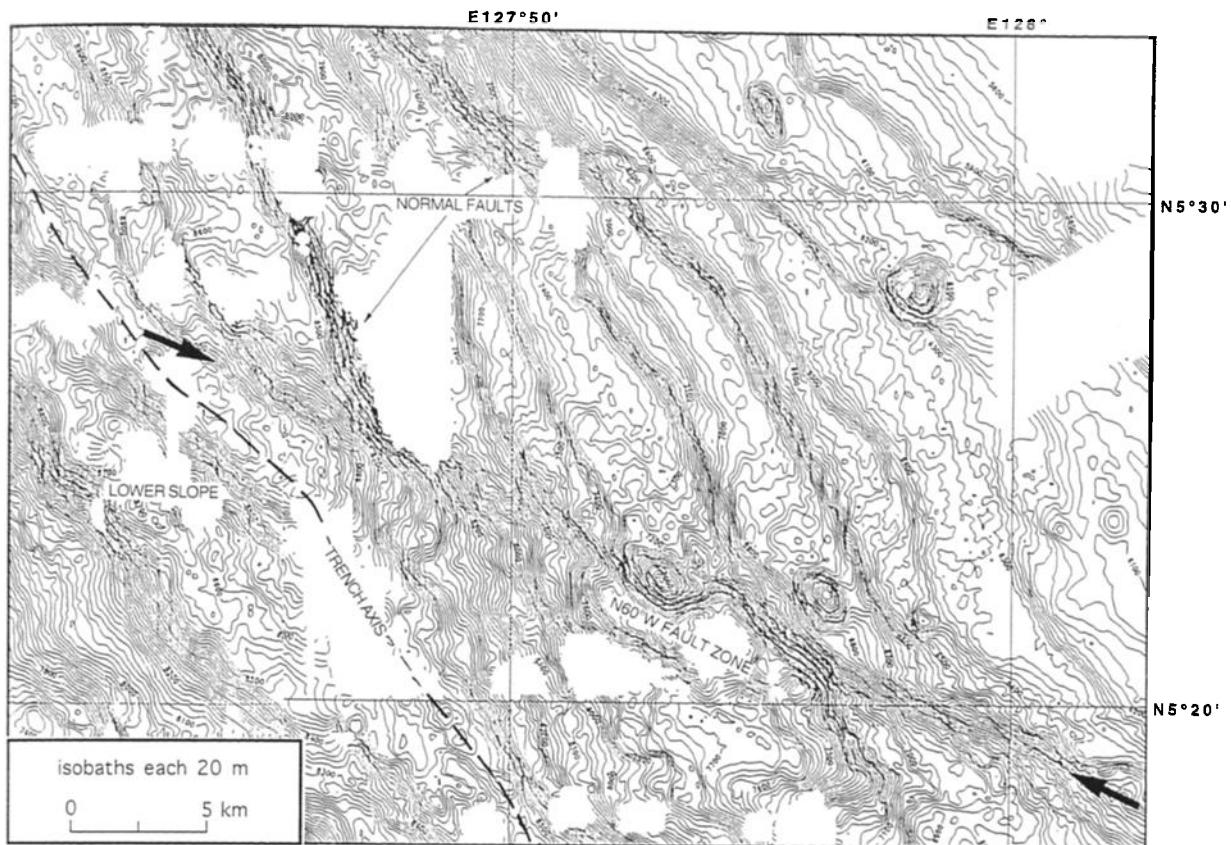


Figure 12. Bathymetric map focused on the main N60°W Fault Zone, showing both normal and left-lateral strike-slip components (see text for details).

the Sangihe Arc volcanism. The Snellius Ridge, which represents the relict of the northern extension of the Halmahera Arc, and the forearc domain are subducted beneath the Sangihe forearc, causing the uplift of Talaud island. The former Halmahera Trench is now buried underneath nearly 100 km of lithosphere, and the relative motion between the subducted Halmahera forearc and the west dipping Molucca slab could now occur in the other sense, compared with the previous convergence between the arc and the east dipping slab. According to seismicity distribution, the Philippine Sea slab and the east dipping Molucca slab should join at depth.

5.6.2. The 6°N section. Earthquakes deeper than 200 km might reflect the presence of the sinking Molucca slab. We interpret the 200-km-thick seismic zone below the Miangas islands as related to the stacking of the Sangihe forearc and Halmahera Arc and forearc lithospheres. The positive buoyancy of arc and forearc material prevents their subduction deeper in the mantle. Their subcrustal accretion may cause the local steepening of the Philippine Sea slab with eventual intraplate shearing associated with the 50- to 80-km-deep swarm of earthquakes. The eastward verging thrusts associated with the Sarangani Peninsula and the Miangas Ridge were reported by *Rangin et al.* [1996].

5.6.3. The 7°N section. At this latitude, the Molucca Sea slab is only detectable by earthquake hypocenters deeper than 400 km. The plate configuration is similar with those of the previous section at 6°N. The section crosses the southernmost termination of the Philippine Fault which bounds the accreted Halmahera Arc [*Hall, 1987; Pubellier et*

al., 1991]. A swarm of earthquakes occurred at about the same depth as 1° to the south within the subducting PSP, suggesting a strong intraplate deformation.

5.7. Transfer of Convergence From the Sangihe Trench to the Philippine Trench and the Origin of the Philippine Trench

Combining data from various sources, we propose a simple geodynamic story for the study area. We consider that the present situation at 1°N prevailed 6 m.y. ago at 8°N. At that time, the Sangihe Trench and the Halmahera Arc extended northward until 8°N. The Halmahera Arc consisted of en échelon N-S trending arc segments offset left-laterally along NW-SE transform faults. The cross-section along 5°N (Figure 14) could be representative of the situation along 8°N, 4 m.y. ago. The northern segment of the Halmahera Arc was accreted to the Eurasia margin and the subduction jumped eastward from the old Sangihe Trench to the nascent Philippine Trench. The failure of the Philippine Sea lithosphere just east of the Halmahera Arc initiated either at 8°N or slightly north, as suggested by the deepest trench floor and present PSP Benioff zone and rapidly propagated both northward and southward. The deformed suture zone between the host margin and the accreted terrane was then reactivated into a strike-slip fault: the Philippine Fault, as a response of slip partitioning under oblique convergence. Today, the old Sangihe Trench is inactive north of 6°N, because the Philippine Trench and Philippine Fault can accommodate most of the convergence,

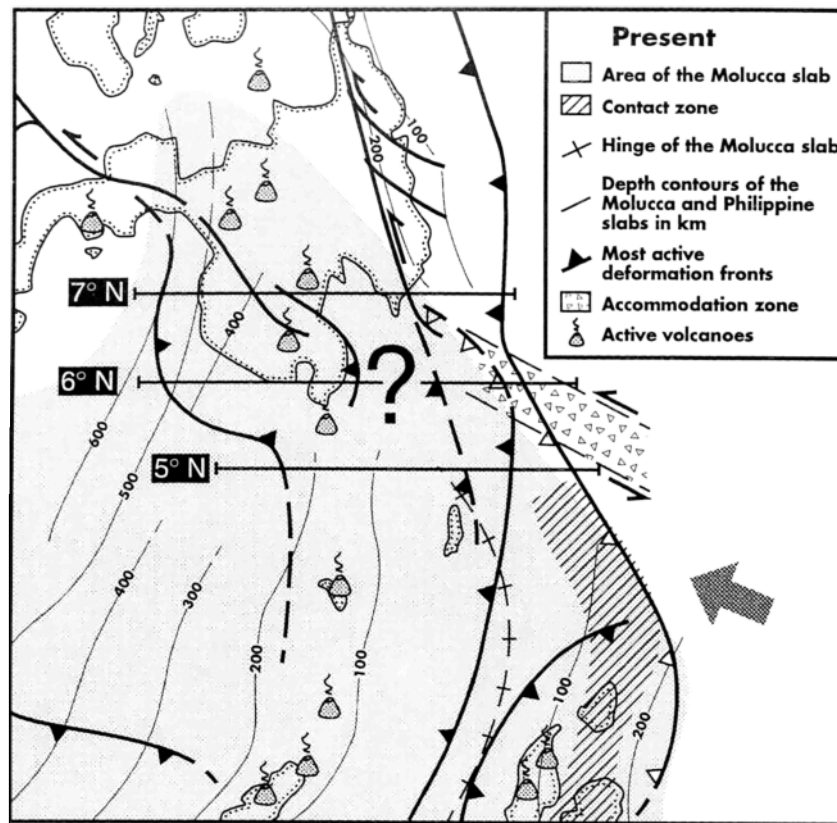


Figure 13. Interpretative structural map of the surveyed area. The grey pattern corresponds to the surface area of the Molucca slab subducting westward beneath the Sangihe Arc and eastward beneath the Halmahera Arc. Its lateral extent and depth contours of its Benioff zone estimated from cross sections of seismicity (see Figure 5). The solid arrow represents the plate convergence vector between Philippine Sea and Eurasia plates. Its length is 90 km, i.e., 1 m.y. of convergence. Depth contours of the Philippine Sea slab beneath Mindanao are also plotted. The hatched area corresponds to the joining of the east dipping Molucca slab and the west dipping Philippine Sea slab at depth (contact zone). The three E-W transects locate the interpretative cross sections of Figure 14.

while it is still active to the south because the Philippine Sea slab joined the east dipping slab at depth soon after its subduction. A possible scenario for the near future in the study area could be the following: (1) the Philippine Fault will propagate along the Talaud-Miangas Ridge, (2) the collision complex located between the ridge and the trench will be uplifted and eroded, allowing the Snellius Ridge to outcrop, and (3) the sinking of the Molucca Sea slab in the north will unblock the presently decelerating southern PSP subduction.

5.8. Agreement of the Geodynamic Model With the MODEC Observations

1. The deepest segment of the Philippine Trench near 9°N, as well as the maximum depth reached by the PSP slab between 7°N and 10°N, coincides with the area of possible accretion of the northern segment of the Halmahera Arc 4 to 5 m.y. ago, and subsequent initiation of the Philippine Trench.

2. The middle slope outlines the Sangihe deformation front, called the Sangihe Trench south of 6°N where the Sangihe subduction is still active, and the Sangihe suture zone, north of 6°N, between the accreted Halmahera Arc (lower slope) and the deformed Sangihe accretionary wedge.

3. The strong bending of the PSP at the trench north of 6°N, as indicated by earthquake solutions and vertical offsets of normal faults, can be caused by accreted terranes which locally steepen the subducting PSP.

4. The N60°W zone of accommodation could be inherited from an ancient transform zone between the northernmost segment of the Halmahera Arc and the "Snellius segment of the arc," which is reactivated near the trench as the PSP subduction is slowed down south of 5°N.

5. The wide gravity low observed beneath the middle and lower slopes between 5° and 7°N corresponds to the area where the hinge of the Molucca slab detaches from the overlying lithospheres (Figure 14). This process starts near 5°N in the northwestern extent of the accommodation zone, suggesting a possible common origin. Once the Molucca slab has detached, one may expect an isostatic rebound and thus uplift of the overlying lithosphere, as observed north of 7°N.

6. Conclusion

The detailed analysis of the geophysical data acquired during the MODEC cruise, combined with other regional data, allowed us to better understand the distribution of the

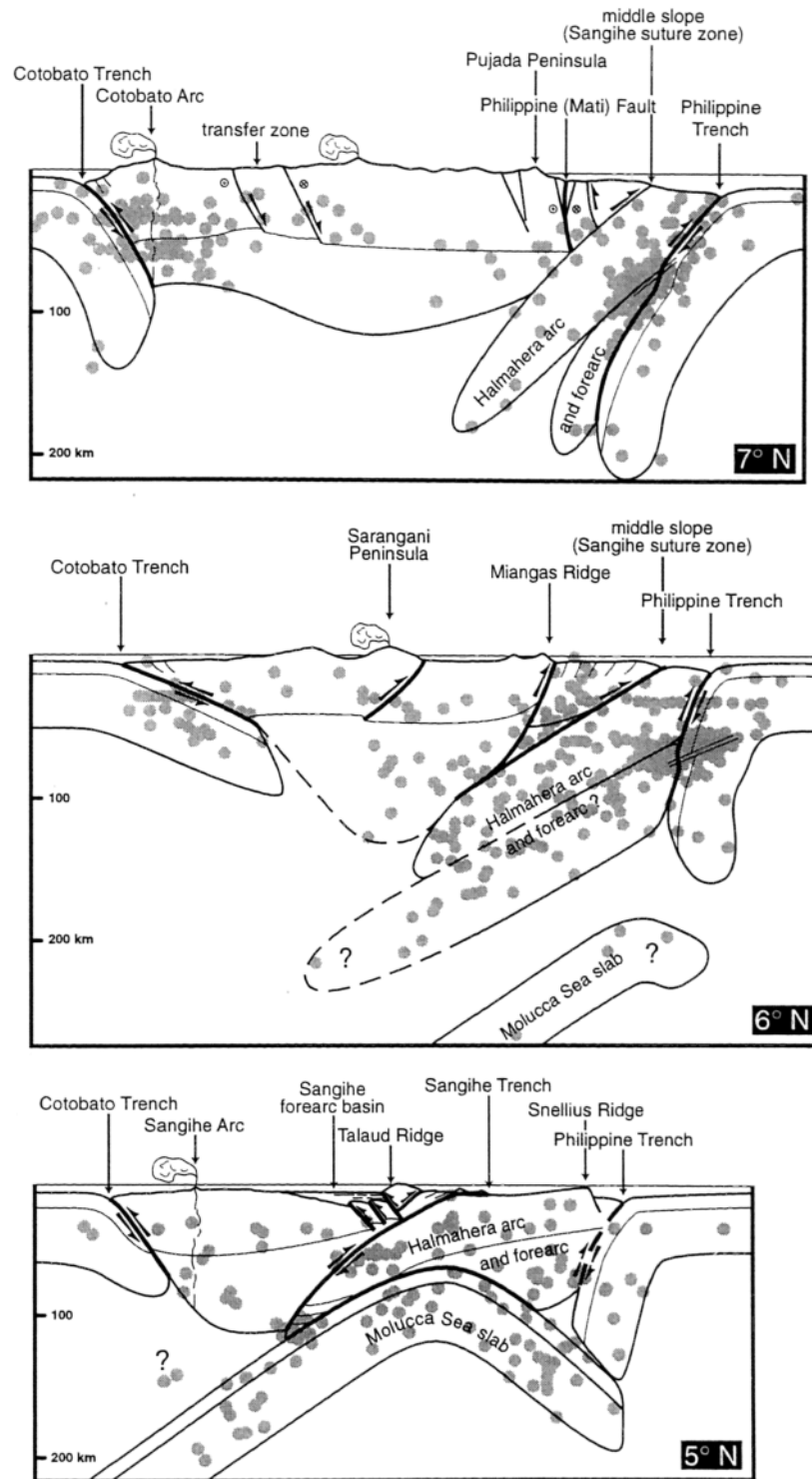


Figure 14. Interpretative lithospheric cross-sections along 5°N (southern segment), 6°N (trench junction), and 7°N (south-central segment). These sections are based on seismicity (grey dots), global geodynamic context, and surface observations from the MODEC cruise. Thick lines are plate boundaries. Depths are in kilometers. See text for details and Figure 13 for location.

deformation in the vicinity of the Philippine Trench junction near 6°N. The origin of the Philippine Trench is controversial in that it is commonly attributed to the 8 to 9 Ma collision between the Palawan and Zamboanga continental terranes, while arc volcanism and slab length suggested a younger age of about 4 to 5 Ma. We suggest that the accretion of the

northern part of the Halmahera arc and forearc to Mindanao during early Pliocene triggered the failure of the PSP along the Philippine Trench. The trench has propagated both north and south soon after and was recently slowed down along the southern branch because the PSP slab joined the Molucca Sea slab at depth.

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