

Collision and strike-slip faulting in the northern Molucca Sea (Philippines and Indonesia): preliminary results of a morphotectonic study

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Abstract: A swath mapping, gravity and single channel seismic survey was carried out in the northern Molucca Sea with R.V. *L'Atalante*. Preliminary interpretation of these data reveals the presence of an almost complete Sangihe arc and forearc. The Miangas-Pujada-Talaud ridge in the central part of the Molucca Sea appears to be a backstop within the Sangihe forearc. East of the ridge very contrasting terranes are separated by a major NW-SE crustal discontinuity interpreted as a left-lateral strike-slip fault. North of 6°N the Philippine Trench inner wall is dissected by NW-SE trending left-lateral strike-slip faults, resulting from the dominantly oblique convergence between colliding arcs. South of 6°N the westward subduction of the buoyant Snellius volcanic plateau, a fragment of the Halmahera arc terrane, has induced the formation of a new plate boundary, the Philippine Trench along what is interpreted as a former strike-slip fault zone. East of the Miangas-Pujada-Talaud ridge there is a wide sedimentary wedge separated from the Snellius Ridge to the south by the major NW-SE crustal discontinuity. The thickness of this wedge cannot be explained by subduction along the very young Philippine Trench. It could be either an accretionary wedge developed at the deformed leading edge of the Sangihe forearc or be part of a former intra-arc basin which was part of the colliding Halmahera arc terrane. There is no clear evidence for accreted oceanic crust belonging to the recently subducted Molucca Sea. The Miangas-Pujada-Talaud ridge is part of the Sangihe forearc, and the ophiolites could represent its basement, uplifted along the outer arc ridge. The dog-leg-shaped Philippine Trench is propagating southward across the fragmented Halmahera arc terrane and its southern segment could reactivate a former strike-slip fault zone.

The collision of the Halmahera arc (a fragment of the Philippine Sea plate) with the Sangihe arc (Fig. 1) has been described by Silver & Moore (1978), Hamilton (1979), and Moore & Silver (1983). The ophiolites and melanges exposed in Talaud, Mayu and Tifore Islands have been interpreted as fragments of the almost completely subducted Molucca Sea floor formerly separating the two colliding island arcs (Silver & Moore 1978; McCaffrey *et al.* 1980). The creation of a new plate boundary, the Philippine Trench, east of the collision zone therefore marks a step in the incorporation of the intra-oceanic Halmahera island arc into the Eurasian continental margin,

if the Sangihe arc is considered to be built on the thinned margin of Eurasia (Rangin *et al.* 1990a).

In this paper the geometry of this collision zone is documented by a study of the geomorphology of the northern Molucca Sea, based on large coverage multibeam mapping, with gravity and single channel seismic data. This dataset was recorded during a cruise of R.V. *L'Atalante* in April and May 1994 (MODEC cruise), in co-operation with the Indonesian Institute of Development and Technological Research, Jakarta (BPPT) and the Philippines Bureau of Mines and Geosciences, Manila (BMG).

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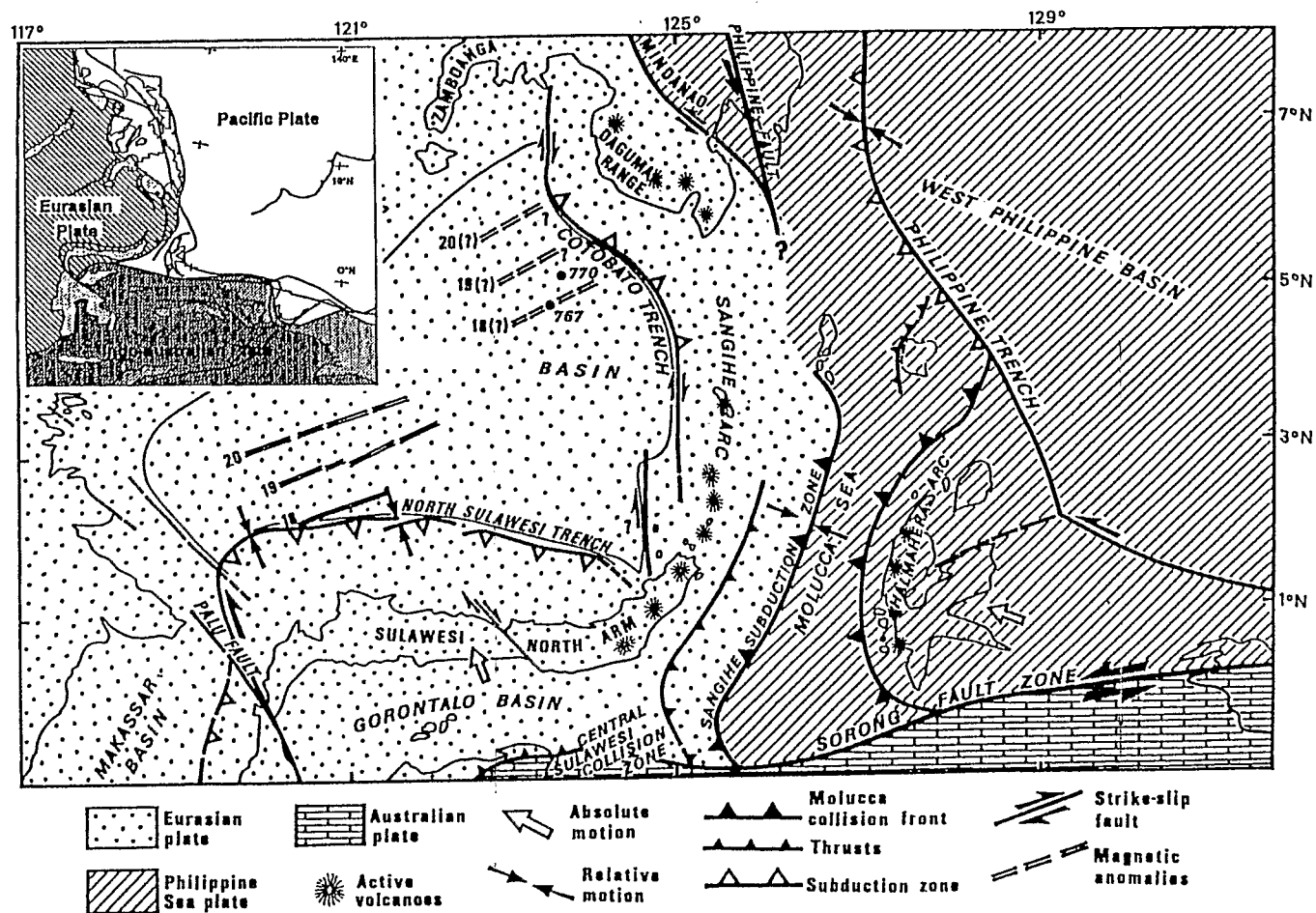


Fig. 1. Geodynamic framework of the Molucca Sea. The inset shows the main lithospheric plates, much simplified.

The preliminary interpretations of these data and attempts to answer some basic questions are presented here. How does the collision zone between the Molucca Sea basin margins change from frontal to oblique collision, after oceanic crust of the Molucca Sea has been entirely subducted between the two colliding arcs? What is the morphotectonic signature of a newly created plate boundary, the Philippine Trench?

Gravity and seismological data from the Molucca Sea were published by Silver & Moore (1978) and McCaffrey *et al.* (1980) but the only detailed bathymetric map available before the cruise was that of Krause (1966). Seabed mapping should allow a better understanding of the geometry of this diachronous collision and the rapid structural variations expected in the transition zone between collision and oblique subduction. Here, the focus is on the interpretation of newly acquired seabed surface data (bathymetry and reflectivity, 3.5 kHz echo sounder and single channel seismic reflection with a maximum pene-

tration of 2 s twt). Gravity, magnetic, seismic reflection and swath mapping surveys were conducted to map geological structures and the thickness of sediments between the Halmahera and Sangihe arcs and the Philippine and Cotabato Trenches. The position, speed and direction of the ship were given by the GPS (Global Positioning System) navigation system. The preliminary interpretation of the structures in the survey area is based on the morphological and geophysical data gathered on board in real time. A total of 3725 nautical miles were surveyed during the cruise providing a detailed bathymetric map (Fig. 2). *L'Atalante* is equipped with a SIMRAD EM-12 dual multibeam echo sounder which provides bathymetry and reflectivity imagery of the sea floor. Only the bathymetric data are discussed here. The MODEC cruise also involved continuous gravity and magnetic measurements and six channel seismic recording. The few seismic data presented here are single channel records acquired on board and are not yet reprocessed.

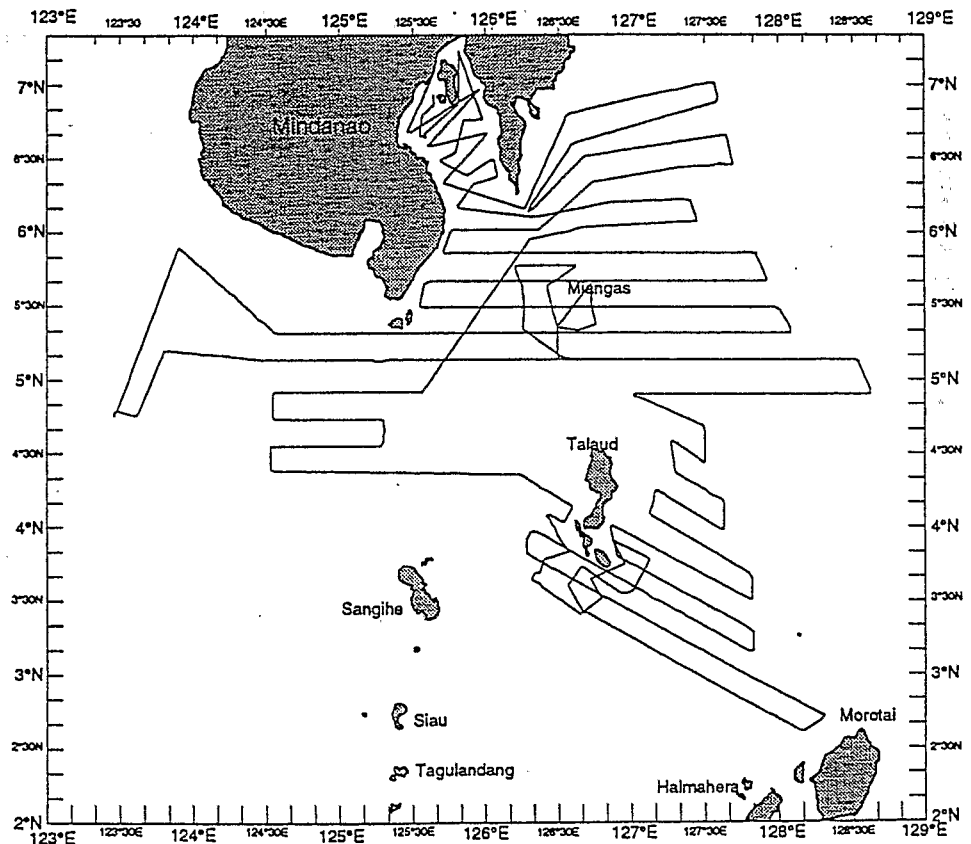


Fig. 2. MODEC cruise tracks.

Geodynamic framework

The Molucca Sea is located at the junction of three convergent major lithospheric plates (Fig. 1). The Eurasian plate is bounded by active volcanic arcs (west Mindanao, Sangihe, and north Sulawesi) and includes the marginal basins of the Celebes Sea and South China Sea which opened in Palaeogene times. The northern margin of the Australian plate extends from New Guinea in the east to central Sulawesi in the west. The Philippine Sea plate has a western part formed largely of Palaeogene and older oceanic crust (the West Philippine Basin) which probably formed in a backarc environment. The associated arc currently comprises a major part of the Philippine archipelago, now orientated approximately north-south between Luzon and Mindanao, and extending southwards into the Halmahera arc.

Kinematically, the Australian plate is moving northward with respect to Eurasia at a rate of 7–8 cm a⁻¹. The Philippine Sea plate is moving westwards with respect to Eurasia about a pole of rotation located at approximately 48°N and 157°E (Seno *et al.* 1993), at a rate which varies from 8–10 cm a⁻¹ from north to south along the Philippine Trench. The West Philippine Basin therefore subducts along the Philippine Trench more obliquely in the north than in the south. The Philippine fault, parallel to the trench, accommodates part of the lateral component of this movement, assuming a simple model of shear partitioning. As a result the East Philippine crustal fragment is displaced to the north.

The recent development (3 to 5 Ma) of subduction at the Philippine Trench is suggested by (1) the presence of a slab extending to less than 200 km depth (Cardwell *et al.* 1980; McCaffrey 1982); (2) recent arc volcanism in eastern Mindanao (Quebral *et al.* 1995); and (3) young arc volcanism in Leyte, Samar and Bicol (Aurelio *et al.* 1991). The formation of this new active margin is interpreted to be the result of a jump in the position of the subduction zone from west to east after the Philippine arc collided with the Eurasian margin.

Further south in the Molucca Sea, the Halmahera arc, carried on the Philippine Sea plate, is in frontal collision with the Sangihe arc (McCaffrey *et al.* 1980). The Philippine Trench terminates at this latitude (Nichols *et al.* 1990). The collision zone is marked by a thickening of the crust below the basin, mainly deduced from gravity data and interpreted as oceanic crust imbrication in the central part of the basin (Miangas–Talaud–Mayu–Tifore ridge). The oblique movement of the Philippine plate with respect to Eurasia has therefore been interpreted to have resulted in the diachronous closure of the Molucca Sea basin. The

presence of a slab more than 700 km below the Celebes Sea (Cardwell *et al.* 1980) provides an indication of the extent of the subducted oceanic basin.

The Philippine archipelago is the site of the active collision between the Philippine Sea plate carrying an extinct volcanic arc and continental fragments rifted away from the Eurasian margin (Holloway 1982; Rangin *et al.* 1990a). The present tectonic setting of the Philippines shows an elongated Philippine Mobile Belt, fringed by two recent subduction zones (Lewis & Hayes 1983), and traversed axially by the 2000 km long left-lateral Philippine fault (Willis 1937; Allen 1962; Aurelio *et al.* 1991). The volcanic arc of Oligocene age, which forms the basement to the eastern part of the mobile belt, is in tectonic contact with the Eurasian margin represented by continental fragments exposed in the western part of this belt, and rifted away from the Eurasian mainland in south China (Holloway 1982; Rangin *et al.* 1990a).

Southeast of Mindanao, the collision between the Halmahera arc and the along-strike equivalent of the western part of Mindanao occurred during the Late Pliocene and Pleistocene (Moore & Silver 1983; Hawkins *et al.* 1985; Mitchell *et al.* 1986; Pubellier *et al.* 1991; Quebral *et al.* 1995). According to many authors (Roeder 1977; Cardwell *et al.* 1980; McCaffrey *et al.* 1980; Moore & Silver 1983; Hawkins *et al.* 1985), the arc–arc collision of the Molucca Sea should be traceable onshore into Mindanao, and the Philippine fault has been interpreted as the inferred suture. However, geological observations (Mitchell *et al.* 1986; Pubellier *et al.* 1991) indicate that the Philippine fault is not a former suture although a possible suture candidate may be traced through the Cotabato basin.

Transect across the Northern Molucca Sea

On the basis of the newly acquired bathymetric data (Fig. 2), this paper presents first a summary of the key features and preliminary interpretations of a NE–SW transect across the Molucca Sea south of Mindanao island. This northern transect extends from the Philippine Sea plate to the Celebes Sea immediately south of Mindanao. We then discuss a shorter but complementary transect carried out further south, around the Talaud Islands.

1. Philippine Trench to the Cotabato Trench

Various morphostructural provinces are distinguished from east to west along this transect (Fig. 3).

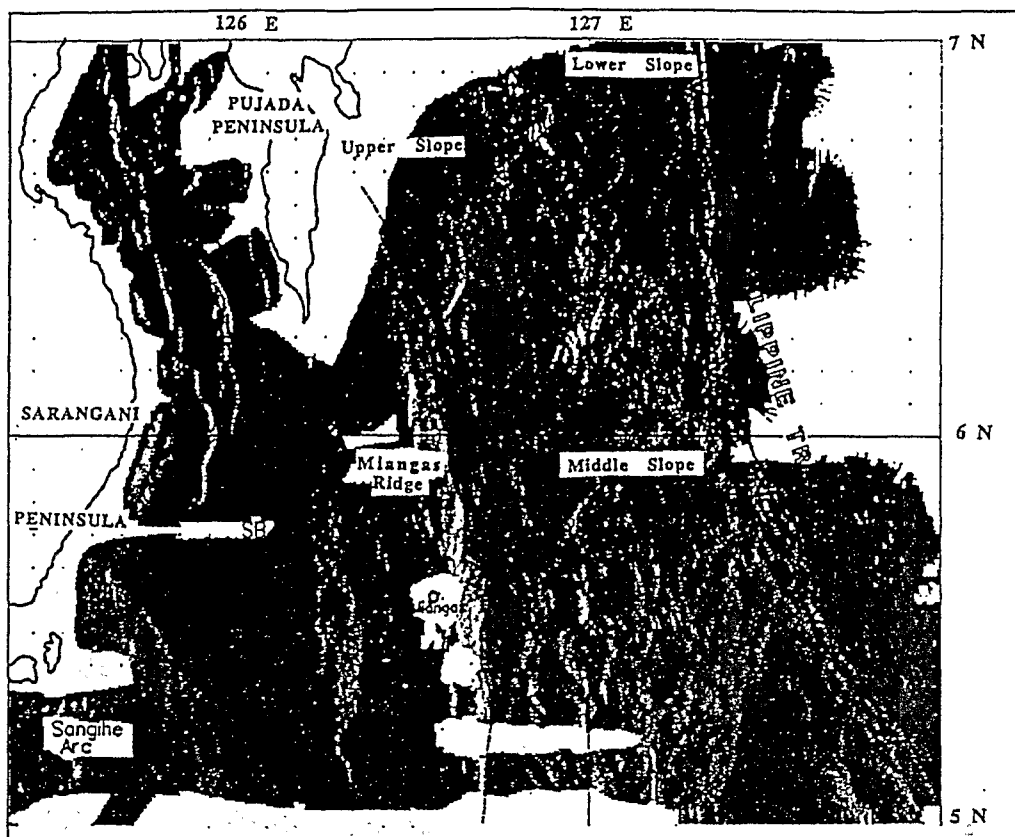


Fig. 3. Shaded image of the sea bottom in the northern most part of the Molucca Sea, south of Mindanao. The main morphological units of the area are shown. DB: Sarangani-Davao Depression; SB: Sangihe forearc Basin; PR: Pujada ridge; CD: Central Depression.

Outer slope of the Philippine Trench

Close to 6°N, there is a dog-leg bend of the Philippine Trench. The trench trends north-south in the north and suddenly changes to a mean direction of NNW-SSE further south. North of 6°N, the outer slope shows regularly spaced west-facing fault scarps interpreted as parallel normal faults, down-thrown towards the trench, with vertical offsets which are up to 900 m (Fig. 4). The outer slope is one of the steepest outer slopes observed at a trench anywhere in the world with gradients of up to 11° to the west. South of 6°N, the outer slope is less steep with an average gradient of 6°. Linear sub-parallel scarps trend at 160° to 170° and are slightly oblique to the north-south trend of the trench. The normal faults dissecting the outer slope vary in orientation from 160° to 140° and are parallel to the trench axis. In some places the faults are slightly oblique to the trench axis and trend 125° (Fig. 4). The very deep (9600 ± 100 m) V-shaped trench is characteristic of a non-

accretionary convergent margin. Its north-south trend north of 6°N is slightly *en echelon*. South of 6°N the trench consists of a series of *en echelon* basins offset along left-lateral faults resembling Riedel fractures, and its depth shallows from north to south by almost 1000 m.

The inner slope of the Philippine Trench

The inner slope of the Philippine Trench, which descends eastwards towards the trench, can be divided into three morphological areas in the northern part of the area surveyed: the lower, middle and upper slope regions (Fig. 3). South of 6°N the lower and upper slope areas lose their distinct character and merge with the middle slope. The middle slope is separated from the trench by the Snellius Ridge (Figs 3 and 4).

Lower slope. The lower slope of the upper plate (Figs 3 and 4) is geomorphologically very different

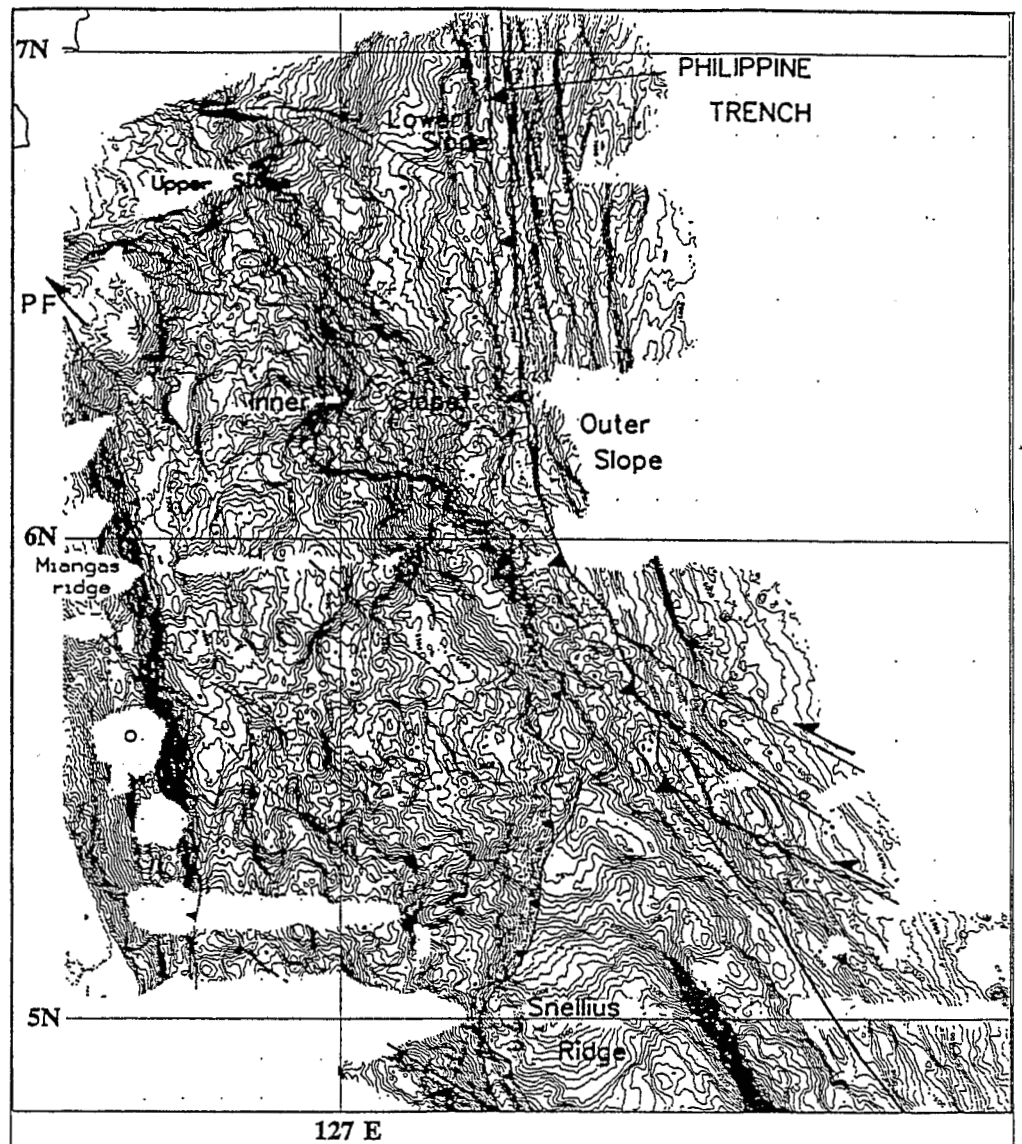


Fig. 4. Bathymetric map of the Philippine Trench Inner wall. Main structures are also indicated. South of 6°N, the complex morphostructural zone between the Snellius Ridge and the Miangas ridge is the middle slope unit.

in the areas north and south of 6°N. North of 6°N it consists of an 8000 m deep terrace. In this area, the scarps at the base of the inner wall that define the front of the margin could be interpreted either as normal or thrust faults. It is very difficult to trace the true plate boundary since no decollement is observed on seismic profiles. South of 6°N a triangular-shaped terrace lies between the Philippine Trench and the middle slope. The major feature observed in this area is a 50 km linear scarp

facing the trench with a 140° trend. A vertical offset of more than 2 km is observable along this scarp that could be interpreted as a major normal fault. West of the scarp the lower slope dips gently towards the NE and pinches out along the trench close to 5°30'N. This surface is part of the flank of the Snellius Ridge which broadens southwards.

Middle slope. The middle slope has an average gradient of 10° to the east across the whole of the

area surveyed. In the northern part of the area, north of 6°N, it is a complex morphostructural zone of interfering structures. The major characteristic of this area is a series of NW-SE trending features, interpreted as a strike-slip faults. One of these fractures appears to be the offshore extension of the Philippine fault (Quebral *et al.* 1995) exposed in Mindanao (Fig. 5). Discrete 045° trending structures are also observable and may represent a fold axial trend. South of 6°N, the orientation of the middle slope break changes from 140° to north-south, and 010° close to 5°40'N, and then turns again to 140° south of 5°N. This morphology is interpreted as a combination of NW-SE trending left-lateral strike-slip faults and 010° trending folds and thrusts. The middle slope break is probably seismically active in the southernmost part of the area since thrusts were observed on seismic profiles.

To the west, the middle slope unit is in tectonic contact with the Miangas ridge. At the base of the steep east-facing scarp of this ridge there is a narrow area of broken topography which descends over about 200-300 m to the middle slope (Figs 3 and 4). This large area (Fig. 3) has an average depth of about 3800 m between 5°30'N and 5°50'N and rises to the south and north. A number of lineaments can be seen on the bathymetric and reflectivity maps which mark irregular ridges with principal orientations of 015°, 140°, 170° and 180°. The intersection of these ridges outline a number of small rhomb-shaped, flat-bottomed basins.

Upper slope. The upper slope is steeper than the middle slope north of 6°N and absent further south. In its southern part east-verging thrusts were imaged on seismic profiles. Further to the north, lobate bodies with edges which are convex to the east, are interpreted as the manifestation of flat east-verging thrusts crossed by NW-SE trending strike-slip faults (Figs 3 & 4).

Miangas-Pujada ridges

This north-south trending bathymetric high is a complex broad feature formed by two ridges which rise from depths of 3000 m on each side (Fig. 5). To the north the western ridge continues into the Pujada peninsula and to the south the eastern ridge widens considerably to form a bank connecting southward with the Talaud Islands (Fig. 2). For most of its length this high is divided by a depression (the Central Depression of Fig. 5). In the north, the Central Depression is little more than an irregular deeper part of a single bathymetrically high area with steep east- and west-facing slopes (Figs 3 and 5). Further south the Central Depression becomes more pronounced and deeper.

The Miangas ridge. This eastern ridge remains high along all its length and is emergent on the island of Miangas at 5°36'N. In most of the area surveyed its depth is typically less than 1200 m. The ridge trends broadly towards 160° but in detail the eastern face can be seen to be composed of *en echelon* north- and 140° trending segments. It is asymmetrical in cross-section, and the highest points are on its eastern side, with a very steep east slope (average gradient 20°), and a much more gently sloping west face (average gradient 9°). This ridge has a consistently high reflectivity, and seismic lines indicate an absence of sediment on most of the upper parts of the ridge and on the very steep east-facing slope.

The Miangas ridge is interpreted to be thrust eastwards over the middle slope of the Philippine Trench. This interpretation is supported by preliminary seismicity data obtained in an OBS (Ocean Bottom Seismometer) network installed around Miangas Island during the MODEC Cruise. This temporary network revealed the possible presence of a west-dipping thrust plane below the ridge. This thrust is not observed on seismic profiles due to the steepness of the slope and the absence of sediments. The inferred thrust trace at the western base of the ridge is offset by 140° trending lineaments at 5°30'N and 5°40'N, south and north of Miangas Island respectively. These features are interpreted as left-lateral strike-slip faults offsetting the ridge (Fig. 5).

The Pujada ridge. The summit of the western ridge deepens southwards, narrows and disappears at 5°05'N (Fig. 3 & 5). South of 5°30'N, the ridge turns east and has an overall orientation parallel to the base of the Sangihe arc (*c.* 155°). Its western slope becomes somewhat less steep and more irregular although there remains a steep section about half-way up. Its eastern face has a broad, gently east-dipping upper terrace between 2000 m and 2250 m which then descends more steeply, but irregularly, to the well-marked Central Depression with a flat surface at 3700 m. The ridge has a steep west-facing slope. The reflectivity map and the seismic lines show little sediment cover and only a few discontinuous reflectors (Fig. 6); where there are reflections they mainly dip west but no structure can be identified with confidence. It is suggested that these areas are underlain by basement rocks such as ophiolites or arc volcanics. Two principal lineament orientations, 150° and 050° are parallel to the steeper slopes on the upper part of the ridge. There are no clear offsets on these lineaments and no clear indications that they are faults on seismic lines although the 150° direction is close to the orientation of the western margin of the Sangihe trough and inferred axial directions of folds within

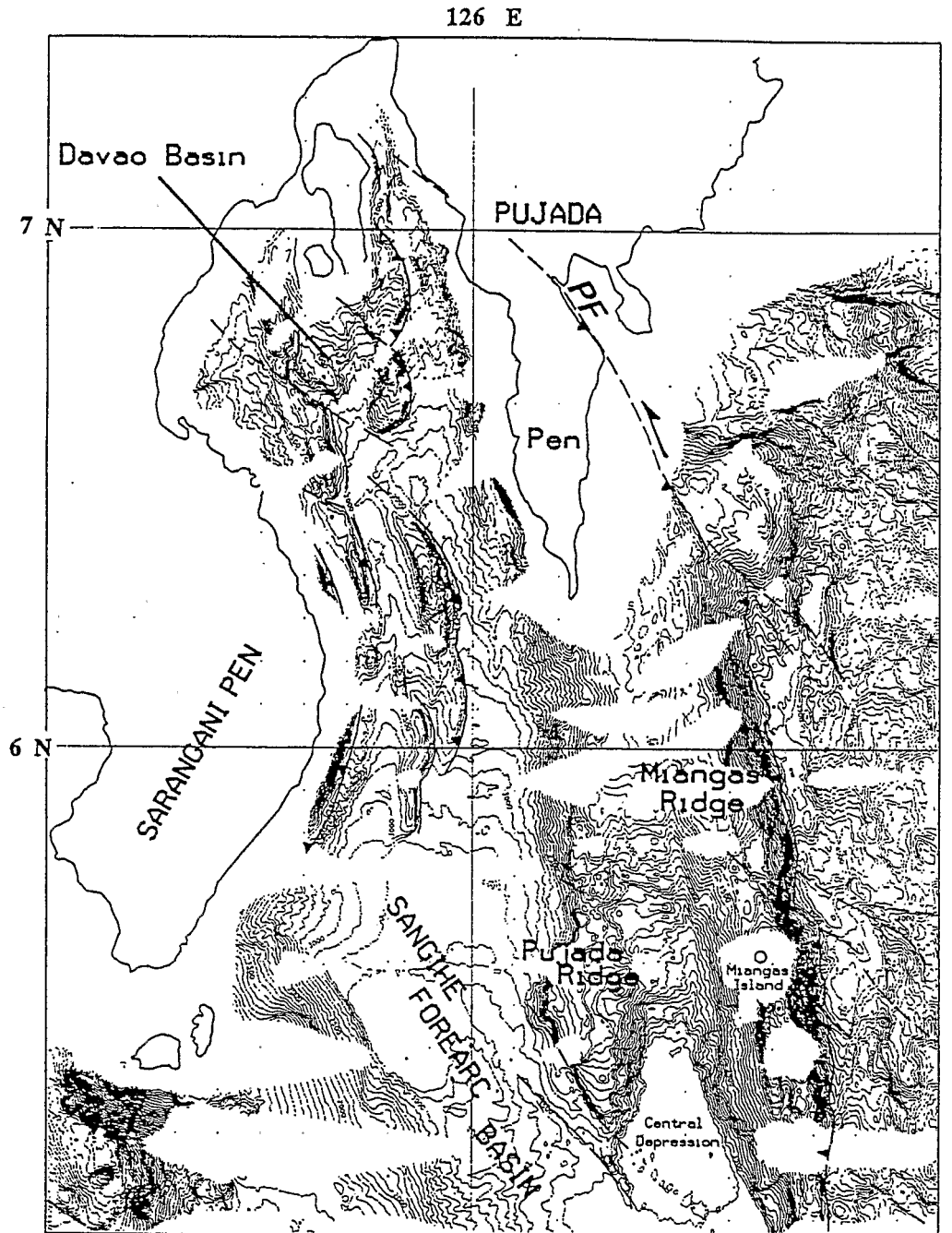


Fig. 5. Bathymetric map of the Miangas-Pujada ridges and Sangihe forearc, in the northernmost part of the Molucca Sea. Main structures deduced from analysis of seismic profiles and data collected by the Ocean Bottom Seismometers are also indicated. PF = Philippine fault.

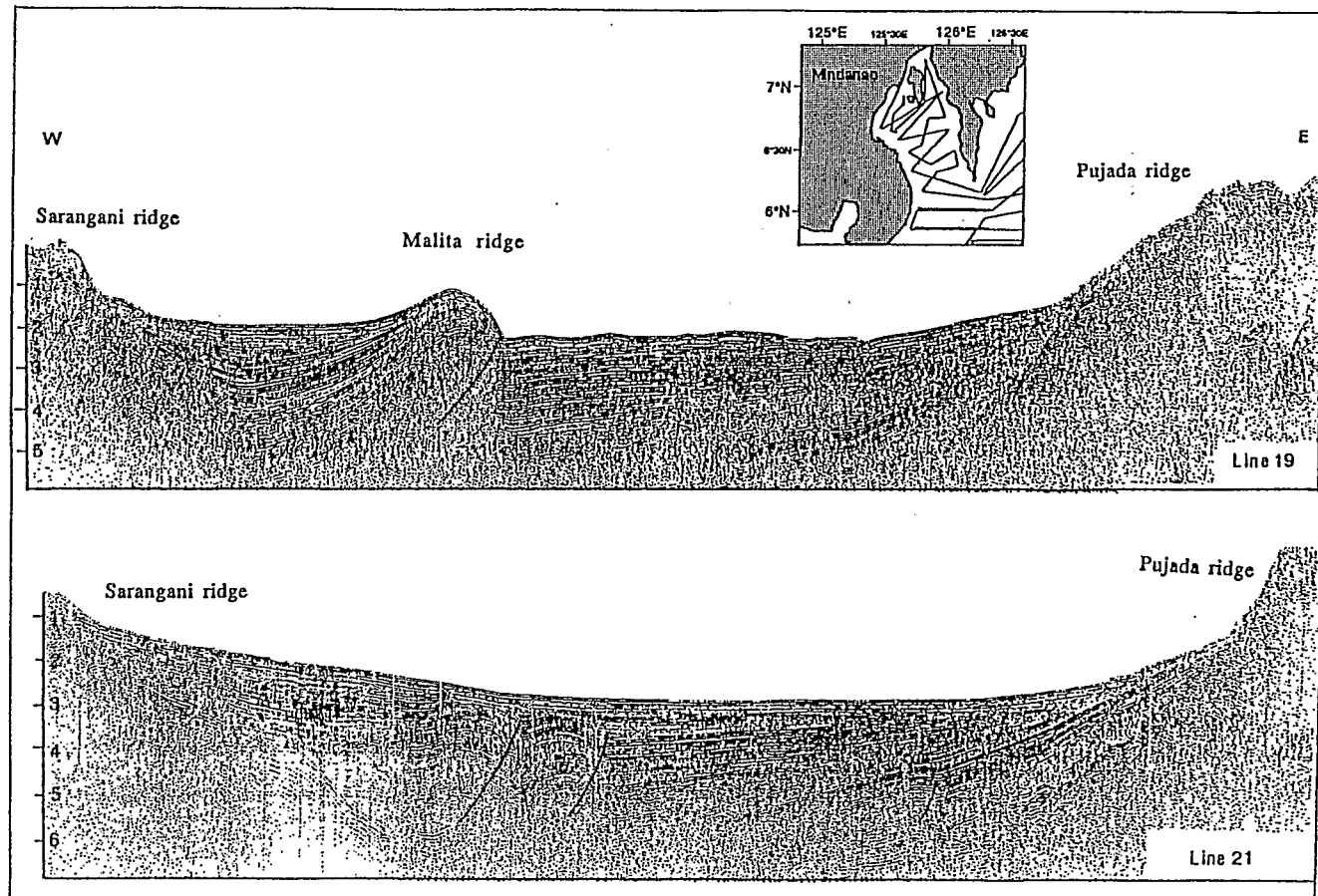


Fig. 6. Single channel seismic profiles and interpreted line drawings across the Sangihe forearc basin. Note increasing deformation in the basin from south to north.

the Sangihe trough (see below). These lineaments may represent a conjugate fault/joint set within the basement. The eastern side of the Pujada Ridge is locally steeper than the western side, but includes a number of irregular terraces which become wider southwards. Medium to low reflectivity and seismic profiles indicate that there is a sediment cover although the thickness is not great (< 1 s twt).

Over both the Pujada and Miangas ridges, the free-air anomaly map is well correlated with the bathymetry (Fig. 7). The slope descending from

the Sangihe arc is characterized by a regular gradient of the free-air anomaly with values decreasing towards the Sangihe forearc basin. The minimum (-80 mGal) is situated at the northern end of this basin at $5^{\circ}50'N$ and $125^{\circ}50'E$, above an area of thrusting, where the sedimentary thickness is probably larger. The Pujada and Miangas ridges are underlain by north-south aligned positive anomalies separated by a low corresponding to the Central Depression. The Miangas ridge, which is topographically higher than the Pujada ridge, is

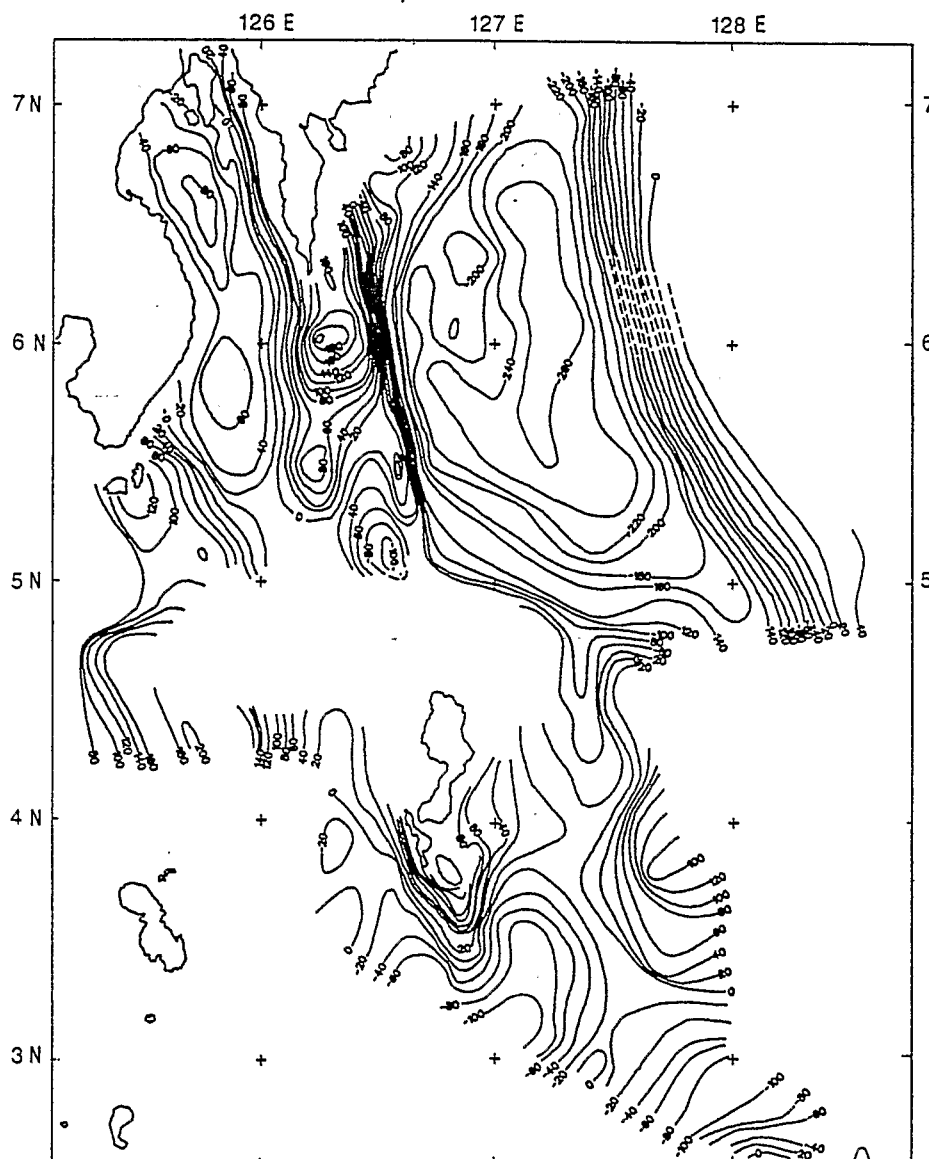


Fig. 7. Free-air gravity anomaly map of the surveyed area.

associated with a smaller anomaly. Northwards, the two anomalies merge into a single one, as the ridges do. On the eastern edge of the Miangas ridge, a steep gradient (more than 15 mGal/km) can be correlated with its steep eastern flank.

The Sangihe forearc

The Sangihe forearc basin (Figs 3 and 5) is located east of the Sangihe volcanic arc and its northern extension in Mindanao, the Sarangani peninsula, and west of prominent ridges (Pujada and Miangas) formed by ultramafic and mafic material (Fig. 3). This basin pinches out to the north in the Davao Gulf (Fig. 5), between the Sarangani and Pujada peninsulas, where we term it the Sarangani-Davao depression (Fig. 3). Between 5°37'N and 5°45'N there is a marked change in orientation of the eastern slope of the Sangihe volcanic arc, from 155° in the south to the 015° in the north. At this latitude the basin becomes wider and structurally simpler, and has a different orientation.

The Sarangani-Davao depression. With a central plain at depths of about 3200 m, the basin has an arcuate shape parallel to the Sarangani peninsula. Field work in Mindanao (Pubellier *et al.* 1991) has shown this arcuate peninsula is a large recumbent fold verging towards the east. The Sarangani-Davao depression corresponds to the northern extension of the Sangihe Basin and sediments in the basin are folded and thrust in the Davao Gulf. This is related to the active compressive tectonics affecting the island of Mindanao (Pubellier *et al.* 1991; Quebral *et al.* 1995). At the western edge of the basin, the slope of the eastern edge of the Sarangani peninsula is very steep (Fig. 5) and is interpreted as the manifestation of a buried thrust. In the central part of the basin, three broadly north-south trending, arcuate, and west-verging thrust anticlines are well marked in the bathymetry (Figs 3 & 5). Reverse faults or thrusts are observed along their eastern flanks. The free-air anomalies deduced from six gravity profiles across the basin (Fig. 7) show an asymmetric form with a clear minimum (-80 mGal) close to Sarangani shoreline on the west side of Davao Gulf. This anomaly is correlated with the thickness of sediment, suggesting a flexure of the basin due to loading, by overthrusting from the west, of the Sarangani peninsula.

The Sangihe basin. Seismic profiles across this basin show at least 2 s twt of well-stratified sediments (Fig. 6). Buried folds with a clear west-vergence are observed on seismic profiles, with an axial trend of 155°. This direction is parallel to bathymetric features at the basin margins. South of 5°25'N the seabed surface in the basin changes from a flat smooth surface to an irregular surface

cut by numerous channels. Silver & Moore (1978) extended their East Sangihe Thrust through this part of the Sangihe trough. Data presented here do not support the presence of any west-verging thrust along the western edge of the forearc basin.

Sangihe backarc and Cotabato Trench

East of the Sangihe arc, the survey was extended into the Celebes Sea and along the southeast termination of the Cotabato Trench. At about 5°N the Cotabato Trench bends from north-south to an approximately ENE-WSW orientation parallel to the southern coast of Mindanao. In the Celebes Sea basin the ship track crossed ODP sites 767 and 770 (Fig. 8).

South of 4°50'N the feature corresponding to the continuation of Cotabato Trench is a broad flat-bottomed area, sloping gently northwards. A large meandering canyon running south to north down to 5°N probably originates from the large island of the Sangihe group indicating the trench dies out morphologically further south. To the east volcanoes are aligned north-south on the western flank of the Sangihe arc. At 4°40'N a conical seamount, probably belonging to the nearby Sangihe volcanic arc, rises 3500 m above the sea floor. Between 4°50'N and 5°20'N the Cotabato Trench bends from an orientation of 000° in the south to 120° in the north. The trench floor deepens from 5100-5900 m as it approaches the Sangihe arc. At the northern end of the north-south trending section (north of 4°50'N), which is marked by a 100 mGal negative gravity anomaly, a narrow NNE-trending accretionary wedge is observed at the foot of the steep western flank of the Sangihe arc.

At the trench bend there is an intermediate zone which trends 145° and is separated from the Sangihe arc by a non-linear ridge and a plateau which could be the physiographic equivalent of an outer arc high. A NNW-SSE trough 5100 m deep, is parallel to these on their landward side. Here, the trench-fill sediment sequence thickens significantly up to 2 s twt. A re-entrant in the wedge associated with bending of an anticline axis is interpreted as the effect of a subducted asperity (ridge or seamount) on the sea bottom. This is supported by the presence of a 1600 m high curved scar observed in the bathymetry of the wedge at 5°20'N, 124°50'E, which could be attributed to the collapse of the margin following the subduction of a seamount.

Along the Cotabato active margin, which trends at 120°, the lower slope consists of a series of anticlines, 20-30 km apart, with curved axial traces which are concave upslope, forming a wide fold-and-thrust belt typical of an accretionary wedge.

The trend of the anticlines is roughly parallel to the trench axis with an *en echelon* pattern in several places. An outer arc high, 400–500 m in elevation, separates the accretionary complex from what is suspected to be a forearc basin with an upper surface dipping slightly towards the southeast. A large gravity low is located over the accretionary wedge probably reflecting a thick sedimentary prism.

The 4600–5500 m deep abyssal plain of the Celebes Sea basin shows several ridges and seamounts sitting on the oceanic crust. On seismic profiles the basin floor has a very rough undulating surface (amplitude of a hundred metres) which possibly reflects the original grain of the oceanic crust overlain by no more than 0.5 s twt thick sediment cover. The first sediments deposited onto the basement were dated at 43 Ma during ODP Leg 124 (Rangin *et al.* 1990b). In the vicinity of the trench no clear normal faults were observed on seismic lines. The bathymetric map (Fig. 8) shows lineaments, ridges and troughs trending 110° in the northwestern part of the area surveyed. An elongated positive feature, 1.5 km above the sea floor and without a magnetic signature, interpreted as a group of seamounts, trends WSW, parallel to the magnetic lineations proposed by Weissel (1980) in the basin. Another major feature, trending north-south, is more than 100 km long and 10 km wide and rises 1 km above the sea floor.

2. Talaud Islands to Morotai Basin

A second transect, orientated NW–SE, south of the Talaud Islands, was surveyed in the deep waters between the Morotai Basin and the Sangihe trough. It was chosen to be perpendicular to the regional morphology. South of 5°N , the Miangas ridge merges into a very shallow area covered by reefs around the Nanusa Islands (Fig. 9). To the east, the Snellius Ridge which flanks the Philippine Trench between $4^\circ50'\text{N}$ and $5^\circ30'\text{N}$, becomes very shallow south of $4^\circ50'\text{N}$. Consequently, most of the area at the latitude of the Talaud Islands was not surveyed because it is too shallow. Various morphological provinces were identified from west to east.

Sangihe trough

Only a small part of the undeformed Sangihe fore-arc basin (Sangihe trough on Fig. 9) was surveyed in this area (Fig. 9). The flat part of the trough is much narrower here than in the north. The area deeper than 3500 m is less than 25 km wide. The trough is slightly deeper in its central parts and reaches depths of 4000 m. The West Talaud Bank rises from the Sangihe trough towards the Talaud

Ridge and its lower slopes form two terraces (Fig. 9) which occupy a triangular area which is narrow in the north and widens southward. The eastern margin of the West Talaud Bank is bounded by west-verging thrusts following the base of the cliffs of the Talaud ridge where a second OBS temporary network has been deployed (Fig. 9). The West Talaud Bank is thus thrust towards the west above the undeformed Sangihe trough.

Talaud ridge

The Talaud ridge forms a high area between the 2000 m bathymetric contours. Little of the ridge appears on the map (Fig. 9) because of the very shallow depths of the ridge summit. In the northern part of the area surveyed the Talaud and Nanusa Islands are part of the same wide ridge, but further to the south the Talaud ridge narrows and swings southeastward. These trends are reflected by the shape of the islands' coastlines. On seismic profiles the ridge lacks any continuous reflectors and a very thin sediment cover was observed above basement rocks, possibly ophiolites or arc volcanic rocks, as indicated by the geology of the Talaud Islands on land (Sukanto *et al.* 1980; Moore *et al.* 1981). Both east and west flanks are fault controlled. These are most likely to be thrust faults because the fault contacts are sub-parallel to the curved isobaths.

East Talaud Bank

The eastern margin of the Talaud ridge is a wide area, named the East Talaud Bank, which connects northwards to the middle slope of the Philippine Trench inner slope (Figs 3, 9, 10). South of $3^\circ55'\text{N}$, the East Talaud Bank is very wide (about 35 km) and has an irregular surface which is convex-upwards. North of $3^\circ55'\text{N}$, it becomes considerably narrower (about 18 km wide), and forms a north-south trending feature between depths of 1500 and 3000 m. South of 4°N (Fig. 9), the bank is separated from the Talaud ridge by NW-dipping thrusts. Seismic profiles show that the East Talaud Bank resembles the West Talaud Bank which is interpreted as the deformed margin of the Sangihe Basin to the west.

Along the east flank of the bank, a major low angle thrust can be traced southwards from $4^\circ40'\text{N}$ to $4^\circ00'\text{N}$ where it has a north-south trace; it then turns, first towards 140° , and then further south towards 030° . There are at least 3 s twt of sediments in the slice above the thrust plane, which carries the East Talaud Bank eastwards onto the Snellius Ridge, an observation reported previously by Silver & Moore (1978).

The Talaud ridge, and the East and West Talaud Banks on each side, are cut by 140° scarps that

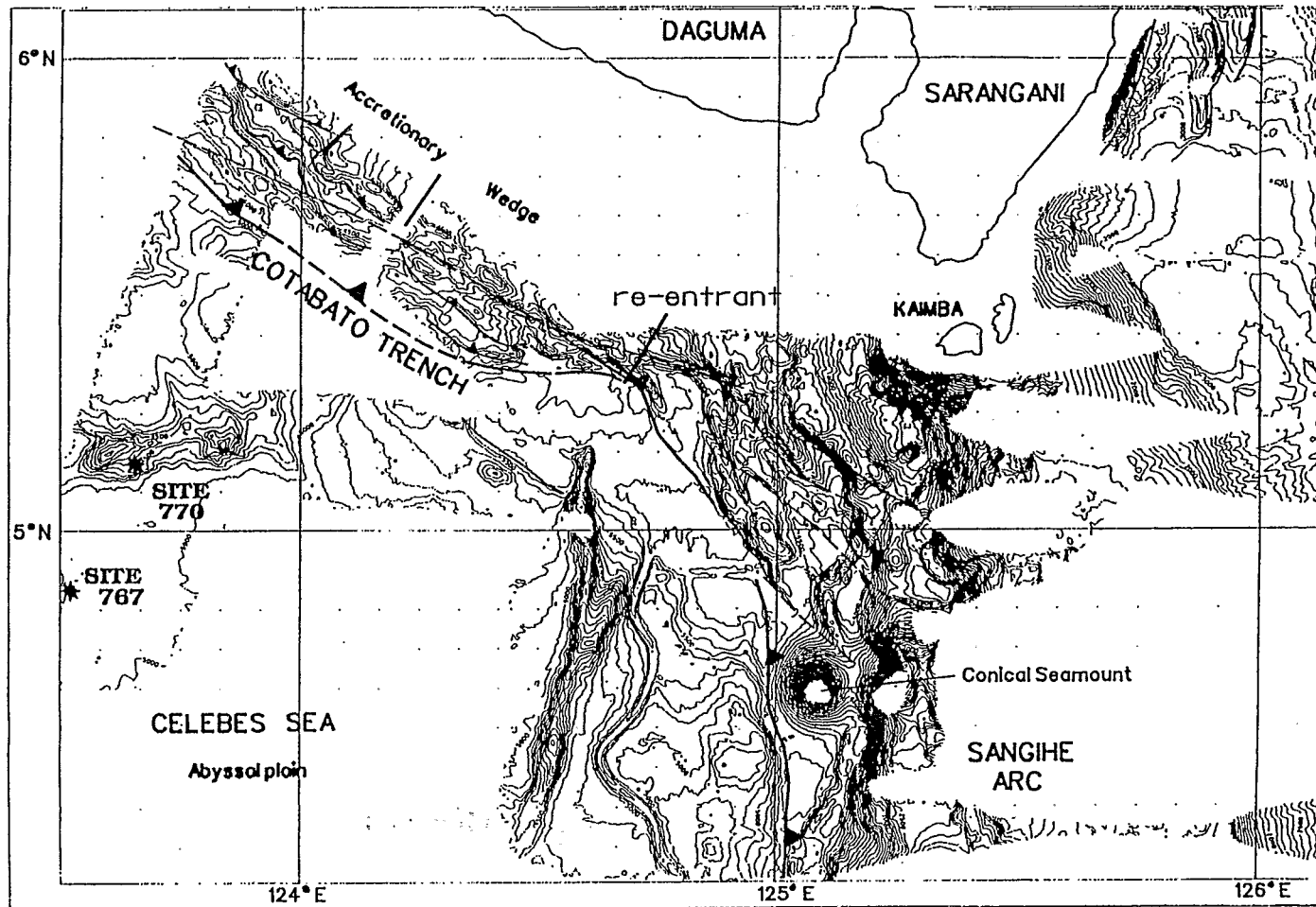


Fig. 8. Bathymetric map of the Cotabato Trench (Sangihe backarc area). Note the sharp bend of the trench and large volcanoes built along the trench axis. Major structures observed on seismic profiles and 3.5 kHz echo-sounder recordings are shown.

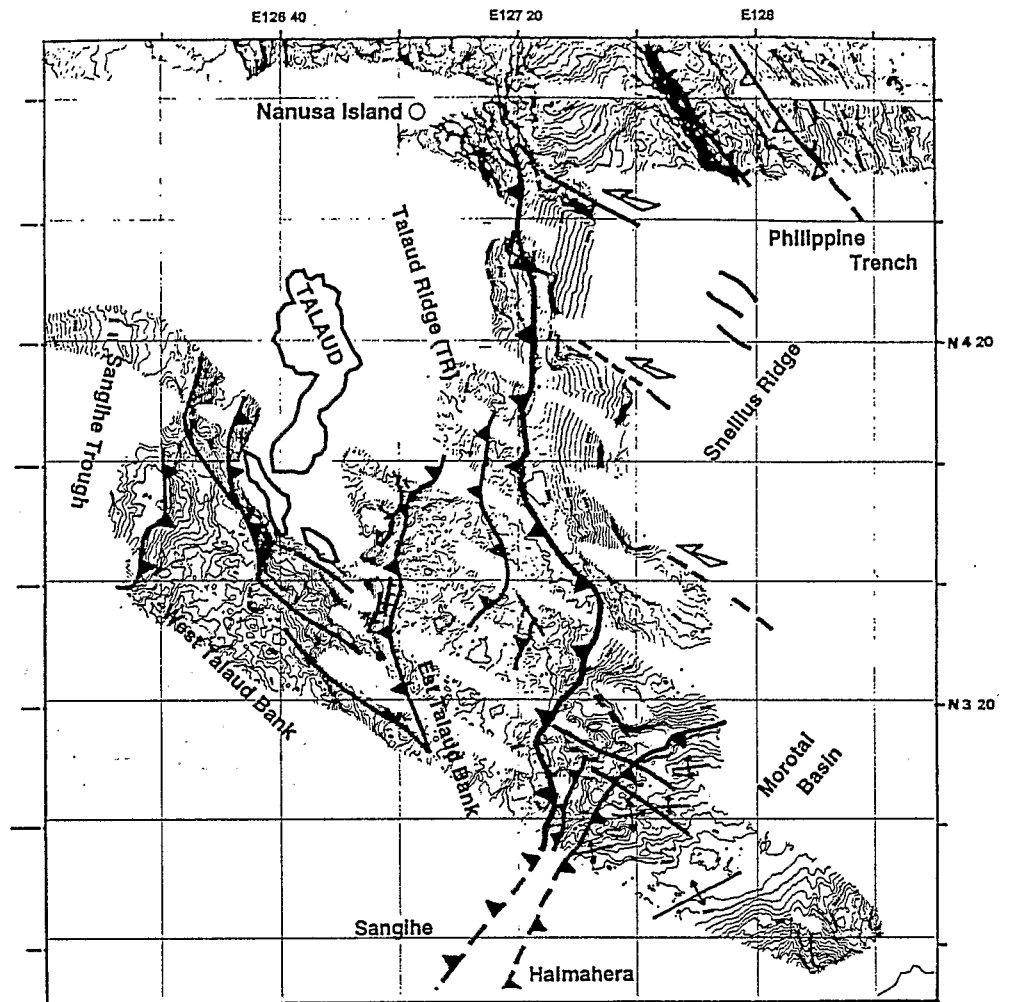


Fig. 9. Bathymetric map of the area around the Talaud Islands showing the main interpreted structural elements.

could be strike-slip fault zones. This is supported by the evidence of earthquakes in this area with strike-slip focal mechanisms (McCaffrey 1991). The progressive offset of morphological units towards the northwest suggests left-lateral motion on these faults.

Snellius Ridge

East of the main thrust separating it from the East Talaud Bank, the Snellius Ridge is a large submarine plateau sloping to the west with a gradient of 3–6°. South of 3°40'N (Fig. 9) the plateau is dissected by SW-facing fault scarps trending 140°. These features also dissect the northern margin of the plateau (Fig. 9) and are interpreted as the trace of major strike-slip fault zones (see above). Well

developed reflectors at the top of the Snellius Ridge could be platform carbonates capping the plateau. The positive gravity anomaly over the Snellius Ridge suggests a dense crust compatible with an ophiolitic or arc origin for the basement.

In the southern and deepest end of the Snellius Ridge is the Morotai Basin. This basin has an elongate shape with its major axis orientated 070°, and has a maximum depth of about 3500 m. Along its northwestern margin, it is thrust westwards onto the Snellius Ridge, and folds trending 075° deform the basin sediments. These structures terminate abruptly to the west at the curved thrust zone where the Morotai Basin margin is thrust on top of the Snellius Ridge. Further south the basin is filled by more than 1.5 s twt of almost undeformed sediments. There is no evidence for significant

deformation at the southern side of the basin close to Morotai Island within the area surveyed, although a little further south the sea bottom rises rapidly from depths of more than 3000 m to emerge at the steep fault-controlled coasts of the island.

The southwest end of the Snellius Ridge is situated between two convergent thrust fault zones, and is beneath the East Talaud Bank and the Morotai Basin (to the NW and SE respectively). The superficial convergent thrusts in this area are thus compatible with interpretations at depth that show two convergent subduction zones and an inverted U-shape of the subducted Molucca Sea oceanic slab. More precise correlations need to be done between the superficial data collected during the cruise and structures at depth.

Discussion

During the MODEC cruise in the northern Molucca Sea it was possible to trace the Sangihe forearc

continuously over 500 km from north to south. Between the eastern edge of the forearc and the Philippine Trench, three major crustal units or terranes were also mapped almost continuously from north to south (Fig. 10), and are interpreted to be separated by major lithosphere-scale boundaries.

Miangas-Pujada-Talaud unit

The Miangas-Pujada-Talaud unit is probably formed by ophiolite slivers and melanges; it can be traced from the Pujada peninsula to the Talaud Islands, with a major offset between Miangas and Talaud north of the Nanusa Islands. The Pujada-Miangas ridge is overlapped westward by the sediments of the Sangihe forearc basin; further south at the southern end of the Talaud ridge there are west-vergent thrusts moving the ridge onto the edge of the Sangihe forearc basin. This ridge could be interpreted as the backstop of the Sangihe subduction zone, implying it is underlain by

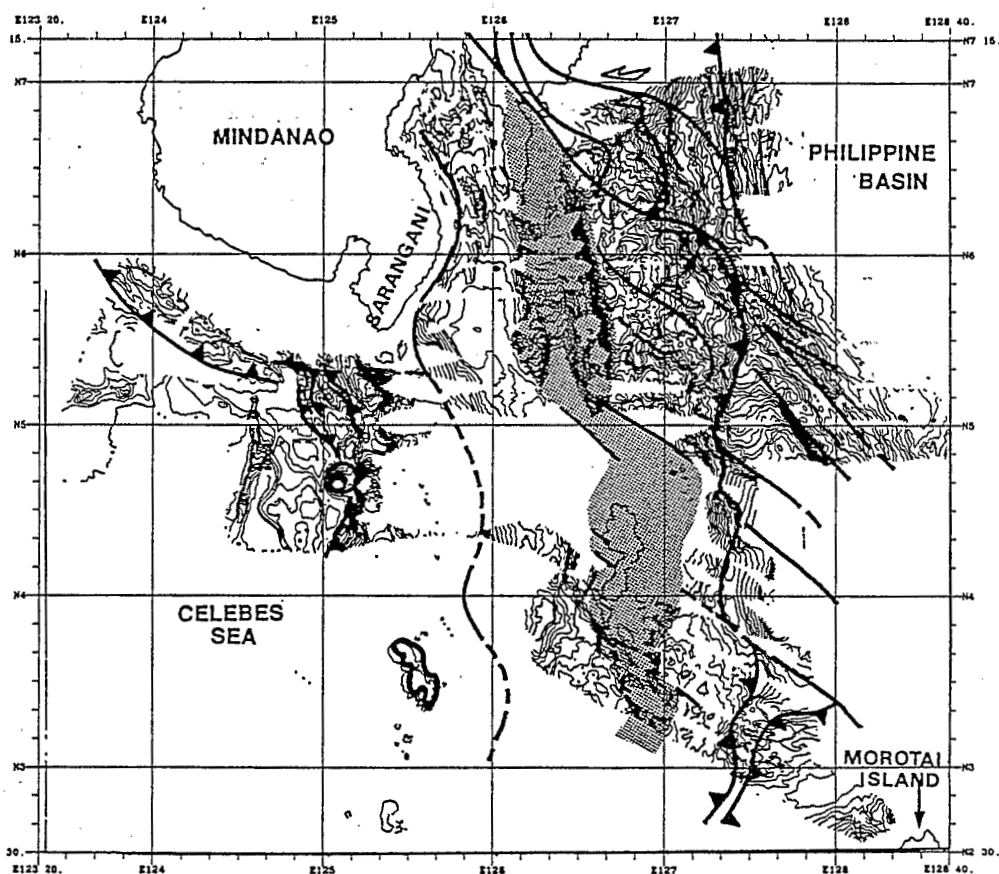


Fig. 10. Overall interpretation of the northern Molucca Sea. The shaded area is the Miangas-Pujada-Talaud unit probably formed by ophiolite slivers and melanges. Immediately east of this is the middle slope unit.

Sangihe forearc basement rather than oceanic crust of the subducted Molucca Sea. The Miangas-Pujada-Talaud unit is separated from the Philippine Trench middle slope terrace by a major discontinuity that could be a lithospheric-scale thrust. Seismic focal mechanisms associated with this thrust are clearly compressive with east-west P axes. This thrust can be traced south at least to 3°N at the foot of the Talaud ridge.

Middle slope unit

The middle slope unit, lying immediately to the east of the Pujada-Miangas ridge, is formed by low density material as indicated by the free-air gravity data. The middle slope unit can be traced southward into the East Talaud Bank which is thrust eastwards onto the Snellius Ridge, almost certainly a fragment of the Halmahera arc terrane. North of 5°30'N, this thrust fault approaches the Philippine Trench. A broad gravity low trending north-south, about 100 km long and with minimum values of -260 mGal is centred on the middle slope unit (Fig. 7) and is clearly shifted to the west with respect to the Philippine Trench (-220 mGal). This anomaly cannot therefore be attributed to the classical gravity low associated with deep trenches. The juxtaposition of the low density material of the middle slope unit in the north and the high density material of the Snellius Ridge in the south, could be explained by the presence of a major crustal discontinuity trending 140°. The orientation of isogals on the free-air gravity map above the middle slope unit changes from north-south to NW-SE approaching the northern edge of the Nanusa Islands and the Snellius Ridge (Fig. 7). The discontinuity is also marked by a pronounced NW-SE steep gravity gradient. It is also sub-parallel to the orientation of the Philippine Trench south of 6°N (Fig. 10). Such a gradient and discontinuity is also clear in recent satellite FAA data. This supports the presence of a major crustal-scale fault zone separating two contrasting terranes.

The middle slope unit could be composed of accreted sediments, and be part of the Sangihe accretionary wedge, with the Snellius Ridge representing part of the Halmahera arc. In this interpretation the boundary between the colliding arcs would be the thrust at the base of the middle slope and East Talaud Bank. An alternative interpretation is to consider this unit as a part of the Halmahera arc like the Snellius Ridge to the south. The middle slope unit would then represent an intra-arc basin. Such contrasting features are known within the Halmahera arc system to the south (Hall *et al.* 1988a, b; Nichols & Hall 1991). In this case the major west-dipping thrust located east of the Miangas-Talaud ridge would be the

main tectonic boundary between the Sangihe and Halmahera arcs. The major crustal discontinuity trending 140° which offsets the Pujada-Miangas ridge relative to the Talaud ridge is interpreted as a left-lateral strike-slip fault zone.

Philippine Trench

The dog-leg shaped Philippine Trench has two distinct segments. The north-south trending segment north of 6°N is the trace of the recently established west-dipping subduction zone as indicated by the short subducted slab. The trend of this trench segment is completely independent of the dominant oblique NW-trending structures observed in the inner slope. In contrast, south of 6°N, the NW-SE trending segment of the Philippine Trench is parallel to the interpreted left-lateral strike-slip fault zones observed in the whole forearc area. The southern segment of the Philippine Trench is tentatively interpreted as the trace of a major left-lateral strike-slip fault zone dissecting the Halmahera terrane. The small faults in Riedel position observed along this part of the trench support this hypothesis. However, thrust fault focal mechanisms of seismic events reported by Ranken *et al.* (1984) along this trench segment reveal this strike-slip fault zone is now turning into a thrust (Nichols *et al.* 1990). This suggests a migration of the Philippine Trench towards the south along pre-existing strike-slip fault zones. It is also possible that, although focal mechanisms support a thrust interpretation of this fault zone, the main long-term motion is strike-slip, possibly aseismic.

Conclusion

The area surveyed in the northern Molucca Sea reveals the presence of two distinct geodynamic settings east of the Miangas-Pujada-Talaud ridge. A major NW-SE trending tectonic boundary separates these two areas.

South of 6°N, the Snellius Ridge, a volcanic plateau capped by carbonates, is subducting below the Sangihe forearc terrane. The buoyancy of this plateau, a fragment of the Halmahera arc terrane, has induced deformation in the upper and lower plates (Talaud ridge and Morotai Basin). Its buoyancy also induces incipient subduction along a new plate boundary, the Philippine Trench. This neotectonic feature is developed along a former strike-slip fault zone cross-cutting the Halmahera terrane.

North of the major NW-SE crustal discontinuity crossing the area surveyed, a wide accretionary prism is present within the inner slope of the present Philippine Trench. The thickness of this wedge cannot be explained by subduction along

this trench because it is very recent (Cardwell *et al.* 1980; Quebral *et al.* 1995). This wedge could be interpreted either as an accretionary wedge developed at the deformed leading edge of the Sangihe forearc or be part of a former intra-arc basin which was part of the colliding Halmahera arc terrane. There is no evidence from gravity data of dense material comparable to the Snellius Ridge below this wedge. If the ridge extended originally north of 6°N, it could have been already subducted to some greater depth, or be considerably displaced left-laterally, as suggested by the presence of a similar buoyant terrane in central Mindanao (Pubellier *et al.* 1991).

This survey also reveals no clear evidence for

accreted oceanic crust belonging to the recently subducted Molucca Sea. The Miangas-Pujada-Talaud Ridge is clearly in a back-stop position for the Sangihe arc, and the ophiolites of this ridge could therefore have very different origin from either the Molucca Sea or the Halmahera arc.

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