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Seabeam survey at the southern end of the Manila trench. Transition between subduction and collision processes, offshore Mindoro Island, Philippines

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Abstract

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The morphological and structural study conducted at the southern tip of the Manila trench, reveals that convergence between the South China Sea basin and Luzon is accommodated differently depending on the nature of the subducted slab.

When the oceanic crust is subducted, a simple accretionary prism–fore arc basin pattern is developed. Conversely, where the continental margin of this basin is subducted, intraplate deformation is randomly distributed across the major part of the fore arc area which is fragmented into various crustal microblocks. Results of seabeam mapping, and detailed geophysical surveying conducted at this subduction–collision transition zone, during the POP2 cruise, with R.V. "Jean Charcot" are presented and discussed here, and allow us a new insight into the mechanism of such a subduction–collision transition zone.

Introduction

The subduction front of the Manila trench is the emergence of an important plate boundary between the South China Sea basin and its margins which belong to the Eurasian plate, and the Luzon island arc which can be considered as part of the Philippine Sea plate (Fig. 1). This island arc extends from Taiwan in the north to Luzon and Mindoro in the south (Wolfe, 1981; Stephan et al., 1986).

The seismicity along this plate boundary attests

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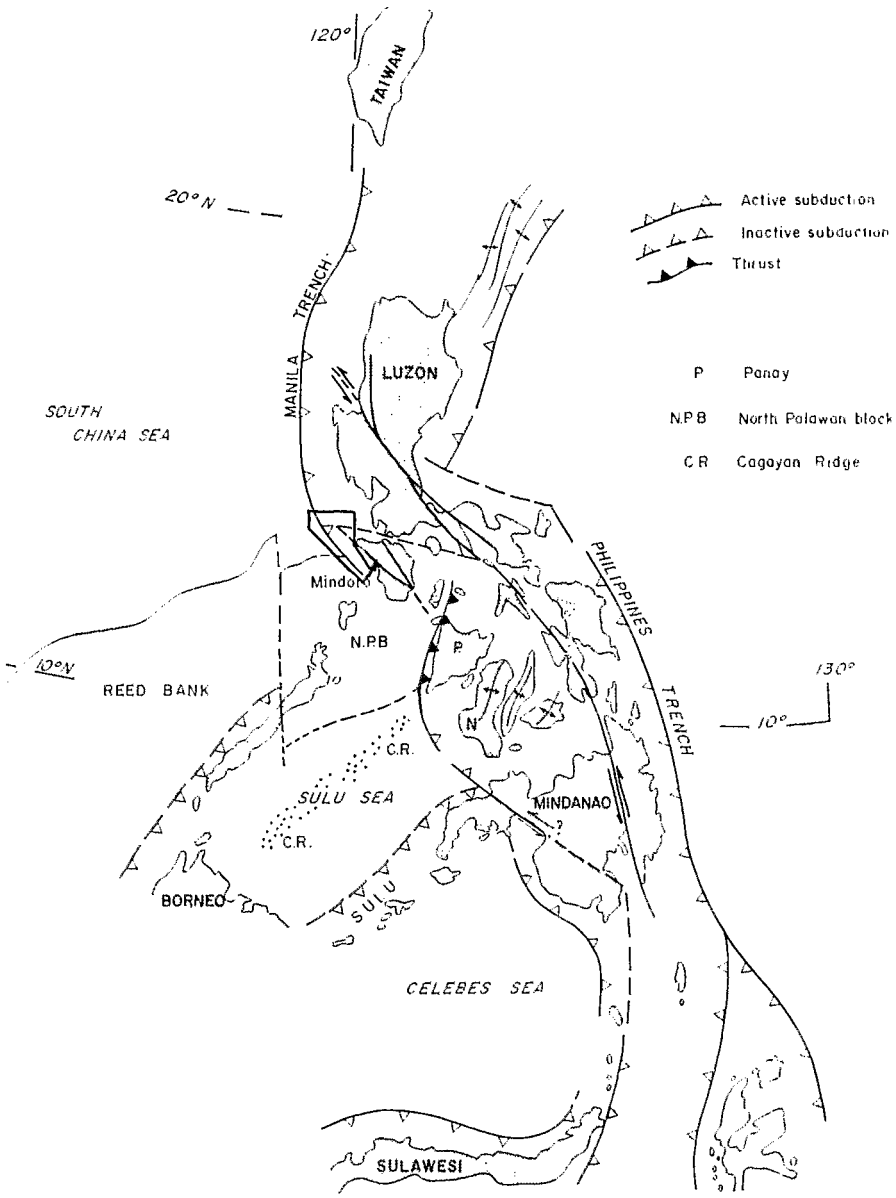

Fig. 1. Structural geology sketch map of the Philippines showing the area studied at the southern tip of the Manila trench.

to an active subduction zone (Cardwell et al., 1980; Hamburger et al., 1983) with a significantly more important subduction rate in the southern part of the trench than in the northern part, and a down going plate which dips more steeply southward approaching the Mindoro coast. The multichannel seismic profiles located between 20° and 14° N, published by Hayes and Lewis (1984) show a quite typical fore arc pattern, with a well-developed fore arc basin and accretionary prism, as is documented in other convergent zones (Dickinson and Seely, 1979).

However, the way in which the Manila trench terminates to the south is poorly understood, and available offshore data are scarce. Karig (1983) is the only author to propose a quite understandable structural sketch map for this area on the basis of some unpublished seismic profiles, revealing that the fore arc basin does not exist south of 14° N and that it is limited to the south by the E–W-

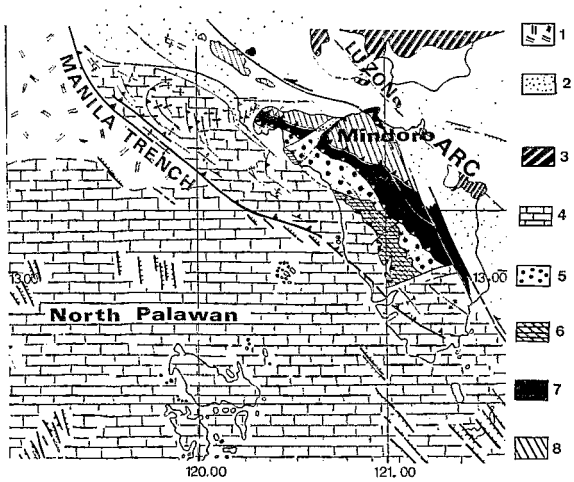

Fig. 2. General structural geology sketch map of the southern tip of the Manila trench. *1* = South China Sea oceanic crust; *2* = Late Miocene–Present clastic sedimentary basins; *3* = Luzon arc volcanoes; *4* = North Palawan–San José Mindoro platform; *5* = Eocene–Lower Miocene clastic sediments; *6* = Middle Oligocene Mindoro ophiolites; *7* = Cretaceous ophiolites; *8* = Mindoro metamorphic Paleozoic basement.

trending Lubang ridge, connecting to the east with the Verde Passage suture, a speculative left-lateral strike-slip fault zone. South of the Lubang ridge, the fore arc area is poorly known offshore, and only scarce industrial seismic lines are located close to the Mindoro coast by Sarewitz and Karig (1986).

The trench shows an important change in trend approaching the Mindoro coast, towards an area of important on shore active thrust faults (PNOC unpublished seismic profiles). Here, both the upper plate and the lower plate are formed of the same sedimentary units, both belonging to the continental margin of the South China Sea (Fig. 2) and outlining the intracontinental setting of this convergent zone.

The objective of the survey carried out off Mindoro during the autumn of 1984, with R.V. "Jean Charcot", was to document the intersection of the Manila trench with the South China Sea continental margin, and to compare the fore arc geomorphological situation along this subduction–collision transition zone. In the studied area, about 3300 nautical miles have been covered during the POP 2 cruise off southern Luzon and Mindoro Island (Fig. 3). The principal equipment used was the seabeam coupled with single channel seismic, magnetic and gravimetric recording. The fine structure of the first 100 m of sediments was studied using 3.5 kHz echo sounding. The seabeam lines were reset on the R.V. "Jean Charcot", and the bathymetric maps redrawn with a maximum overlapping at the line intersections. The identified structures interpreted on seismic profiles were plotted on the respective bathymetric profiles, allowing a three-dimensional picture of the studied area.

The lower plate morphostructure

The downgoing plate is formed by the South China Sea oceanic crust and its southern passive margin which is formed of continental crust (Holloway, 1982).

According to Taylor and Hayes (1980, 1983), spreading of this oceanic basin occurred between 32 and 17 Ma, but the opening history of this basin is characterized by two probable episodes of spreading with two distinct extensional trends (Pautot et al., 1986). The axis of the basin clearly shows a N60°E structural trend, outlined by normal faults, but the deeper part of the oceanic basin is apparently outlined with poorly documented N80°E-trending faults.

The southern margin of this basin displays a clear structural pattern trending N60°E, crosscut by N130°E-trending fault scarps, interpreted as possible strike-slip faults. (Hinz and Schluter, 1985). However, Fricaud (1984), has revealed that the N60°E-trending normal fault pattern postdates the N80°E one, thus documenting various episodes of normal faulting in this area.

In the surveyed area, the seismic profiles show a clearly kinked lower plate, dipping steeply toward the trench axis and affected by small scarce E-facing fault scarps (Fig. 4). North of 13°40′N, the faults trend N10°W–N30°W, while south of 13°20′N they trend N130°E.

There is no clear evidence of reactivated normal faults on the seismic profiles (as is documented in the Middle America trench (Aubouin et al., 1986) or along the Nankai and Japan trenches (Le Pichon et al., 1986) that could suggest that the major part of the observed minor faults are the

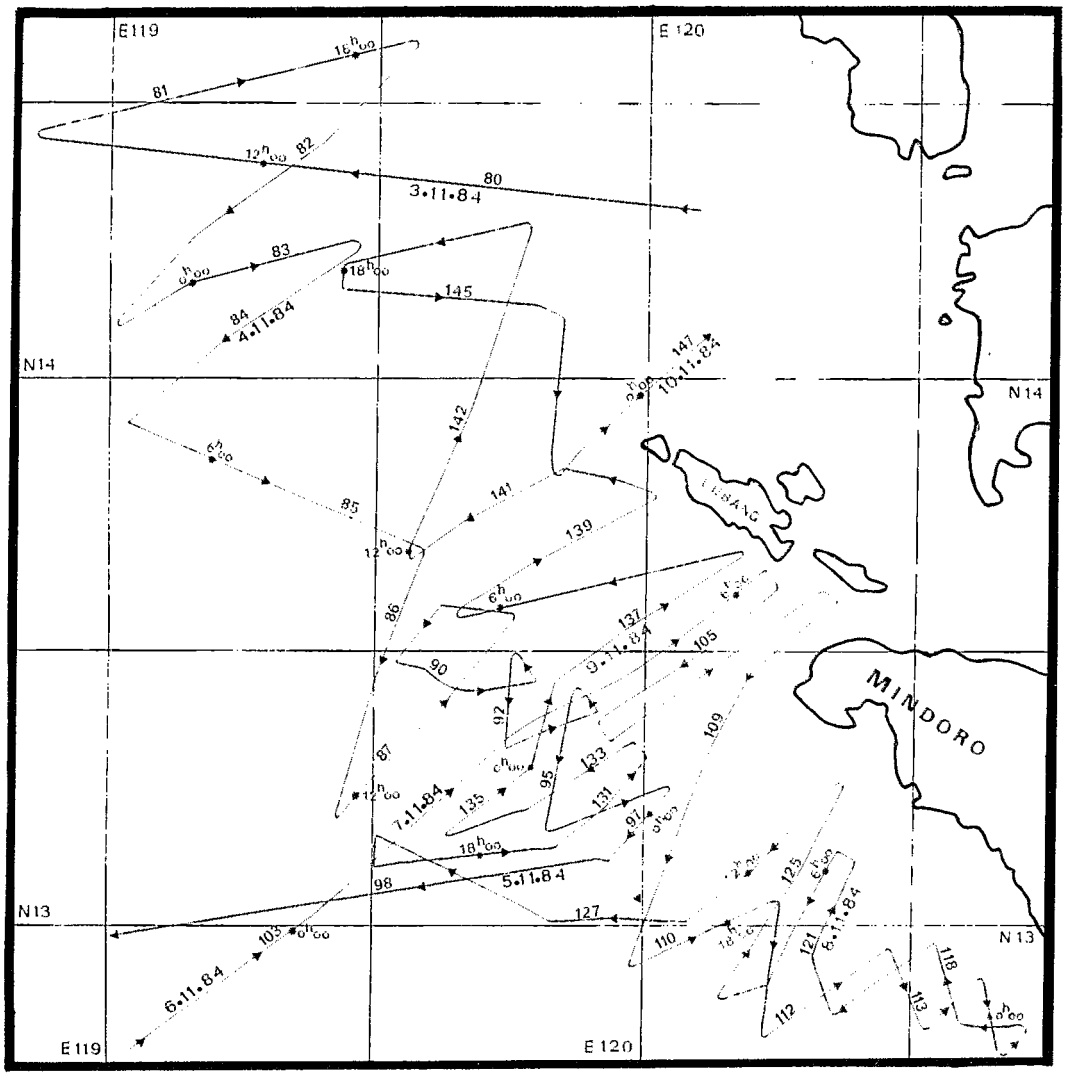

Fig. 3. Track lines of the surveyed area.

result of the elastic bending of the subducting lithosphere as it approaches the trench (Watts and Talwani, 1974). However, seabeam data collected north of this area, suggest that the inherited fabric of the subducted plate is clearly reactivated close to the trench axis. (Rangin and Pautot, in prep.).

The continental–oceanic crust boundary is still poorly defined in the South China Sea basin. The southern margin of this basin is characterized by a quiet magnetic zone with high-frequency and low length anomalies: the first identified anomaly trending E–W enters the trench at about 13°20′N (Taylor and Hayes, 1983). Farther south of 13°20′N, the structure of the downgoing plate notably differs from its extension to the north. Here, the continental slope rises rapidly to a shallow depth south of the Calamian Islands. This slope is covered by more than 2.5 s (TWT) of sediments and the acoustic basement is poorly defined on the seismic profiles. It contrasts with the relatively thin sedimentary cover identified to the north which overlies the oceanic crust. On the basis of these data and with the lack of available information concerning the deep crustal structure of the crust, we suggest that in the surveyed area, the continental–oceanic crust boundary is located between 13°20′ and 13°30′N.

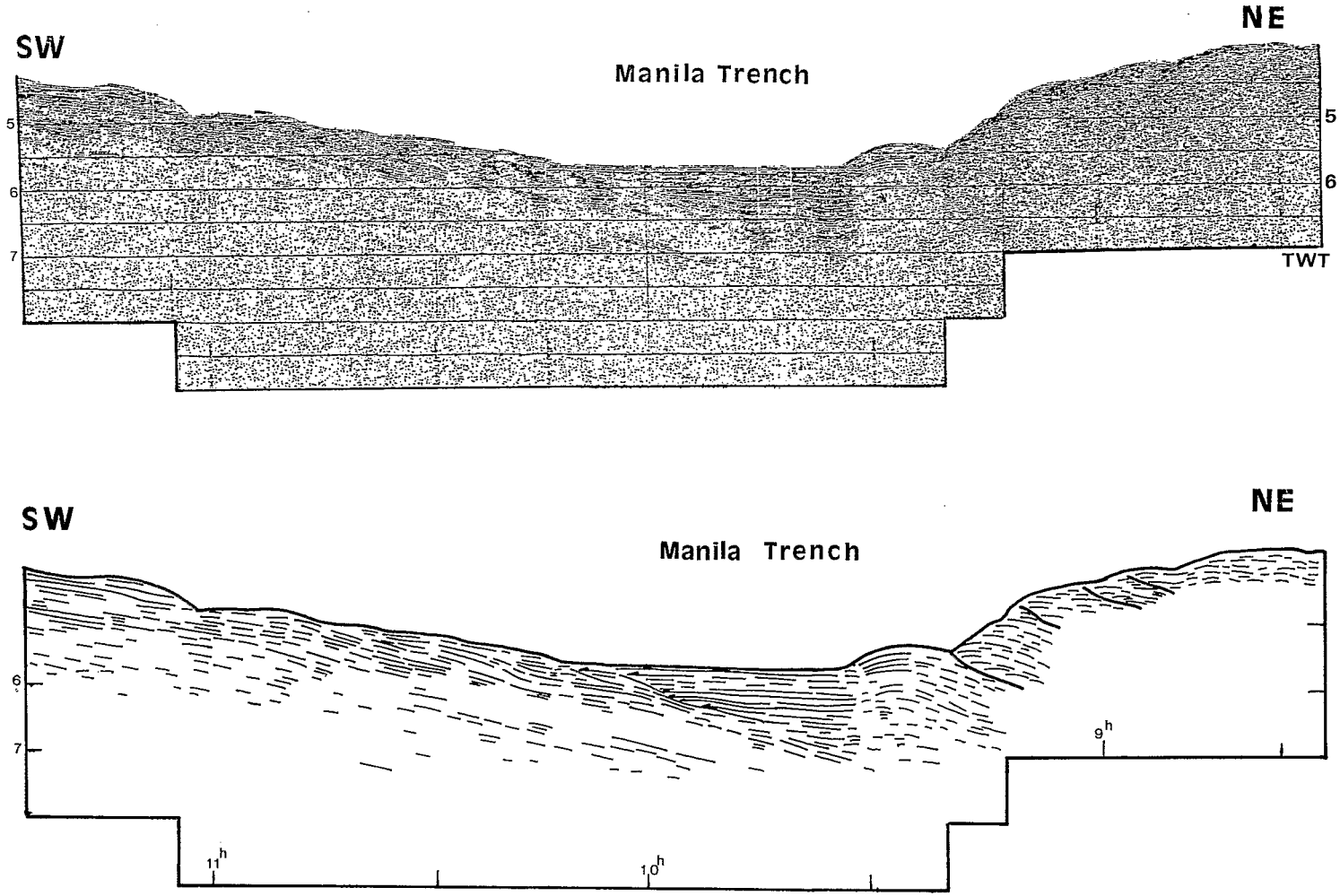

Fig. 4. Single channel seismic profile across the Manila trench, close to the continent–ocean boundary of the South China Sea. Vertical exaggeration is 1.5.

The morphology of the trench

The trench axis displays important morphological variations between 12°40′ and 15°00′N. It extends to 5000 m west of Manila Bay, but its depth decreases rapidly southward (Fig. 6). It is characterized by a gravity anomaly (−75 mGals) between 14°00′ and 15°00′N, where the oceanic crust is undergoing subduction but no clear anomaly was identified to the south where the trench intersects with the continental margin. The walls of the trench become progressively steeper to the south (Fig. 5), and its width also decreases in the same direction. The turbidites of the trench fill clearly overlap the tilted sediments of the lower plate all along the base of the outer wall (Fig. 4). These trench-fill sediments are not deformed southwest of the trench-fill axis, except at the southernmost tip of the trench where minor folds have been identified at the base of the outer wall. In this area (Fig. 6), thrust faults are present all along the trench, on both sides of the trench axis which rapidly emerges to a shallow depth to the southeast. The trench-fill axis, trends quite consistently N–S, north of 14°00′N, and it curves progressively southeastward, approaching the Mindoro coast. A detailed bathymetric map of off-shore Mindoro reveals that the outer wall is characterized by a stair step morphology associated with N130°E-trending vertical faults. Multichannel seismic data collected in this area by BGR, reveal that some of these faults have a noticeable strike-slip component and some are important wrench faults (Schluter, pers. commun., 1986).

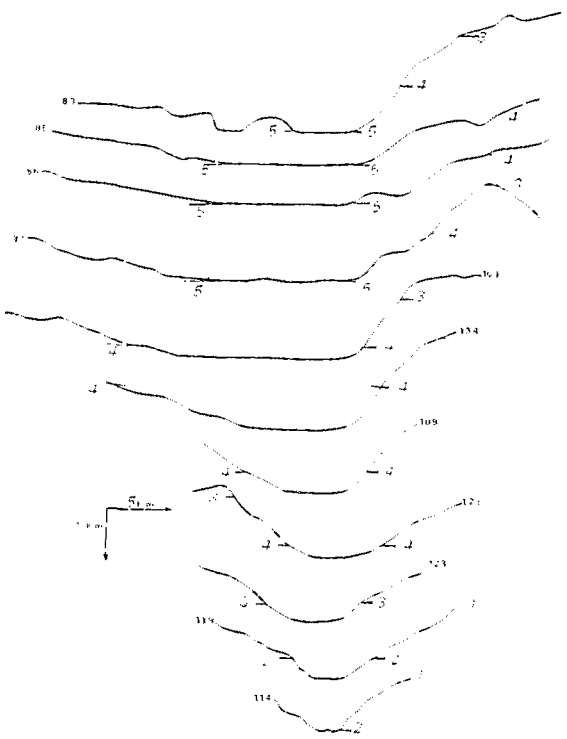

Fig. 5. Bathymetric profiles across the Manila trench. See location of profiles in Fig. 3. Depth in km.

Together, these data suggest that approaching the Mindoro coast, where the trench intersects with the continental margin, compressive deformation is acting either on the inner wall or on the outer wall of the trench. Consequently, the relatively efficient decoupling process which takes place to the north between the two convergent plates, disappears to the south, into the intracontinental deformation zone, and the stress regime is accommodated by thrusting and folding on both convergent plates.

The fore arc region

The Lubang ridge (Fig. 7) represents an important boundary between two distinct morphostructural units of the Manila trench fore arc area.

In the west and north of this transverse structure, the accretionary prism as well as the fore arc basin can be easily identified. In contrast in the south, the fore arc region reveals a very complex morphological and structural framework, completely distinct from that in the north.

The fore arc region between 14° and 15°N. The structural pattern related to subduction

In this area, both the accretionary prism and the fore arc basin are very distinct. Onshore, the Luzon island arc is largely developed along the western coast of Luzon, two of the most significant volcanoes being Taal and Laguna de Bay.

The accretionary prism is evenly developed with an average width of 60 km, the inner wall dipping gently towards the trench. Upslope, folds associated with reverse or thrust faults can be traced for a long distance along the trench axis. The single

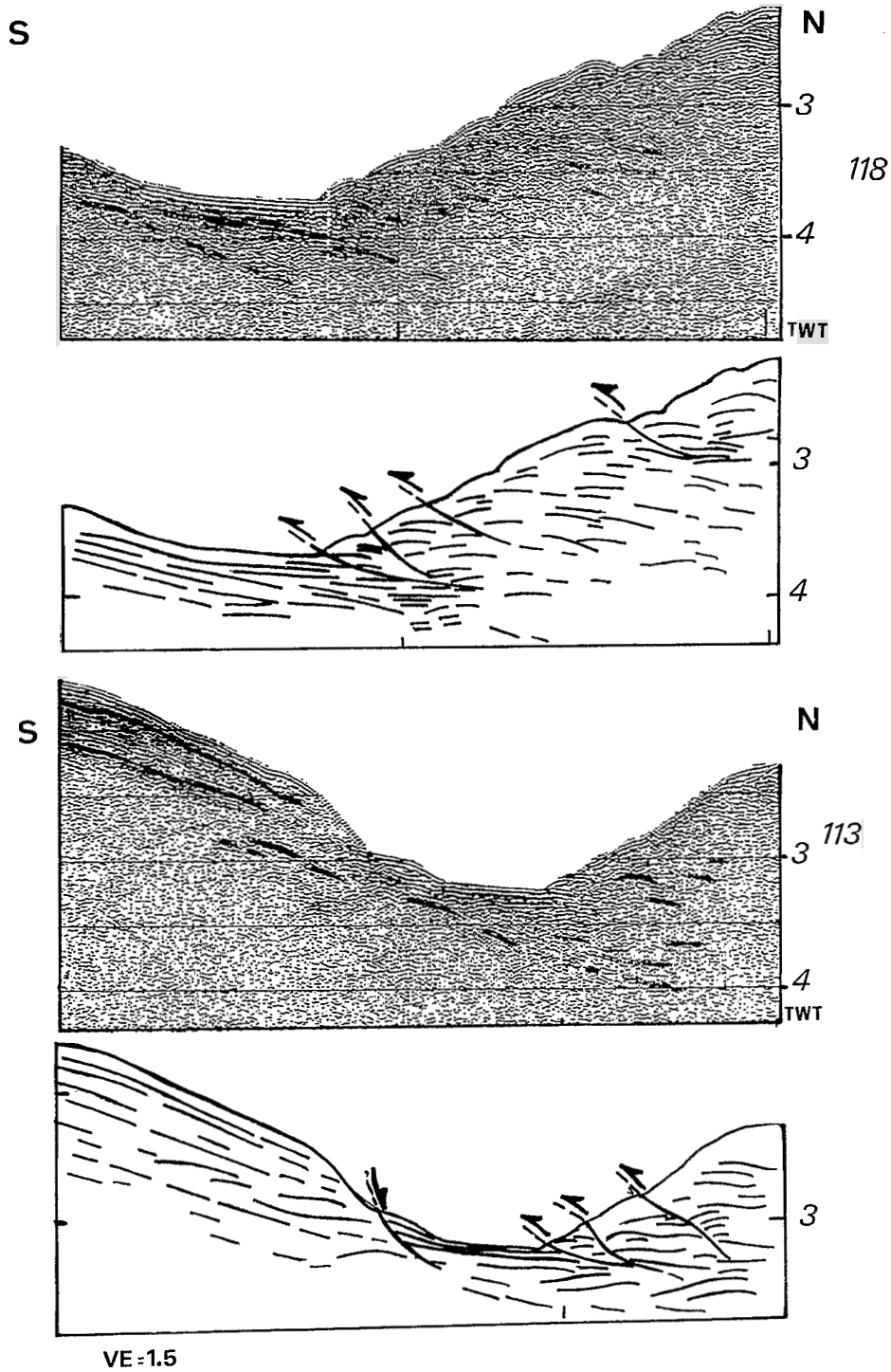

Fig. 6. Single channel seismic profiles across the southernmost tip of the Manila trench. The interpreted profiles reveal the same structural fabric as those present to the north where oceanic subduction is taking place.

channel seismic profiles obtained during the cruise do not provide a good image of the internal structure of the accretionary wedge that was described in detail by Hayes and Lewis (1984) using multichannel seismic profiles but our seabeam data do outline the great linearity of the folds which are well expressed morphologically, and are all parallel to the trench axis.

The data presented by Hayes and Lewis (1984), reveal an obvious convergence of the thrust faults at depth, into a possible parting plane located at the interface between the pelagic and hemipelagic sediments overlying the subducting oceanic crust and the accreted turbidites earlier deposited in the trench. There is no clear evidence for accreted oceanic basement slices in the prism, except for a debatable duplication of the top of the downgoing plate at depth, observable on a single seismic profile (Hayes and Lewis, 1984, p. 9185). However, we can reasonably consider the seismically imaged Manila accretionary prism as being formed only of sediments, without the involvement of the oceanic basement. A relatively good decoupling along a decollement could exist at the boundary between the two convergent plates. Such a situation does not exist south of the Lubang ridge.

The fore arc basin has been described in detail by Lewis and Hayes (1984), revealing that it is mainly filled with up to 2600 m of turbidites coming from the Luzon trough submarine canyons which cut into the continental slope. Rapid subsidence of this fore arc is well documented, and the filling of the basin is a relatively steady state process only disrupted by short periods of excess turbidite mass supply, not balanced by the subsidence of the basin.

Along its eastern boundary the basin is sinuous, and does not reveal the presence of major active strike-slip faults, bordering the continental slope of Luzon as suggested by Karig (1983). Therefore, we can consider that north of the Lubang ridge the convergence between the South China Sea plate and the Philippine Sea plate is mainly accommodated by simple subduction of an oceanic plate, inducing a classical accretionary wedge–fore arc basin couplet.

The fore arc region south of 14°00′N. The structural pattern related to collision

The Luzon volcanic arc is moderately, but significantly, exposed south of Luzon where small active volcanoes extend along the eastern coast of Mindoro (e.g., the Calapan, Naujan and Campo volcanoes; Wolfe, 1981).

The arc–trench gap is very complex here, onshore as well as offshore, and includes the major part of Mindoro. The structural framework of this island is complex and has been widely debated. Sarewitz and Karig (1986) regard this NW–SE-trending orogenic belt as the result of a complex collage of exotic blocks, largely latitudenally displaced along major left-lateral strike-slip faults. On the other hand, Rangin et al. (1985), favour SW-verging thrust faults, which began in Middle Miocene times. Recent work on this island has revealed that large thrust faults are presently active in the southwestern part, and oblique convergence is present elsewhere in Mindoro.

Offshore, the seabeam-derived map (Fig. 7) reveals that the submerged part of the arc-trench gap is structurally complex. Two distinct morphostructural zones can be differentiated:

(1) At the base of the inner wall, the accretionary prism, which is parallel to the trench, is well-developed as far as 119°50′E but it then thins rapidly southeastward. However, active folds and thrust faults could be clearly identified at the base of the inner wall as far as the southern boundary of the surveyed area.

(2) The upper part of the inner wall is characterized by structures which are oblique to the general trend of the deformation front, most of the folds trending N–S. These folds, associated with E-dipping reverse faults (Fig. 8), curve southeastward downslope, and merge with the structures present at the base of the inner wall, parallel to the trench axis.

Some of these transverse structures are also characterized by N–S-trending scarps which face westward and bound small basins filled with flat-lying turbidites. This is particularly evident between 120°10′ and 120°20′E (Fig. 9). These steep walls could represent the emergence of W-verging thrust faults or reverse faults.

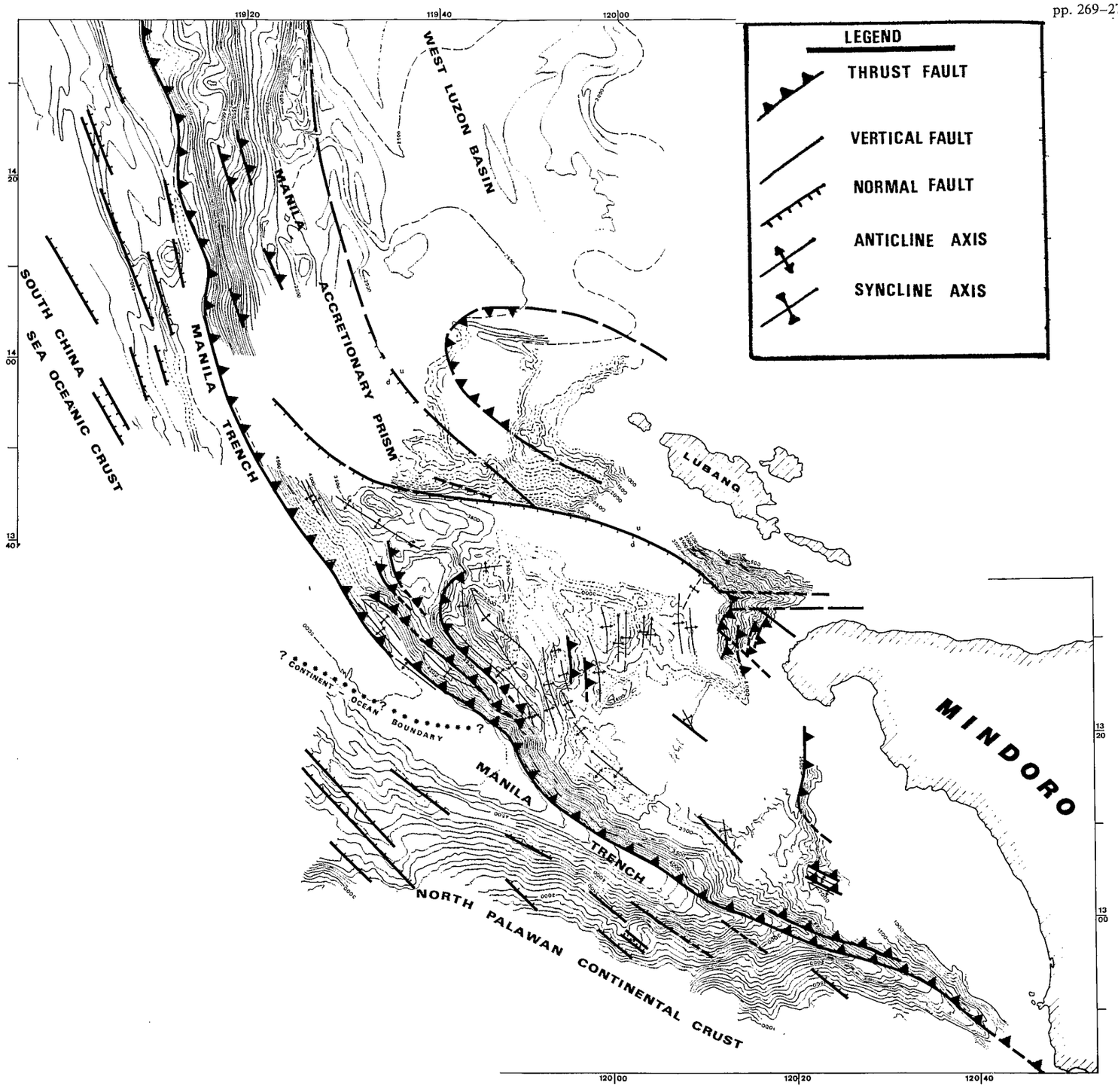

Fig. 7. Structural geology map of the southern part of the Manila trench, drawn from bathymetric data collected with seabeam, and structures observed on seismic profiles. The dashed structures extrapolated between two seabeam tracks.

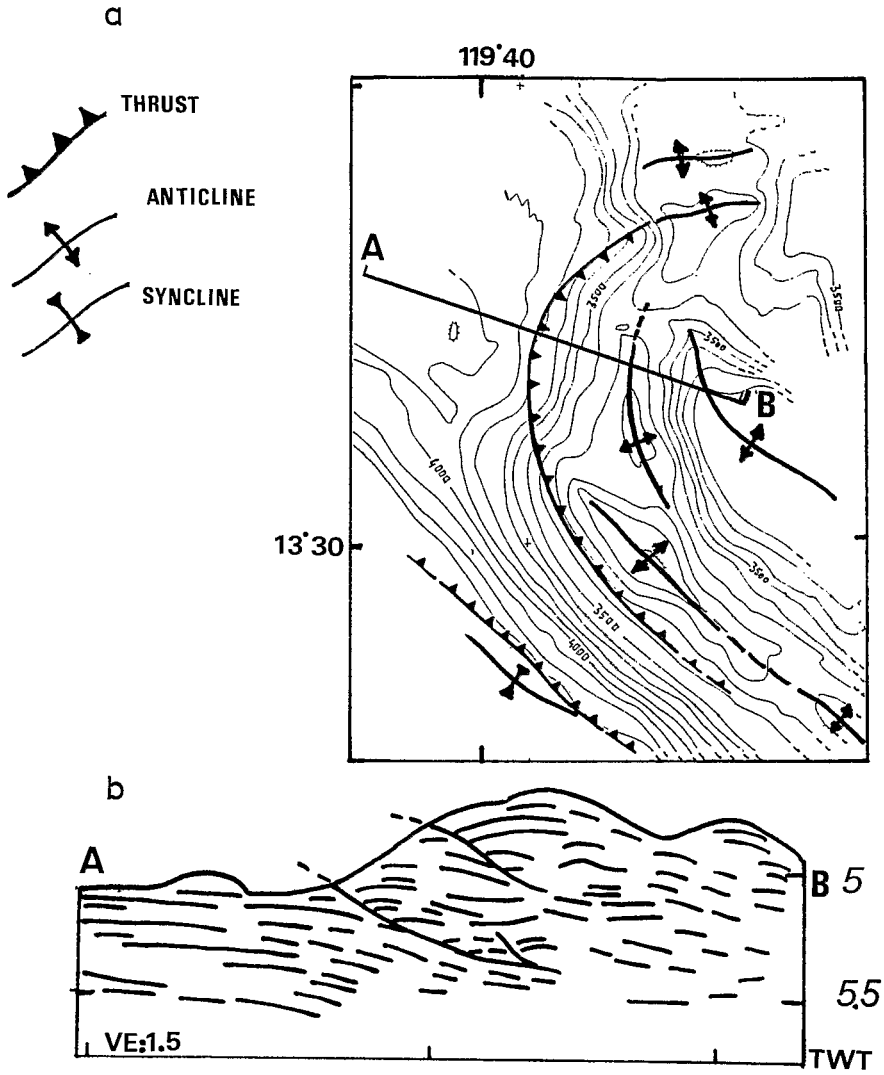

Fig. 8. Vergence of the thrust and folds towards the fore arc area south of Lubang basin. a. Simplified bathymetric map. b. Interpreted single channel profile.

These N–S-trending structures are active across the entire offshore fore arc area from 119°40′ to 120°20′E (Fig. 7) as is documented by the emergence of the thrust faults on the sea bed and folding of the sediments up to the sea floor.

The Lubang ridge

The Lubang, Golo and Ambil islands represent the emerged parts of a ridge elongated N60°W, which disappears westward into the West Luzon basin and rapidly decreases in size eastward along the North Mindoro coast. According to Karig (1983), this ridge is bordered to the north by the Verde Passage suture, a poorly defined fault zone separating the Zambales ophiolite terrane from the Mindoro metamorphic complex and extending into Lubang Island. The southern flank of this ridge is bordered by a prominent fault scarp, 3000 m high, which fringes a small trough—the Lubang basin (Fig. 7–10).

The fault scarp, probably outlined by vertical faults not observable on seismic profiles, anastomoses westward. One of these faults slightly curves N80°W and probably dies out in the Manila trench accretionary prism, while the other

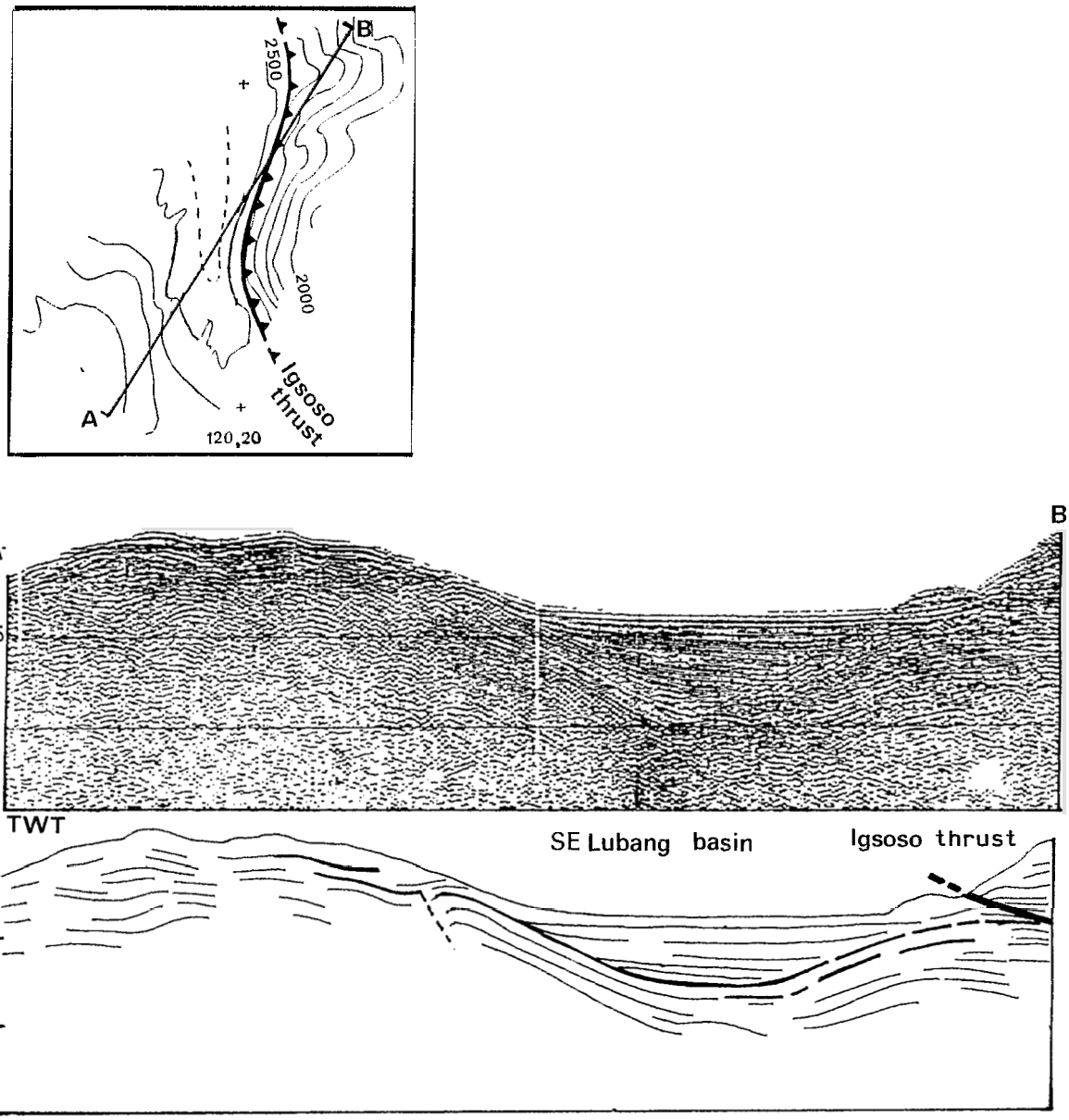

Fig. 9. The eastern end of the Lubang basin. Here, this small basin is developed west of the Igsoso thrust

is trending N50°W and probably links with the wedge–fore arc basin boundary (Fig. 7). Eastward, this fault scarp suddenly strikes to the south and apparently encloses the coast of the northwestern tip of Mindoro (Calavite Cape), where reverse faults are in evidence. At the junction of these two sets of faults, steep submarine canyons trend westward and may be the trace of possible E–W-trending minor vertical faults, already reported by Karig (1983). On seismic profiles, the Lubang basin is a structure filled with 1.5 s (TWT) of sediments, flat-lying at the base of the fault scarp to the north, and progressively more folded moving south across the basin (Fig. 10).

We suggest that the Lubang scarp is probably an important strike-slip fault zone with some vertical motion, connecting with the Calavite reverse faults to the east and the compressive structures of the accretionary prism in the west. It can be interpreted as an important transtensional fault

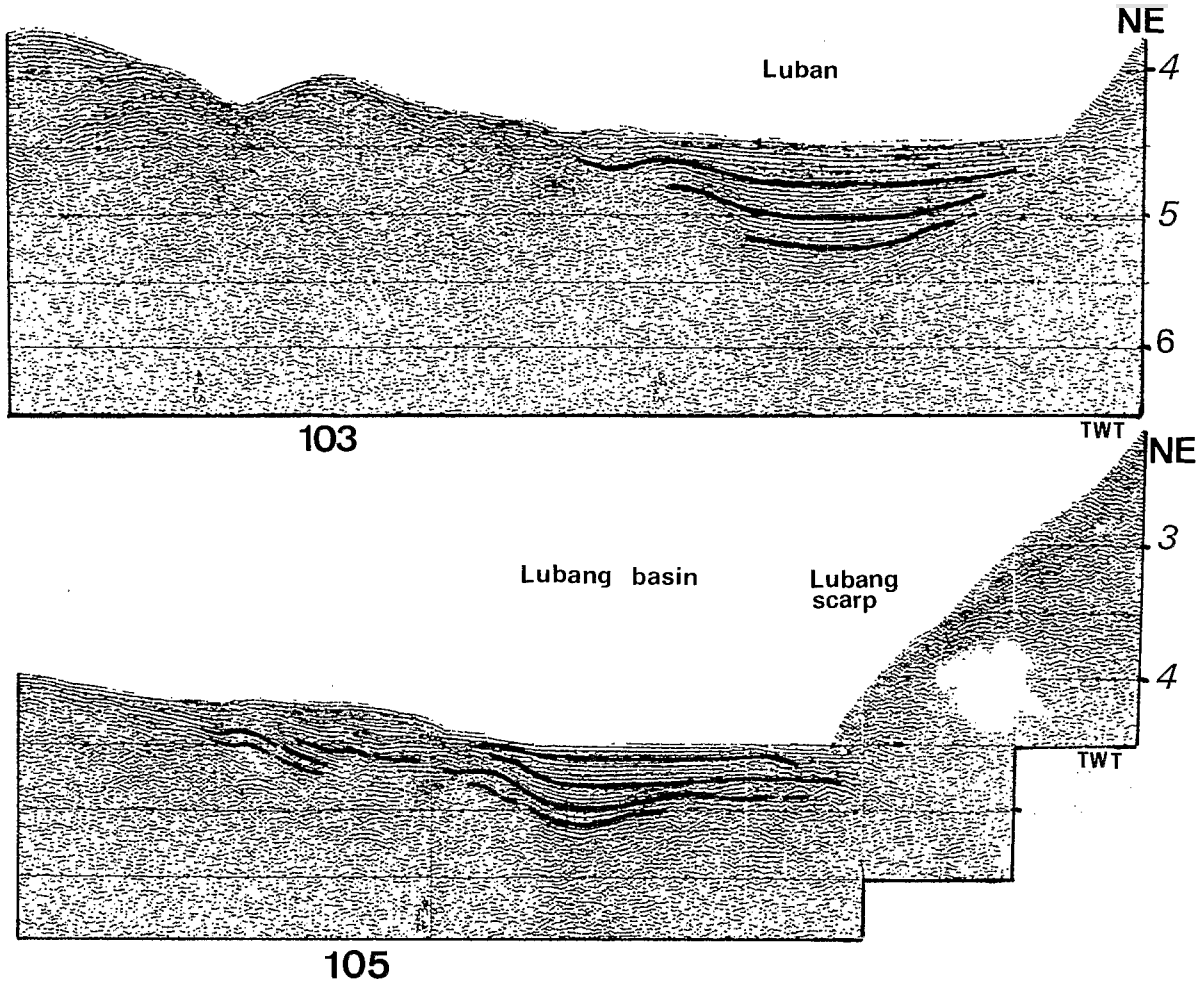

Fig. 10. The Lubang basin lying southward of the Lubang fault scarp which is interpreted as a transtensional fault. Note the slightly deformed basin-fill sediments along its southwestern margin.

with a left-lateral motion. The Lubang ridge itself dies out rapidly northwestward along a regular slope into the fore arc basin. At the base of the slope, the sediments are folded with a N130°E trend, curving northward and trending to the west. Here, potential thrust faults connect with a N110°-trending vertical fault that could be the western extension of the Verde Passage suture of Karig (1983).

Consequently, the Lubang ridge and associated basin, is the site of a complex left-lateral wrench fault system, which is difficult to image on seismic profiles and seabeam data. Thin slices of continental material are apparently creeping along vertical faults which connect with reverse faults and thrust faults.

Structural arrangement of the subduction–collision transition zone: An interpretation of the data

The morphostructural study conducted at the southern tip of the Manila trench reveals that convergence between the South China Sea and Luzon is accommodated differently, according to where the lower plate is oceanic or continental.

We have previously described in this paper the very simple tectonic pattern demonstrated in the case of oceanic subduction, while a complex pat-

tern with various structural trends is documented in the case of continental subduction.

Concerning this collision, the first important result is the presence of a wide zone of intraplate deformation, compared to the subduction setting to the north, where a narrow zone of deformation testifies to a relatively good decoupling between the upper and the lower plates. Furthermore, important thrust fault and strike-slip fault zones delineate distinct crustal microblocks present in the fore arc area, which are jammed between the North Palawan block in the southwest and the Luzon block in the East.

The West Mindoro block (WMB), is bounded to the west by the Manila trench, and to the East by the active thrusts located offshore Igsoso and Calavite capes in Mindoro which link to the north with the Lubang fault, the latter being interpreted as a strike-slip fault (Fig. 11). These two microblock boundaries nearly coalesce in Southern Mindoro, where they are identified as closely-spaced active thrust faults in the San José area (PNOC unpublished seismic profiles; Marchadier, in prep.).

The East Mindoro block (EMB), bounded to the west by the Igsoso–Calavite thrust, and to the east by the Verde Passage fault which links farther to the east with the East Mindoro fault, is a NW-elongated block including the major part of Mindoro and Lubang Island. This crustal block is presently colliding along its northwestern tip with the West Luzon basin (Fig. 11).

These microblocks are also affected by internal deformation. It is evident in the WMB where numerous N–S-trending folds are documented south of the Lubang basin, attesting the nonrigid behaviour of this block. The same observations are made onshore in the EMB, which is characterized by a complex structure resulting from superimposed Tertiary tectonic events (Rangin et al., 1985; Sarewitz and Karig, 1986).

The seismicity registered at the southern tip of

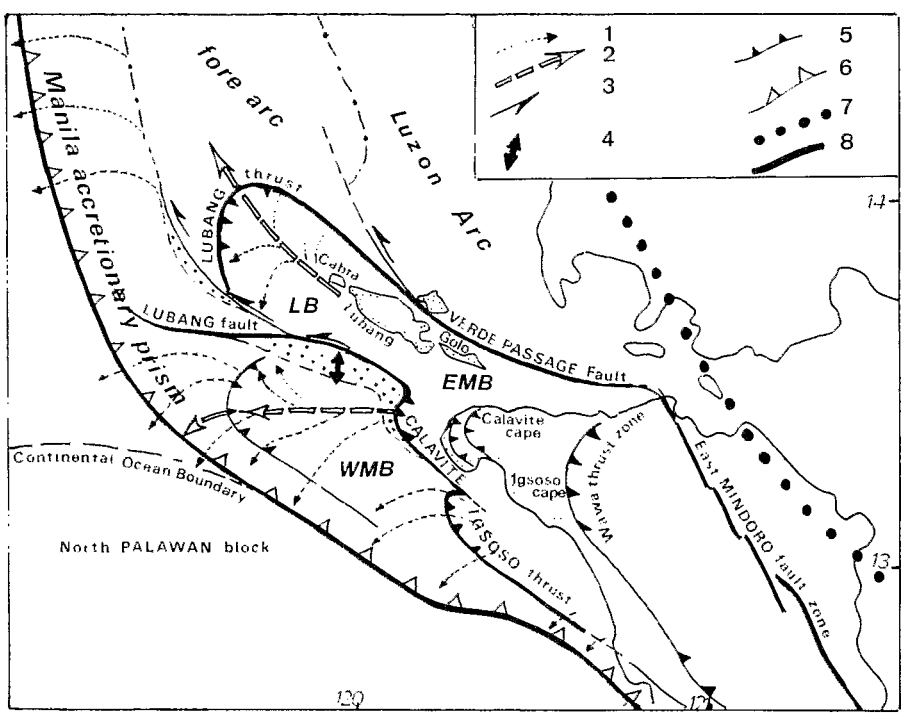

Fig. 11 Interpretation of the southern tip of the Manila trench. *WMB*—West Mindoro block; *EMB*—East Mindoro block; *1*—stress trajectory; *2*—hypothetical motion of the EMB and the WMB; *3*—sense of motion of strike-slip fault; *4*—extension direction in Lubang basin, *5*—thrust fault; *6*—deformation front of the Manila trench; *7*—axis of the Luzon volcanic arc; *8*—boundary of major blocks (WMB and EMB).

the Manila trench demonstrates the occurrence of several processes (Cardwell et al., 1980; Hamburger et al., 1983).

(1) The intermediate and deep seismicity indicate the vertical dip of the Benioff zone approaching the Mindoro collision zone.

(2) The Verde Passage fault can be traced by plotting the shallow seismicity, and several focal mechanisms attest to a left-lateral motion along this fault (Seno and Kurita 1978).

(3) The intense and randomly distributed regional microseismicity attests to a quite important internal deformation within the WMB and the northern part of the EMB (Marchadier in prep.).

The direction of motion of the distinct microblocks can be tentatively deduced from the geometry of the structures (Fig. 11). If we consider the folds affecting the most recent sediments up to the sea floor as active and representative of the present state of stress, and if we accept that the principal vector σ_1 is perpendicular to these active folds, the stress trajectory of σ_1 can be drawn for these microblocks. These trajectories, shown in Fig. 11 are rotated counterclockwise upslope, down towards the trench in the WMB for instance. The stress trajectories are fan-shaped, and distributed at the nose of the two distinct microblocks. These protrusions can be interpreted as large-scale, sheath-like folds, which are presumed not to be exclusively present in the deep deformation level of the crust (Hibbard and Karig, 1986). We speculate here that the symmetrical axis of these sheath-like folds could indicate the absolute motion of the related microblock. If this hypothesis is valid, the WMB has an absolute motion toward the west while the EMB is moving towards the northwest. This could indicate that the WMB is being expelled left-laterally during a northwestward motion of the EMB. The divergent trajectory of these blocks is compensated by the opening of a small basin, the Lubang basin, with an approximately NE-directed extension. The observed vertical faults (the Lubang and Verde Passage faults), interpreted as left-lateral faults with a relatively important component are consistent with the proposed motion of the EMB. Additionally, during the northward migration of the Luzon terrane along the Eurasian plate boundary, various microblocks are created.

Conclusion

This study reveals a complex structural arrangement in the Mindoro collision zone south of 14° N which can be opposed to the simple situation to the north where oceanic crust is subducted.

In the collision area the whole arc–trench gap is fragmented into various blocks with distinct apparent absolute motion. Their boundary and kinematics is poorly controlled and was tentatively deduced from the geometry of the superficial structures. In Mindoro Island the Middle Miocene boundary between the North Palawan block (Eurasian plate), and the Mindoro block to the east, is outlined by obducted Middle Oligocene ophiolites (Rangin et al., 1985), interpreted as a jammed fragment of the South China Sea oceanic crust between the North Palawan and Luzon convergent terranes. This suture zone is presently inactive attesting to a rapid rearrangement of the suture zones within the collision area. The observed structural arrangement of this collision zone is probably unstable and may be again rapidly rearranged in another way. The unsteady nature of the sutures within collision zones can be easily confronted to the relatively stable and well-defined decoupling surface of the subduction zone.

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