The Island Arc (2000) **9**, 627–637

Thematic Article

Contrasting morphological trends of islands in Central Philippines: Speculation on their origin

Graciano P. Yumul Jr,[1]* Carla B. Dimalanta,[1,2] Rodolfo A. Tamayo Jr[1,3] and Jenny Anne L. Barretto[1]

[1]*Rushurgent Working Group, National Institute of Geological Sciences, College of Science, University of the Philippines, Diliman, 1101, Quezon City The Philippines, (email: rwg@i-next.net),*
[2]*Ocean Research Institute, University of Tokyo, Tokyo, Japan,*
[3]*UMR 6538 Domaines Océaniques, Université de Bretagne Occidentale, Brest, France*

Abstract The Palawan microcontinental block collided with the Philippine Mobile Belt in the Central Philippine region resulting in the counterclockwise rotation of Mindoro–Marinduque and clockwise rotation of Panay. The collision also brought about the clockwise rotation of north-east Negros, Cebu, north-west Masbate and Bohol (collectively called the Western Visayan block), resulting into their present-day northeast–southwest trend. This suggests a far more dramatic role of the collision than was previously recognized. Furthermore, the south-east Sulu Sea sub-basin is inferred to have also undergone collision-related clockwise rotation which can account for the observed east-west trending magnetic lineations in the basin. Aside from explaining the contrasting morphological trends of the different islands in Central Philippines, the rotation can also explain, albeit in a different way, how the belts of sedimentary basins, ophiolites and arcs in Panay and Negros can extend to Northern Luzon. Published paleomagnetic data suggest that the collision-related rotation commenced during the early to middle Miocene and had ceased by the late Miocene.

Key words: collision, indenter tectonics, microcontinent, ophiolites, Philippines, rotation.

INTRODUCTION

The Philippines is a very good laboratory setting for studying various geological processes as it has an unique tectonic setting. Located at the boundary of the Eurasian and West Philippine Sea plates and, at the same time, affected by the north-north-westward motion of the Australian plate, the end products of the interaction of these plates give us an overview on how older island and continental arc systems have evolved through time. For that matter, the Philippine island arc system is recognized to be made up of amalgamated terranes of oceanic, continental and island arc affinities (e.g. Hawkins *et al.* 1985; Faure *et al.* 1989; Yumul *et al.* 1997a).

*Correspondence

Accepted for publication 7 July 2000.

Paleomagnetic data for the Philippine island arc system show, in spite of the accompanying controversies and questions, that most of its terranes have undergone latitudinal translation from various origins. Most of these geologic blocks have also rotated (e.g. Fuller *et al.* 1983; McCabe *et al.* 1993). It is noteworthy to point out that microplate rotations and observed bending/indentation in other arc systems are attributed to motions related to differential response to marginal basin opening, large-scale wrench faulting (‘ball-bearing tectonics’) or collision/subduction of oceanic bathymetric highs (‘indenter tectonics’) (e.g. McCabe & Uyeda 1983; Pubellier *et al.* 1991; Hall 1996; Dominguez *et al.* 1998).

It is in this context that the contrasting morphological trends of the islands in Central Philippines will be explained. The islands of Panay, north-east Negros, Cebu, Bohol and north-west Masbate, which are collectively called the Western

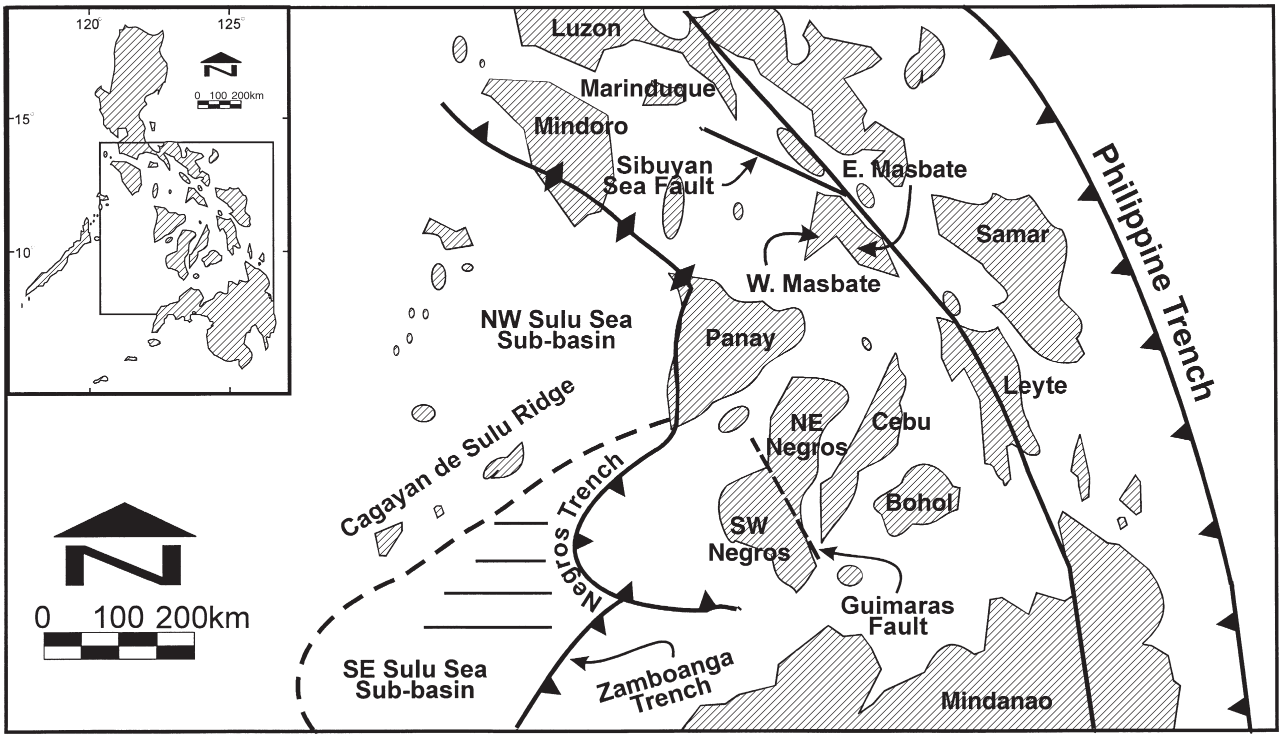

Fig. 1 Present-day geologic setting of Central Philippines. Note the two contrasting morphological trends of islands in the study area. The south-east Sulu Sea sub-basin is an oceanic basin characterized by weak east-northeast–west-southwest trending magnetic lineations as shown by the horizontal lines. Latitudes in degrees north, longitudes in degrees east. See text for details.

Visayan block in this paper, trend northeast–southwest, whereas Samar, Leyte, Eastern Masbate and south-west Negros are oriented northwest–southeast (Fig. 1). We will discuss that the collision and indentation of the Palawan microcontinental block against the Philippine Mobile Belt may have had a more dramatic effect than was previously recognized (e.g. McCabe *et al.* 1985; Rangin *et al.* 1989). In addition, the contrasting geological features in the south-east Sulu Sea sub-basin may also be explained in relation to this collision event. It is hoped that an understanding of the geological evolution which this part of the Philippine archipelago had undergone, will not only elucidate how this arc system had changed through time, but will also help in the interpretation of areas with similar setting.

GEOLOGIC OUTLINE

The Philippine island arc system is a composite terrane which is made up of two major blocks—the aseismic Palawan microcontinental block and the seismically active Philippine mobile block (e.g. Gervasio 1971). Stresses generated within the whole island arc system are dominantly accommodated by the discontinuous east dipping Manila–Negros–Sulu–Cotabato trench system, the west-dipping East Luzon Trough–Philippine Trench system and the left-lateral Philippine Fault (e.g. De Boer *et al.* 1980; Hamburger *et al.* 1983; Aurelio *et al.* 1991).

The middle Oligocene to Miocene (*ca* 32–16 Ma) South China Sea east sub-basin subducts along the Manila Trench, whereas the early to middle Miocene (*ca* 19–15 Ma) south-east Sulu Sea sub-basin goes down along the Negros and Sulu Trenches (e.g. Taylor & Hayes 1983; Rangin 1991a). The early to middle Eocene (*ca* 55–42 Ma) Celebes Basin subducts along the Cotabato Trench (e.g. Weissel 1980; Kaminsky & Huang 1991; Rangin & Silver 1991a; Shyu & Muller 1991), whereas the Eocene (*ca* 50–37 Ma) West Philippine Basin obliquely subducts along the East Luzon Trough–Philippine Trench (e.g. Hilde & Lee 1984; Barrier *et al.* 1991; Lallemand *et al.* 1998). Focal mechanism solutions along the southern portion of the Manila Trench, in the vicinity of Mindoro island, show a steeply dipping subducted slab (Cardwell *et al.* 1980). This is a result of the collision of the Palawan microcontinental block with the Philippine Mobile Belt (e.g. Marchadier & Rangin 1990). The collision is believed to have started during the early Miocene and was completed by the Pliocene (e.g. Karig 1983; Sarewitz & Karig 1986).

The islands of Central Philippines, as depicted in Fig. 1, are bounded on the east and west by the west-dipping Philippine Trench and the east-dipping Negros Trench, respectively. Traversing the islands of Leyte and Masbate is the left-lateral Philippine Fault Zone (Fig. 1).

OPHIOLITES AND MELANGES

The basement complex in Central Philippines is defined by complete to dismembered crust-mantle sequences with regionally metamorphosed rocks and intrusive/extrusive igneous rock complexes ranging in age from Cretaceous to Eocene. Pelagic cherts intercalated with tuffaceous sediments and volcanic rock suites showing back-arc basin basalt geochemical signatures from the Cretaceous Antique (Panay island), Eocene Tacloban (57–45 Ma; Leyte island) and Late Cretaceous Southeast Bohol ophiolite complexes (SEBOC) suggest that these were formed in restricted ocean basins (e.g. Rangin *et al.* 1991; Sajona *et al.* 1997; Tamayo 1997). These ophiolite complexes, including those exposed in Cebu and Samar, contain rocks with transitional mid-ocean ridge basalt (MORB) and island arc tholeiite (IAT) geochemical signatures. This indicates extrusion in subduction-related marginal basins. Although it may be argued that the disposition of the different ophiolite and ophiolitic complexes in Central Philippines does not necessarily represent plate boundaries, their presence must still be accounted for. A distinct possibility, nonetheless, is that the emplacement of these oceanic crust-mantle sequences is related to the closure of ephemeral marginal basins (e.g. Rangin *et al.* 1995; Yumul *et al.* 1997b).

The emplacement of some oceanic crust-mantle sequences in Central Philippines is also associated with the formation of melanges. Two good examples are the early Tertiary Cansiwang Melange, a tectonic melange associated with the Late Cretaceous SEBOC and the late Pliocene glaucophane-bearing Paniciuan Melange in Panay (e.g. Mitchell *et al.* 1986; Barretto *et al.* 2000). Both melanges are characterized by harzburgite, basalt, gabbro and sedimentary-rock clasts in a serpentinite matrix. These melanges are subduction-related deposits formed most probably in sediment-starved trenches (e.g. De Jesus *et al.* 2000). The distribution of the ophiolites and melanges is critical in pinpointing the locations of possible paleo-subduction zones in the Central Philippines.

MARGINAL BASIN

Understanding the geological evolution of the Central Philippines is incomplete without considering the Sulu Sea basin and the Cagayan de Sulu ridge (e.g. Lee & McCabe 1986). The Sulu Sea basin is made up of two sub-basins. The north-west sub-basin is of island arc-continental affinity while the south-east sub-basin is oceanic (e.g. Murauchi *et al.* 1973). The south-east Sulu Sea sub-basin formed by back-arc rifting, although the possibility of it opening similar to an 'Atlantic-type' South China Sea was also suggested (e.g. Rangin & Silver 1991b; Lee & Lawver 1994). The opening of this sub-basin is attributed either to subduction along a north-west-dipping proto Cotabato–Zamboanga trench or the subduction of the proto-South China Sea along the Palawan Trough (e.g. Holloway 1982; Rangin 1989). Recent works show that an east-dipping early Oligocene (35–33 Ma) subduction occurred along the leading edge of the Palawan block resulting in the formation of the early to middle Miocene Cagayan de Sulu ridge and ultimately the south-east Sulu Sea back-arc basin (e.g. Cambray *et al.* 1995; Encarnacion *et al.* 1995).

The main tectonic grain in the western part of Central and Southern Philippines is northeast–southwest as manifested by the trend of Palawan, the Cagayan de Sulu Ridge and the Zamboanga Peninsula–Sulu group of islands (Fig. 1). Palinspathic reconstructions suggest that the south-east Sulu Sea sub-basin opened in a northwest–southeast direction consistent with a northeast–southwest trending spreading center (e.g. Jolivet *et al.* 1989; Rangin 1991b) (Fig. 2). However, the weak magnetic anomalies recognized in this sub-basin manifest eastnortheast–westsouthwest trending lineations. Although caution must be observed in making interpretations with respect to these magnetic lineations (Rangin & Silver 1991b), the generally north-south striking offset of the magnetic lineations led Roeser (1991) to conclude that the south-east Sulu Sea sub-basin opened in a north-south direction. Roeser (1991) further opined, based on magnetics model, that the south-east Sulu Sea sub-basin opened during the early Oligocene (35–30 Ma) and continued to spread until the early late Miocene (*ca* 10 Ma). Assuming

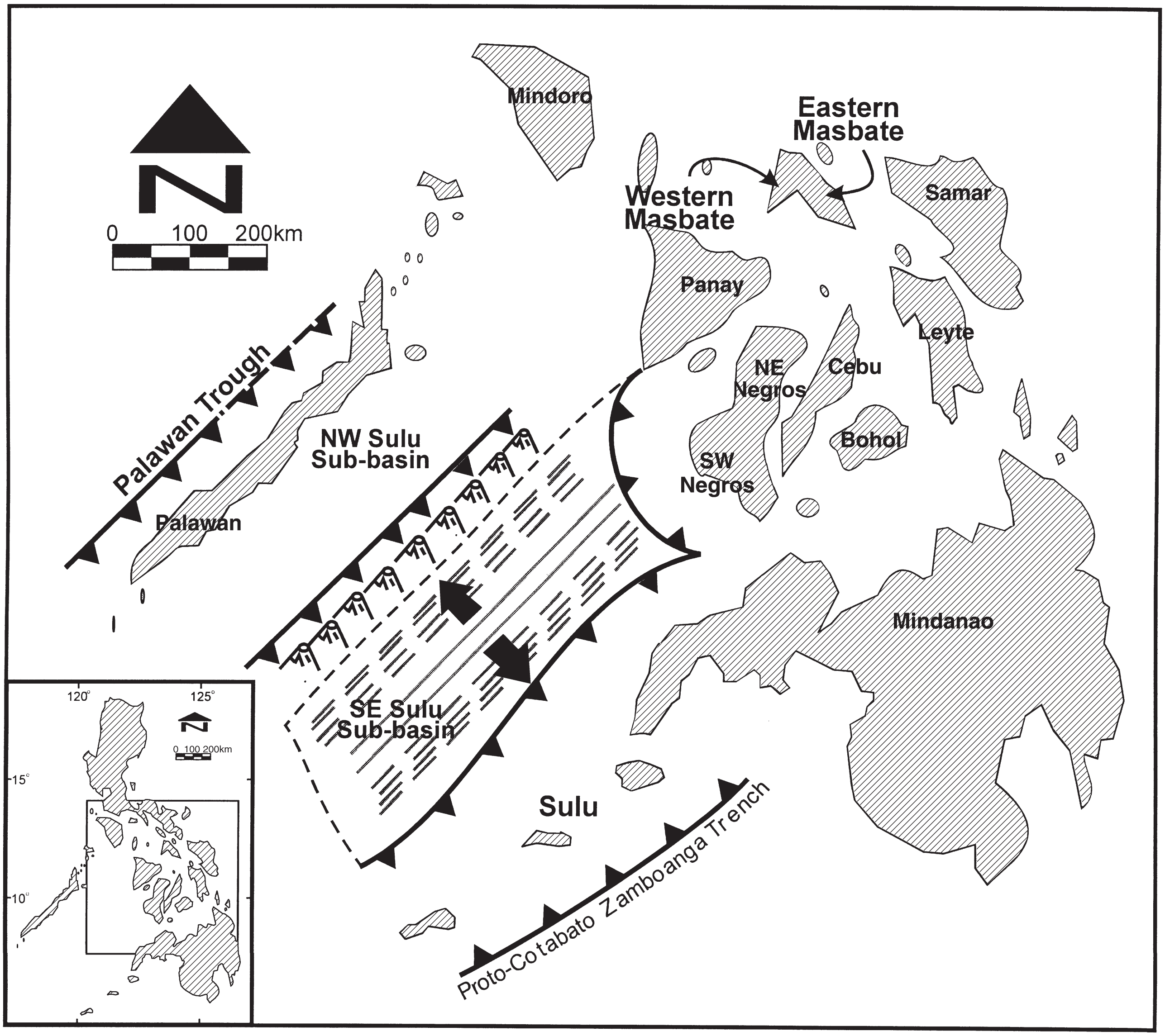

Fig. 2 Palinspathic reconstruction and the dominant tectonic grain in the western part of the Central-Southern Philippine region suggest a northeast–southwest trending spreading center for the south-east Sulu Sea basin. The Palawan Trough, Palawan island, Cagayan de Sulu Ridge and the Zamboanga–Sulu arc describe a dominant northeast–southwest tectonic grain. Latitudes in degrees north, longitudes in degrees east. See text for discussion.

that the observed east-west trending magnetic lineations are for real, an explanation on why they appear to diverge from their original northeast–southwest orientation is needed.

PALEOMAGNETIC DATA

Disturbances which may be related to timing of magnetization, remagnetization and rotations/motions caused by local shearing events are some of the problems that complicate the interpretation of paleomagnetic data (e.g. Fuller *et al.* 1991). In spite of these uncertainties, some information can be gathered from the available Philippine paleomagnetic data. Paleomagnetic results show that during the early Miocene, Mindoro and Marinduque had rotated counterclockwise, while Panay rotated clockwise (e.g. McCabe *et al.* 1982b). This was attributed to the collision of the Palawan microcontinental block with the Philippine Mobile Belt. It will be argued later that the other islands in Central Philippines, specifically Bohol, Cebu, north-west Masbate and Negros, were also affected by this collision event. This is consistent with the observation that the early to middle Miocene period is characterized by major kinematic adjustments in the region (e.g. Bellon & Rangin 1991).

The absence of rotation in the Central Philippine region during late Miocene was recognized based on paleomagnetic data collected from the northwest–southeast trending south-west Negros region (e.g. McCabe *et al.* 1987) (Fig.1). This portion of Negros island may not have rotated during the collision event as will be expounded later. A late Miocene Cebu sample was also reported to indicate the absence of a rotation, although another late Miocene Cebu sample was not reported due to the large uncertainty associated with the site (Cole *et al.* 1989). It is, hence, difficult to conclude with certainty that there was no rotation during the late Miocene in Central Philippines.

Although the Central Philippine data do not equivocally show the absence of rotation during the late Miocene (5–10 Ma), the Northern Luzon data distinctly show no substantial anticlockwise motion during this period (McCabe *et al.* 1982a). These observations strongly suggest that the collision of the Palawan microcontinental block with the Philippine Mobile Belt may not have caused any rotation, either in Luzon and Central Philippines, during the late Miocene. The Pliocene clockwise rotation reported for Northern Luzon is attributed to its collision with Taiwan (Fuller *et al.* 1983).

DISCUSSION

OPPOSITE TRENDS OF CENTRAL PHILIPPINE ISLANDS: A POSSIBLE EXPLANATION

The difference in the morphologic trends exhibited by the islands in Central Philippines could be related to microblock rotations brought about by the collision of the Palawan microcontinent with the Philippine Mobile Belt. The effect of the collision was more dramatic and regional than what was previously thought. The whole Western Visayan block, which is considered to be one composite terrane, rotated clockwise explaining the present-day northeast–southwest trends of the islands. This implies that the northeast–southwest trending islands in Central Philippines could have originally been northwest–southeast trending (Fig. 3). Another implication of this is that rotation was only made feasible by the presence of large-scale structures that bounded the Western Visayan block. These structures, based on present-day geographic setting, may corrrespond to the progenitors/extensions of a Philippine Fault (?)-related structure on the east, the middle Miocene Negros Trench on the north and the west, and the Cretaceous proto-Southeast Bohol Trench on the south (Fig. 4). Offshore bathymetric and regional gravity maps show that the location of these inferred paleo-structures is characterized by deep bathymetric and low gravity anomaly signatures (Sandwell & Smith 1997). The paleomagnetic data suggest also that the Western Visayan block, together with Northeastern Mindanao, Leyte and Luzon have acted as one coherent plate since late Miocene (e.g. McCabe *et al.* 1982a).

The northwest–southeast trend of south-west Negros is an enigma and is not readily explained by the clockwise rotation model. One can speculate that this portion of Negros island may not have rotated at all, since late Miocene rock samples from the area did not register any rotation. The northwest–southeast orientation may also be either a pristine morphological structure of the island or the result of the juxtapositioning of two blocks. The evolution of south-west Negros is believed to have been affected by the left-lateral northwest–southeast trending Guimaras Fault (e.g. Rangin *et al.* 1989) (Fig. 1). Future studies will have to resolve this enigma. The same can be said for the juxtapositioning of the northeast–southwest trending western Masbate and the northwest–southeast oriented eastern Masbate. Although it may simply be explained as the suturing of two different terranes, this has to be looked into in future works.

The collision-related rotation model for the northeast–southwest trending group of islands that make up the Western Visayan block can be made consistent with the findings of Bischke *et al.* (1990). They have opined that the belts of sedimentary basins, ophiolite and volcanic arc complexes in Panay and Negros islands may have their northern extension in Luzon. To achieve this, they have rotated Luzon along the Sibuyan Sea Fault and the Luzon branch of the Philippine Fault clockwise (Fig. 14 in Bischke *et al.* 1990). In the model presented here, the sedimentary basins, ophiolites and arcs in Panay and Negros can still be made to define coherent belts with Luzon. The main difference is that it is the Western Visayan block that must be rotated counterclockwise to its perceived original northwest–southeast orientation (Fig. 5). Furthermore, the Western Visayan block rotation model appears to be consistent with observations made in the south-east Sulu Sea sub-basin.

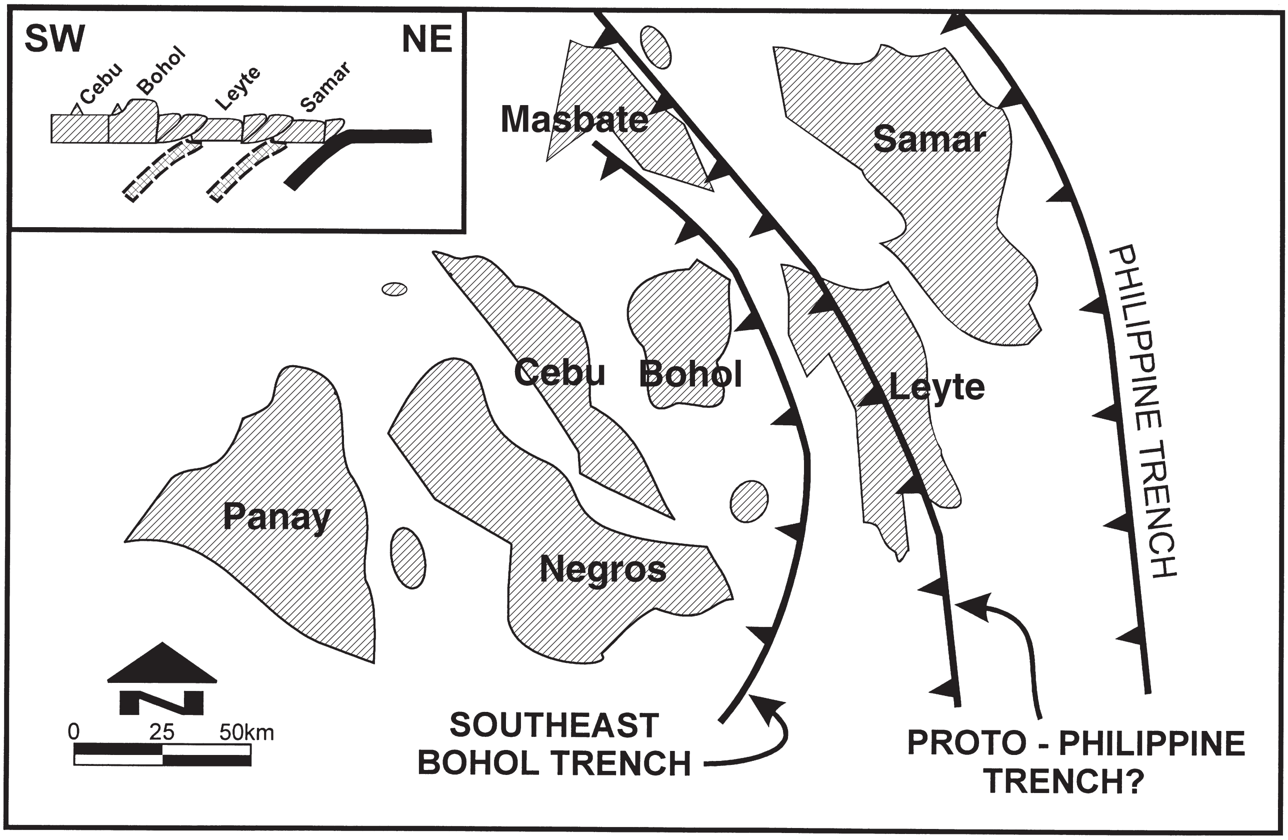

Fig. 3 The western group of islands which include Panay, Negros, Cebu and Bohol are inferred to be originally oriented northwest–southeast. Rotation associated with the collision of the Palawan microcontinental block with Central Philippines resulted into the present-day northeast–southwest trend of these islands. A geologic structure is inferred to exist between Bohol and Leyte. South-west Negros is still an enigma and will have to be studied in detail. See text for details.

SOUTH-EAST SULU SEA SUB-BASIN: PRODUCT OF A NORTH-SOUTH SPREADING EVENT?

As mentioned above, palinspathic reconstructions of the Philippines show the south-east Sulu Sea oceanic sub-basin opened up in a northwest–southeast fashion with the spreading center trending northeast–southwest. However, the weak generally east-northeast–west-southwest trending magnetic lineations recognized in the sub-basin are not consistent with this (Roeser 1991). Although Rangin and Silver (1991b) cautioned making interpretations on the basis of these weak magnetic lineations, Roeser (1991) believed that the magnetic lineations suggest the existence of an east-west trending spreading center that had undergone north-south opening. If this is correct, it is difficult to reconcile a north-south spreading scenario with existing models for this sub-basin.

Notwithstanding, this enigma can be explained by two possibilities. The first possibility is that the observed east-northeast–west-southwest lineations may be products of a younger magmatic/spreading event that was superimposed on the original northeast–southwest trending magnetic lineations. Multiple stages of magmatism and basin spreading histories have been recognized in other oceanic marginal basins (e.g. Briais *et al.* 1993; Honza 1995; Ohara *et al.* 1997). Available Ocean Drilling Program (ODP) Leg 124 results, however, do not show any evidence of overlapping magnetic lineation trends. The other possibility is if the recognized east-northeast–west-southwest magnetic lineations were originally northeast–southwest trending and were rotated clockwise due to the Palawan collision event. The rotation of the south-east Sulu Sea sub-basin would require the presence of bounding structures which initially could have been strike–slip faults (left-lateral?). The south-eastern slope of the Cagayan de Sulu ridge is steep with south-east-facing normal faults consistent with the presence of a structure (Mascle and Biscarrat 1978). The eastern and southern boundaries could have served as the progenitors of

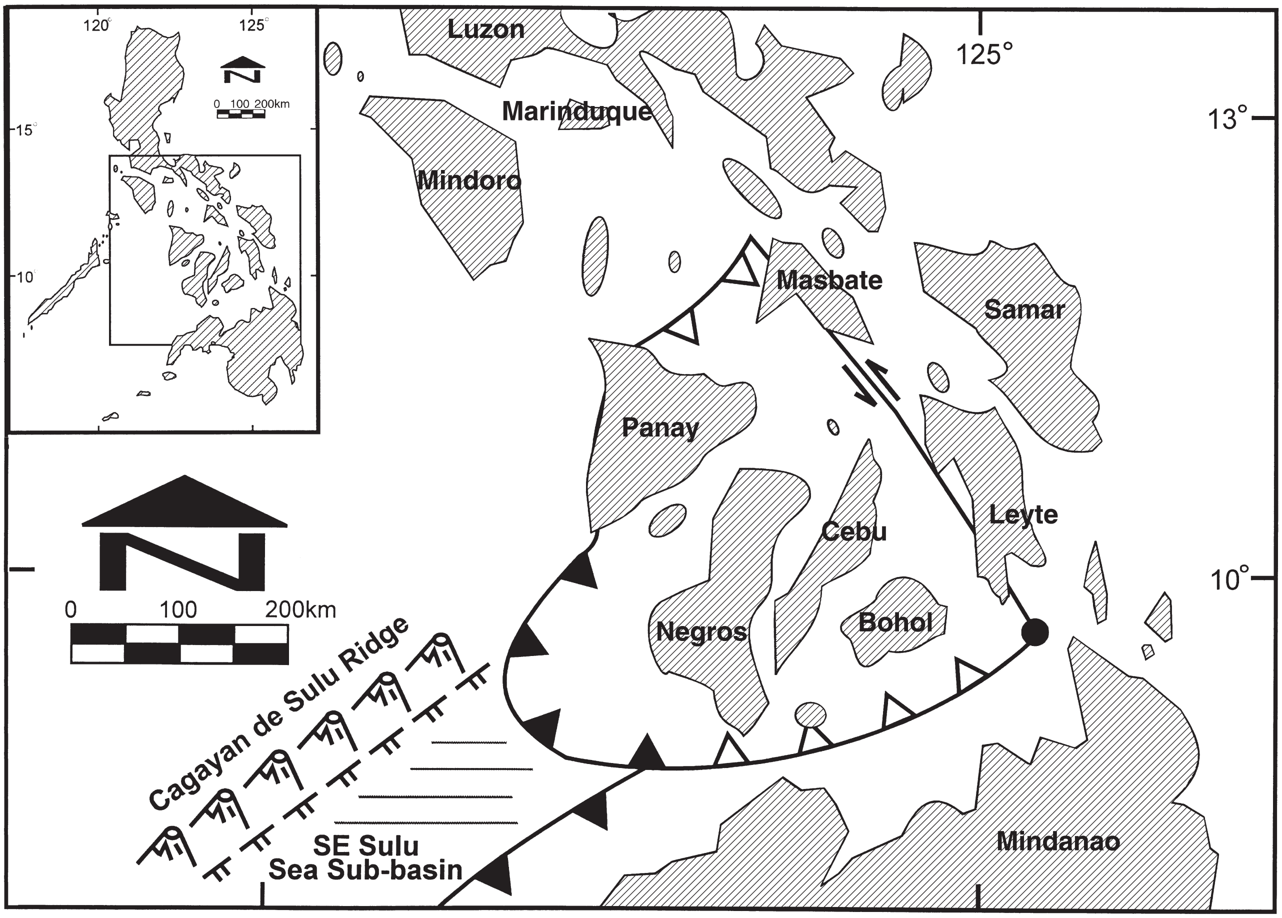

Fig. 4 The western group of islands in Central Philippines could have been part of one composite terrane bounded by geological structures. At present, these geological structures are characterized by deep bathymetric and low gravity signatures. Latitudes in degrees north, longitudes in degrees east.

the present-day Negros and Sulu trenches, respectively. The perceived western and northern structural boundaries remain covered by thick sediments in the sub-basin and there is no way of determining their presence. Paleomagnetic results show that the Cagayan de Sulu ridge has not rotated or migrated since early middle Miocene time (e.g. Hsu *et al.* 1991). A corresponding paleomagnetic study of the south-east Sulu Sea sub-basin's early to middle Miocene rocks will shed light on whether the sub-basin has indeed rotated or not.

CENTRAL PHILIPPINE PALEO-SUBDUCTION ZONES: LOCATIONS AND IMPLICATIONS

Another interesting facet in the tectonic reconstruction of Central Philippines is the location of possible paleo-subduction zones. The present-day setting only shows the presence of the east-dipping middle Miocene Negros Trench, west-dipping Pliocene Philippine Trench and the left-lateral Pliocene Philippine Fault in Central Philippines. These tectonic features cannot explain the distribution of all the observed melanges, older arc volcanic rocks and ophiolite complexes in the region.

The Cretaceous arc volcanism in Cebu may be attributed to a north-west-dipping proto-Southeast Bohol Trench (present-day geographic setting) or, to be exact, to a west-dipping proto-Southeast Bohol Trench since the subduction-related magmatism occurred prior to the inferred clockwise rotation (Fig. 3) (e.g. Yumul *et al.* 1998). The presence of a proto-Southeast Bohol Trench can account, not only for the Cretaceous volcanic rocks of Cebu, but also the location and distribution of the SEBOC and the associated Cansiwang Melange (Yumul *et al.* 1996). Ophiolite and dismembered ophiolitic complexes with mid-oceanic ridge basalts (MORB) to transitional MORB–IAT geochemical characteristics are present in Leyte and Samar. The existence of these exposed crust-mantle sequences hints at the possible presence

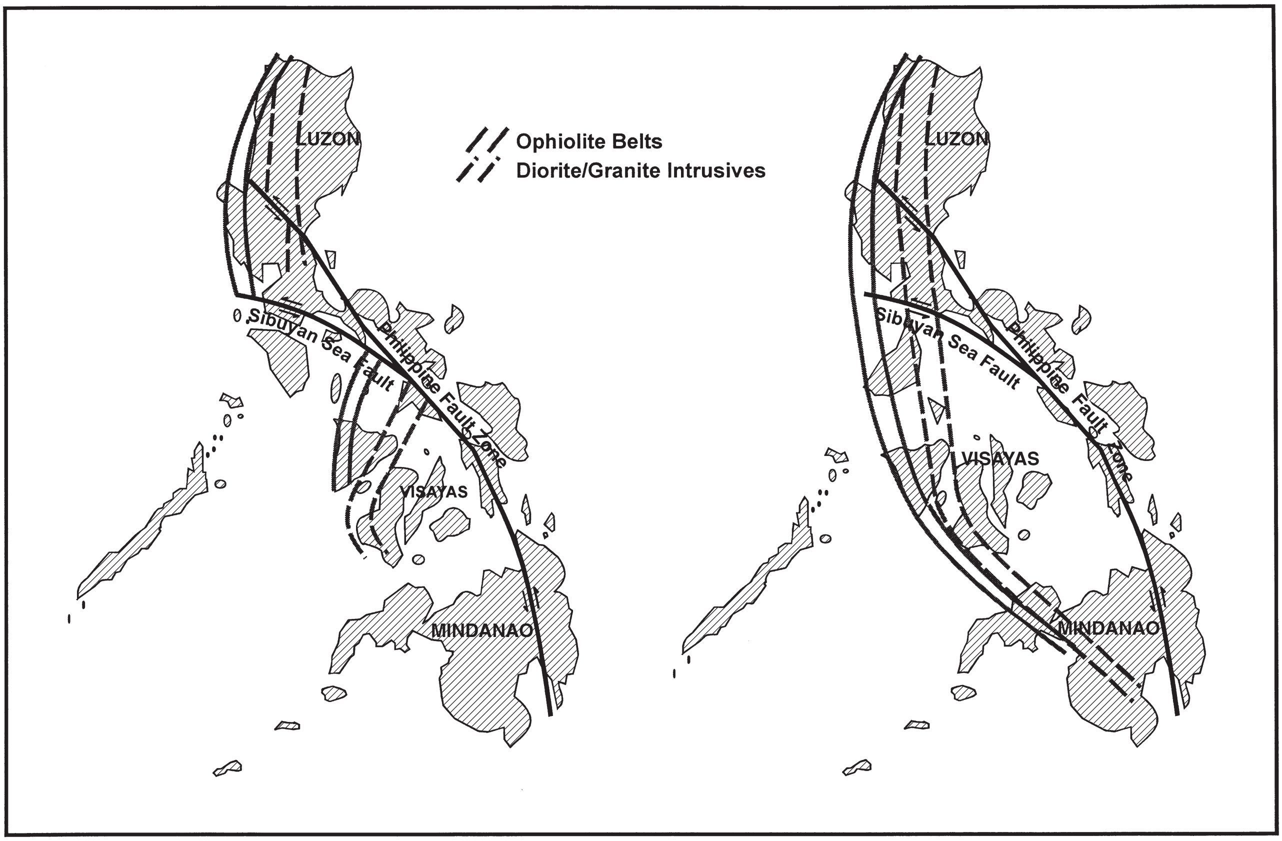

Fig. 5 The sedimentary basins, ophiolites and old volcanic arcs in Negros and Panay define a coherent belt extending to Northern Luzon if Panay and Negros are rotated counterclockwise to their inferred original northwest–southeast trend.

of subduction zones in Central Philippines that migrated oceanward towards what is now the West Philippine Sea basin (Fig. 3). Available 3-D attenuation structural data show west-dipping low attenuation values in the Central Philippine region, along the Cebu–Bohol transect, which may correspond to one of the inferred west-dipping subducted slabs (G. Besana, pers., comm., 1999). The plate boundary between the Western Visayan block (including the south-east Sulu Sea sub-basin before the initiation of the present-day Sulu Trench) and the Mindanao block need to be studied in detail, too (e.g. Pubellier *et al.* 1996). Future work in the region must determine if the inferred paleo-subduction zones presented here existed or, if not, point out the corresponding structures.

CONCLUSIONS

The two opposing trends (northeast–southwest versus northwest–southeast) exhibited by the islands in Central Philippines and the recognized weak east-northeast–west-southwest magnetic lineations found in the south-east Sulu Sea sub-basin oceanic crust can be accounted for if the islands comprising the Western Visayan block (Panay, north-east Negros, Cebu, Bohol, north-west Masbate) together with the south-east Sulu Sea sub-basin, have undergone clockwise rotation. This early to middle Miocene clockwise rotation is in response to the collision of the Palawan micro-continental block with the Philippine Mobile Belt. This suggests a more dramatic effect of the collision to the different islands of Central Philippines than was previously proposed. This model can also account for the observation that the sedimentary basins, arcs and ophiolites in Panay and Negros can be correlated and extended with those of Luzon. This can be achieved by having the Western Visayan block rotated counterclockwise to its inferred original northwest–southeast trend, an alternative to Luzon rotating clockwise along the Sibuyan Sea Fault and the Philippine Fault as previously suggested (Bischke *et al.* 1990). This results not only in the same alignment of geological features, but also is in agreement with the available paleomagnetic data. Lastly, the rotation of the islands and south-east Sulu Sea sub-basin could have been facilitated by the presence of bounding structures. These bounding structures, which must be at least early to middle Miocene in age, included paleo-strike–slip faults and subduction zones which may have served as progenitors/extensions of present-day tectonic features in the Philippines. A more systematic paleomagnetic study of this part of the Philippine island arc system will determine whether the model presented here is feasible or not.

ACKNOWLEDGEMENTS

The National Institute of Geological Sciences, Department of Science and Technology and a Lepanto Consolidated Co. Professorial Chair in Geology (G. P. Yumul) are acknowledged for their support of projects whose results were freely consulted in writing this paper. Field and laboratory support were provided by Mr J.V. De Jesus and Ms D. V. Faustino. Discussions with Dr M. A. Aurelio, Messrs F. T. Jumawan, E. J. Marquez, K. L. Queano, C. L. Querubin, and F. A. Jimenez, Jr helped clarify some aspects of Central Philippine geology. Logistic support from the Philippine Mines and Geosciences Bureau regional offices (Tacloban and Cebu) greatly facilitated our surveys. Comments and suggestions by Professor E. Honza and Professor C-S. Lee improved the paper and are appreciated. The unlimited use of the facilities of the Petrology/Geochronology laboratories (UMR 6538 Domaines Oceaniques) of Professor R. Maury and Professor H. Bellon at the University of Bretagne Occidentale during the revision of this paper is appreciated. Support extended by the Japan Society for the Promotion of Sciences and the French Ministry of Foreign Affairs through its Embassy in the Philippines are likewise acknowledged with thanks.

REFERENCES

Aurelio M. A., Barrier E., Rangin C. & Muller C. 1991. The Philippine Fault in the Late Cenozoic evolution of the Bondoc– Masbate–N. Leyte area, central Philippines. *Journal of Southeast Asian Earth Sciences* **6**, 231–8.

Barretto J. L., Dimalanta C. B. & Yumul G. P. Jr. 2000. Gravity variations along the Southeast Bohol Ophiolite Complex (SEBOC), Central Philippines: Implications on ophiolite emplacement. *The Island Arc* **9**, 576–84.

Barrier E., Huchon P. & Aurelio M. A. 1991. Philippine fault: a key for Philippine kinematics. *Geology* **19**, 32–5.

Bellon H. & Rangin C. 1991. Geochemistry and isotopic dating of Cenozoic volcanic arc sequences around the Celebes and Sulu Seas. *In* Silver E., Rangin C., von Breymann M. T. *et al.* (eds.) *Proceedings of the Ocean Drilling Program, Scientific Results* **124**, 321–38.

Bischke R. E., Suppe J. & Del Pilar R. 1990. A new branch of the Philippine fault system as observed from aeromagnetic and seismic data. *Tectonophysics* **183**, 243–64.

Briais A., Patriat P. & Tapponier P. 1993. Updated interpretation of magnetic anomalies and seafloor spreading stages in the South China Sea: Implications for the Tertiary tectonics of Southeast Asia. *Journal of Geophysical Research* **98**, 6299–328.

Cambray H., Pubellier M., Jolivet L. & Pouclet A. 1995. Volcanic activity recorded in deep-sea sediments and the geodynamic evolution of Western Pacific island arcs. In: Taylor B. & Natland J. (eds.) *Active Margins and Marginal Basin of the Western Pacific, Geophysical Monograph* 88, 97–124.

Cardwell R. K., Isacks B. L. & Karig D. E. 1980. The spatial distribution of earthquakes, focal mechanism solutions and subducted lithosphere in the Philippines and northern Indonesian regions. *In* Hayes D.E. (ed.) *The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands Part 1, Geophysical Monograph* **23**, 1–35.

Cole J., McCabe R., Moriarty T. *et al.* 1989. A preliminary Neogene paleomagnetic data set from Leyte and its relation to motion on the Philippine fault. *Tectonophysics* **168**, 205–20.

De Boer J., Odom L. A., Ragland P. C., Snider F. G. & Tilford N. R. 1980. The Bataan orogene: Eastward subduction, tectonic rotations and volcanism in western Pacific (Philippines). *Tectonophysics* **67**, 251–82.

De Jesus J. V., Yumul G. P. Jr & Faustino D. V. 2000. The Cansiwang Melange of Southeast Bohol (Central Philippines): Origin and tectonic implications. *The Island Arc* **9**, 566–75.

Dominguez S., Lallemand S. E., Malavieille J. & Von Huene J. 1998. Upper plate deformation associated with seamount subduction. *Tectonophysics* **293**, 207–24.

Encarnacion J. P., Essene E. J., Mukasa S. B. & Hall C. H. 1995. High pressure and temperature sub-ophiolitic kyanite-garnet amphibolites generated during initiation of mid-Tertiary subduction, Palawan, Philippines. *Journal of Petrology* **36**, 1481–503.

Faure M., Marchadier Y. & Rangin C. 1989. Pre-Eocene synmetamorphic structure in the Mindoro-Romblon-Palawan area, West Philippines and implications for the history of Southeast Asia. *Tectonics* 8, 963–79.

FULLER M., HASTON R., LIN J.-L., RICHTER B., SCHMIDTKE E. & ALMASCO J. 1991. Tertiary paleomagnetism of regions around the South China Sea. *Journal of Southeast Asian Earth Sciences* **6**, 161–84.

FULLER M., MCCABE R., WILLIAMS I. S. *et al.* 1983. Paleomagnetism of Luzon. *In* Hayes D. E. (ed.) *The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands, Part 2*, *Geophysical Monograph* **27**, 235–46.

GERVASIO F. C. 1971. Geotectonic developments of the Philippines. *Journal of the Geological Society of the Philippines* **25**, 18–38.

HALL R. 1996. Reconstructing Cenozoic SE Asia. *In* Hall R. & Blundell D. J. (eds.) *Tectonic Evolution of Southeast Asia*, *Geological Society of London Special Publication* **106**, 153–84.

HAMBURGER M. W., CARDWELL R. K. & ISACKS B. 1983. Seismotectonics of the northern Philippine island arc. *In* Hayes D.E. (ed.) *The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands, Part 2, Geophysical Monograph* **27**, 1–22.

HAWKINS J. W., MOORE G. F., VILLAMOR R., EVANS C. & WRIGHT E. 1985. Geology of the composite terranes of East and Central Mindanao. *In* Howell D. (ed.) *Tectonostratigraphic Terranes of the Circum-Pacific*, pp. 437–63, Circum-Pacific Council on Energy and Mineral Resources Series 1.

HILDE T. W. C. & LEE C.-S. 1984. Origin and evolution of the West Philippine Basin: a new interpretation. *Tectonophysics* **102**, 85–104.

HOLLOWAY N. H. 1982. The stratigraphy and tectonic relationship of Reed Bank, North Palawan and Mindoro to the Asian Mainland and its significance in the evolution of the South China Sea. *Bulletin of the American Association of Petroleum Geologist* **66**, 1357–83.

HONZA E. 1995. Spreading mode of backarc basins in the western Pacific. *Tectonophysics* **251**, 139–52.

HSU V., SHIBUYA H. & MERRILL D. 1991. Paleomagnetic study of deep sea sediments from the Cagayan Ridge in the Sulu Sea: Results of Leg 124. *In* Silver E., Rangin C., von Breymann M. T. *et al.* (eds.) *Proceedings of the Ocean Drilling Program, Scientific Results* **124**, 511–6.

JOLIVET L., HUCHON P. & RANGIN C. 1989. Tectonic setting of western Pacific marginal basins. *Tectonophysics* **160**, 23–47.

KAMINSKY M. A. & HUANG Z. 1991. Biostratigraphy of Eocene to Oligocene deep-water agglutinated foraminiferas in the red clays from Site 767, Celebes Sea. *In* Silver E., Rangin C., von Breymann M. T. *et al.* (eds.) *Proceedings of the Ocean Drilling Program, Scientific Results* **124**, 171–80.

KARIG D. E. 1983. Accreted terranes in the northern part of the Philippine archipelago. *Tectonics* **2**, 211–32.

LALLEMAND S. E., POPOFF M., CADET J. *et al.* 1998. Genetic relations between the Central and Southern Philippine Trench and the Sangihe Trench. *Journal of Geophysical Research* **103**, 933–50.

LEE T.-Y. & LAWVER L. A. 1994. Cenozoic plate reconstruction of the South China Sea region. *Tectonophysics* **235**, 145–80.

LEE C.-S. & MCCABE R. 1986. The Banda–Celebes–Sulu basin: a trapped piece of Cretaceous–Eocene oceanic crust? *Nature* **322**, 51–3.

MCCABE R., ALMASCO J., SHIBUYA H., ZANORIA W., PAGAUITAN H. & TORII M. 1982a. Evidence against Late Neogene rotations of the island of Luzon. *Committee for co-ordination of Joint Prospecting for Mineral Resources in Asian offshore areas (CCOP) Technical Publication* **13**, 117–29.

MCCABE R., ALMASCO J. & DIEGOR W. 1982b. Geologic and paleomagnetic evidence for a possible Miocene collision in western Panay, Central Philippines. *Geology* **10**, 325–9.

MCCABE R., ALMASCO J. & YUMUL G. P. JR. 1985. Terranes in the Central Philippines. *In* Howell D. (ed.) *Tectonostratigraphic Terranes of the Circum-Pacific*, pp. 421–35, Circum-Pacific Council on Energy and Mineral Resources Series 1.

MCCABE R., HARDER S., COLE J. T. & LUMADYO E. 1993. The use of paleomagnetic studies in understanding the complex Tertiary tectonic history of East and Southeast Asia. *Journal of Southeast Asian Earth Sciences* 8, 257–68.

MCCABE R., KIKAWA E., COLE J. *et al.* 1987. Paleomagnetic results from Luzon and the Central Philippines. *Journal of Geophysical Research* **92**, 555–80.

MCCABE R. & UYEDA S. 1983. Hypothetical model for the bending of the Mariana arc. *In* Hayes D.E. (ed.) *The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands, Part 2, Geophysical Monograph* **27**, 281–93.

MARCHADIER Y. & RANGIN C. 1990. Polyphase tectonics at the southern tip of the Manila trench: Mindoro-Tablas islands, Philippines. *Tectonophysics* **183**, 273–88.

MASCLE A. & BISCARRAT P. A. 1978. The Sulu Sea: A marginal basin in Southeast Asia. *In* Watkins J. S., Montadert L. & Dickerson P. W. (eds.) *Geological and Geophysical Investigations of the Continental Margins*, *Memoir of the American Association of Petroleum Geologists* **29**, 273–88.

MITCHELL A. H. G., HERNANDEZ F. & DELA CRUZ A. P. 1986. Cenozoic evolution of the Philippine archipelago. *Journal of Southeast Asian Earth Sciences* **1**, 3–22.

MURAUCHI S., DEN LUDWIG W. J. N., HOTTA H. *et al.* 1973. Structure of the Sulu Sea and the Celebes Sea. *Journal of Geophysical Research* **78**, 3437–47.

OHARA Y., KASUGA K., OKINO K. & KATO Y. 1997. Survey maps Philippine Sea structures. *EOS Transactions of the American Geophysical Union* **78**, 555.

PUBELLIER M., QUEBRAL R., AURELIO M. & RANGIN C. 1996. Docking and post-docking escape tectonics in the southern Philippines. *In* Hall R. & Blundell D. J. (eds.) *Tectonic Evolution of Southeast Asia, Geological Society Special Publication* **106**, 511–24.

PUBELLIER M., QUEBRAL R., RANGIN C. *et al.* 1991. The Mindanao collision zone: a soft collision event within a continuous Neogene strike-slip setting. *Journal of Southeast Asian Earth Sciences* **6**, 239–48.

RANGIN C. 1989. The Sulu Sea, a back-arc basin setting within a Neogene collision zone. *Tectonophysics* **161**, 119–41.

RANGIN C. 1991a. Southeast Asian marginal basins (South China, Sulu and Celebes Seas): New data and interpretations. *Committee for co-ordination of Joint Prospecting for Mineral Resources in Asian offshore areas (CCOP) Technical Publication* **24**, 156–74.

RANGIN C. 1991b. The Philippine Mobile Belt: a complex plate boundary. *Journal of Southeast Asian Earth Sciences* **6**, 209–20.

RANGIN C., MULLER C. & PORTH H. 1989. Neogene geodynamic evolution of the Visayan region. *Geologisches Jahrbuch B* **70**, 7–27.

RANGIN C. & SILVER E. A. 1991a. Geological setting of the Celebes and Sulu Seas. *In* Silver E., Rangin C., von Breymann M. T. *et al.* (eds.) *Proceedings of the Ocean Drilling Program, Scientific Results* **124**, 35–42.

RANGIN C. & SILVER E. A. 1991b. Neogene tectonic evolution of the Celebes-Sulu basins: New insights from Leg 124 drilling. *In* Silver E., Rangin C., von Breymann M. T. *et al.* (eds.) *Proceedings of the Ocean Drilling Program, Scientific Results* **124**, 51–63.

RANGIN C., SILVER E. A. & TAMAKI K. 1995. Closure of western Pacific marginal basins: rupture of the oceanic crust and the emplacement of ophiolites. *In* Taylor B. & Natland J. (eds.) *Active margins and marginal basins of the western Pacific. Geophysical Monograph* **88**, 405–17.

RANGIN C., STEPHAN J.-F., BUTTERLIN J. *et al.* 1991. Collision neogene d'arcs volcaniques dans le centre des Philippines: stratigraphie et structure de la chaine d'Antique (ile de Panay). *Bulletin Societe Geologique France* **162**, 465–77.

ROESER H. A. 1991. Age of the crust of the southeast Sulu Sea basin based on magnetic anomalies and age determined at site 768. *In* Silver E., Rangin C., von Breymann M. T. *et al.* (eds.) *Proceedings of the Ocean Drilling Program, Scientific Results* **124**, 339–43.

SAJONA F. G., BELLON H., MAURY R. C. *et al.* 1997. Tertiary and Quaternary magmatism in Mindanao and Leyte (Philippines): Geochronology, geochemistry and tectonic setting. *Journal of Asian Earth Sciences* **15**, 121–53.

SANDWELL D. T. & SMITH W. H. F. 1997. Exploring the ocean basins with satellite altimeter data. *http://topex.ucsd.edu/marine_grav/explore_grav.html sat_alt.*

SAREWITZ D. & KARIG D. E. 1986. Processes of allochthonous terrane evolution in Mindoro Island, Philippines. *Tectonics* **5**, 525–52.

SHYU J.-P. & MULLER C. 1991. Calcareous nannofossil biostratigraphy of the Celebes and Sulu Seas. In: Silver E., Rangin C., von Breymann M. T. *et al.* (eds.) *Proceedings of the Ocean Drilling Program, Scientific Results* **124**, 133–57.

TAMAYO R. A. JR. 1997. Etude petrologique et geochemique de l'ophiolite d'Antique (1 le de Panay, Philippines). University of Bretagne Occidentale, Unpublished *DEA Memoir*, 46pp.

TAYLOR B. & HAYES D. E. 1983. Origin and history of the South China Sea Basin. *In* Hayes D.E. (ed.) *The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands Part 2, Geophysical Monograph* **27**, 23–56.

WEISSEL J. K. 1980. Evidence for Eocene oceanic crusts in the Celebes Sea Basin. *In* Hayes D.E. (ed.) *The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands Part 1, Geophysical Monograph* **23**, 37–48.

YUMUL G. P. JR, BALCE G. R., DIMALANTA C. B. & DATUIN R. T. 1997a. Distribution, geochemistry and mineralization potentials of Philippine ophiolite and ophiolitic sequences. *Ofioliti* **22**, 47–56.

YUMUL G. P. JR, DIMALANTA C. B., BARRETTO J. L., QUEAO K. L., FAUSTINO D. V. & DE JESUS J. V. 1997b. Tectonic evolution of Central Philippines and its implications on oil and gas exploration. pp. 52–4. *Proceedings, 3rd Conference on Oil and Gas Exploration and Production Equipment, Technology and Services and Refining and Petrochemical Engineering Technology,* 27–28 November 1997, Manila.

YUMUL G. P. JR, DIMALANTA C. B., FAUSTINO D. V. *et al.* 1998. Ephemeral ocean basins, melanges and metamorphic complexes. *Manuscript of GEOCON 1998 of the Geological Society of the Philippines*, 89–92. 2 December 1998, Quezon City.

YUMUL G. P. JR, TAMAYO R. A. JR, JUMAWAN F. T. & DAVID C. P. C. 1996. Cretaceous Cebu magmatic arc—Southeast Bohol forearc ophiolite: Products of a Paleo-Southeast Bohol Trench? pp. 80–92. *Proceedings Third Symposium on the Cretaceous Environmental Change in East and South Asia (IGCP 350), Manila.*