Shear partitioning in the Philippines: Constraints from Philippine Fault and global positioning system data

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Thematic Article

Shear partitioning in the Philippines: Constraints from Philippine Fault and global positioning system data

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Abstract The Philippine Fault is a major left-lateral structure formed in an island arc setting. It accommodates a component of the oblique convergence between the Philippine Sea Plate and the Philippine archipelago. This observation is quantified through a series of global positioning satellite experiments between 1991 and 1996. The formation of the Fault marks the onset of a new geodynamic regime in the Philippine region. In the central Philippines, this event corresponds to the creation of a new tectonic boundary separating the Philippine Mobile Belt and the Philippine Sea Plate, following the latter's kinematic reorganization that occurred around 4 Ma ago. During this event, the Philippine Sea Plate changed its relative movement with respect to Eurasia from a northward to a northwestward motion, favoring the formation of a Philippine Fault–Philippine Trench system under a shear partitioning mechanism.

Key words: GPS, Philippine Fault, Philippine Mobile Belt, Philippine Sea Plate, Philippine Trench system.

INTRODUCTION

Recent studies on the Philippine Fault add new constraints in deciphering the geodynamic evolution of the Philippine region and its surroundings during the last 5 Ma. Aurelio (1992) and Aurelio *et al.* (1991) presented a tectonic appraisal of the fault's central segment by employing a detailed fault data set analysis and arrived at a post-Miocene age for that segment of the fault. In separate works, Pinet (1990) and Ringenbach (1992) conducted similar studies on its northern segment and estimated an older age of around middle Miocene for that portion. By employing slip vectors of earthquakes from 1964 to 1991 and regional kinematic data, Barrier *et al.* (1991) presented an estimation of the rate of slip along the fault from Mindanao to southern Luzon. Slip rate values of 2–3 cm/yr computed by Barrier *et al.* (1991) were confirmed at least in the central segment in Leyte island by Duquesnoy *et al.* (1994) through global positioning satellite (GPS) and classical geodesic measurements conducted between 1991 and 1993. With data gathered under the GEODYnamics of South and South-east Asia project (GEODYSSEA), Aurelio *et al.* (1998) determined displacement rates along known active faults within the Philippine archipelago, particularly those associated with the Philippine Fault. This fresh data set provides new constraints in clarifying certain points regarding the mechanism and origin of the Philippine Fault as well as its implications to the recent (< 5 Ma) kinematic evolution of the Philippine Sea Plate and of the Philippine region in general.

ON THE MECHANISM OF THE PHILIPPINE FAULT

The Philippine Fault is a 1200 km long left-lateral strike–slip fault situated behind the Philippine Trench (Fig. 1). The latter is a west-dipping subduction zone believed to be a recent feature as estimated from the length of subducted slab (250 km—Cardwell *et al.* 1980; Aurelio 1992) and the rate at which plates are moving in the trench (6–8 cm/yr—Barrier *et al.* 1991; Aurelio 1992). This

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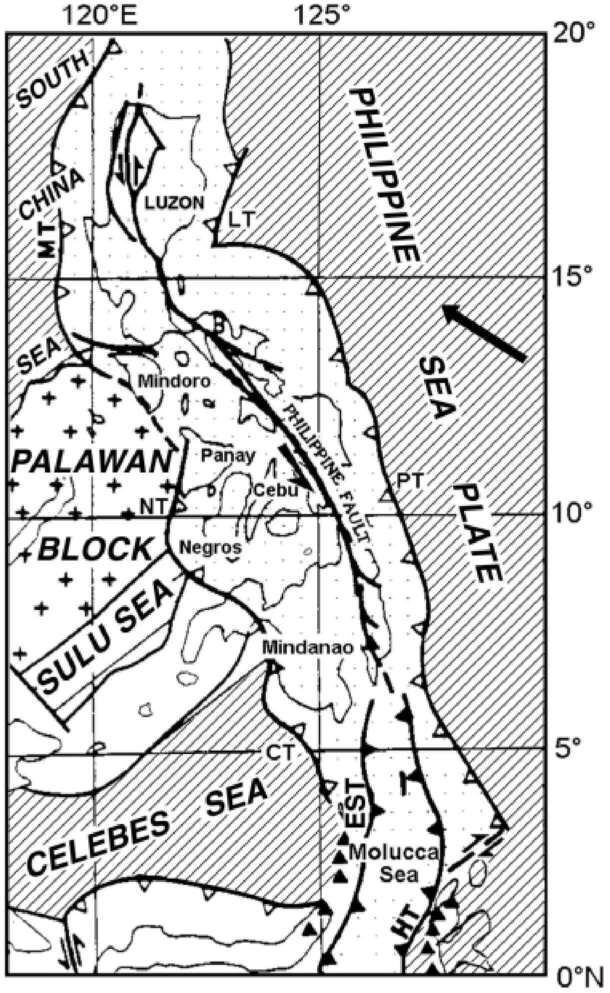

Fig. 1 Major tectonic elements of the Philippine region. MT, Manila Trench; LT, East Luzon Trough; PT, Philippine Trench; NT, Negros Trench; CT, Cotabato Trench; ST, Sulawesi Trench; EST, Sangihe Thrust; HT, Halmahera Thrust; (▲) corresponding arcs; (⊡), Philippine Mobile Belt. Arrow indicates approximate direction of Philippine Sea Plate–Eurasia relative motion at a rate of between 8 and 10 cm/yr.

young age of < 5 Ma is consistent with the absence of a well-developed subduction-related accretionary prism (Karig & Sharman 1975). The Philippine Sea Plate moves obliquely with respect to the trench (e.g. Seno 1977). A very basic question arises as to the existence of the Philippine Fault in such a tectonic setting—why is it necessary for the Philippine Fault to exist while the convergence between the Philippine Sea Plate and Eurasia could as well be completely absorbed along the Philippine Trench? Is there decoupling between lithospheric plates or does subduction occur as oblique slip? To answer these questions, a discussion on the shear partitioning model is presented with new geologic and kinematic arguments for the Philippine Fault. Implications in the geodynamic evolution of the Philippines in particular and the south-east Asian region in general for the last 5 Ma are consequently presented.

THE SHEAR PARTITIONING MECHANISM

Here, the term ‘mechanism’ refers to a process that explains *how* a tectonic structure functions in terms of physical and kinematic (movements) parameters. It does not in any case make reference to forces related to the creation of such a structure.

The Philippine Fault is flanked by subduction zones of opposing polarities (Fig. 1). To the west, subduction is hindered in the central Philippines by the collision between the continental North Palawan Block and the Philippine Mobile Belt. To the east, the Philippine Trench is the site of subduction of the Philippine Sea Plate under the archipelago. Philippine Sea Plate–Eurasia rotation pole computations (Seno 1977; Ranken *et al.* 1984; Huchon 1986) imply that the Philippine Sea Plate moves obliquely with respect to the Philippine Trench (Fig. 1). An old but durable hypothesis on the mechanism of the Philippine Fault is that it accommodates a lateral component of the oblique convergence between the Philippine Sea Plate and Eurasia, the other component being absorbed perpendicularly by subduction along the Philippine Trench. In such a case, the displacement vector of Philippine Sea Plate/Eurasia is decomposed into two vectors, one perpendicular to the trench, the other parallel to the fault.

Fitch (1972) proposed a model of oblique convergence between two lithospheric plates wherein the component of convergence parallel to the plate boundary generates the formation of major strike–slip faults behind the subduction zone which, for its part, accommodates the component perpendicular to it (Fig. 2). Coining the term ‘shear partitioning’, this author later took the Philippines as a possible example, without citing any direct arguments.

Fitch’s (1972) shear partitioning mechanism requires *synchronism* in the formation and activity of the strike–slip fault and the subduction zone. This appears to be the case in the Philippines. Through extensive tectonic and kinematic studies, Aurelio (1992) and Aurelio *et al.* (1991) estimated that the central segment of the Philippine Fault was formed between 3.8 and 2.7 Ma. Then Barrier *et al.* (1991) predicted, through a simplified plate model, subduction rates along the Philippine Trench averaging 7 cm/yr in the central

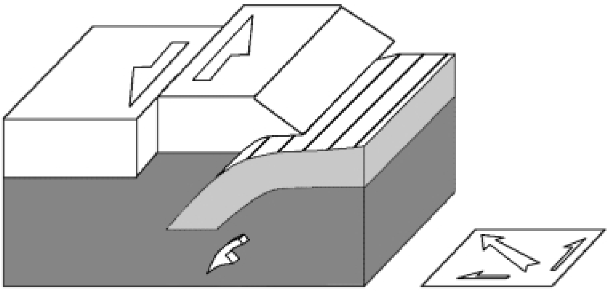

Fig. 2 Shear partitioning at the lithospheric scale drawn from Fitch's 1972 hypothesis. Oblique convergence is decomposed into a component perpendicular to a trench and another parallel to a strike–slip fault located behind the trench.

Philippines. Taking into account the length of subducted slab in this portion of the trench (250 km) and assuming that it still represents the original length, the appearance of the Philippine Trench can be estimated at about 3.6 Ma. The synchronism between these two major lithospheric structures is thus demonstrated which favors the shear partitioning mechanism. In this case, the total relative movement between the Philippine Sea Plate and the Eurasian Plate in this region would be decomposed into a component parallel to the Philippine Fault moving at a rate varying from 1.9 to 2.5 cm/yr (Barrier *et al.* 1991), the other component being accommodated by subduction perpendicular to the Philippine Trench at a rate ranging from 6 to 8 cm/yr. A detailed calculation for the Philippine Fault displacement parameters was shown by Aurelio *et al.* (1994) by using earthquake slip vectors along the Philippine Trench and regional kinematics gathered along the Philippine Fault. These observations suggest that decoupling occurs between plates.

The oblique convergence, however, appears to be distributed in a more complex manner in the northern (Luzon) and southern segments (Southern Mindanao–Moluccas) of the Philippine Fault, where other structures such as more fault branches and collision zones are also present (Fig. 1) (Luzon: Maleterre 1989; Pinet 1990; Ringenbach 1992; Southern Mindanao–Molucca Sea: Pubellier *et al.* 1991; Quebral 1994). In the central Philippines, where the Philippine Fault is restricted to a single, narrow zone (Aurelio 1992), decoupling appears to be easily manifested.

Mechanically, the phenomenon of decoupling in an oblique convergence setting has been modeled experimentally by Pinet and Cobbold (1992) at the lithospheric scale. Citing the Philippines as an analogy, these authors arrived at two major conclusions: (1) in a homogeneous media (single layer), oblique convergence is accommodated completely along a single structure represented by a major thrust–fault (subduction) by oblique slip, while (2) in a heterogeneous media (multiple layers), decoupling occurs. In the latter experiment where the brittle crust, ductile mantle and asthenosphere are modeled by quartz sand, silicone and honey, respectively, the strike–slip—subduction couple is well-developed in the latter stages of convergence. At this stage, there exists a system of a perfect subduction and pure strike–slip faulting, that is, subduction occurs by dip slip (orthogonal to trench) while strike–slip faulting occurs by horizontal slip along a vertical plane. It is thus demonstrated that in an oblique convergence domain set in a multilayer media analogous to the tectonic layers of the earth, subduction occurs orthogonal to the trench and not obliquely to it. The direction of slip vectors of earthquakes associated to the Philippine Trench are essentially orthogonal to it (Barrier *et al.* 1990, 1991; Aurelio 1992; Aurelio *et al.* 1994).

ON THE ORIGIN OF THE PHILIPPINE FAULT: PREVIOUS MODELS

The questions we have just tried to answer in fact lead to more questions. To which geodynamic events can the origin of the Philippine Fault–Philippine Trench system be associated? What are its implications in the evolution of the Philippine region?

Here, we briefly discuss the origin of the Philippine Fault by first recalling previous models and then by presenting later a model constrained by data in this work. Earlier models proposed for the origin of the Philippine Fault were essentially based on works conducted in the southern Philippines and Indonesia, particularly in the Molucca Sea–Halmahera–Sangihe region (Roeder 1977; Silver & Moore 1978; Moore & Silver 1983; Hawkins *et al.* 1985; Barrier *et al.* 1990) and in northern Luzon (Haeck & Karig 1983; Karig *et al.* 1986; Pinet 1990; Ringenbach 1992).

CONSEQUENCE OF AN ARC-ARC COLLISION IN THE MOLUCCAS

Certain authors (Roeder 1977; Silver & Moore 1978; Moore & Silver 1983; Hawkins *et al.* 1985) consider that the Philippine Fault originated from the collision of two arcs in the Moluccas that started sometime in upper Miocene times. This model proposes that the double subduction of the Moluccas Sea Plate generates the convergence of the respective arcs: the Sangihe and Halmahera arcs, followed by their eventual collision and appearance of a suture zone that would ultimately evolve into a large strike–slip zone. It implies the presence of two distinct arcs separated by a suture zone. Through detailed structural studies on the onland traces of the alleged distinct arcs in the island of Mindanao, Pubellier *et al.* (1991) and Quebral (1994) have, however, shown that only a single arc terrane exists and that there are no traces of a suture zone in this region.

CONSEQUENCE OF INDENTION BY HALMAHERA

The Philippine Fault appears to connect with the collision and subduction complex in the Halmaheras. Studies by Nichols *et al.* (1990) and Hall and Nichols (1990) suggest that Halmahera belongs to the Philippine Sea Plate and forms an indenter to the Philippine Mobile Belt (Fig. 1). Barrier *et al.* (1990) proposed that the westward indention by Halmahera of an East Philippine Mobile Belt would cause the extrusion of this belt northwards, with the displacement occurring along the Philippine Fault. This implies that the Philippine Fault extends into the collision zone in the Moluccas, a hypothesis strongly contested by several authors like Quebral (1994) and Pubellier *et al.* (1991) and which in effect still needs to be demonstrated.

CONSEQUENCE OF OBLIQUE CONVERGENCE IN LUZON

Pinet (1990) and Pinet and Cobbold (1992) applied their model of lithospheric decoupling in the Luzon region. Their model revolves around the hypothesis that, in this segment, the Philippine Fault is created from an oblique convergence between the South China Sea Plate (Fig. 1) and Luzon Island. In this scenario, the oblique convergence would be decomposed into a component parallel to the Philippine Fault and another perpendicular to the Manila Trench.

In Luzon, the earliest movements associated with the Philippine Fault have been estimated to have started in middle Miocene times (Maleterre 1989; Pinet 1990; Ringenbach 1992). This implies that, during this period, oblique convergence must have been already existing. Although kinematics along the Philippine Fault in Luzon is now relatively well understood after the works of Maleterre (1989), Pinet (1990) and Ringenbach (1992), the oblique convergence between the South China Sea and Luzon is still to be demonstrated. The relatively small number of earthquakes along the Manila Trench that show incoherent slip vector directions (Aurelio 1992) and the presence of several Philippine Fault branches in Luzon suggest that the system is a lot more complicated.

EXPRESSION OF AN OLD STRIKE–SLIP SYSTEM

To other authors who worked on the western part of Luzon, the present-day Philippine Fault is the expression of an old system of strike–slip faults that dominated the Philippine region throughout the Cenozoic. In this sector, Haeck and Karig (1983) interpreted the presence of melanges characterized by north-trending schistosity lineations as the result of a major shear zone probably active since Oligocene (or even earlier). Karig *et al.* (1986) further elaborated this model and invoked the significance of strike–slip faulting in the transport of allochthonous terranes in the whole Philippines. According to these authors, the strike–slip faults have occurred alternately with major thrust zones, also in an oblique convergence regime.

More recently however, Ringenbach (1992) showed that in southern Luzon, the present-day Philippine Fault *cuts* across north-trending structures belonging to the old strike–slip faults of Haeck and Karig (1983) and Karig *et al.* (1986). The Philippine Fault is thus younger than these north-trending strike–slip faults. In its northern segment however, the main branches of the Philippine Fault are generally oriented in a north-south direction (Maleterre 1989; Pinet 1990; Ringenbach 1992). Here, it may be a case where there is reactivation of the old system by the present Philippine Fault regime.

DISPLACEMENT VECTORS FROM GLOBAL POSITIONING SYSTEM (GPS)

Computed GPS results from GEODYSSEA (Aurelio *et al.* 1998) show varying degrees of complexity in terms of the expected relative motion vectors between plates within the whole Southeast Asian region. Motion vectors on the western sector, including continental China, the Malayan Peninsula and the western and southern Indonesian Islands show a consistency in interaction between the Indian and Eurasian Plates. However, computed motion vectors on the eastern and south-eastern sectors, including the Philippines, Halmahera, Borneo, Banda, Papua New Guinea and northern Australia, imply a more complicated geodynamic setting. For the Philippines, the complexity of the computed motion vectors assuming acceptable repeatability values of measurements, can be interpreted in terms of the archipelago's character as a complex plate boundary itself. When the station in Puerto Princesa, Palawan (PUER) representing the stable platform of the North Palawan Block is fixed (Fig. 3), most of the motion vectors in the Philippines can be explained by active deformation along major structures such as the Philippine Fault, the Legaspi Lineament, the Sibuyan Sea Fault, the Lianga Bay Fault, the Cotabato Fault, the Cotabato, Negros and Sulu Trenches and in regional compressional areas such as the Panay–Negros–Cebu–Bohol area and extensional regions such as the Agusan–Davao Basin.

Table 1 shows the vector parameters in each of the Philippine stations, while Table 2 presents the results of recalculating relative movements in selected pairs of adjoining stations. Plots of these tables are shown on Figs 3 and 4, respectively.

PHILIPPINE VECTORS

All the computed motion vectors relative to the station PUER show negative east components and positive north components (Table 1), implying north-westerly movement of the stations relative to Palawan (Fig. 3). With respect to Palawan (PUER), Zamboanga (ZAMB) and Davao (DAVA) are moving west-northwesterly at approximately 17 and 54 mm/yr, respectively, while Surigao (SURI) and Catanduanes (VIRA) are moving north-westerly at 57 and 74 mm/yr, respectively. Panay Island (ILOI) has a strong northerly component and is moving at a rate of about 21 mm/yr. Standard deviations of the northing values range from about 1.5–1.8 mm/yr while those of the east values range from around 1.7–1.9 mm/yr. The islands ILOI, SURI and Laoag (LAOA) registered upward movements (20, 3 and 8 mm/yr, respectively) while VIRA, DAVA and ZAMB exhibited downward movements (−9, −11 and −29 mm/yr, respectively). Vertical motion standard deviations range from about 3.6–4.1 mm/yr).

Except for LAOA, the computed motion vectors are within the order of the relative plate motions between the Philippine Sea Plate and Eurasia

Table 1 Computed displacement vectors from GPS measurements within the Philippine Archipelago when the station in Puerto Princesa, Palawan (PUER) is held fixed. See also Fig. 3

Station Name	Station Number	North mm/yr	East mm/yr	Up mm/yr	Result mm/yr	Azimuth degrees	Std. North	Std. East	Std. Up
PUER	21	0.000	0.000	0.000	0.000		0.000	0.000	0.000
ILOI	17	20.502	−1.280	20.038	20.5419	356.428	1.672	1.881	4.088
SURI	22	35.463	−44.929	3.287	57.2384	308.284	1.523	1.786	3.770
VIRA	25	8.182	−45.266	−8.939	73.7167	322.117	1.604	1.701	3.623
DAVA	28	11.926	−52.252	−10.928	53.5957	282.857	1.496	1.781	3.723
LAOA	30	33.542	−82.357	8.256	88.9255	292.160	1.838	1.665	3.655
ZAMB	38	6.151	−16.242	−28.848	17.3677	290.742	1.551	1.783	3.893

PUER, Puerto Princesa, Palawan; ILOI, Panay Island; SURI, Surigao; VIRA, Catanduanes; LAOA, Laog; ZAMB, Zamboanga.

Table 2 Computed relative displacement vectors from GPS measurements in between selected stations within the Philippine network. See also Fig. 4

Relative Stations	North mm/yr	East mm/yr	Up mm/yr	Result mm/yr	Azimu. deg
SURI-DAVA	23.537	7.323	14.215	24.6499	017.2820
SURI-ILOI	14.961	−43.649	−16.751	46.1418	288.9195
VIRA-ILOI	37.680	−43.986	−28.977	57.9185	310.5846
SURI-ZAMB	29.312	−28.687	32.135	41.0139	315.6174

SURI–DAVA, Surigao–Davao; SURI–ILOI, Surigao–Iloilo; VIRA–ILOI, Catanduanes–Iloilo; SURI–ZAMB, Surigao–Zamboanga.

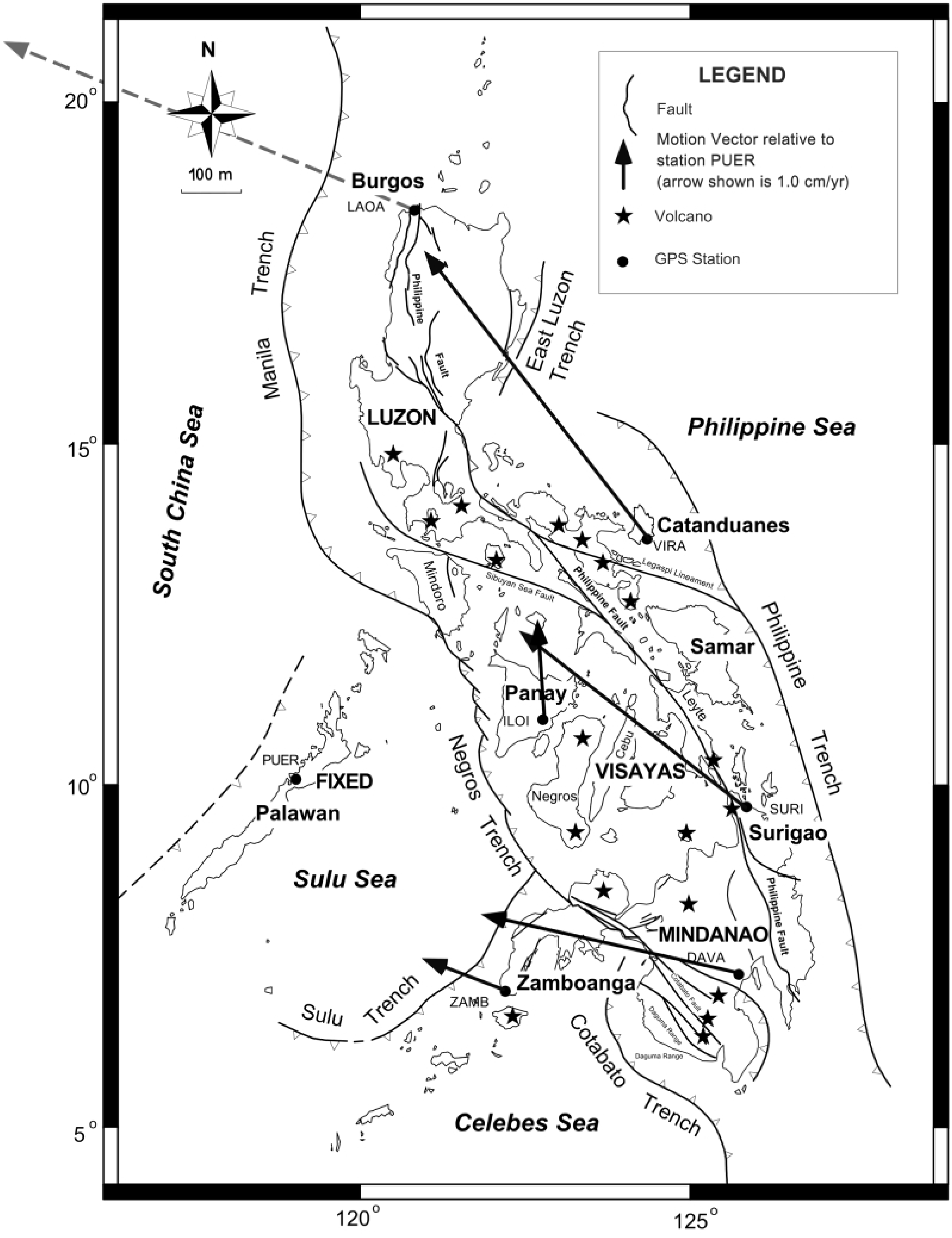

Fig. 3 Displacement vectors from GPS measurements (GEODYSSEA) within the Philippine Archipelago when the station in Puerto Princesa, Palawan (PUER) is held fixed. See upper right corner for symbol explanation. Latitudes in degrees north, longitudes in degrees east. See also Table 1. Adopted from Aurelio *et al.* (1998).

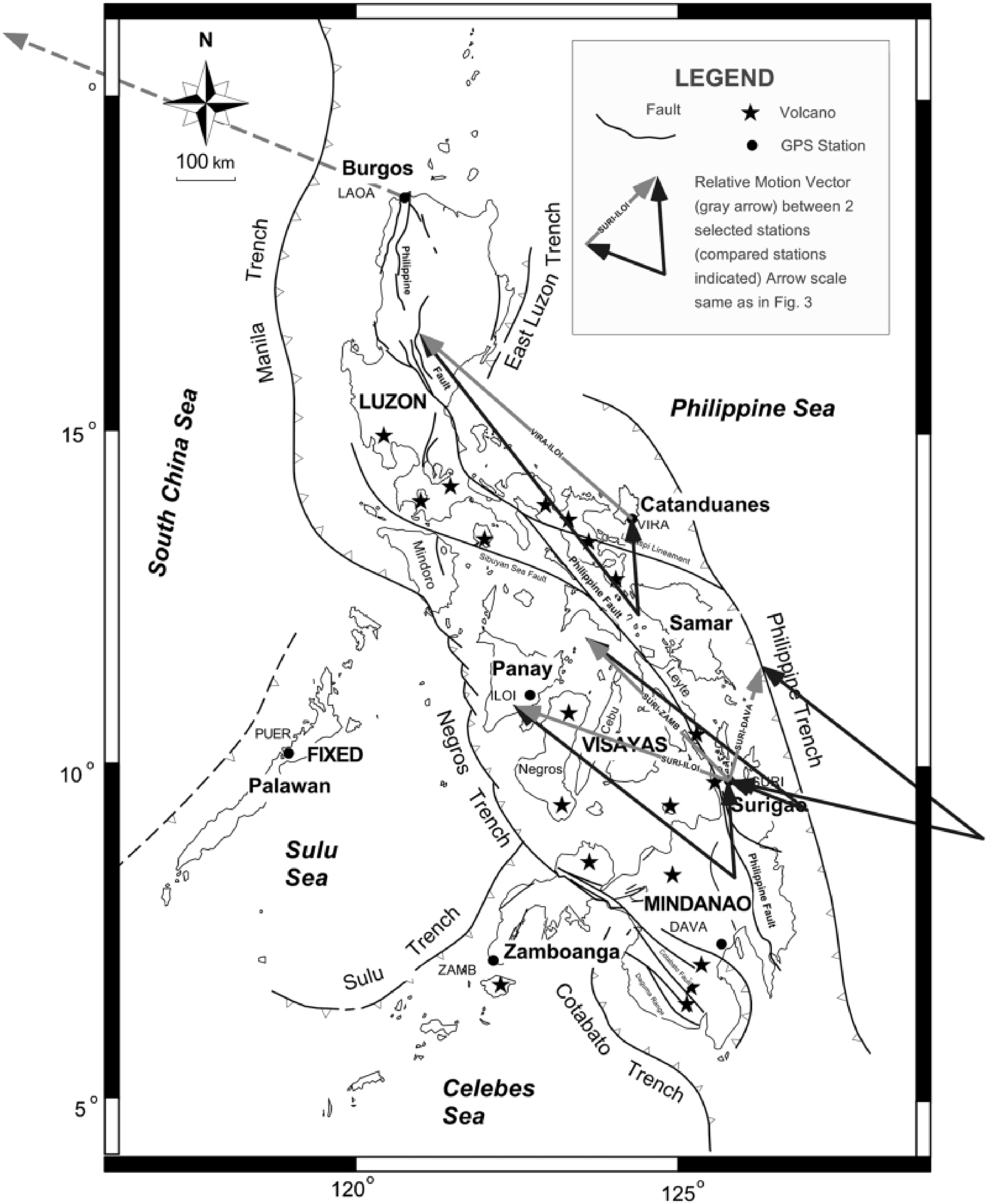

Fig. 4 Relative displacement vectors from GPS measurements (GEODYSSEA) in between selected stations and their relationship with the Philippine Fault and other major strike–slip faults. See upper right corner for symbol explanation. Latitudes in degrees north, longitudes in degrees east. See also Table 2. Modified from Aurelio *et al.* (1998).

which ranges from 84 mm/yr in the latitude of Luzon to 97 mm/yr east of Mindanao (Seno 1977). These movements can therefore be interpreted in terms of active deformation occurring within the Philippine region. The case of LAOA which registered an 88 mm/yr rate, is interpreted as an artefact arising from a medium-magnitude earthquake which occurred in between measurements.

The Philippine Fault is more likely accommodating a good portion of the northwesterly and northerly components of the motion vectors in the Visayas and Mindanao regions, respectively. There can be major contributions from other active faults such as the Legaspi Lineament, Sibuyan Sea–Verde Passage Faults (Visayas) and Lianga, Mati and Cotabato Faults (Mindanao) and from internal deformation in compressional (e.g. Negros–Cebu–Bohol) and extensional (e.g. Agusan–Davao Basin) areas.

DISPLACEMENT RATES ALONG THE PHILIPPINE FAULT DETECTED IN BETWEEN GLOBAL POSITIONING SYSTEM STATIONS

The component of the rate parallel to a given section of the Philippine Fault can be estimated by comparing the vectors computed in each of the individual blocks separated by the structure. In the Philippine GEODYSSEA network, four comparisons can be performed.

Suri–Dava

The relative movement between Davao and Surigao is markedly divergent (Fig. 4; Table 2). The resultant vector has a north-northeasterly azimuth (N017°) with a magnitude of about 25 mm/yr. A major component of this movement is most likely accommodated along the Philippine Fault which trends N165 here. This would imply a left-lateral movement along this fault at a rate of approximately 21 mm/yr. This value appears to be consistent with that computed from GPS measurements to the north in Leyte Island where the Philippine Fault is believed to be creeping at about 24 mm/yr (Duquesnoy *et al.* 1994). It is also possible that the southeasterly trending Lianga and Mati Faults, both branching out from the Philippine Fault in eastern Mindanao (Quebral 1994) are contributing a combined left-lateral movement below 10 mm/yr. All of these faults are seismically active. It can, however, be noted that due to the strong northerly component of the resultant vector, strike–slip faulting may be greater on the northerly trending segments of the Philippine Fault (e.g. Quebral 1994).

The divergent component would be accommodated along extensional regions well manifested in the Lake Mainit and in the Prosperidad–San Francisco portion of the Agusan–Davao Basin. These areas are controlled mainly by pull-apart and subsident regimes.

Suri–Iloi

The resultant vector between Surigao and Iloilo is generally compressive with a magnitude of about 46 mm/yr oriented at an azimuth of N289° (Fig. 4 & Table 2). Resolving now for the component parallel to the Philippine Fault in the vicinity of Southern Leyte–Surigao strait yields a value of about 29 mm/yr. This implies either that the southern segment of the fault may be moving a few mm/yr faster than its northern segment, or that it is accommodating about the same rate (24 ± 10 mm/yr), the rest being accommodated by compression in the Negros–Cebu–Bohol region. With a deformational axis trending about N015°, this region may be accommodating about 33 mm of compression per year.

This young deformation is manifested in the axes of major fold belts in the Visayas (Fig. 4). Cebu is essentially made up of Pleistocene limestones (Carcar Formation) affected by a broad anticline along a north-northeast axis. Similar trends can be observed in the young sedimentary sequences of Negros and Bohol Islands. Recent earthquakes in offshore Bohol have exhibited shallow strike–slip faulting coherent with an west-northwest–east-southeasterly compression. It may also merit to mention that the western peninsulas of Leyte island are also formed of north-northeast trending anticlines affecting Pleistocene limestone formations.

Vira–Iloi

The computed relative motion vector between Catanduanes and Iloilo suggests that the former is moving at a fast rate of about 58 mm/yr towards the north-west with respect to the latter (Fig. 4; Table 2). The vector's azimuthal direction of N310° is subparallel to the three major active strike–slip faults located between the stations, namely, the Philippine Fault (Strike: about N142°), the Legaspi Lineament and the Sibuyan Sea–Verde Passage Fault System (strike: about N110°). The northwestward vector may therefore be interpreted in terms of left-lateral movements along these faults, the Philippine Fault contributing about 25 mm/yr, leaving about 10 mm/yr each of left-lateral movements to the two other faults.

Suri–Zamb

Surigao is moving north-westwards (azimuth: N316°) relative to Zamboanga at a rate of around 41 mm/yr. This movement may be accommodated in two major strike–slip zones, namely, the Philippine Fault and the Cotabato Fault Zone. Assuming that its Surigao segment is moving at the same rate as the fault's Leyte segment, the Philippine Fault may be accommodating a component of 24 mm/yr oriented north-northwestwards (azimuth: N345°). Subtracting this component from 41 mm/yr (azimuth: N316°) yields a remaining vector of about 23 mm/yr oriented north-westwards (azimuth: N285°). This is almost parallel to the strike of faults forming the Cotabato Fault Zone. Such a movement implies left-lateral movements along these faults, and this may be substantiated by the occurrence of several earthquakes with left-lateral focal mechanism solutions (Pubellier *et al.* 1993).

INTERPRETATION

Taken in the context of Philippine tectonics, displacement vectors resulting from GEODYSSEA GPS data can be explained by previously known structures, particularly the Philippine Fault.

Central Philippines

The GPS stations in the central Philippines are located on either side of the Philippine Fault. The ILOI station is west of the structure, while the VIRA station is to the east of it. The VIRA–ILOI motion vector implies a left-lateral displacement along the fault, although a compressive component perpendicular to the strike of the fault is noticeable. This may imply that although the interaction between the eastern and western portions of the Philippine Mobile Belt is essentially characterized by strike–slip faulting, an east-west compressive component is possibly being accommodated along thrust and fold zones. This transpressive regime is also evident in the northern Luzon area where recent GPS measurements by Yu *et al.* (1999) indicate very high block motions (86 mm/yr) with respect to stable Eurasia. Slip along the Philippine Fault is estimated at between 17 and 31 mm/yr.

In Leyte island, results of GPS surveys from 1991 to 1994 show a generally strike–slip faulting region where displacement rates were estimated at 24 mm/yr ± 10 mm/yr (Duquesnoy *et al.* 1994) with a noticeable extensional component oriented perpendicular to the strike of the Philippine Fault. This extensional component is consistent with geomorphological evidence and fault tectonic studies along this segment which cuts along an active geothermal area (Aurelio 1992). This characteristically differs from what is observed in the GEODYSSEA network where the stations in ILOI, VIRA and SURI register a generally compressive regime (Aurelio *et al.* 1998). The Leyte network is built around a more local area (longest baseline is about 50 km only) where faults have been recognized to show transtensional characteristics (Aurelio 1992). The difference in tectonic regimes as observed from the two separate networks may mean that, at the regional scale, the central Philippine Mobile Belt is undergoing a transpressive deformation (strike slip plus compression), while at the local scale, Leyte Island is under transtensional tectonics (strike–slip plus extension) (Aurelio *et al.* 1993, 1998).

Southern Philippines

Relative motion observed on the southernmost station in Davao shows a strong westerly component. This direction is perpendicular to the Philippine Fault and Cotabato Trench, but oblique to the Cotabato Fault Zone. Although this may imply that all the convergence is consumed by frontal subduction along the trench, it is not discounted that lateral movement along the Philippine Fault along this segment does not occur. This appears to coincide with some indications of a possible seismic gap in the Tagum–Davao area (Quebral 1994). Further north in Nabunturan town, however, there are clear indications of recent activity along the fault (e.g. overturned recent alluvial deposits, Pleistocene anticlines cut by fault) while to the south in Mati and offshore Pujada, earthquakes possibly generated by a branch of the fault there, have been recorded for the past 100 years.

To the west, it is interesting to note the occurrence of the Cotabato Fault, a prominent northwest–southeast trending structure also believed to be a left-lateral strike–slip fault (Pubellier *et al.* 1991, 1993), located behind the Cotabato Trench, an east-dipping subduction zone. Seismicity along this subduction area is fairly high while it is only known to occur on the northern segments of the Cotabato Fault Zone. Furthermore, it is still unclear whether the Celebes Sea is subducting frontally against the Daguma arc, but if it is, the situation may be operating on a shear partitioning mechanism similar to what is observed in the central segment of the Philippine Fault and the Philippine Trench.

Down south in the Mollucas area, what prevails is a complex collision process involving the consumption of the Mollucas sea crust entailing the imminent accretion of Halmahera arc Sangihe. The process is brought about by a strong east-west stress pattern easily observed on focal mechanism solutions (Aurelio 1992; Quebral 1994). This may also have a great influence on the westerly relative plate motion observed in the Davao station.

DISCUSSION

THE PHILIPPINE TRENCH–PHILIPPINE FAULT COUPLE: CONSEQUENCE OF THE KINEMATIC REORGANIZATION OF THE PHILIPPINE SEA PLATE 4 Ma AGO

At this point, three major observations can be put forth: (i) present-day displacement rates along the Philippine Fault from Southern Luzon to Northern Mindanao are in the order of 2–3 cm/yr; (ii) activity on the central segment of the Philippine Fault started between 2.7 and 3.8 Ma, and (iii) formation of the Philippine Trench was between 2 and 4 Ma ago.

The first observation strongly supports a shear partitioning mechanism from the point of view of displacement rates. As the Philippine Sea Plate moves north-westwards at 80–10 mm/yr, the Philippine Fault accommodates about a third of the oblique convergence, the rest being accommodated essentially along the Philippine Trench and, to a certain extent, by other major structures such as the Legaspi Lineament, the Sibuyan Sea Fault and the Cotabato Fault, as well as through internal deformation within the entire Philippine Archipelago (Fig. 3).

The second and third observations argue for synchronism between the Philippine Fault and Philippine Trench. By around 4 Ma, the Philippine Sea Plate underwent a major kinematic reorganization, changing its relative movement to Eurasia from an essentially northward motion to its present-day movement (Fig. 5). Presently, the Philippine Sea Plate moves north-westwardly with respect to Eurasia (Seno 1977; Huchon 1986). Extensive paleostress trajectory studies in the

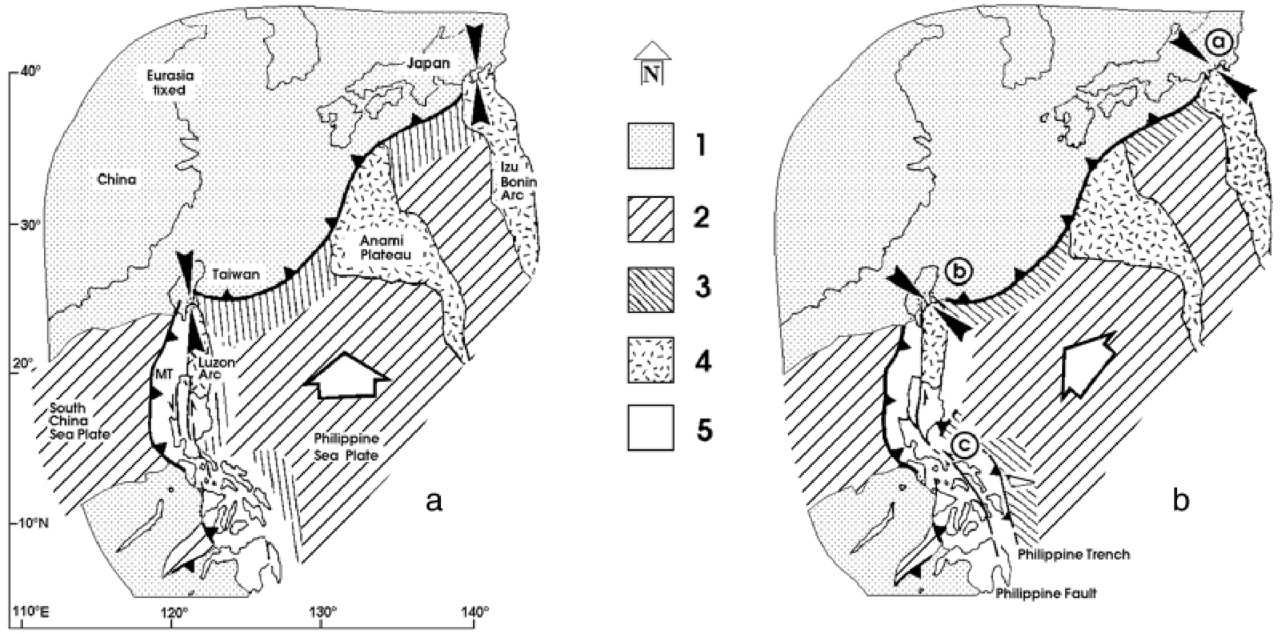

Fig. 5 Formation of the Philippine Fault–Philippine Trench system following kinematic reorganization of the Philippine Sea Plate. 1, continental crust; 2, oceanic crust; 3, crust to be subducted; 4, volcanic arc; 5, Philippine Mobile Belt. (A), Stage characterized by a northward motion of the Philippine Sea Plate relative to Eurasia (pre 4 Ma); MT, Manila Trench. (B) Stage characterized by a north-westward displacement of the Philippine Sea Plate relative to Eurasia (post 4 Ma). ⓐ and ⓑ are directions of $\sigma 1$ determined by Angelier & Huchon (1986) and Barrier (1985) in Japan and Taiwan, respectively. ⓒ Formation of the Philippine Fault–Philippine Trench system, this work.

collision zones of Taiwan (Barrier 1985; Angelier *et al.* 1986; Chu 1990; Lee *et al.* 1990) and Izu in Japan (Huchon 1985; Angelier & Huchon 1986; Huchon & Angelier 1987) have demonstrated, however, that prior to this present-day kinematics, the Philippine Sea Plate was moving relative to Eurasia at a northward course, the change in direction of relative movement occurring at about 4 Ma ago. This observed plate reorganization based on paleostresses corroborates with volcanic evidence in the Southwestern Japan arc and Ryukyu arc (Kamata 1999, 1997; Kamata & Kodama 1999, 1994). These authors suggest remarkable changes in volcanism between 6 and 2 Ma. In these arcs, there is evidence reflective of a change in plate motion of the Philippine Sea Plate from a northwesterly to a west north-westerly direction. A good synchronism of the formation of the Philippine Trench–Philippine Fault couple with the recent kinematic reorganization of the Philippine Sea Plate is thus observed. This strongly suggests that the formation of the trench-strike–slip system in an oblique convergence regime is associated with the change in the direction of movement of the Philippine Sea Plate. It would appear that prior to this kinematic change, the northward motion of the Philippine Sea Plate did not require the creation of a subduction zone on the eastern part of the Philippines (Fig. 5a). It would be only when the Philippine Sea Plate changed course to a northwestward direction that oblique convergence would ensue, thus creating the subduction-strike–slip system (Fig. 5b). It is important to note that the old north-south trending strike–slip faults of Luzon which are consistent with a northward moving Philippine Sea Plate, would have already been active prior to the kinematic reorganization.

IMPLICATIONS TO THE RECENT GEODYNAMIC EVOLUTION OF THE PHILIPPINE REGION

The birth of the Philippine Fault marks the onset of a new geodynamic regime in the Philippine region. In the central Philippines, this event corresponds to the creation of a new tectonic boundary separating the Philippine Sea Plate and the Philippine Mobile Belt. Although its northern segment appears to have formed earlier in Luzon, the present-day Philippine Fault is continuous in space, but presents a polyphase evolution in time. The main branches of the Philippine Fault in Luzon show northerly orientations, in general parallel to the Manila Trench (Fig. 1). At the start of activity of the Philippine Fault there in middle Miocene times (~10 Ma) (Maleterre 1989; Pinet 1990; Ringenbach 1992), the South China Sea oceanic crust was already being consumed along the Manila Trench (Taylor & Hayes 1983; Briais 1989; Rangin *et al.* 1990). Backed up by their analogic modeling arguments, this contemporaniety of events led Pinet and Cobbold (1992) to propose that the Manila Trench–Philippine Fault (probably still a narrow zone at the time of formation) system was formed in a setting involving the oblique convergence of the South China Sea Plate with the Luzon arc (Fig. 6a). However, the formation of the Philippine Fault (central segment)–Philippine Trench system came much later at around 4 Ma (Fig. 6b). We thus observe the formation of a Philippine Fault system in two stages: first at around 10 Ma for its northern segment, followed by its central segment at around 4 Ma. Geodynamically, this two-stage evolution implies that the two segments were formed independently. The northern segment could have reactivated pre-existing strike–slip faults related to a different geodynamic setting (Karig *et al.* 1986). On the contrary, the central segment does not appear to have reactivated any pre-existing strike–slip faults. Here, the Philippine Fault is a young feature.

It is interesting to note that the Philippine Trench– Philippine Fault system is situated in front of the Mindoro–Panay collision zone. This collision process, generally believed to have started between 14 and 8 Ma (McCabe *et al.* 1982; Rangin *et al.* 1985, 1991; Marchadier 1988), has been considered by several authors (Karig 1973; Roeder 1977; Silver & Moore 1978) as having caused the blocking of the western edge of the Philippines and the eventual flip of an east-dipping subduction system situated to the west (proto-Manila Trench) to a west-dipping subduction system to the east (Philippine Trench). We have just demonstrated, however, that the Philippine Trench was formed only at 4 Ma, thereby leaving a gap of not less than 4 Ma since the start of the collision. What happened during this tectonic gap now remains the question to be looked into and the key to this problem is a detailed tectonic study of the region between the collision zone and the Philippine Fault that includes the islands of Mindoro, Panay, Negros and Cebu (Figs 3,4).

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Earthquake data mentioned in this paper and presented in detail by Aurelio (1992) refer to Centroid

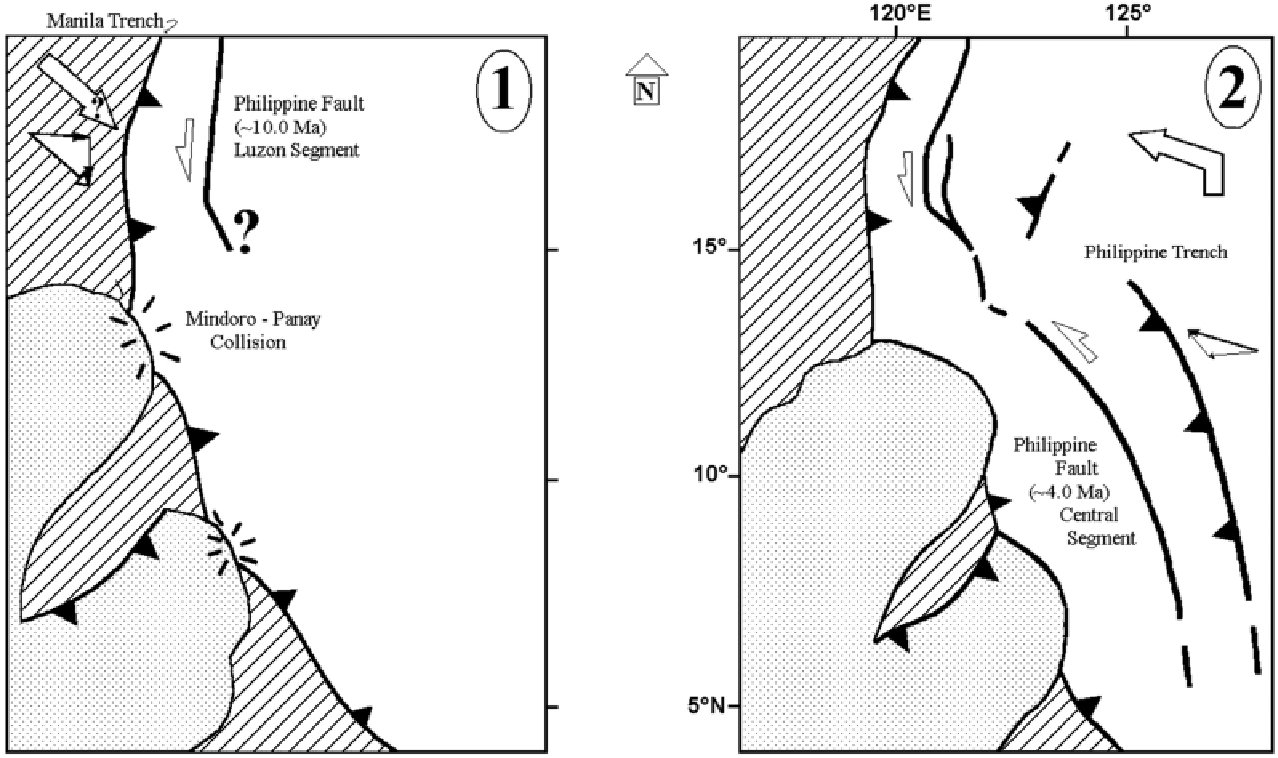

Fig. 6 Polyphase temporal evolution of the presently continuous Philippine Fault system. 1, Formation of the northern segment probably by shear partitioning along Manila Trench and the Philippine Fault; 2, Formation of the central segment by shear partitioning along the Philippine Trench and the Philippine Fault. The north and central (south) segments eventually connect to form the fault's present-day trace. See text for discussion.

Moment Tensor Harvard data sets accessed in collaboration with R. Gaulon of the Laboratoire de Sismologie of the Institut de Physique du Globe de Paris. The first half of this paper was written during a postdoctoral fellowship in 1995 at the Universite Pierre et Marie Curie in Paris, France, awarded by the European Economic Commission to M. Aurelio under a Fixed Contribution Contract No. CI1*-CT-93–0164. The GPS results presented in the second half of this paper come from data gathered between 1994 and 1996 by the Project GEODYSSEA headed by P. Wilson, then from the GeoForschungsZentrum, Potsdam, Germany. GEODYSSEA was under an EEC Associated Contract with ASEAN.

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REFERENCES

ANGELIER J., BARRIER E. & CHU H. T. 1986. Plate collision and paleostress trajectories in a fold-thrust belt: the Foothills of Taiwan. *Tectonophysics* **125**, 161–78.

ANGELIER J. & HUCHON P. 1986. Tectonic record of convergence changes in a collision area: The Boso and Miura peninsulas, Central Japan. *Earth and Planetary Science Letters* **81**, 397–408.

AURELIO M. A. 1992. Tectonique du segment central de la faille philippine (etude structurale, cinÈmatique et Èvolution gÈodynamique). *Thèse de Doctorat*: Universite Pierre et Marie Curie, Paris, France.

AURELIO M. A., BARRIER E., RANGIN C. & MÜLLER 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**, 221–38.

AURELIO M. A., HUCHON P. H., BARRIER E. & GAULON R. 1994. Displacement rates along the Philippine Fault estimated from slip-vectors and regional kinematics. *Journal of the Geological Society of the Philippines* **49**, 65–78.

AURELIO M. A., PAGADO E. S. & TEBAR H. J. 1993. Kinematics of the Philippine Fault System at the Tongonan Geothermal Field, N. Leyte: implications for geothermal exploration and development. *Journal of the Geological Society of the Philippines* **48**, 1–20.

AURELIO M. A., WALPERSDORF A., SIMONS W., ALMEDA R. L., THE EC-PHILIPPINE G. P. S. & TEAM. 1998. Displacement rates and block rotation in and around the Philippines—results from

GEODYSSEA data Part II. *Program and Abstracts: GEOSEA 98—Ninth Regional Congress on Geology, Mineral and Energy Resources of Southeast Asia*, p. 238.

Barrier E. 1985. Tectonique d'une chaÓne de collision active (Taiwan). *Thèse de Doctorat d'Etat*: Paris, Université Pierre et Marie Curie, Paris, France.

Barrier E., Aurelio M. A., Müller C., Pubellier M., Quebral R. D. & Rangin C. 1990. The Philippine Fault: an active strike slip fault along an oblique convergence zone. *Acadèmie Des Sciences Comptes Rendus* **311**, 181–8.

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

Briais A. 1989. CinÈmatique d'ouverture de la Mer de Chine du Sud (Nanhai) (implications pour la tectonique tertiaire de l'Asie). *Thèse de Doctorat*. Université Pierre et Marie Curie, Paris, France.

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

Chu H. T. 1990. Neotectonique cassante et collision plio-quaternaire à Taiwan. *Thèse de Doctorat*, Université Pierre et Marie Curie, Paris, France

Duquesnoy T., Barrier E., Kasser M. *et al.* 1994. Detection of creep along the Philippine Fault: first results of geodetic measurements in Leyte Island, central Philippines. *Geophysical Research Letters* **21**, 975–8.

Fitch T. J. 1972. Plate convergence, transcurrent faults, and internal deformation adjacent to southeast Asia and the western Pacific. *Journal of Geophysical Research* **77**, 4432–60.

Haeck G. D. & Karig D. E. 1983. Strike-slip genesis of the Ilocos Norte Melange. *EOS Transactions of the American Geophysical Union* **64**, 871.

Hall R. & Nichols G. J. 1990. Terrane amalgamation in the Philippine Sea margin. *Tectonophysics* **181**, 207–22.

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. G. (ed.) *Tectonostratigraphic Terranes of the Circum-Pacific Region.* Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series no. 1, Houston, Texas, 437–63.

Huchon P. 1985. GÈodynamique de la zone de collision d'Izu et de la jonction du Japon central (leur place dans l'Èvolution de la plaque philippine). *Thèse de Doctorat d'Etat*. Université Pierre et Marie Curie, Paris, France.

Huchon P. 1986. Comment on "Kinematics of the Philippine Sea Plate" by B. Ranken, R.K. Cardwell and D.E. Karig. *Tectonics* **5**, 165–8.

Huchon P. & Angelier J. 1987. From subduction to collision: the Suruga-Fujigawa belt, Izu collision zone, Central Japan. *Bulletin de la Société Géologique de France* **3**, 511–21.

Kamata H. 1997. Quaternary volcanic front at the junction of the South-west Japan Arc and the Ryukyu Arc. *Journal of Asian Earth Sciences* **16**, 67–75.

Kamata H. 1999. Significance of tectonic events at 6 Ma and 2 Ma in the northern part of the Philippine Sea Plate. *Proceedings of the Joint Meeting on Comparative Studies of Island-Arc Seismicity and Volcanism in the Western Pacific Region*. Quezon City, Philippines, 16–17 February, 1999.

Kamata H. & Kodama K. 1994. Tectonics of an arc-arc junction: an example from Kyushu Island at the junction of the Southwest Japan Arc and the Ryukyu Arc. *Tectonophysics* **233**, 69–81.

Kamata H. & Kodama K. 1999. Volcanic history and tectonics of the Southwest Japan Arc and the Ryukyu Arc since 2 Ma. *The Island Arc* **8**, 393–403.

Karig D. E. 1973. Plate convergence between the Philippines and the Ryukyu islands. *Marine Geology* **14**, 153–68.

Karig D. E., Sarewitz D. R. & Haeck G. D. 1986. Role of strike-slip faulting in the evolution of allocthonous terranes in the Philippines. *Geology* **14**, 852–5.

Karig D. E. & Sharman G. F. 1975. Subduction and accretion in trenches. *Geological Society of America Bulletin* **86**, 377–89.

Lee T. Q., Angelier J., Chu H. T. & Bergerat F. 1990. Rotations in the northern collision belt of Taiwan: preliminary results from paleomagnetism. *Tectonophysics* **199**, 109–20.

McCabe R., Almasco J. & Diegor W. 1982. Geologic and paleomagnetic evidence for a possible Miocene collision in western Panay, central Philippines. *Geology* **10**, 325–9.

Maleterre P. 1989. Histoire sédimentaire, magmatique, tectonique et métallogénique d'un arc océanique déformé en régime de transpression. *Thèse de Doctorat.* Brest, Université de Bretagne Occidentale, Brest, France.

Marchadier Y. 1988. La terminaison de la fosse de Manille en domaine continental (études stratigraphique et tectonique des îles de Mindoro-Tablas—Philippines). *Thèse de Doctorat*. Université Pierre et Marie Curie, Paris, France.

Moore G. F. & Silver E. A. 1983. Collision processes in the northern Molucca Sea. *In* Hayes D. E. (ed.) *The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands, Part 2.* American Geophysical Union Monograph **27**, 360–72.

Nichols G., Hall R., Milsom J. *et al.* 1990. The southern termination of the Philippine Trench. *Tectonophysics* **183**, 289–304.

Pinet N. 1990. Un exemple de grand dÈcrochement actif en contexte de subduction oblique: la faille philippine dans sa partie septentrionale (études régionale, thématique et modélisation analogique). *Thèse de Doctorat* Université de Nice-Sophia Antipolis., Nice, France.

PINET N. & COBBOLD P. 1992. Experimental insights into the partitioning of motion within zones of oblique subduction. *Tectonophysics* **206**, 371–88.

PUBELLIER M., QUEBRAL R. D., DEFFONTAINES B. & RANGIN C. 1993. Neotectonic Map of Mindanao Island, Philippines, with 23-page Explanatory Note. Printed and distributed by: *Asia Geodyne Corporation*, Quezon City, Philippines.

PUBELLIER M., QUEBRAL R. D., 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.

QUEBRAL R. D. 1994. Tectonics of the southern segment of the Philippine Fault, eastern Mindanao, Philippines: transition from a collision zone to a strike-slip fault. *Thèse de Doctorat de l'Université de Paris* 6, Université Pierre et Marie Curie, Paris, France.

RANGIN C., JOLIVET L., PUBELLIER M. & THE TETHYS PACIFIC WORKING GROUP. 1990. A simple model for the tectonic evolution of southeast Asia and Indonesian region for the past 43 m.y. *Bulletin de la Société Géologique de France* **6**, 889–905.

RANGIN C., STEPHAN J. F. & MÜLLER C. 1985. Middle Oligocene oceanic crust of South China Sea jammed into the Mindoro collision zone (Philippines). *Geology* **13**, 425–8.

RANGIN C., STEPHAN J. F., BUTTERLIN J. *et al.* 1991. Collision néogène d'arcs volcaniques dans le centre des Philippines: stratigraphie et structure de la chaÓne d'Antique (île de Panay). *Bulletin Société Géologique de France* **162**, 465–77.

RANKEN B., CARDWELL R. K. & KARIG D. E. 1984. Kinematics of the Philippine Sea Plate. *Tectonics* **3**, 555–75.

RINGENBACH J. C. 1992. La faille philippine et les chaînes en décrochement associées—centre et nord Luzon (évolution cénozoïque et cinématique des déformations quaternaires). *Thèse de Doctorat*: Nice, Université de Nice-Sophia Antipolis, Nice, France.

ROEDER D. 1977. Philippine arc system—collision or flipped subduction zones? *Geology* **5**, 203–6.

SENO T. 1977. The instantaneous rotation vector of the Philippine Sea Plate in relation to the Eurasian Plate. *Tectonophysics* **42**, 209–26.

SILVER E. A. & MOORE J. C. 1978. Philippine arc system—collision or flipped subduction zones? Comment. *Geology*, **6**, 199.

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.* American Geophysical Union Monograph **27**, 23–56.

YU S. B., KUO L. C., PUNONGBAYAN R. S. & RAMOS E. G. 1999. GPS observation of crustal deformation in the Taiwan-Luzon region. *Geophysical Research Letters* **26**, 923–6.