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Seismotectonics of Mindoro, Philippines

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ABSTRACT

Mindoro Island is located where the Palawan Continental Block indented into the Philippine Mobile Belt during the Early Miocene and where the Manila Trench terminates, having ceased convergence due to collision. The seismotectonics of Mindoro are crucial to understanding the processes of arc-continent collision and slab dynamic responses of convergence cessation. This study was conducted using data from both the EHB and Global Centroid Moment Tensor catalogues. It is shown that following the southeasterly reduction of convergence rates from the Manila Trench offshore NW Mindoro to onshore SW Mindoro, the slab dipping angles steepen, were initiated at depth (~200 km) and propagate upwards. The horizontal distances of the trench and slab, as measured from the Wadati–Benioff zone at 200 km depth, also reduce in a southeasterly direction. Observations of intermediate-depth earthquakes that exhibit predominantly down-dip extensional stress patterns attest that the steepening of slab dipping angles is due to the negative buoyancy of the slab. In contrast, a broad region covered by central and south Mindoro, the Romblon group, and NW Panay, is characterized by a sporadic distribution of shallow earthquakes of mostly strike-slip type. Among these, the significantly sized events ($M_w > 5.5$) tend to distribute around the borders suggesting that the region roughly acts as a unit block, moving or rotating coherently. Events in the vicinity of the Wawa–Mamburao valley exhibiting normal faulting of NW–SE horizontal extension suggest rifting of the Macolod Corridor extending southwestward to NW Mindoro.

1. Introduction

Mindoro Island in the west-central Philippines is located where the Palawan Continental Block (PCB) indented into the Philippine Mobile Belt (PMB) during the Miocene (Yumul et al., 2003) and where the southern Manila Trench currently terminates and progressively turns into vague surface expressions southeastward from offshore NW Mindoro to onshore SW Mindoro (Marchadier and Rangin, 1990) (Fig. 1). The seismically active PMB and the aseismic PCB together constitute the Philippine archipelago where the Sundaland Plate (SUND) to the west and the Philippine Sea Plate (PSP) to the east converge at a rate of ~9 cm/year, trending NW–SE (DeMets et al., 2010). The opposite polarity of subduction systems on two sides of the PMB—predominantly east-dipping SUND slab along the Manila–Negros–Cotabato trenches to the west and west-dipping PSP slab along the East Luzon Trough and the Philippine Trench to the east—together with the Philippine Fault systems mostly accommodate the SUND-PSP relative plate motions. The Philippine Fault, which transects the PMB in a generally NNW–SSE direction, mainly absorbs components of oblique convergence and is occasionally ruptured by left-lateral strike–slip earthquakes (Barrier et al., 1991).

The PMB represents accreted terranes of ophiolites, island arcs, and continental fragments, whereas the PCB is essentially a continental fragment that rifted off the Eurasia continents during the mid-Tertiary and subsequently drifted southward with the opening up of the South China Sea (Karig, 1983). According to tectonic reconstruction of tectonic terranes based on paleomagnetic and stratigraphic studies (Holloway, 1982; Karig, 1983; Sarewitz and Karig, 1986), the Oligocene counterclockwise rotation and northward movements of the PMB, together with the southward drift of the PCB, have resulted in collision in the vicinity of Mindoro during the Miocene. The Miocene collision played a key role in the geological evolution of the Philippine archipelago. Several of its impacts have been inferred, including the initiation of sinistral strike–slip movements in the central PMB, resulting in the Philippine Fault Systems (Holloway, 1982); inception of double polarity subductions (Holloway, 1982; Yumul et al., 2003); counterclockwise rotation of Mindoro–Marinduque and clockwise rotation of Panay and the Western Visayan block (Holloway, 1982; Yumul et al., 2000); and steep dipping of the Wadati–Benioff zone beneath NW Mindoro and SW Luzon (Bautista et al., 2001).

Understanding the processes of the PCB–PMB collision is thus critical for the study of the complex tectonics and geological characteristics of

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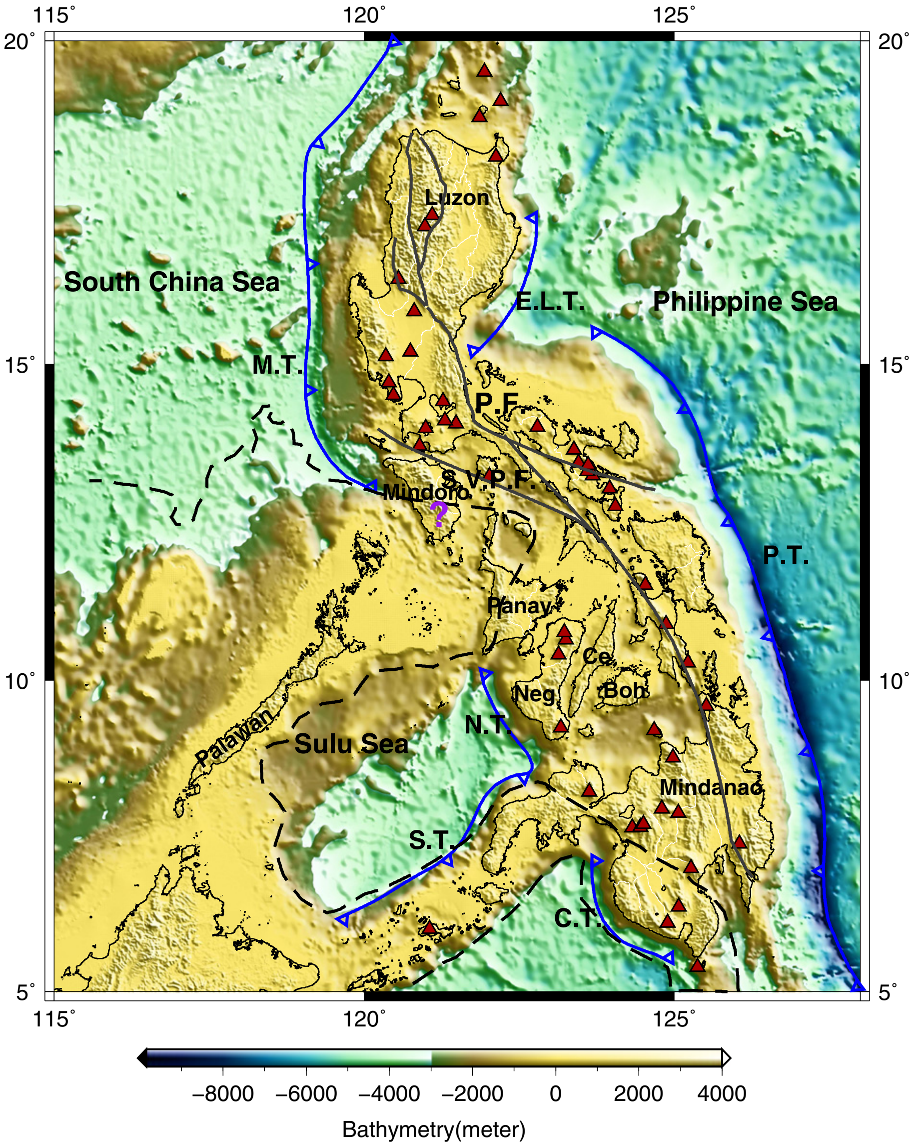

Fig. 1. Tectonic settings of the Philippine archipelago. Blue lines are trenches, with dipping polarities shown in triangles. Gray solid lines are fault traces. Black dashed lines are the continent–ocean-boundary from Yumul et al. (2009) and red triangles are distributions of Quaternary volcanoes. Abbreviations: E.L.T. (East Luzon Trough), P.T. (Philippine Trench), M.T. (Manila Trench), N.T. (Negros Trench), C.T. (Cotabato Trench), S.T. (Sulu Trench), P.F. (Philippine Fault), S.V.P.F. (Sibuyan Verde Passage Fault), Neg (Negros), Ce (Cebu), Boh (Bohol).

the Philippines and may help identify areas that are prone to earthquake, volcano, and tsunami hazards. In this regard, Mindoro Island, situated at the site of the collision, provides crucial data. However, the locations of the Miocene PCB–PMB collision boundaries in the vicinity of Mindoro are difficult to ascertain geologically due to multiple collision episodes, as shown by various ophiolite belts on the island, with the earlier imprints often blurred by later ones (Marchadier and Rangin, 1990; Yumul et al., 2003). As a result, proposals of the PCB–PMB boundary vary from offshore east Mindoro (Dimalanta et al., 2009), through central Mindoro (Sarewitz and Karig, 1986) to southwest Mindoro (Karig, 1983; Marchadier and Rangin, 1990).

On the other hand, the Quaternary crustal deformations and relative block motions in the vicinity of Mindoro as revealed by geodetic and seismological studies may help understand the processes of the Miocene collision, by which they are strongly influenced. Joint inversions of recent geodetic and focal mechanism data indicate that Sundaland, Mindoro, and Central Visayas are moving westward relative to the Central Luzon Block (SUND, MIND, CENV, and CLUZ, respectively, in Fig. 8 of Galgana et al., 2007). However, as recognized by Galgana et al. (2007), the results are based on a first-order approximation of block identification, due to the limited density of GPS sites, whereas some blocks still exhibit internal deformation as shown by earthquake occurrence (e.g., MIND). In this study, we decipher patterns of crustal deformations and block movements in and around Mindoro using seismological data. Unlike previous similar studies dealing with a relatively broad area (e.g., Galgana et al., 2007; Hamburger et al., 1983; Ramos et al., 2005), we focus on regions in and around Mindoro and use two types of datasets to study various aspects of the Mindoro seismotectonics: (1) overall seismic distributions from the EHB global catalogue (Engdahl et al., 1998), (2) states of stress, slip directions, and distributions of earthquakes from the Global Centroid Moment Tensor (GCMT) catalogue (Dziewonski et al., 1981; Ekström et al., 2012). We concluded from the lack of significant interplate thrust earthquakes offshore NW Mindoro that convergence rates across the southernmost segment of the Manila Trench are in a transition from minor to total cessation. Coupled with the transition, EHB seismic distributions exhibit a southeasterly trend of steepening slab dip, initiated from deep (~200 km) and eventually reaching shallow depths (~100 km), and a trend of shortening trench–slab distances, reducing from ~160 km to ~100 km as measured from the slab at 200 km depth.

2. Tectonics and geology in and around Mindoro

The two main tectonic lineaments in the vicinity of Mindoro are the Manila trench bounding the west and the Sibuyan Verde Passage Fault passing through north and northeast offshore Mindoro (Fig. 2). The Manila trench terminates offshore near west central Mindoro (near Mamburao) and dies out southward as marked by parallel folds and thrusts on land in SW Mindoro (Marchadier and Rangin, 1990). Based on stratigraphical analysis, Karig (1983) proposed that the SW Mindoro thrust belt is likely to represent a section of PCB–PMB collision boundary. The Sibuyan Verde Passage Fault branches out of the Philippine Faults near Masbate and extends westward near the Manila trench (Fig. 2). Pubellier et al. (2000) pointed out that as a result of reducing convergence at both the southern Manila trench and the northern Philippine trench, a northwest shearing, probably partitioned by the Philippine and Sibuyan Verde Passage Faults, is necessary to accommodate the residual PCB–PMB plate motions and that a transtensional motion along the NE–SW Macolod Corridor may be predicted (Fig. 2). Pubellier et al. (2000) further argued that the Sibuyan Verde Passage Fault and the Manila trench must be connected for the accommodation to be sustained, despite the fault trace being obscured beneath sediments of the forearc basin. The islands of Marinduque, the Romblon island group, and the Panay are located to the east of Mindoro. The Marinduque basin offshore eastern Marinduque island is a marine intra-arc basin formed by a process analogous to sea-floor spreading (Sarewitz and Lewis, 1991). The Romblon island group comprising Tablas, Romblon, and Sibuyan is dominated by a metamorphic suite and ophiolite complex, which are believed to be emplaced along east-verging thrust faults developed consequent to PCB–PMB collision (Dimalanta et al., 2009). On Panay island, the metamorphic complex on the NW corner (Buruanga peninsula) and the Antique ophiolite to the west (Antique Range) are believed to be located along northwest-verging thrust faults (Yumul et al., 2009).

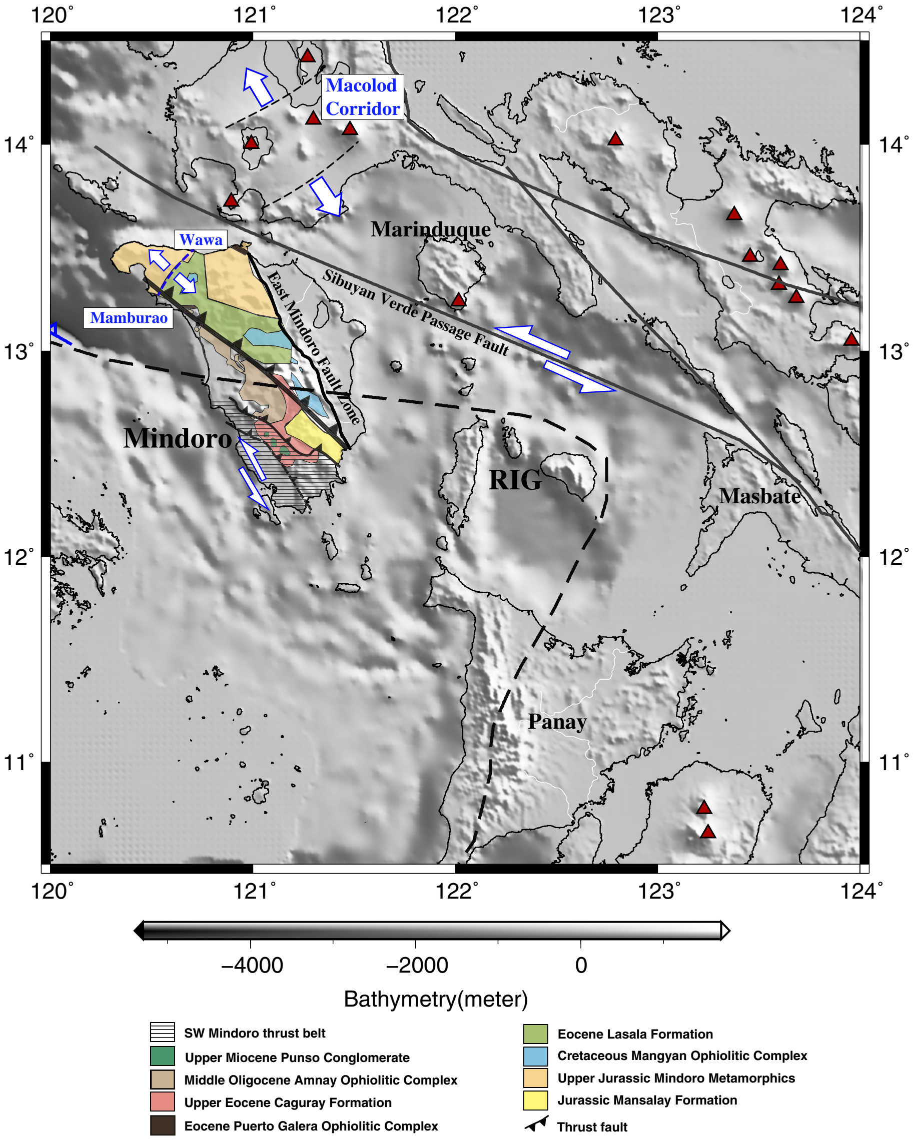

Fig. 2. Tectonic settings around Mindoro and geological stratigraphy in Mindoro edited from Yumul et al. (2009). Black dashed lines and red triangles are the same as those in Fig. 1. Blue dashed line is the Wawa–Mamburao valley. Arrows indicate relative motions across structures.

Tectonic configurations in Mindoro generally trend NW–SE parallel to that of the Manila trench, including the Central Range and the San Jose Platform (Fig. 2). The mid-Oligocene Amnay, Cretaceous Mangyan, and Eocene Lubang-Puerto Galera complexes are three Ophiolite belts distributed distantly from the Manila trench that have been emplaced through strike–slip faulting, spreading ridge thrusting, and/or scissor-type collision (Yumul et al., 2009) (Fig. 2). The basement rock of NW Mindoro is Upper Jurassic Halcon Metamorphics overlain by the Eocene Lasala Formation (Canto et al., 2012). On South Mindoro, the Jurassic Mansalay Formation is the oldest sedimentary sequence overlain by the Eocene Caguray Formation. The Punso Conglomerate outcrops a large NW–SE belt on SW Mindoro (Marchadier and Rangin, 1990). Karig (1983) reported the PCB–PMB collision boundary to be the SW Mindoro thrust belt and suggested that the Upper Miocene to Lower Pliocene Punso Conglomerate on top of the colliding blocks indicate the termination of collision by Pliocene time.

3. Data and methods

Both the EHB and the GCMT global catalogues of earthquakes were used in this study. The EHB catalogue (1960–2008) first uses *P* and later phases (*pP*, *sP*) to relocate earthquakes and is more complete for minor earthquakes (up to *mb* ~ 3.0), whereas the GCMT catalogue (since 1976) uses normal modes of the Earth to invert for earthquake centroid and moment tensors, is only complete for greater earthquakes ($M_c = 5.8$; Kagan and Jackson, 2011), but contains more related information such as focal mechanisms, **P** and **T** axes, and slip vectors. Moments greater than 10^{25} dyne-cm ($M_w > 5.9$) with rakes between 45° and 135° were selected from the GCMT catalogue to show the frequencies of significant interplate thrust earthquakes along trenches in the Philippine archipelago (Fig. 3). To study the seismotectonics associated with Mindoro, a region bounded by 119°E/123°E and 11°N/15°N was selected (Fig. 4). Distributions of overall seismicity are shown

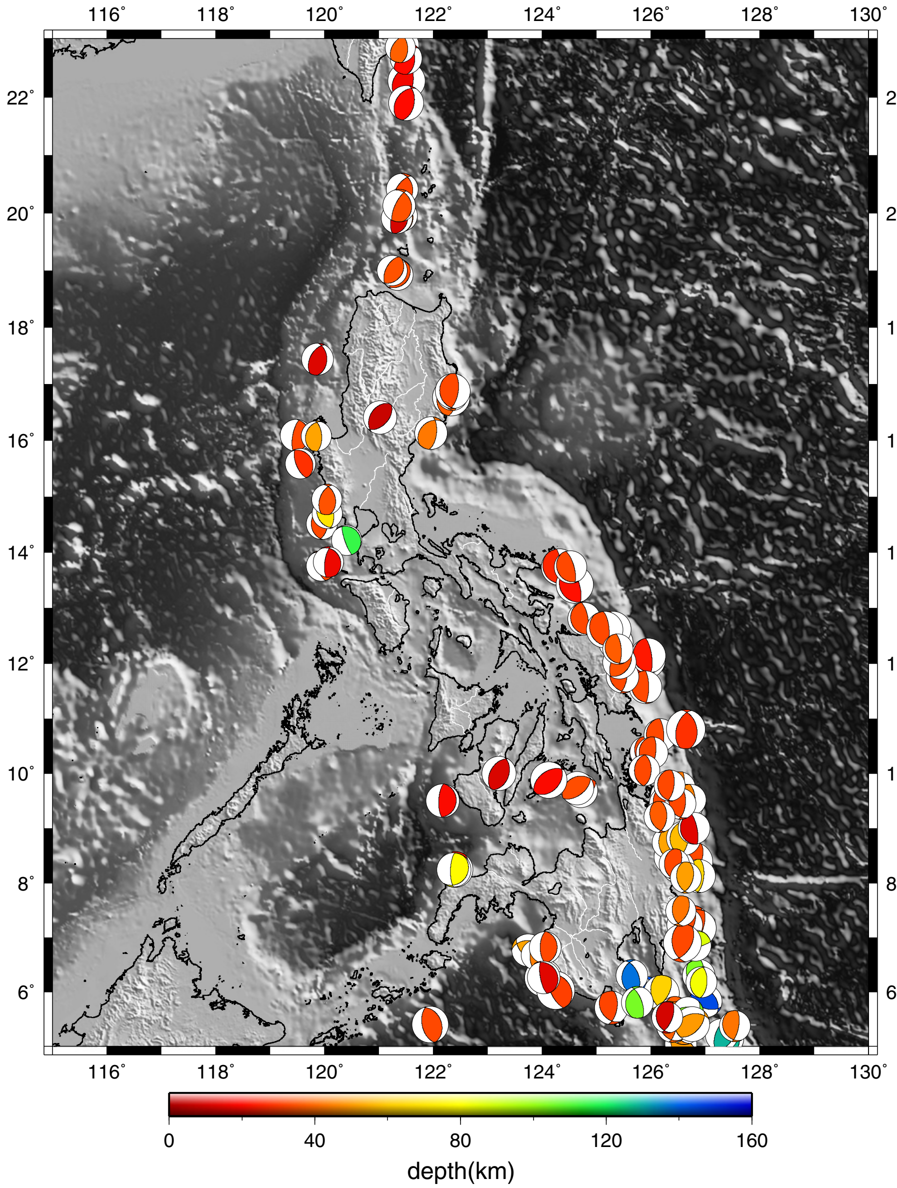

Fig. 3. Distributions of significant thrust earthquakes ($M_w > 5.9$ and 45° < rake < 135°) in the Philippine archipelago from the GCMT catalogue with symbols scaled to moment and depths color-coded. Most of focal mechanisms are representative of interplate thrust earthquakes. Note the significant accumulative seismic moment release along the Philippine trench and the lack of events offshore NW Mindoro.

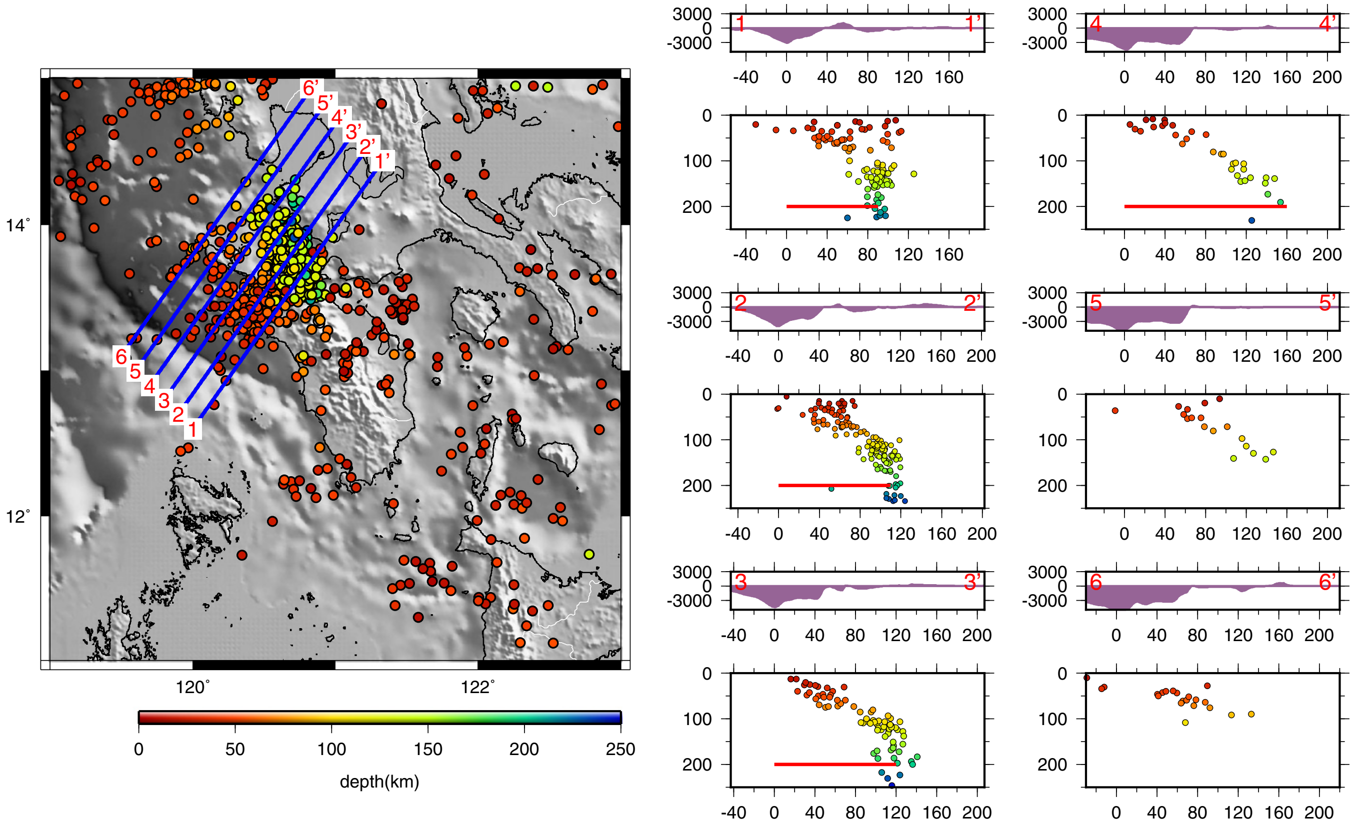

Fig. 4. Distributions of earthquakes from the EHB catalogue (left) categorized into three groups—those associated with east-dipping subduction north of 14°N (group I), those clustered in NW Mindoro and SW Luzon (group II), and those sporadically covering central and south Mindoro, the Romblon group, and west Panay (group III). Group II seismicity is projected on six profiles northeasterly to show the variations of Wadati–Benioff zones and distance relative to the trench (red lines), taken as reference points (right).

using earthquakes from the EHB catalogue. Earthquakes offshore NW Mindoro and SW Luzon were projected on six profiles roughly normal to the Manila Trench. Positions of the projected trench were taken as reference points to measure horizontal distances relative to the slab at depths or to volcanoes on the surface. The horizontal distances of the Wadati–Benioff zones at 200 km depth to the trench are indicated in Fig. 4.

Based on the double-couple components of focal mechanisms, the calculated **P**, **N**, **T** axes of the GCMT earthquakes in the region were categorized into normal, strike–slip, or thrust type according to the angles between the vertical and the three axes. Categorization was based on a ternary diagram with pure normal (vertical **P** axis), pure strike–slip (vertical **N** axis), and pure thrust (vertical **T** axis) as end member plots (Frohlich and Apperson, 1992). Events projected in the middle sub-triangle of the ternary diagram are those where all three angles between the vertical and the **P**, **N**, **T** axes were greater than 45°, and are grouped into none of the above categories (Fig. 5). Fig. 6 shows the distributions of earthquakes in each group, with symbol size proportional to magnitude and depth color-coded.

There are no deep earthquakes (depth > 300 km). The associations of intermediate-depth earthquakes (80 ~ 300 km) with the subducting slab were investigated. To mimic the geometry of the Wadati–Benioff zone offshore NW Mindoro, a slab coordinate system (strike N305°E, dip 70°) was constructed using along strike, slab normal, and down-dip as the x, y, and z directions in Cartesian coordinates. The coordinates were used to project the **P** and **T** axes of non-shallow earthquakes (here, mostly intermediate-depth) from the GCMT catalogue (Chen et al., 2004a) (Fig. 7). The associations of shallow earthquakes (depth < 80 km) with the geodynamics of Mindoro are shown in Fig. 8, displaying focal mechanisms on earthquake locations with depth color-coded. As we focused on the seismotectonics of Mindoro in analyzing the spatial distributions of focal mechanism, those north of 14°N and west of 120°E were ignored (Fig. 8).

4. Results

Significant thrust earthquakes ($M_w > 5.9$) tend to distribute along known trenches of the Philippine archipelago (Fig. 3). The majority of these, especially those with depths of less than 20 km and exhibiting one plane shallowly dipping to the direction of subduction with strikes resembling those of trenches, belong to the type of interplate thrust earthquakes. Their occurrence represents a release of strain energy accumulated by relative plate motions, which in turn suggests that convergences across the trenches are currently active and their sizes are significant ($M_w > 5.9$). The Philippine Trench is the area with the highest frequency of occurrences, followed by the Manila Trench, the Cotabato Trench, and the East Luzon Trough (Fig. 3). We draw attention to the segment of the South Manila Trench offshore NW Mindoro where interplate thrust earthquakes are absent (Fig. 3). Given that major earthquakes dominate the majority of seismic moment release, the lack of significant interplate earthquakes suggests insignificant seismic slip in the segment over the past 40 years. The causes could be attributed to aseismic slip, accumulation of stain energy, or reduction of convergence rates. The latter appears to be the most likely explanation because GPS data show a southward decrease of the western Luzon movements relative to the Sundaland Block (Yu et al., 2011) and because the Manila trench terminates to the south, where PCB has indented into PMB since the Early Miocene.

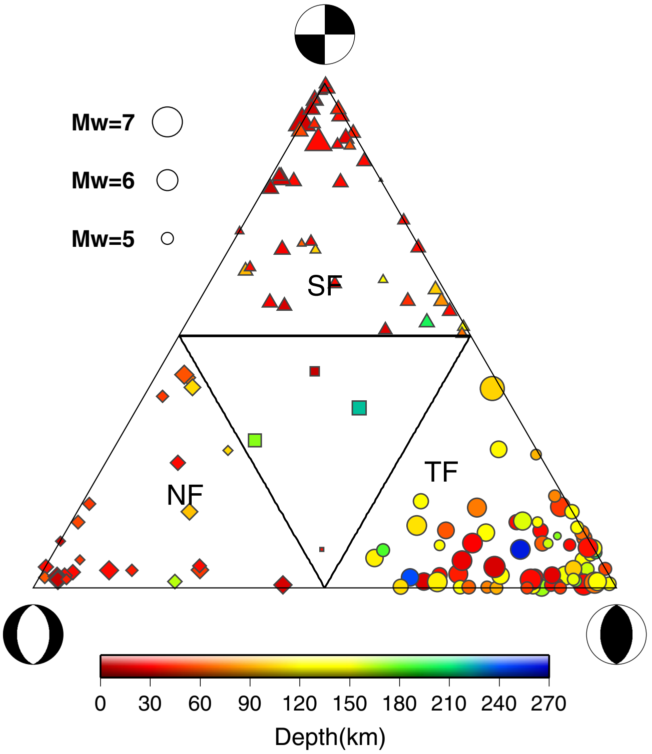

Fig. 5. Ternary diagram of earthquake focal mechanisms with symbol size scaled to earthquake magnitude and depth color-coded. The three apexes indicate a pure strike–slip (top), a pure normal fault with 45° dipping plane (left), and a pure reverse fault with 45° dipping plane (right). The three solid lines inside the ternary represent **N** (top), **P** (left), **T** (right) axes of earthquakes being 45° from the vertical, respectively, which are the boundaries used to define the strike–slip fault (SF) group (triangles), the normal fault (NF) group (diamonds), the thrust fault (TF) group (circles), and others (squares).

The distributions of seismicity from the EHB catalogue in the bounded region can be roughly categorized into three groups of patterns (Fig. 4). Group I is associated with subduction along the Manila Trench north of 14°N and is relatively far away from Mindoro, and will therefore be disregarded in the following. Group II refers to the cluster in NW Mindoro and SW Luzon and displays distinctive features of a steeply dipping Wadati–Benioff zone (Fig. 4). There is a progressive variation southeasterly from profiles 66′ to 11′: the slab dipping angles steepen initially at the deep section (~200 km, profiles 33′ and 22′), followed by upward propagation and eventually the entire slab dipping steeply (profile 11′). Coupled with the upward propagation of steep dip angles is the progressive shortening of trench–slab horizontal distances as measured from the trench to slab at 200 km depth (Fig. 4)—reduced from 160 km (profile 44′), to 120 km (profiles 33′ and 22′), and eventually to 100 km (profile 11′). There is a gap of intermediate-depth earthquakes to the NW of profile 55′ (Fig. 4). Whether it is caused by absence of slab or presence of an aseismic slab (Chen et al., 2004b) remains an open queston. Group III is characterized by a broad region of widespread sporadic shallow seismicity covering central and south Mindoro, the Sibuyan Sea, the Romblon Island Group, the NW Panay, and the Southwest Mindoro Thrust Belt (Figs. 2 and 4). It is notable that other than Mindoro, the major areas covered by Group III are marine intra-arc basins (e.g., the Marinduque basin; Fig. 4).

Earthquakes from the GCMT catalogue bounded by 119°E/123°E and 11°N/15°N projected on the ternary diagram (Fig. 5) demonstrate that the majority are thrust fault and strike–slip fault type. The former are predominantly non-shallow (depth > 80 km) and the latter shallow (depth < 40 km). Plotting the distributions of each type of earthquake with corresponding symbols (Fig. 6) shows that thrust fault type earthquakes tend to cluster to form Group I and Group II, suggesting their association with subduction processes. In contrast, Group III earthquakes are constituted mainly of strike–slip type earthquakes. The shallow earthquakes (depth < 40 km) of normal fault type are those of outer-rise events in Group I, on NW Mindoro in Group II (see discussion below), and in central Mindoro roughly on the East Mindoro Fault Zone (Fig. 2). It is clear that earthquakes with depths greater than 80 km only occurred in Group II and are associated with a steeply dipping slab. The associations can be attested by projections of **P** and **T** axes of those GCMT earthquakes (Fig. 7) using slab coordinates constructed from distributions of the EHB earthquakes (Fig. 4). Results reveal that patterns of stresses within the slab are of predominantly down-dip extension (Fig. 7), which in turn indicates that the negative buoyancy of the steeply dipping slab is the main cause of those intermediate-depth earthquakes.

More detailed analyses on patterns of crustal seismic deformations were conducted investigating the focal mechanisms of shallow earthquakes, M_W greater than 5.5, and bounded by 120°E/123°E and 11°N/14°N (Fig. 8). In the Group II region, there remain a few moderate earthquakes ($M_w < 6$), potentially of interplate thrust type but at depths between 40 and 80 km. A feature of interest is the three shallow (less than 20 km) normal fault type earthquakes in this region, with NW–SE horizontal **T** axes resembling the pull-apart direction of the Macolod Corridor located just to the northeast. In the Group III region, the relatively large earthquakes ($M_w > 5.5$) tend to be distributed around the border of the Group III area, which can be roughly divided into two southeast-trending lineaments to the north and south (Fig. 8). While most of the northern ones likely ruptured on the NW–SE trending nodal planes of the Sibuyan Verde Passage Fault, the southern ones seem to rupture on trending planes similar to the Southwest Mindoro Thrust Belt. In this regard, both the Sibuyan Verde Passage Fault and Southwest Mindoro Thrust Belt are moving in a left-lateral sense. However, the November 14th, 1994 Mindoro earthquake ($M_w = 7.1$) in the Verde Island Passage remains a notable exception to the overall pattern due to its right-lateral slip on the Agluban fault, as based on surface ruptures (Tanioka and Satake, 1996) (Fig. 8).

5. Discussion

The PCB–PMB collision during the Miocene not only terminates the Manila trench but also caused a southward reduction of Luzon–Sundaland Block relative motions. In this study, we point out that the seismic slips across the segment of the Manila trench offshore NW Mindoro have been insignificant for the past 40 years. We conclude that the manila trench from offshore SW Luzon to NW Mindoro currently experiences a decrease in convergence rates that approaches total cessation. Consequently, southeastward variations of seismic features exhibit a modern evolution of the subducting slab upon collision of an island arc with continental fragments. First, the majority of intermediate-depth earthquakes exhibit down-dip extension (Fig. 7), suggesting that the steep dipping of the slab exerts significant negative buoyancy and induces abundant Wadati–Benioff seismicities, despite the fact that convergences are inferred to be minor. Secondly, southeasterly variations of convergence from minor to total cessation (profile 66′ to 11′ in Fig. 3) compared with those of Wadati–Benioff geometries illustrate that the negative buoyancy of the subducting slab dominates in shaping slab geometry when convergence rates become insignificant and the processes are initiated at the deep section propagating upwards. It is interesting to note that the two deepest earthquakes have **T** axes pointing steeply to the SW, and exhibit rollback opposite to subduction and not in the down-dip direction (Fig. 7). Thirdly, as slab dipping angles steepen, horizontal distances relative to the trench as measured from the Wadati–Benioff zone at 200 km depth also decrease in a southeasterly manner (Fig. 8). Assuming that the island arcs were formed prior to the reduction of convergence rates and initiation of slab steepening, the positions of those calc-alkaline volcanoes (DeBoer et al., 1980) were regarded as fixed; we then investigated whether the trench–arc

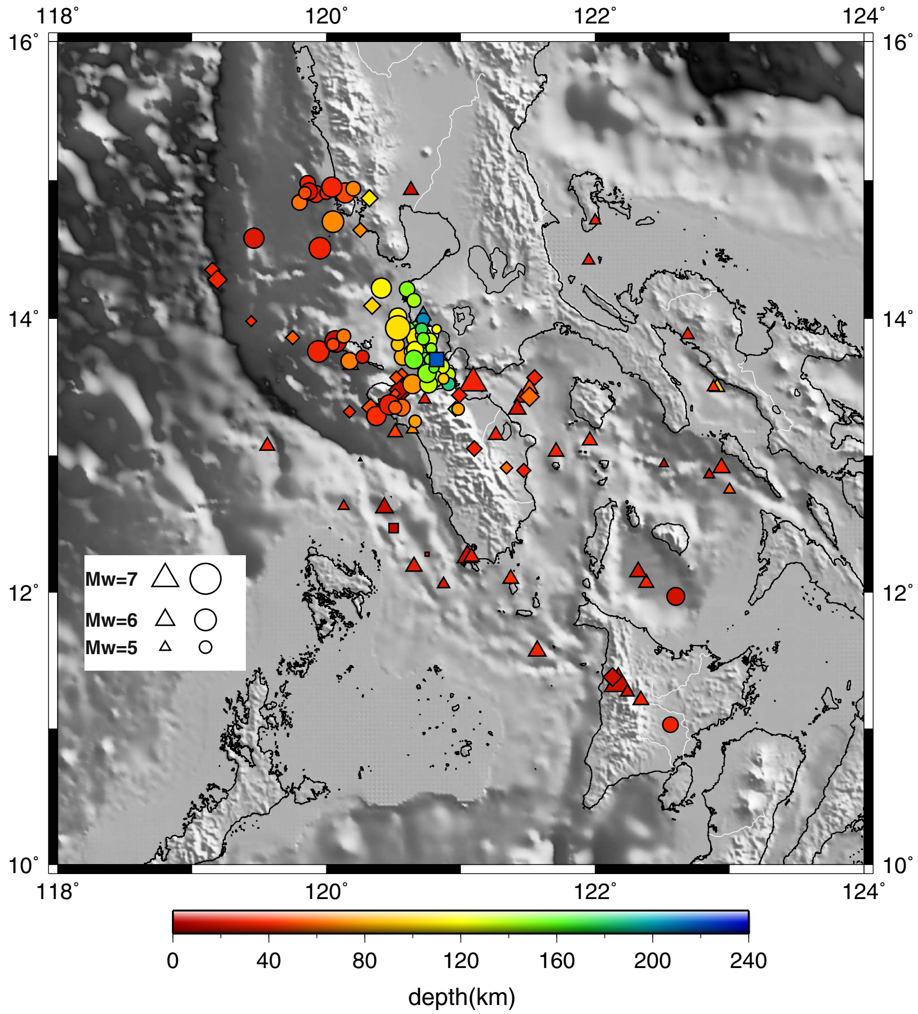

Fig. 6. Distributions of earthquakes from the GCMT catalogue with different symbols (scaled to moment) representing different types of earthquakes. Note that areas of the three groups as shown in Fig. 3 are more distinctively covered by corresponding types of earthquakes, i.e., thrust type for Groups I and II and strike–slip type for Group III.

distances vary as a result of slab steepening, by projecting profiles roughly normal to the Manila Trench (Fig. 9). Results also show a southeasterly shortening of trench–arc distances, indicating that trenches advanced toward the arc once convergence reduced and slab steepening was initiated. We further propose that the bending of the Manila Trench near 13.5°N may be caused by the advance of the trench. The concluded patterns of seismicity and stresses exhibit spatial consistence and are unlikely to be biased by data uncertainties.

The Macolod Corridor in SW Luzon, transecting the island NE–SW, is a zone of approximately 40 km width that is pervaded by extensive volcanism, faulting, and crustal thinning (Föster et al., 1990; Galgana et al., 2007) and may represent a pull-apart rift zone between the Manila and Philippine Trenches (Defant et al., 1988). However, the neotectonically active Macolod Corridor is devoid of seismic activity due to high geothermal activity underneath the Taal/Laguna de Bay volcanic field (Pubellier et al., 2000). The normal-faulting shallow earthquakes in the Group II region with significant magnitudes (M_w: 5.5, 5.7, and 5.9) indicate *in situ* NW–SE tensional stress regimes. Such trench-parallel tensional axes are uncommon in subduction zones. Given that the earthquakes are located on the SW extension of the Macolod Corridor with **T** axes roughly parallel to its pull-apart zone, we propose that the earthquakes result from rifting of the Macolod Corridor extending beyond the Sibuyan Verde Passage Fault southwesterly to reach NW Mindoro. In other words, the normal-faulting earthquakes in NW Mindoro, like the left-lateral strike–slip earthquakes along the Sibuyan Verde Passage Fault, is the seismic expressions of accommodating the transfer of SUND-PSP relative motions (Pubellier et al., 2000). Furthermore, if the valley topography between Wawa and Mamburao in NW Mindoro (Fig. 2) is a result of pull-apart rifting, it may serve as a structural boundary, as the part of Mindoro to the south represents already amalgamated terranes due to arc-continent collision since the Miocene. This theory is supported by the distinctive seismic patterns (Group II versus Group III) on the two sides of the valley. It is also interesting to note that significant strike–slip earthquakes on the Sibuyan Verde Passage Fault almost die out northwesterly passing the valley (Fig. 8).

However, the amalgamations of collision terranes cannot explain the earthquakes on the Southwest Mindoro Thrust Belt and their southeasterly linear extension with similar left-lateral strike–slip focal mechanisms, which correspond to the transpressive regime active at least since the Late Pliocene (Marchadier and Rangin, 1990). We hypothesize that the normal component of the oblique convergences during PCB–PMB collision was accommodated by the processes of amalgamation, which diffuse over a wide zone that probably covers most of the Group III region. Judging by lack of thrust-faulting earthquakes, the amalgamation is presently inactive to the south of the Wawa–Mamburao valley (Fig. 6). The shear components are jointly released by left-lateral strike–slip earthquakes along the Southwest Mindoro Thrust Belt, the

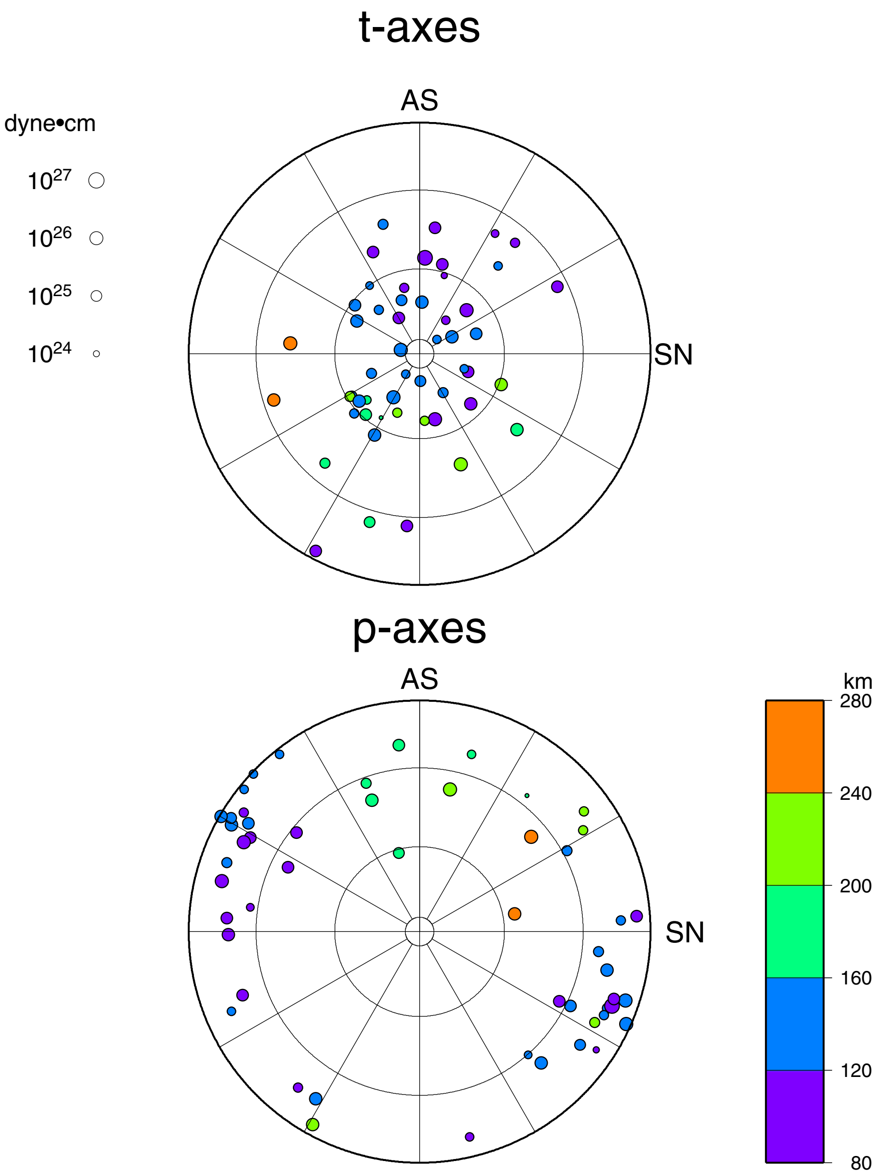

Fig. 7. Projection of **T** (upper) and **P** (lower) axes of earthquakes with depth greater than 80 km from the GCMT catalogue using local slab coordinates (strike 305° and dip 70°). The along-strike (AS) is pointing to the north, slab-normal to the east, and down-dip vertically down at the center. The intermediate-depth earthquakes are exclusively from the Group II area associated with Sundaland subduction. Note that stress patterns are predominantly of down-dip extension.

Sibuyan Verde Passage Fault, and the Philippine Fault. Rifting of the Macolod Corridor was explained by Pubellier et al. (2000) as a kinematical requirement to accommodate the NW–SE shear components of the SUND-PSP plate motion at the trench-trench transformation. To a lesser extent, this also applies to the normal-faulting earthquakes in NW Mindoro. The SUND-PSP NW–SE shear motions released at diffused zones with different mechanisms illustrate various degrees of amalgamations by the PCB–PMB collision. However, the normal-faulting earthquakes on the East Mindoro Fault Zone (Fig. 6) and the 1994 M_w7.1 Mindoro earthquakes do not belong to this category and probably reflect the transitions from rifting to left-lateral movements on strike–slip faults.

The overall distribution of major earthquakes (mostly strike–slip) in the Group III area seems to indicate that the terrane encircled by the Wawa–Mamburao valley, the Sibuyan Verde Passage Fault, offshore east of the Romblon Group, the NW Panay, and the Southwest Mindoro Thrust Belt acts as a relatively rigid unit and shears with the surroundings. Note that the SE boundary is coincident with the area where crustal thickness jumps to greater than 30 km (Dimalanta and Yumul, 2004). It is thus reasonable to hypothesize that the Group III area is a terrane unit isolated by the PCB–PMB collision. Interestingly, the major strike–slip earthquakes distribute offshore east of the Romblon group of islands and NW Panay (Fig. 6), coincident with the proposed PCB–PMB collision boundary based on geological, gravitational, and magnetic observations (Dimalanta et al., 2009; Yumul et al., 2003). Near Mindoro, seismic distributions suggest that the boundary follows the Sibuyan Verde Passage Fault (Fig. 6). In contrast, earthquakes along the Southwest Mindoro Thrust Belt coincide with the proposed PCB–PMB collision boundary based on the reported foreland thrust belt in SW Mindoro (Karig, 1983; Marchadier and Rangin, 1990). However, the GCMT catalogue currently contains no major earthquakes that occurred in the Mindoro Suture Zone, which has also been proposed as the boundary between PCB and PMB (Sarewitz and Karig, 1986).

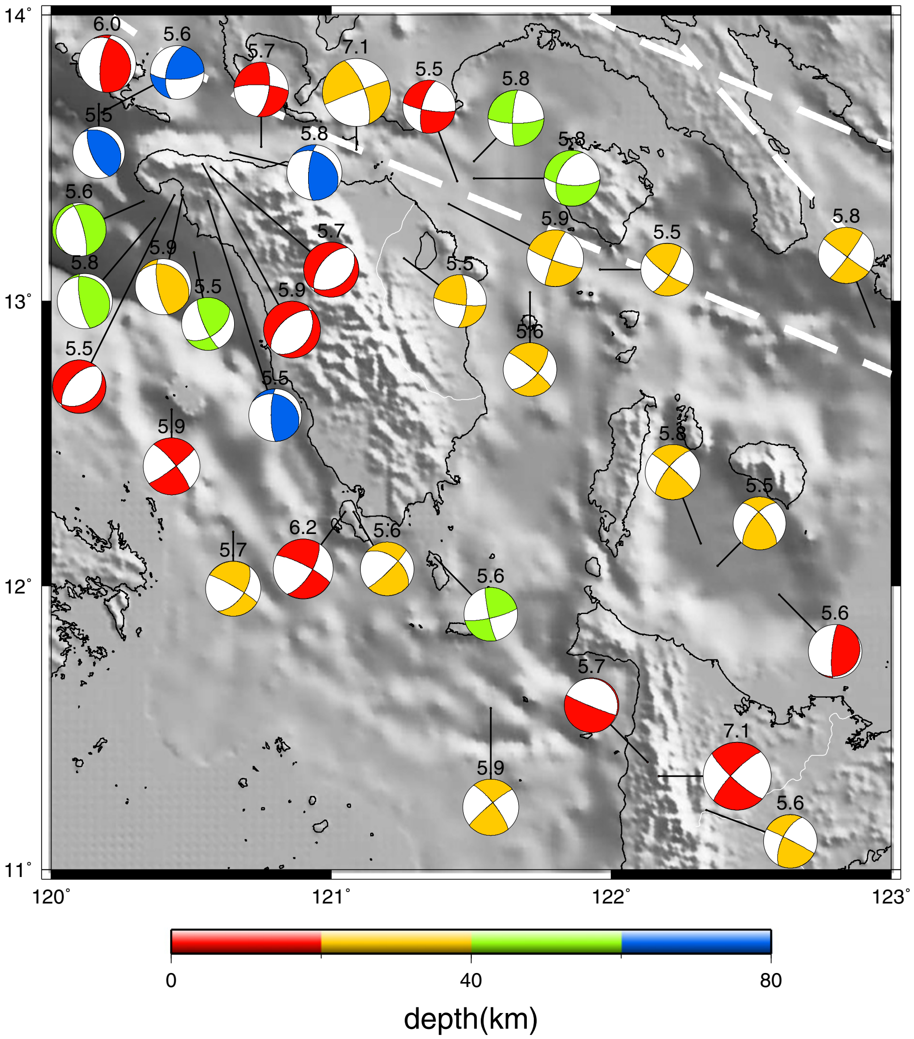

Fig. 8. Spatial distributions of focal mechanisms (depth color-coded) for earthquakes with M_w greater than 5.5 and depth less than 80 km from the GCMT catalogue. The analysis region is within 120°E/123°E and 11°N/14°N, slightly smaller than in Fig. 6 to allow focus on the vicinity of Mindoro. White dashed lines are traces of the Sibuyan Verde Passage Fault and the Philippine Fault.

6. Conclusions

In this study, we use data from the EHB and GCMT catalogue to study the seismotectonics of Mindoro and are able to draw several well-founded conclusions, otherwise not constrained by geodetic and geological observations. First, a lack of significant interplate thrust earthquakes, a southward decrease of Luzon–Sundaland Block relative motions, and the PCB–PMB collision since the Miocene, together suggest that convergences across the Manila Trench vary southeasterly from minor offshore SW Luzon to total cessation in Southwest Mindoro Thrust Belt. Secondly, the comparison of variations between convergence rates and Wadati–Benioff geometries illustrates that the negative buoyancy of the subducting slab dominates in shaping slab geometry when convergence rates become insignificant and the processes are initiated at the deep section propagating upwards. Thirdly, the same negative buoyant forces are attributed to intermediate-depth earthquakes, both because of their abundance and their predominant down-dip extension type.

Fourthly, shallow earthquakes not associated with subduction (mostly strike–slip type) are sporadically distributed in a broad region bordered by the Wawa–Mamburao valley, the Sibuyan Verde Passage Fault, east of the Romblon group and NW Panay, and the Southwest Mindoro Thrust Belt. We hypothesize that the region may be isolated by the PCB–PMB collision and acts as a unit block moving in unison, based on the observations that significant strike–slip earthquakes ($M_w > 5.5$) tend to distribute around the border and the border coincides with the boundary of thick crust (thickness > 30 km). Finally, observations of many significant-sized normal-faulting earthquakes in NW Mindoro with horizontal extension in NW–SE direction suggest that the driving mechanisms that rift the Macolod Corridor in a similar NW–SE azimuth actually apply southwesterly beyond the Sibuyan Verde Passage Fault and dominate crustal deformation in NW Mindoro.

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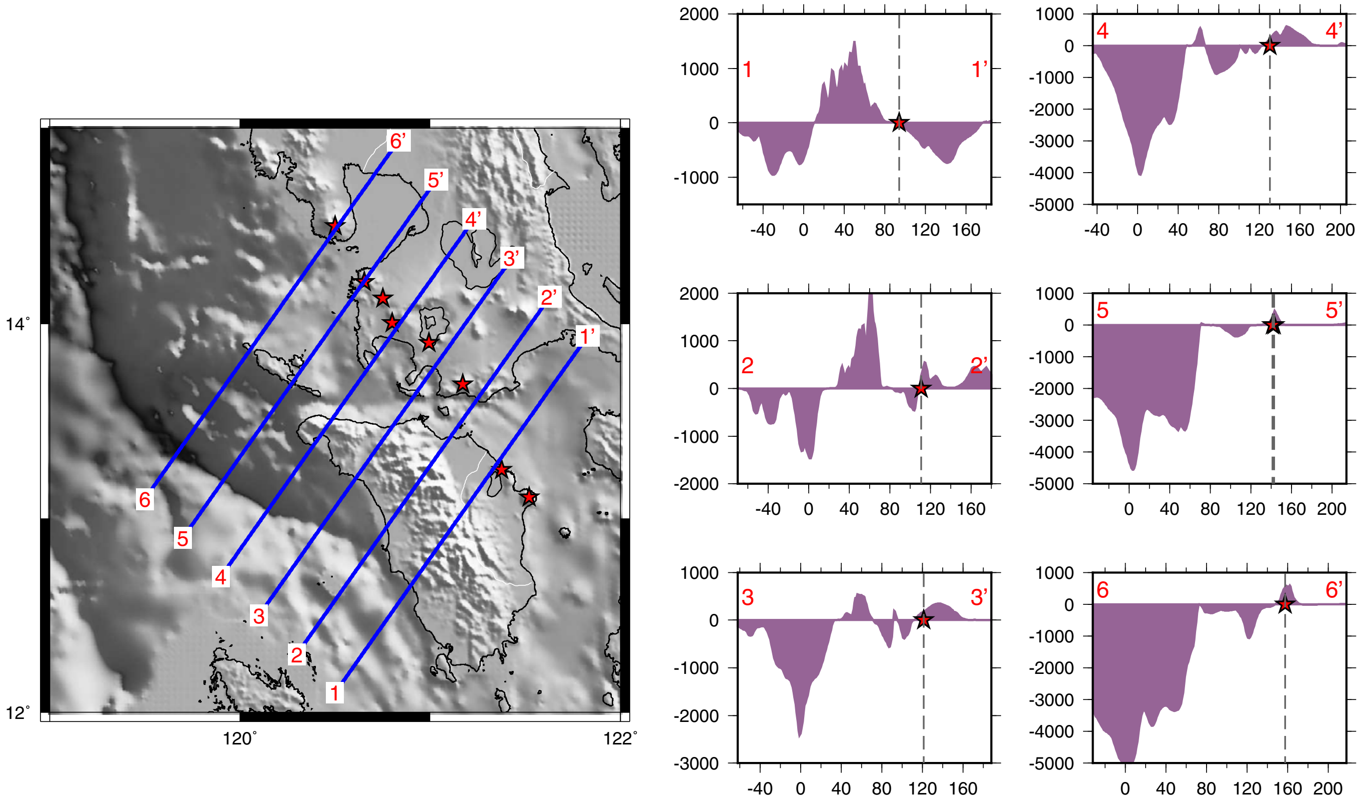

Fig. 9. (Left) Six cross-sections roughly normal to the trench align northwesterly to project topography and the calc-alkaline volcanoes (red stars). (Right) Results of the projection with the positions of the trench taken as reference. Trench–arc distances are determined by the projected locations of volcanoes shown in vertical dashed lines. Note that the trench–arc distances progressively decrease southeasterly, coupled with an decrease of trench–slab distance and an increase of slab dip angle.

References

Barrier, E., Huchon, P., Aurelio, M., 1991. Philippine fault—a key for Philippine kinematics. Geology 19, 32–35.

Bautista, B.C., Bautista, M.L.P., Oike, K., Wu, F.T., Punongbayan, R.S., 2001. A new insight on the geometry of subducting slabs in northern Luzon, Philippines. Tectonophysics 339 (3), 279–310.

Canto, A.P.B., Padrones, J.T., Concepcion, R.A.B., Perez, A.D.C., Tamayo Jr., R.A., Dimalanta, C.B., Faustino-Eslava, D.V., Queaño, K.L., Yumul Jr., G.P., 2012. Geology of northwestern Mindoro and its offshore islands: implications for terrane accretion in west Central Philippines. J. Asian Earth Sci. 61, 78–87.

Chen, P.-F., Bina, C.R., Okal, E.A., 2004a. A global survey of stress orientations in subducting slabs as revealed by intermediate-depth earthquakes. Geophys. J. Int. 159, 721–733.

Chen, P.-F., Huang, B.-S., Liang, W.-T., 2004b. Evidence of a slab of subducted lithosphere beneath central Taiwan from seismic waveforms and travel times, Earth Planet. Sci. Lett. 229, 61–71.

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, 251–282.

Defant, M.L., De Boer, J.Z., Oles, D., 1988. The western Central Luzon Arc, two arcs divided by rifting? Tectonophysics 145, 305–317.

DeMets, C., Gordon, R.G., Argus, D.F., 2010. Geologically current plate motions. Geophys. J. Int. 181, 1–80.

Dimalanta, C.B., Yumul Jr., G.P., 2004. Crustal thickening in an active margin setting (Philippines): The whys and the hows. Episodes 27, 260–264.

Dimalanta, C.B., Ramos, E.G.L., Yumul, G.P., Bellon, H., 2009. New features from the Romblon Island Group: key to understanding the arc–continent collision in Central Philippines. Tectonophysics 479, 120–129.

Dziewonski, A.M., Chou, T.-A., Woodhouse, J.H., 1981. Determination of earthquake source parameters from waveform data for studies of global and regional seismicity. J. Geophys. Res. 86, 2825–2852. http://dx.doi.org/10.1029/JB086iB04p02825.

Ekström, G., Nettles, M., Dziewonski, A.M., Nettles, M., 2012. The global CMT project 2004–2010: centroid-moment tensors for 13,017 earthquakes. Phys. Earth Planet. Inter. 200-201, 1–9. http://dx.doi.org/10.106/j.pepi.2012.04.002.

Engdahl, E.R., van der Hilst, R., Buland, R., 1998. Global teleseismic earthquake relocation with improved travel times and procedures for depth determination. Bull. Seismol. Soc. Am. 88, 722–743.

Föerster, H., Oles, D., Knittel, U., Defant, M.J., Torres, R.C., 1990. The Macolod corridor: a rift crossing the Philippine island arc. Tectonophysics 183, 265–271.

Frohlich, C., Apperson, K.D., 1992. Triangle diagrams: ternary graphs to display similarity and diversity of earthquake focal mechanisms. Phys. Earth Planet. Inter. 75 (1), 193–198.

Galgana, G., Hamburger, M., McCaffrey, R., Corpuz, E., Chen, Q.Z., 2007. Analysis of crustal deformation in Luzon, Philippines using geodetic observations and earthquake focal mechanisms. Tectonophysics 432, 63–87.

Hamburger, M., Cardwell, R., Isacks, B., 1983. Seismotectonics of the Northern Philippine Island Arc. In: Hayes, D.E. (Ed.), The tectonics and geologic evolution of Southeast Asian Seas and Islands, Part II American Geophysical Union. Geophysical Monograph 27, pp. 1–22.

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. Bull. Am. Assoc. Pet. Geol. 66, 1357–1383.

Kagan, Y.Y., Jackson, D.D., 2011. Global earthquake forecasts. Geophys. J. Int. 184, 759–776.

Karig, D.E., 1983. Accreted terranes in the northern part of the Philippine archipelago. Tectonics 2 (2), 211–236.

Marchadier, Y., Rangin, C., 1990. Polyphase tectonics at the southern tip of the Manila trench, Mindoro-Tablas Islands, Philippines. Tectonophysics 183 (1), 273–287.

Pubellier, M., Garcia, F., Loevenbruck, A., Chorowicz, J., 2000. Recent deformation at the junction between the Visayas and the North Luzon blocks, from ERS-1 images. In: Yumul, J. (Ed.), The Island Arc. vol. 9 (4), pp. 599–611.

Ramos, N.T., Dimalanta, C.B., Besana, G.M., Tamayo Jr., R.A., Yumul Jr., G.P., Maglambayan, V.B., 2005. Seismotectonic reactions to the arc-continent convergence in Central Philippines. In: Imai, A., et al. (Eds.), Achievements on Earth Resources from AUN/SEED-Net. Resource Geology vol. 55, pp. 199–206.

Sarewitz, D.R., Karig, D.E., 1986. Geologic evolution of western Mindoro Island and the Mindoro suture zone, Philippines. J S. E. Asian Earth Sci. 1 (2), 117–141.

Sarewitz, D.R., Lewis, S.D., 1991. The Marinduque intra-arc basin, Philippines: Basingenesis and in situ ophiolite development in a strike-slip setting. Geol. Soc. Am. Bull. 103, 597–614.

Tanioka, Y., Satake, K., 1996. Tsunami generation by horizontal displacement of ocean bottom. Geophys. Res. Lett. 23 (8), 861–864.

Wessel, P., Smith, W.H.F., 1998. New, improved version of the Generic Mapping Tools Released. Eos, Trans. Am. Geophys. Union 79, 579.

Yu, S.-B., Hsu, Y.-J., Bacolcol, T., Yang, C.-C., Tsai, Y.-C., Solidum, R., 2011. Present-day crustal deformation along the Philippine Fault in Luzon, Philippines. J. Asian Earth Sci. 65, 64–74. http://dx.doi.org/10.1016/j.jseaes.2010.12.007.

Yumul Jr., G.P., Dimalanta, C.B., Tamayo Jr., R.A., Barretto, J.L., 2000. Contrasting morphological trends of islands in Central Philippines: speculation on their origin. Island Arc 9, 627–637.

Yumul, G.P., Dimalanta, C.B., Tamayo, R.A., Maury, R.C., 2003. Collision, subduction and accretion events in the Philippines: a synthesis. Island Arc 12 (2), 77–91.

Yumul Jr., G.P., Dimalanta, C.B., Marquez, E.J., Queaño, K.L., 2009. Onland signatures of the Palawan microcontinental block and Philippine mobile belt collision and crustal growth process: a review. J. Asian Earth Sci. 34 (5), 610–623.