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ORIGINAL RESEARCH PAPER

Possible northward extension of the Philippine Fault Zone offshore Luzon Island (Philippines)

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Abstract The Philippine Fault Zone, a system of left-lateral strike-slip faults traversing the length of the Philippine Islands, is associated with the oblique convergence between the Philippine Sea Plate (PSP) and the Eurasian Plate (EP). Although it is a major deformational structure within the diffuse PSP–EP convergent boundary, some of its segments, particularly its marine extensions, are not well studied. To investigate the crustal deformation in the marine prolongation of the Philippine Fault Zone offshore Luzon Island, multi-channel seismic (MCS) data, gravity data and centroid moment tensor solutions were used in this study. Focal mechanism solutions from the Global CMT catalog were inverted to determine the average principal stress directions and consequently understand the prevailing stress regime in the study area. The stress inversion results indicate that the direction of maximum compression ($\sigma1$) is 321°N, which coincides with the PSP–EP convergence direction. From the MCS profiles, the study area was subdivided into deformation zone and a relatively stable zone. Thrust faulting, folding and general uplift are observed in the deformation zone. This zone is further subdivided into the active and inactive segments. In the active segment, uplift is occurring in the submarine ridge. This deformation pattern can be related to the ongoing uplift in some regions bisected by the PFZ. The inactive segment, characterized by intense folding of the sequences and faulting of the basement and overlying sequences, is suggested as the precursor of the Philippine Fault Zone. Deformation appears to be recently shifted to the east as delineated by an uplifted N-NW trending submarine ridge offshore NW Luzon Island.

Keywords Philippine Fault Zone · Forearc basin · Strike-slip fault

Introduction

The Philippine Islands form part of the broad zone of deformation between the converging Eurasian Plate (EP) and Philippine Sea Plate (PSP), encompassing the Ryukyu and Taiwan areas in the north to the Celebes and Moluccas Seas in the south. Deformation along this boundary is accommodated by various subduction and collision zones in the western margin of the Philippine Sea (Rangin et al. 1999). In the Philippines, two oppositely dipping subduction zones accommodate the stresses associated with this convergence. To the west, the South China Sea subducts beneath the Philippines along the Manila Trench while the Philippine Sea crust is being subducted along the Philippine Trench in the east (Yumul et al. 2003) (Fig. 1). The island arc system bounded by these subduction zones is undergoing deformation along the Philippine Fault Zone

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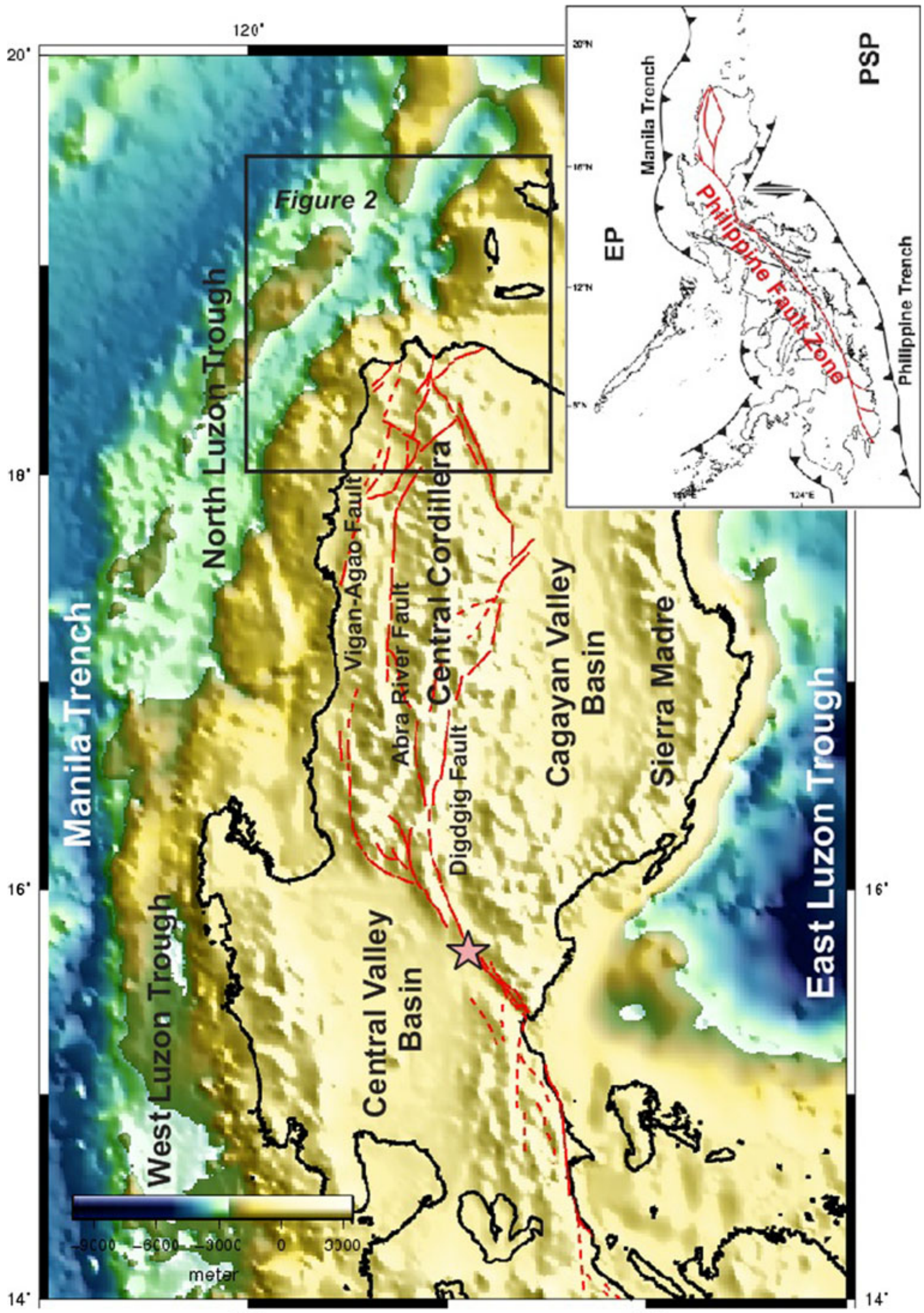

Fig. 1 The tectonic map of Luzon Island. The segments of the Philippine Fault Zone are shown as *red lines* (PHIVOLCS 2000). The trace of the northern splays of the PFZ terminates near the NW corner of the Luzon Island. The most recent large magnitude earthquake was in 1990 with an epicenter located along the Digdig branch of the PFZ indicated by the *star symbol*. The *smaller rectangle* indicates the location of Fig. 2

(PFZ), a system of left-lateral strike-slip faults traversing a total length of about 1,200 km (Barrier et al. 1991).

The occurrence of the Philippine Fault Zone can be explained by the shear partitioning mechanism as suggested by Fitch (1972). The oblique convergence of the Philippine Sea and Eurasian plates induces the compressional deformation within the Philippine island arc system; wherein the perpendicular component of the deformation is taken up by the dip-slip along the Philippine trench while the parallel component is occurring as the left-lateral strike-slip motion along the PFZ (Aurelio et al. 1997).

In the Luzon Island, the trace of the Philippine Fault Zone (PFZ) cuts through the southern Sierra Madre mountains, the Central Cordillera Mountains to the north and finally terminates at the northern coast of Luzon Island (Fig. 1). Although the PFZ is generally trending northeast-southeast, from the southern Sierra Madre region it branches into north–south segments in the Central Cordillera (Barrier et al. 1991). These segments are (from west to east) the Vigan-Agao Fault, the Abra River Fault and the Digdig Fault. Concurrent with this change in general fault trend is the more complex slip along the PFZ in the Central Cordillera area. (Boirat and Maletere 1986) attribute the intense uplift in the Central Cordillera during the Pliocene-Quaternary to the deformation along the Philippine Fault Zone, a consequence of the oblique convergence between the EP and the PSP. Compressional stresses that may cause significant vertical displacement are evident in some segments of the PFZ. Pinet and Stephan (1990) reported a significant thrust component for the slip along the Vigan-Agao Fault, the westernmost splay of the PFZ. The Abra River Fault is characterized by pure strike-slip motion (Ringenbach et al. 1990). The eastern-most segment, the Digdig Fault is characterized by pure strike-slip motion in SE Luzon and acquires some normal slip component towards the northern part of Luzon (Ringenbach et al. 1993). The apparent merging of these two latter segments in the NW corner of the Luzon Island may have an extension on the offshore area, which is the interest of this study. (Aurelio et al. 1997) supposes that the northern segments of the PFZ are expressions of an old strike-slip fault system recently reactivated in the present tectonic regime.

The Philippine Fault Zone (PFZ) is active and has an average fault slip rate of 35 mm/yr based on GPS measurements in the Luzon Island (Yu et al. 1999). Yu et al. (2012) obtained horizontal slip rates along the Digdig Fault. From north to south it increases from 24 to 40 mm/yr. Galgana et al. (2007) proposed significant intra-arc deformation along the PFZ in their study using GPS velocities and earthquake focal mechanism data. Their results support the seismicity along the PFZ. In fact, strong earthquakes have been linked to the activity of the PFZ (Aurelio et al. 1997; Besana and Ando 2004). The latest large earthquake is the 1990 Luzon earthquake with magnitude (M_s) of 7.8 (Punongbayan et al. 2001) which occurred at the Digdig Fault splay of the PFZ (Fig. 1). In terms of seismic hazard, it is important not only to fully understand the tectonic activity along the PFZ, but also to understand the deformation on its possible offshore prolongation. However, the latter was never addressed in previous literature.

The onland trace of the Philippine Fault Zone terminates on the northwest corner of the Luzon Island. This study focuses on the marine area in the North Luzon Trough, which is located on the forearc basin region of the Manila trench subduction system (Lewis and Hayes 1985). Existing earthquake data, multi-channel seismic reflection profiles and gravity data collected offshore northern Luzon are used to investigate the crustal deformation in the marine extension of the PFZ in the North Luzon Trough. It is the objective of this study to locate and characterize the offshore expression of the PFZ deformation on a forearc basin setting.

Methods and data

Seismic data acquisition and processing

Three 2D multi-channel seismic (MCS) reflection profiles were processed and interpreted to examine the crustal structure offshore NW Luzon Island (Fig. 2). The seismic profiles MCS693-4 and MCS693-5 were acquired during the ORI693 cruise. An array of 3 airguns with a total volume of 1,275 cubic inches was used to fire every 20 s (or 50 m at a ship speed of 5 knots). A 48-channel streamer was used in the acquisition, and a 2 ms sampling rate was adopted. However, because of streamer hydrophone problems during the ORI693 cruise, the first 36 channels in the shot records were muted (Ku and Hsu 2009). MGL0908-25, the third seismic profile, was collected off the northern coast of Luzon Island during the fourth leg of the TAIGER cruise aboard the R/V Langseth (in June–July 2009). During this survey, an array of air guns with a total volume of 6,600 cubic inches was used. A 486-channel streamer was deployed. The shots were set at a 50 m interval with a ship speed of about 5 knots). The record length for each shot was 15 s.

The ORI693 seismic profiles were processed with bandpass filter of 8-16-60-110 Hz, and minimum phase predictive deconvolution was performed; and the normal moveout correction, stacking and F–K migration are all applied using a constant seawater velocity of 1,480 m/s (Ku and Hsu 2009). The MGL0908-25 seismic profile data was processed with band-pass filter of 8-16-130-250 Hz, and minimum phase predictive deconvolution was performed. The normal moveout correction, stacking and F–K migration are all applied using an RMS velocity model constructed from the velocity analysis. The processed seismic sections are shown in Figs. 3, 4 and 5.

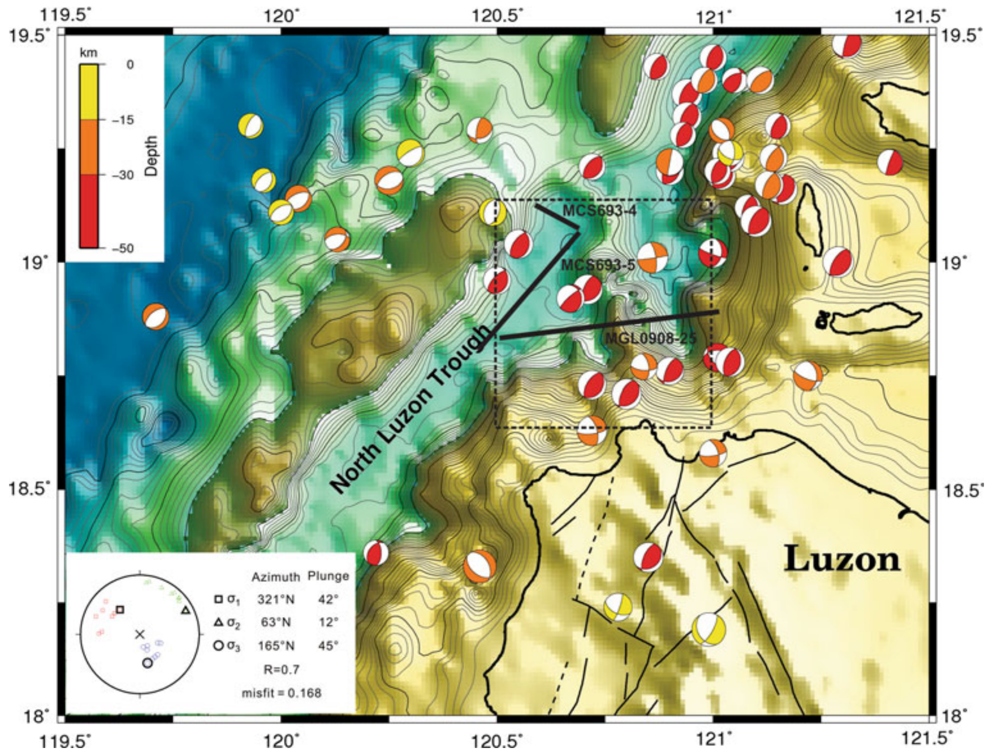

Fig. 2 Focal mechanism solution of earthquakes and MCS profile locations. Stress inversion was done using earthquake events that occurred in the study area enclosed by the *black square*. Thrust mechanism predominate the area with significant number of strike-slip events. *Inset* show the inverted principal stress axes indicating a compressional stress regime in the study area. Also shown are the locations of the 3 MCS lines

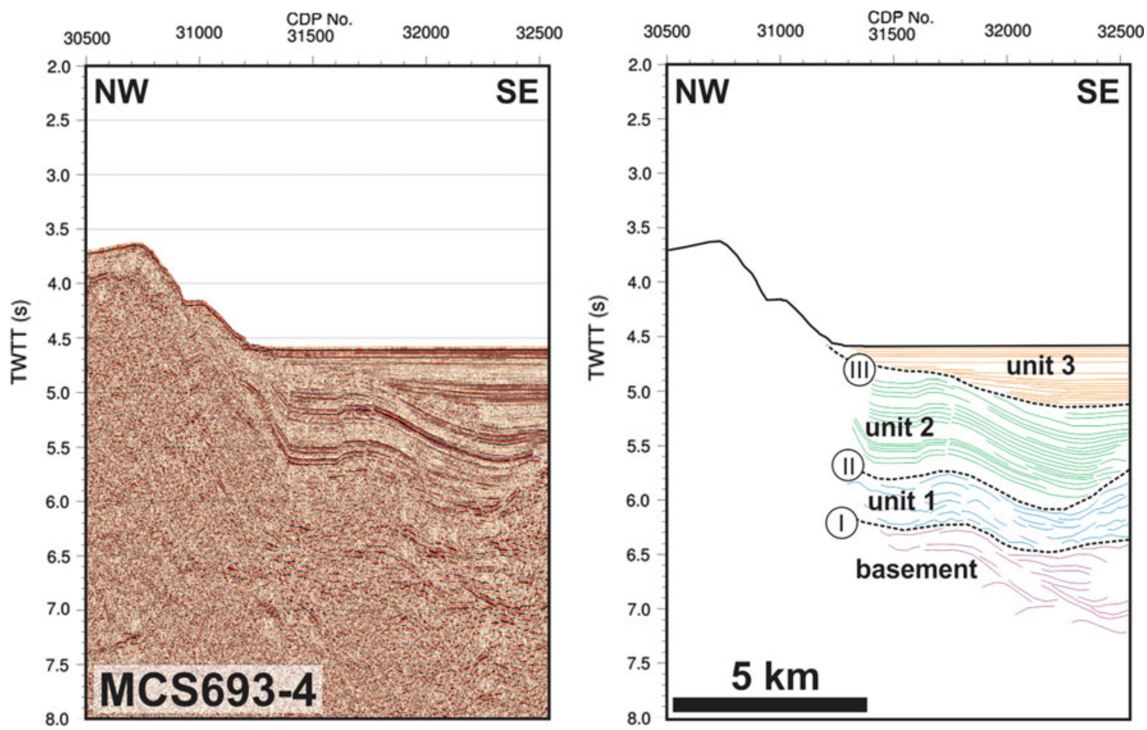

Fig. 3 (*Left panel*) Multi-channel seismic profile MCS693-4. (*Right panel*) Interpreted section. Shows the sedimentary units deposited on the eastern flank of the accretionary prism. Active deformation was apparent in the past. Recent sequence suggests inactivity

Centroid moment tensor solutions and seismicity

In order to understand the general stress regime of the study area, the centroid moment tensor solutions from the Global CMT Catalog (previously the Harvard CMT Catalog) are used (Dziewonski et al. 1981; Dziewonski and Woodhouse 1983). Earthquake events that occurred in the study area from 1976 to 2009 were searched from the

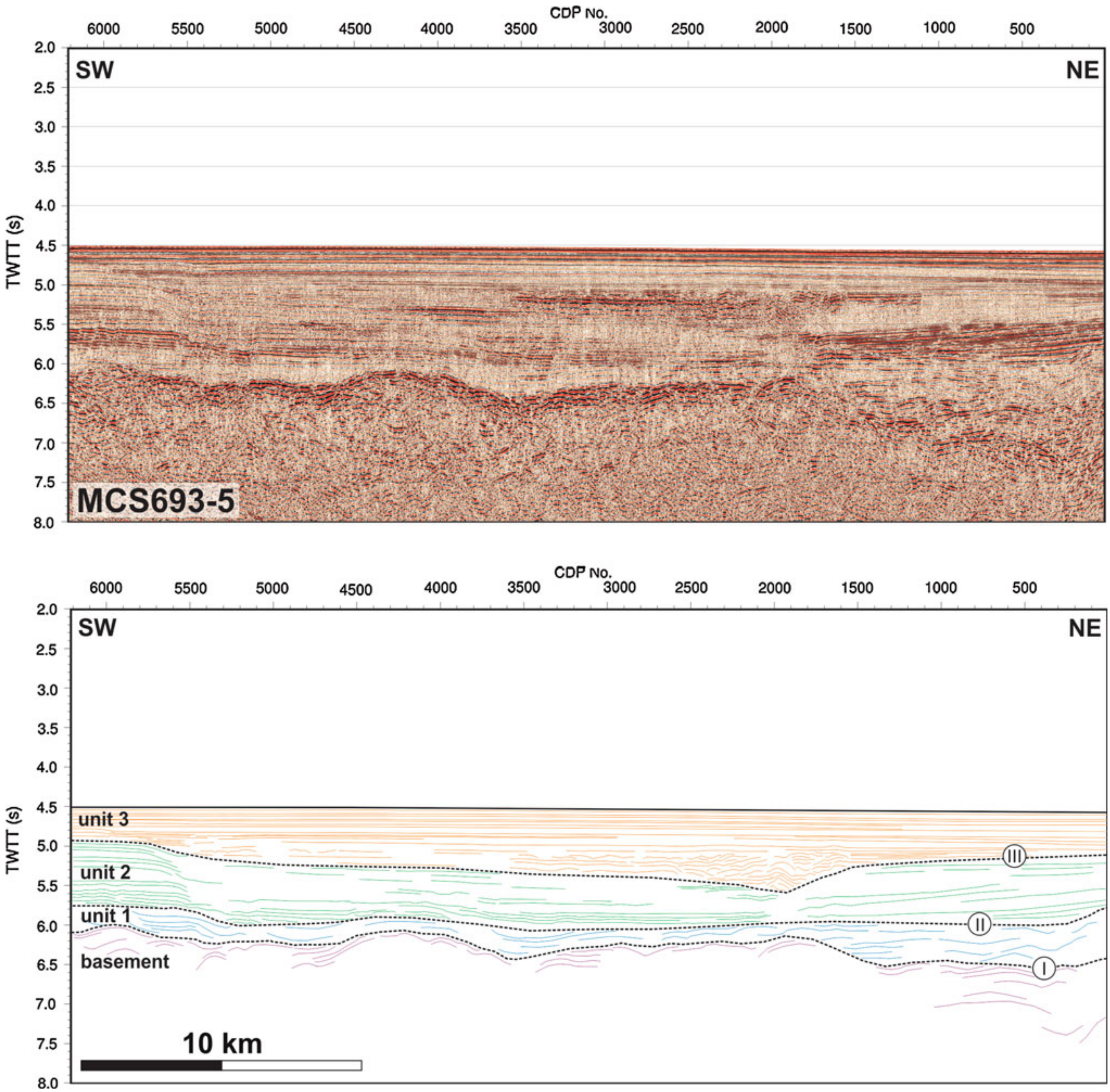

Fig. 4 (*Top panel*) Multi-channel seismic profile MCS693-5. (*Bottom panel*) Interpreted section. Very wide submarine channels are identified in the section. The unconformities show minimal relief

global catalog. The focal mechanism solutions used in this study are plotted in Fig. 2. Principal stress axes were inverted from focal mechanism solution using the Focal Mechanism Stress Inversion method of Gephart and Forsyth (1984) as discussed by Wu et al. (2009).

Gravity modeling

To determine the general crustal structure of the study area, particularly the Moho depth variation that may reflect the deformation attributed to the Philippine fault Zone, gravity modeling was performed. Using the gravity data compiled by Hsu et al. (1998), Bouguer gravity anomaly along a section line coincident with MGL0908-25 was computed (Fig. 6). The gravity modeling was treated as a least squares problem, minimizing the error between the observed and the synthetic Bouguer anomaly. The water density $\rho_w = 1.03$ g/cm^3, sediment density $\rho_s = 2.35$ g/cm^3, crustal density $\rho_c = 2.90$ g/cm^3, and mantle density $\rho_m = 3.35$ g/cm^3 were used in the modeling. The velocity model generated

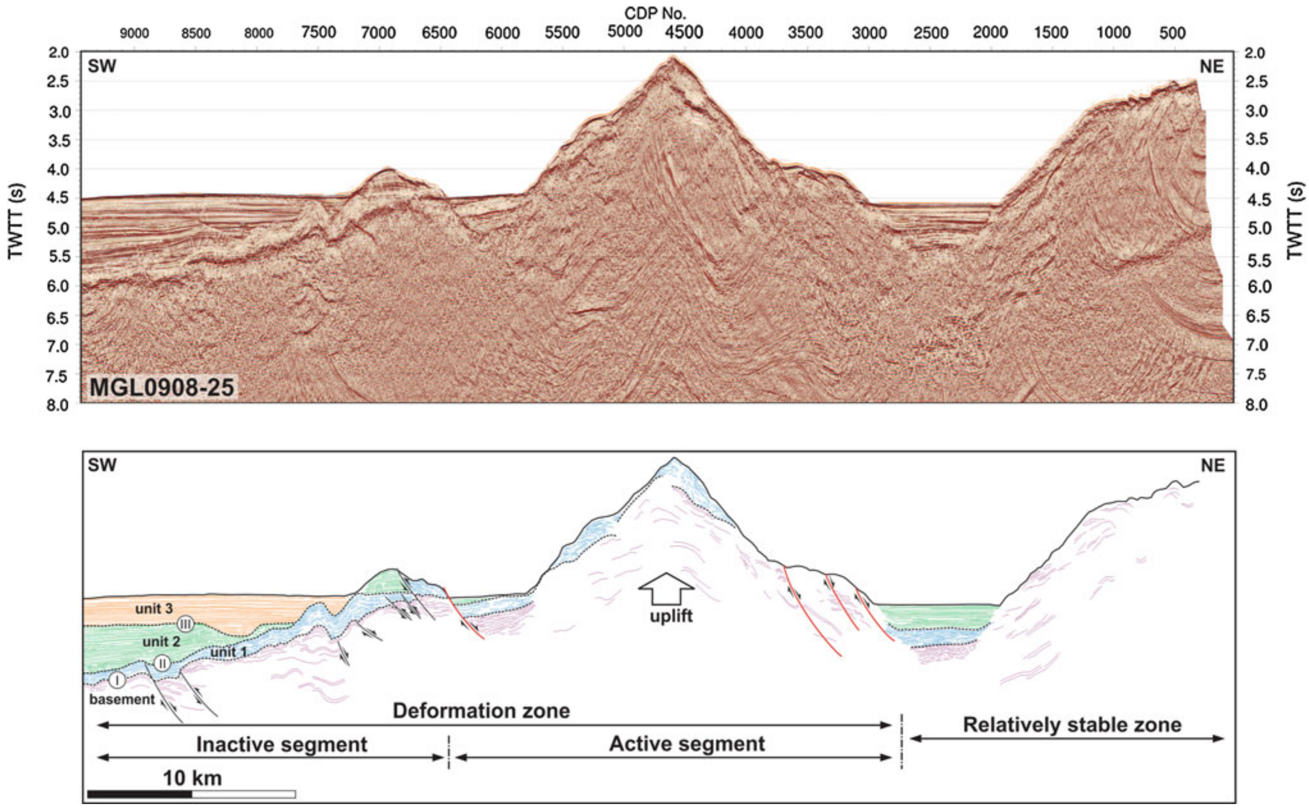

Fig. 5 (*Top panel*) Multi-channel seismic profile MGL0908-25. (*Bottom panel*) Interpreted section. The study area is divided into deformation zone and a relatively stable zone. The zone of deformation is further separated into the inactive segment; and the active segment, being proposed as the offshore manifestation of the Philippine Fault Zone

from the semblance analysis of the MGL0908-25 seismic profile data was used to constrain the gravity modeling, particularly the basin fill and upper portion of the crust.

Interpretation of results and discussion

Forearc morphology and stratigraphy are influenced by sedimentation rate and accretionary prism uplift rate (Lewis and Hayes 1984). This should be the case with the North Luzon Trough (NLT). The NLT is a well-developed forearc basin associated with the active subduction in the Manila Trench system (Hayes and Lewis 1984). However, the possible extension of the PFZ into this region can add to the morphologic and stratigraphic complexities. The relatively flat basin floor is disrupted by a N-NW trending submarine ridge originating from the NW corner of the Luzon Island. Furthermore, the accretionary prism is disrupted near 19.25°N, immediately north of where this ridge terminates in the NW flank of the trough (Figs. 1, 2). This peculiar seafloor morphology may reflect the complex crustal structure and deformation in the area.

The three MCS profiles suggest that the basin fill sedimentary deposits resulted from several episodes of emplacement and erosion. All the profiles show that at least three sedimentary units (unit 1, unit 2 and unit 3) were deposited over the basement; corresponding to three unconformities or sequence boundaries (boundaries I, II and III) (Fig. 3).

The MCS693-4 profile trends on a NW–SE direction. It partially cuts perpendicular to the landward flank of the accretionary prism and continues into the deeper portion of the North Luzon Trough. As observed from the deformed units, deformation in the area persisted until unconformity 3. Sedimentary layers above unconformity 3 are relatively undeformed and are onlapping on the accretionary prism. This observation suggest that the present configuration of sedimentary unit 3 (Fig. 3) is only affected by the uplift rate in the accretionary prism and the sedimentation rate. Although there is no apparent faulting and/or folding observed in the recent sequences (unit 3), past compression extensively folded the underlying sedimentary units 1 and 2, as well as the basement.

The profile MCS693-5 trends on a NE-SW direction, traversing along the North Luzon Trough (Fig. 4). The bathymetry along this survey line is very flat, with a slight downward slope to the NE. As in the previous profile, at least three unconformities are identified in this MCS profile

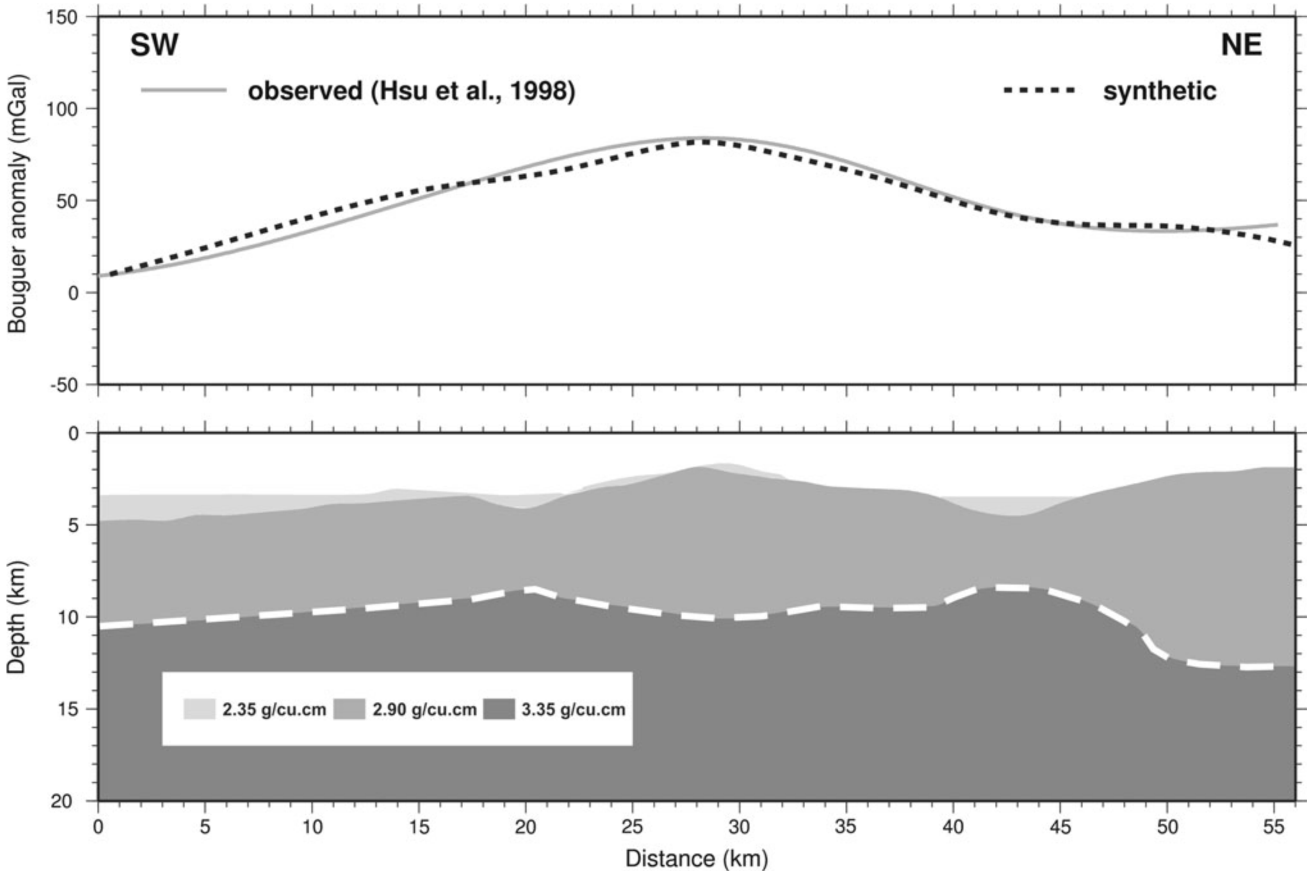

Fig. 6 Gravity model coincident with the seismic profile MGL0908-25. The model shows the shallow roots for the region and the prevailing isostatically uncompensated state of the active zone. *Thick dashed white line* delineates the modeled Moho boundary

(Fig. 4). Deformation is evident on the older units deposited prior to unconformity 3. These sequences are slightly folded. The basement and units 1 and 2 above it are folded. It was noted that an apparent slump deposit is observed on the channel forming part of unconformity 3 (centered at CDP 2000). Besides the slump deposit, sedimentary layers of unit 3 are relatively flat and undeformed.

The MGL0908-25 seismic profile shows an approximately E–W cross-section from 120°30.03′E to 121°04.21′E (Fig. 5). Based on the observed structures or the absence of it in the seismic profile, the profile can be divided into two sides, the deformation zone to the west and the relatively stable zone on the eastern side (Fig. 5). In the relatively stable zone, undeformed sequences are apparent from the start of the seismic section (CDP number 1) to CDP number 2500. No evident deformational structures are observed within this zone.

In the deformation zone (CDP numbers 2500 to the last CDP) faulting, folding and uplift are observed in the basement and overlying sequences. The deformation zone is further separated into the active and the inactive segments. In the active segment, it is apparent that compressive stresses have caused the general uplift of the basement rocks in the study area, resulting to the elevation of the ridge centered at CDP number 4500 (Fig. 5). Normal faults flank the eastern side of the ridge. These normal faults delineate the differential uplift occurring along the axis of the ridge from the relatively stable zone to the east and the recently inactive segment to the west. More recent sedimentary sequences to the east of the ridge remain relatively undisturbed. In the inactive segment of the deformation zone, folded sequences (unit 1) are immediately overlying the faulted basement. These sedimentary sequences are separated by at least three unconformities. Thrust and normal faults are extending from the basement unto some of the overlying sequences (Fig. 5). Intense folding resulted to the uplift of the basement as well as units 1 and 2. The intense deformation observed in the vicinity of CDP 7000 may correspond to the past activity along the Philippine Fault Zone (PFZ). The topmost sedimentary layers of unit 3 deposited over unconformity 3 are relatively flat and undeformed. This indicates the recent inactivity in this segment of the deformation zone. The minimal activity in the area may reflect the decreasing intensity of deformation as observed by GPS studies along the PFZ in Luzon (Yu et al. 2012). The observed distribution of deformation in the zone indicates a shift to the east of the area of concentrated activity. A normal faulting component in the deformation observed in MGL0908-25 may reflect the present movement in the Abra River and Digdig fault segments.

Based on the earthquake focal mechanism data, predominantly thrust earthquakes with significant numbers of strike-slip earthquakes occurred in the vicinity of NW Luzon. Further, above the 30 km depth, strike-slip faulting is the mode of deformation, which can be attributed to shearing along the PFZ. Below that depth, thrust faulting mechanism accounts for the deformation at deeper levels, which may be attributed to the subduction. The principal stress σ_1 direction is 321°N (Fig. 2 inset), similar to the direction of convergence between the Philippine Sea Plate and the Eurasian Plate.

Based on the gravity model generated from the Bouguer anomaly, the crustal thickness varies from about 6 km in the forearc region to about 11 km near the Luzon arc to the east. In terms of isostatic compensation, a highly negative Bouguer anomaly will indicate a fully compensated crust (Thompson and Sandberg 1958). The Bouguer anomaly values in the section line are typified by positive values. This may indicate that the region is actively deforming and isostatically uncompensated. It is apparent from the gravity model that the area is characterized by shallow roots and is isostatically uncompensated, typical of very active regions (Zamani and Hashemi 2000). This activity is being attributed to the deformation along the Philippine Fault Zone as well as forearc basin processes.

Summary and conclusion

In this study, three multi-channel seismic profiles were processed and analyzed to determine the occurrence of the marine extension of the Philippine Fault Zone offshore of NW Luzon Island. Two zones were identified in the profile: the relatively stable zones and the deformation zone. Further, the deformation zone consists of the active and the inactive segments. Overall, the forearc region off coast NW Luzon is characterized by compressional features. Compressional deformation typifies the current tectonic regime in the forearc region, and is concentrated along the northward extension of the PFZ. Observed structures such as thrust and normal faults and folds clearly indicate the past mode of deformation occurring in the study area. These structures, particularly the thrust faults and folds in the basement and the older sedimentary units indicate the past tectonic activity offshore northern Luzon. Considering all the observations and evidences from the seismic profile and the results of the stress inversion and gravity modeling, several conclusions are made. The possible northward extension of the Philippine Fault Zone exists in the offshore area of Luzon Island and manifests as the uplifted N-NW-trending submarine ridge observed in the North Luzon Trough/forearc basin. Results of the stress inversion of focal mechanism solutions of earthquakes indicate that the principal stress direction (321°N) in the vicinity of the possible northward prolongation of PFZ reflects the direction of the oblique convergence between the Philippine Sea Plate and Eurasian Plate. The area is characterized by shallow crustal roots and is isostatically uncompensated, reflecting the tectonic activity in the area. Folding and faulting may have been the predominant mode of deformation in the past but the present general uplift observed may reflect the likely prolongation of the recent motion along the PFZ in this portion of the forearc basin. Recent deformation in the study area manifested as an uplifted submarine ridge being associated with the PFZ resulted in the disruption of the forearc region in the North Luzon Trough. Additional seismic surveys in the area will provide more definitive characterization of the present motion in the PFZ.

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