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A new insight on the geometry of subducting slabs in northern Luzon, Philippines

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Abstract

We used hypocentral and focal mechanism data in order to characterize the tectonic configuration of northern Luzon and propose a model for describing the geometry of the subducted slab of the Eurasian plate beneath the northern segment of the Manila Trench. We took into consideration some of the observed bathymetric features (i.e. the bend in the trench line of the Manila Trench at 20°N lat. and the collision and subduction of an extinct mid-oceanic-ridge at 16–17°N lat.) and the intraplate deformation pattern in the North Luzon Ridge region in depicting a model that is consistent with most of the observed features and phenomena in the study area. An earthquake catalog covering the period from 1619 to 1997 was used in studying the distribution of strain energy released, while earthquakes covering the instrumental years (1963–1997) were used to analyze vertical distributions of earthquakes in sections. We refined the location of some of the historical earthquakes using macroseismic data. The inclusion of historical records despite their inaccurate locations could prevent misidentification of some regions as aseismic zones or gaps in seismicity especially along structures with long return periods. A focal mechanism database that covers the period from 1963 to 1997 was used to decipher intraplate deformation pattern and subduction process of the slab. The focal mechanism database consists of first motion solutions from previous authors and CMT solutions from Harvard University. Seismicity, strain energy release, and focal mechanism maps and cross-sections were drawn in order to have a three-dimensional visualization of the geometry and stress regimes of seismogenic zones.

A new model of the subducted slab of the Eurasian plate beneath the Manila Trench is proposed. The model suggests the collision and subsequent partial subduction of a buoyant plateau at around 20°N lat. to explain the sharp bend in the trench line, the complicated deformation pattern on the overriding plate fronting the bend and the shallow dip of the subducted slab beneath this zone. A tear in the slab is also inferred to be present as evidenced by the observed gap in strain energy release and the abrupt change in dip from shallow to steep south of 18°N lat. The gap in seismicity and strain energy release (65–300 km depth) at around 17°N lat. may be used to infer the trajectory and location of the subducted extinct mid-oceanic ridge (MOR). The aseismic behavior is probably caused by the subducted ridge, which is still hot and is deforming plastically. This is supported by the heatflow data, which shows high values along the extinct MOR. The subducted part of the MOR may serve as the weakest zone where this tear could be localized. The tear may also explain the cause of the abrupt termination of the eastern chain of

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volcanoes south of 18°N lat. The above model, which is a refinement of the model introduced by Yang et al. [Tectonophysics 258 (1996) 85], is consistent with the observed seismicity and deformation pattern, observed bathymetric features, spatial distribution and geochemical character of volcanism in northern Luzon.

Keywords: subduction zones; Northern Luzon; Philippines; bathymetric features; seismotectonics

1. Introduction

The Philippine landmass and its seas are believed to have been derived from continental pieces, island arcs from different sites, obducted crusts and marginal basins and later assembled by various episodes of rifting, collision, subduction, volcanism and accretion that all helped shape its present tectonic configuration. It is located in a boundary between two converging plates: the NW-drifting Philippine Sea plate in the east and the Eurasian plate in the west. Based on the HS2 NUVEL-1 model, the absolute motion of the Philippine Sea plate is around 7 cm/year in the region northeast of Luzon Island and progressively increases to around 9 cm/year in the region southeast of Mindanao. With the Euler Pole being located at around 47°N lat. and 154°E long., the azimuths of the motion vectors also tend to become more westerly southward (Fig. 1). The Eurasian plate, on the other hand, moves in an almost similar direction at a very slow rate of around one cm/year. The relative plate motions between the two plates when computed using the NUVEL-1 model showed a very strong convergence between the two plates despite that their absolute plate motions are almost in the same direction. This is because the motion of the Philippine Sea plate is much faster than that of the Eurasian plate. This strong relative convergence between the two plates resulted in the formation of the two opposing zones of subduction systems. The eastern subduction 294system, which accommodates the northwestward motion of the Philippine Sea plate, consists of the Philippine Trench and the East Luzon Trough. The western subduction system that consists of the Manila, Negros and Cotabato Trenches is induced by plate motion of the Philippine Sea plate. Plate motion not accommodated along the eastern subduction particularly the East Luzon Trough causes the Luzon block to be dragged westward and pushed over the Eurasian plate.

Offshore in western Luzon the east-dipping subduction along the Manila Trench trends almost in a straight line from 13 to 18°N lat. (Fig. 2). At its southern terminus at 13°N lat., it swerves abruptly to the ESE and at around 20°N lat., it forms a broad bend before it continues to Taiwan. The abrupt bend at 13°N lat. is caused by the collision of microcontinental fragments with Mindoro and Panay Islands. Along eastern Luzon is found the East Luzon Trough from 15 to 18°N lat. At 15°N lat., it connects with the Philippine Trench through an E–W-trending transform fault.

Other major seismotectonic features are active intraplate faults that developed in response to compressional and shearing forces induced by the convergence of the Eurasian plate and the Philippine Sea plate. The longest of these is the Philippine Fault Zone. It extends from southern Philippines in Mindanao up to northern Luzon. The northern segment of the Philippine fault divides northern Luzon in a northwesterly fashion. It splays into several branches into northern Luzon. From Masbate, the Philippine Fault splays into a branch, the Sibuyan Sea Fault, trending NW until it enters the thick volcanoclastic deposits of SW Luzon where its trace could not be clearly discerned (Bischke et al., 1990).

2. Area descriptions, previous works and present problems

The seismotectonics of North Luzon region has been studied by many authors and has been the subject of controversy and contradicting opinions. For example, in the North Luzon Ridge area, various interpretations have been made regarding the results of focal mechanism solutions. Seno and Kurita (1978) interpreted the area as a part of the interplate deformation resulting from the proposed cessation of subduction along the Manila Trench and the start of subduction along East Luzon Trough. They proposed that, gradually, convergence is decreasing south of Taiwan and increasing north of East Luzon Trough. By choosing

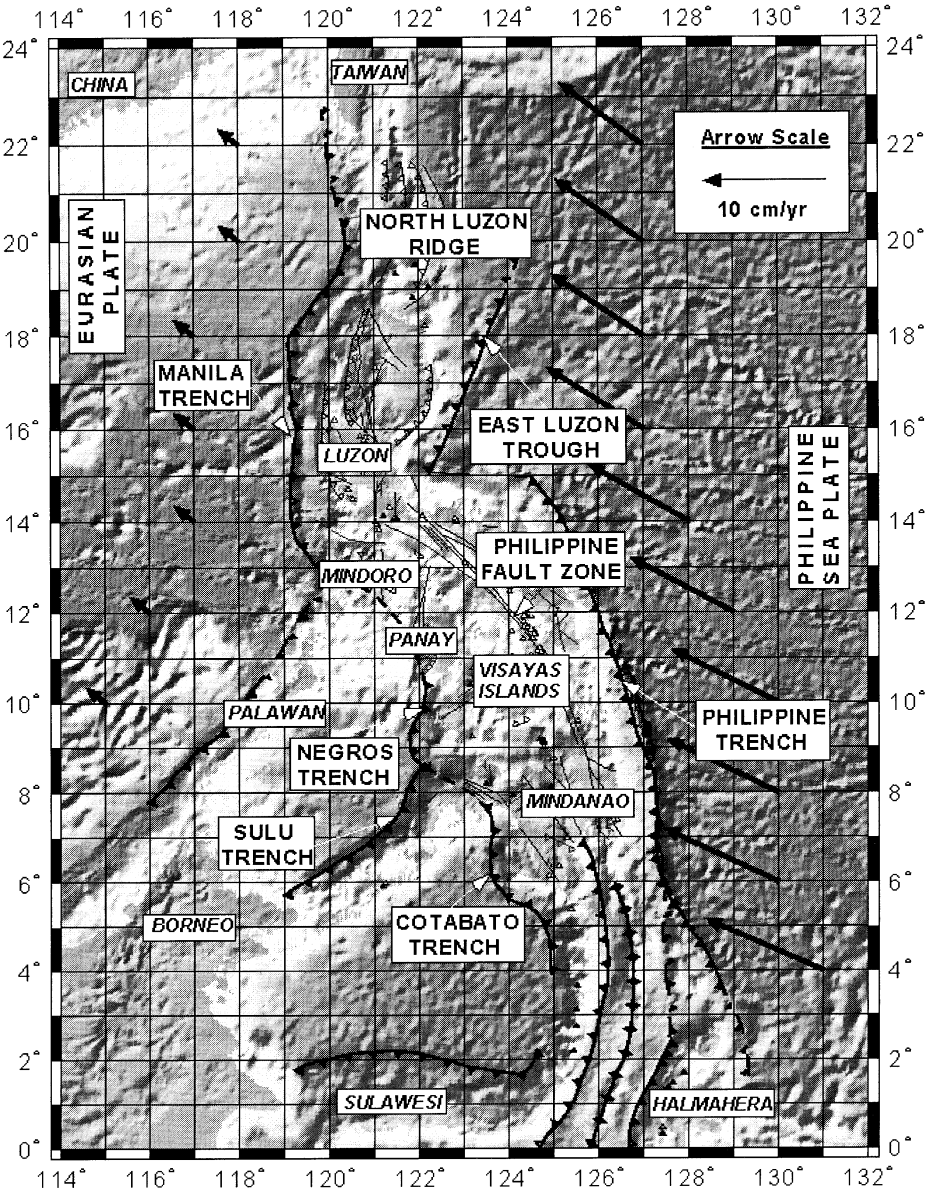

Fig. 1. Map showing the absolute plate motions and tectonic structures in the Philippine region. Arrows represent absolute plate motion of the Eurasian Plate and the Philippine Sea Plate. Arrow lengths are scaled according to plate motion velocity. Location of faults and trenches based on the results of review of Philippine tectonics, digital bathymetry, terrain data and seismic data. Sawtoothed lines are subduction zones, dashed lines are collision zones and lines are faults. Black triangles are active volcanic centers; white triangles are inactive volcanoes. Digital terrain data from the USGS-EROS Data Center, digital bathymetric data from the National Geophysical Data Center (NGDC) and volcano location data from PHIVOLCS.

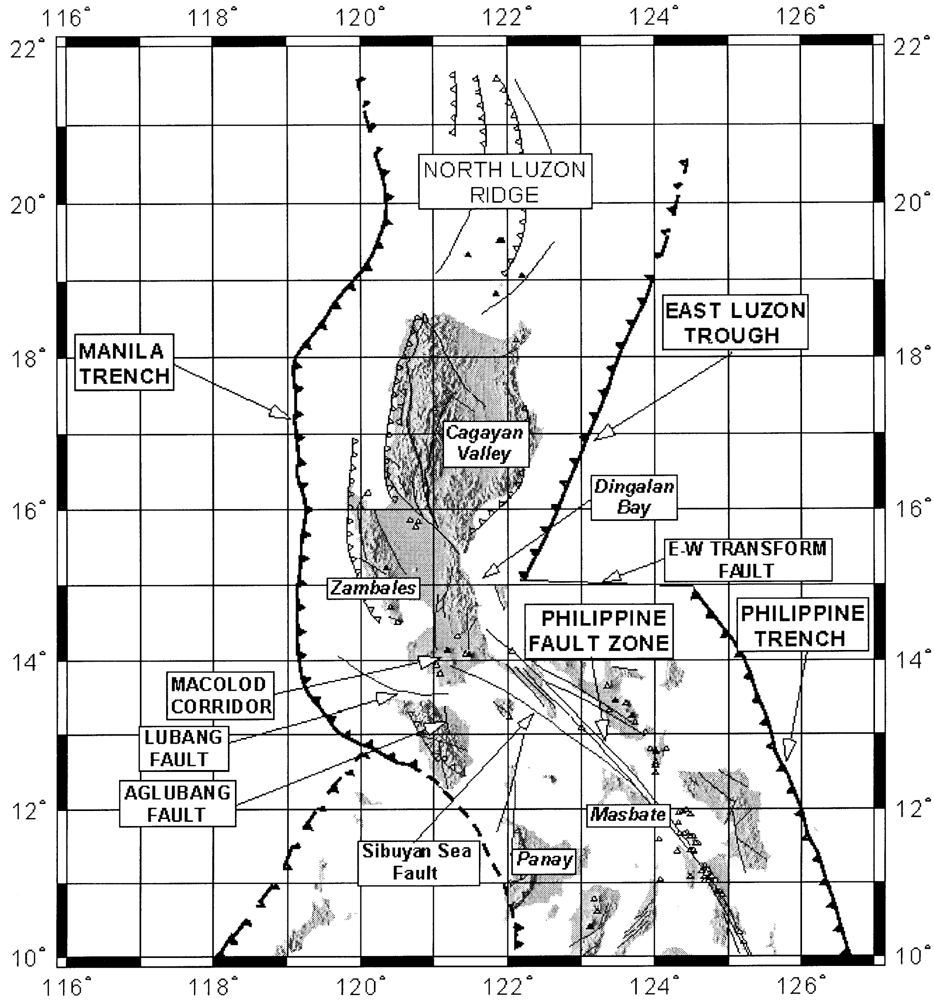

Fig. 2. Map showing the major tectonic features, main islands in Northern Philippines and places mentioned in the discussion.

the NW–SE oriented nodal plane as the fault plane, they also inferred that shearing in the NW–SE direction is taking place. According to them, this direction is opposite that of Karig (1973) who interpreted shearing in the NE–SW direction based on left-lateral offsets of ridges and troughs. However, not seeing these NW-trending faults south of 20°N lat., Hamburger et al. (1983) proposed a right-lateral NE-trending strike slip fault based on the mechanism and aftershock patterns of a large earthquake (Ms 7.1) in 1979 in the region. Hayes and Lewis (1984) also favored the interpretation of Hamburger et al. (1983) despite the difference in the bathymetry and aftershock location of the 1979 earthquake. Although a 35° difference exists between bathymetry/aftershock location and the fault strike selected by Hamburger, they inferred that this might be accounted for by the allowable error in focal mechanism solutions (about 15° in nodal plane). In a later study, Lewis and Hayes (1989) had a chance to map in detail the distribution of faults in the area using both single and multichannel seismic reflection methods and proposed that left-lateral strike slip motion should occur along NW-trending faults based on bathymetric features and seismicity. They interpreted earthquakes to mean that the North Luzon Ridge region represents a non-rigid plate behavior and complex plate boundary and may represent one of the earliest deformational phases associated with arc-continent collision in the region. They also inferred that the western and eastern boundaries of North Luzon Ridge represent a transitional and short-lived geometry that is evolving rapidly under the influence of the southward propagating Taiwan collision and the northward propagating East Luzon Trough.

Meanwhile, the activity itself of the Manila Trench has been questioned by previous authors. At the accretionary prism area between Manila Trench and North Luzon Trough from 17 to 25°N lat., Seno and Kurita (1978) inferred that spreading is being initiated as a result of the collision of the northern Luzon arc with Taiwan based on six earthquakes with extensional mechanisms. Having found abnormally high heatflow values as compared to those found in other areas of the trench, they surmised that rifting is being initiated. Hamburger et al. (1983), on the other hand, related these normal faults to extensional deformation of the subducting slab.

Since Seno and Kurita (1978) also failed to determine any thrust mechanisms for the whole trench, they inferred that tectonic stress regime along the Manila Trench region is turning from compression to extension causing polarity reversal due to the initiation of incipient subduction along the East Luzon Trough. In a later study, Cardwell et al. (1980) and Hamburger et al. (1983) were able to determine mantle earthquakes. Hamburger et al. (1983) were able to determine two underthrusting events and argued that active subduction is still taking place. They also cited the absence of undeformed sediments and presence of Quaternary arc volcanism in western Luzon to support their argument. They also mentioned two large magnitude earthquakes (1934, 1948) and several magnitude 6s that were detected during the early instrumental years. Although their mechanisms are unavailable and locations are not so accurate, their occurrences were cited by Hamburger et al. (1983) to support their contention that the trench is still active. Meanwhile, the 1934 Ms 7.6 event located along the trench was tsunamigenic, too (Heck, 1947; Nakamura, 1978) and could be due to active subduction. Hayes and Lewis (1984) mentioned that the low seismicity might be due to slow convergence rates along the trench. Bautista (1996a) gave further support to active subduction by relating several moment tensor solutions of recent earthquakes to interplate displacement along the trench.

Another plate boundary with not so well understood tectonism is the East Luzon Trough. Many works and interpretations had been done to elucidate the tectonic activity of this plate boundary. The linearity of seismicity and the determination of four well-constrained focal mechanism solutions of shallow, underthrusting earthquakes were considered by Hamburger et al. (1983) as proof that the West Philippine Sea plate is subducting beneath Luzon island and East Luzon Trough is becoming a 'major zone of plate subduction'. They were, however, puzzled why seismicity suddenly vanished starting at around 17–18°N lat. northward. Lewis and Hayes (1983) thought that the absence of seismicity and shallow thrust events north of 17°N lat. might indicate that there is no subduction in this area or that it has just recently started. The lack of normal faulting mechanisms suggested to Hamburger and his co-workers (1983) that flexural bending is not occurring and that incipient subduction is occurring along a relict subduction zone.

Fronting the Mindoro collision–Manila Trench juncture is another seismic zone that exhibits another type of tectonism. In this area is found the Macolod Corridor, a NE-trending tectonic fracture zone (Cardwell et al., 1980) thought to be a pull-apart structure (Forster et al., 1990) or a leaky transform (Divis, 1980; Wolfe and Self, 1983). Volcanism in SW Luzon is attributed to this rifting rather than to the subduction from the nearby Manila Trench. Another fault in this complicated area is the ENE-trending fault called Lubang Fault located offshore north of Mindoro Island and is thought to be the cause of most local, shallow earthquakes in the area. Another fault, the N–S trending Aglubang Fault found in the northern Mindoro island plains, moved in 1994 and generated an Ms 7.1 earthquake. Its right-lateral strike slip rupture was documented southwards along the northern plains of Mindoro Island for about 40 km (PHIVOLCS, 1994). The relationship of these faults to the tectonics of Macolod Corridor is one of the less understood topics in Philippine tectonics.

Recently, Yang et al. (1996) attempted to explain the puzzling issue regarding volcanism in northern Luzon by using mainly geochemistry, geomorphology and ages of volcanoes and augmented by seismic data. After finding the differences in ages and chemistry of volcanoes, they proposed the existence of two distinct volcanic chains that start from southern Taiwan towards Northern Luzon Ridge until southern Luzon (Fig. 3): a western volcanic chain (WVC) and an eastern volcanic chain (EVC). The two chains start as a single volcanic chain from southern Taiwan until 20°N lat. From then on, the two chains diverge to become two distinct chains separated by a distance of around 50 km at around 17.8°N lat. While the WVC continues all the way to Mindoro, the EVC ends with Cagua Volcano at around 17.8°N lat. Using geomorphological investigation and radioactive isotope dating, they found that most of the volcanoes in the EVC are active and are younger in age when compared to the volcanoes in the WVC. They also found mantle-enriched chemistry among the erupted lavas of volcanoes in the EVC. To explain the formation of the two chains and the observed differences in age and geochemical signatures of erupted materials, they proposed a model that takes into consideration the subduction of the mid-oceanic ridge (MOR) west of the Manila Trench at around 16–17°N lat. (Fig. 4). The model suggested that at around 6 Ma the MOR is already approaching the Manila Trench and is about to collide and that collision of the Eurasian continental plate with the northern extent of the Luzon arc in Taiwan is about to take place. At this stage, the subduction of the Eurasian plate along the Manila Trench forms the WVC. At around 4–5 Ma, the MOR is already accreted to the Manila Trench and collision in Taiwan has initiated. At this stage, resistance of the MOR to subduction and collision in Taiwan caused the cessation of volcanism north of the chain. Momentum and weight of the slab caused the lower portion of the slab to be detached. At around 2 Ma, subduction of the slab resumed and formed a second chain of volcanoes east of the western chain. The buoyancy effect of the subducted MOR caused the shoaling of the dip of the slab and this resulted in a tear at the boundary of the oceanic plate and continental crust in Taiwan. The tear, according to the authors, will explain the mantle-

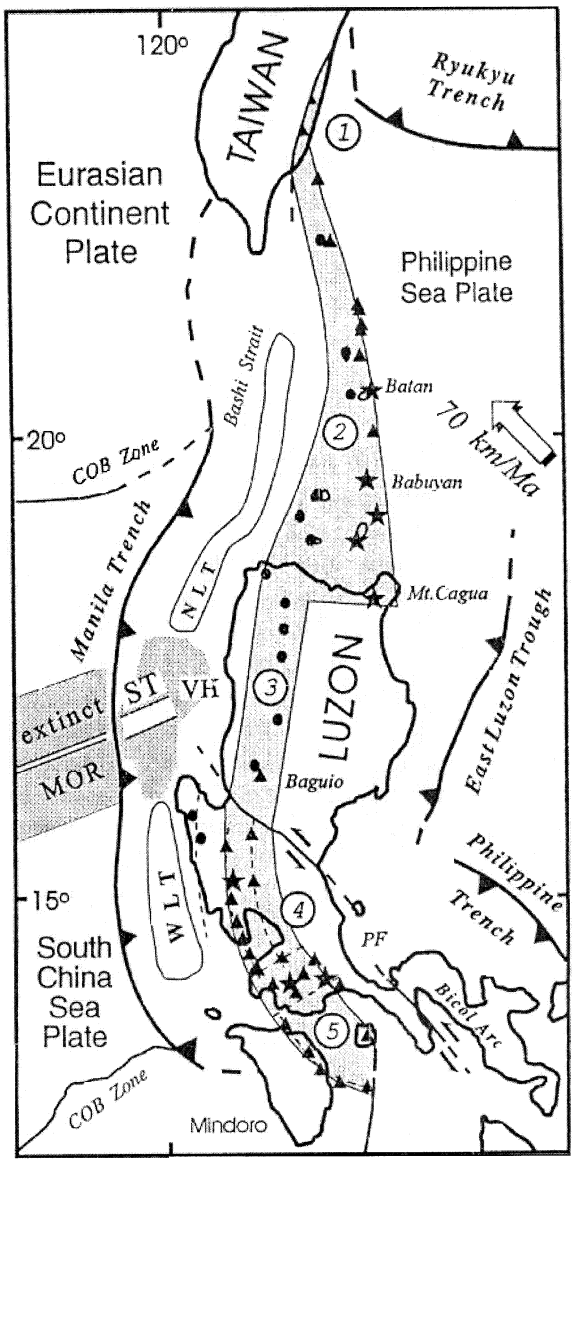

Fig. 3. Map showing the WVC and the EVC identified by Yang et al. (1996) in their study. Numbers 1–5 represent the five volcanic segments identified in the study of Yang et al. The WVC and EVC are shown by the shaded region from southeast Taiwan towards southwest Luzon. Both the WVC and EVC converges from Taiwan. The EVC ends abruptly at Mt. Cagua while the WVC continues all the way to the shaded region identified as volcanic segment number 5 in southwest Luzon island. Solid stars represent active volcanoes while solid triangles stand for inactive volcanoes. Black dots are sampling points where the lavas used for radiometric dating and geochemical analysis were obtained. MOR stands for Mid-Oceanic Ridge, COB for Continental-Oceanic Boundary, VH for Vigan High, ST for Stewart Bank, PF for Philippine Fault, NLT and WLT for North and West Luzon Trough, respectively. (Figure after Yang et al., 1996).

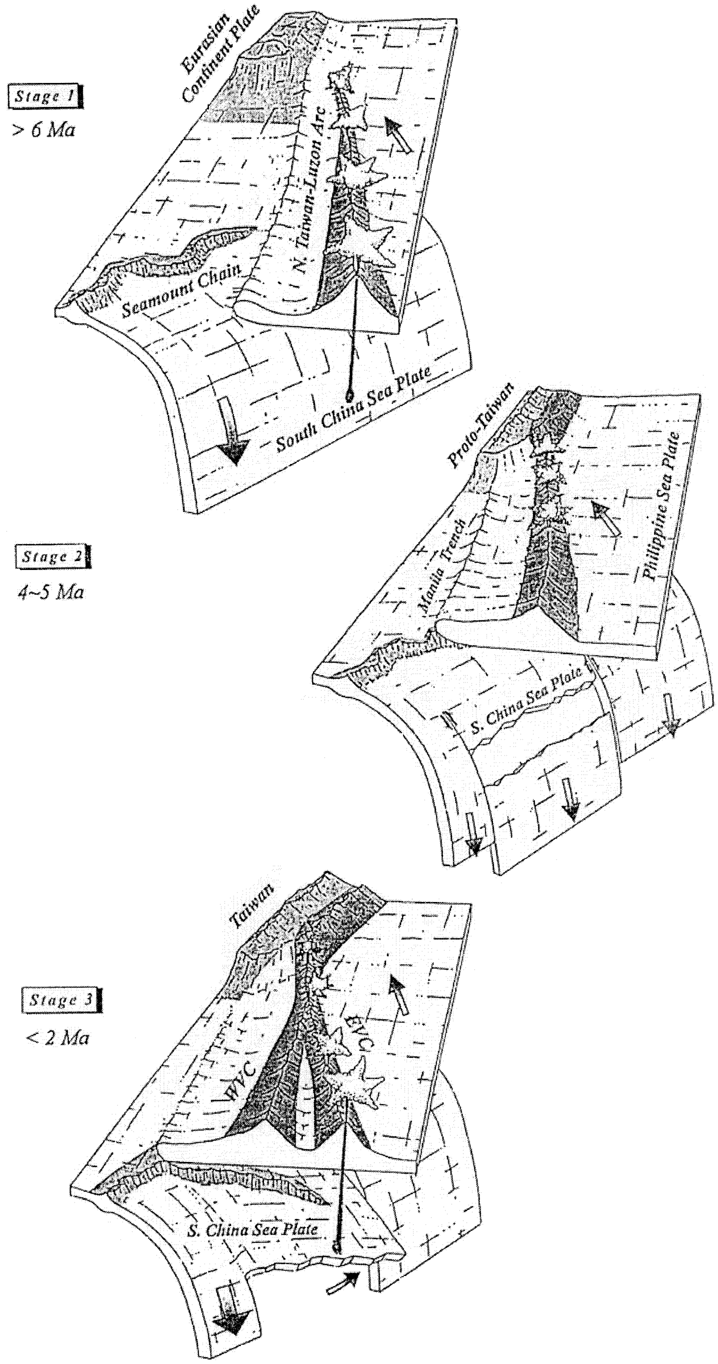

Fig. 4. Model for Northern Luzon proposed by Yang et al. (1996). At stage 1, the WVC formed. At stage 2, the extinct MOR reached the arc and was accreted. Due to its buoyancy, cessation of subduction and volcanism commenced while collision and rapid uplift in Taiwan area took place. This was followed by erosion and deposition of sediments rich in continental materials. At stage 3, the subduction of the MOR resumed but at a less steep slope due to higher buoyancy. The EVC formed as a result of the shift in the position of the magma generation level. A tear in the slab and subduction of sediments in continental materials caused the enriched geochemical signatures of the lavas of the EVC.

enriched characteristics of the erupted lavas in the eastern chain.

We observed noticeable inconsistencies in the above model, in particular with the spatial distribution of volcanoes. If the tear on the slab is on the boundary of the continental crust and oceanic plate in Taiwan as proposed by Yang et al. (1996), then we should be observing the opposite in the spatial distributions of the two chains. This means that instead of diverging towards North Luzon and merging into one volcanic chain towards Taiwan, the two chains should instead diverge towards Taiwan and merge towards northern Luzon. The above model will not result in the abrupt termination of the EVC south of 20°N lat.

Secondly, the proposed tear of the slab near the continental to oceanic crust boundary at around 20°N lat. is not supported by seismicity data and no abrupt jump or gap in seismicity in the mentioned region could be found to indicate its existence. There is also a very small probability for the proposed detachment of the slab due to its momentum and weight to take place since the plate motion of the Eurasian plate is opposite to the subduction direction. We will argue later in the succeeding discussions that it is the WNW translation of the Luzon block that causes subduction of the Eurasian plate along the Manila Trench. Lastly, the model does not take into consideration the presence of other observed features such as the bend in the trench line at 20°N lat., the deformation pattern in the overriding plate in the North Luzon Ridge area, the observance of high heatflow values and other features which may also be related to the formation of the present geometry of the slab. In this study, we will present a refinement of Yang's model that is consistent with all of the above-mentioned features. We shall also use some of their observations and the results of their geochemical study to argue for the plausibility of our proposed model.

3. Methods and material studied

We used hypocentral and focal mechanism data with longer time coverage than previous studies in order to define the geometry and deformation patterns of slabs subducted beneath the northern Luzon region. We also took into consideration some of the observed bathymetric features such as the presence of the bend in the trenchline of the Manila Trench at 20°N lat. and the deformation pattern in the North Luzon Ridge region in depicting a model that will be consistent with all the observed phenomenon in the study area. An earthquake catalog covering the period from 1619 up to 1997 was used in studying the distribution of strain energy release of earthquakes while earthquakes covering the instrumental years were used to analyze vertical distributions of earthquakes in sections. Earthquake parameters during the instrumental period were derived from the catalogs of the International Seismological Centre (ISC) and the U.S. Geological Survey's National Earthquake Information Center (USGS-NEIC). Meanwhile, the inclusion of historical records despite their possible inaccurate locations will prevent misidentification of some regions as gaps in seismicity especially those tectonic structures with long earthquake return period. The methodology in determining the location and magnitude of historical earthquakes is discussed in Bautista (1996b) and further discussed in Bautista and Oike (2000). In their study, Bautista and Oike (2000) determined the magnitudes of historical earthquakes based on felt areas while historical epicenters were estimated using various controls and assumptions like locations of established towns when the earthquake occurred, knowledge of local geological conditions and type of construction. The focal mechanism data used in this study to decipher the faulting pattern and subduction processes of the slabs are those compiled by Bautista (1999) for Philippine earthquakes. For easy processing and retrieval, Bautista (1999) compiled, labeled and computerized the focal mechanism data into a homogeneous database. The database consists of about 1,600 events from 1963 to 1997 and covers an area from 0 to 23°N lat. and from 116 to 130°E long. It consists of first motion solutions from previous authors and CMT solutions from Harvard University. It also includes pre-digital years WWSSN data that were digitized and inverted by Bautista (1999) in order to obtain their solutions and to verify first motion results. The focal mechanism beachballs shown in maps and cross-sections are labeled according to their event number in the Bautista's database. The suffix stands for the data source (H for Harvard CMT solutions, S for first motion solutions compiled by the Southeast Asia Association for

Seismology and Earthquake Engineering or SEASEE, C for Cardwell's first motion solutions and B for the MT solutions determined by Bautista). Seismicity, focal mechanism solutions, earthquake cross-sections showing vertical distribution of seismicity and strain energy release maps at different depth ranges were drawn in order to have a three-dimensional visualization of the geometry and stress regimes of seismogenic zones. In order to verify the location of bathymetric features, active subduction zones and fault structures, we used a $2 \times 2'$ arc bathymetric data from the National Geophysics Data Center (NGDC) and 30×30 s DEM from the USGS-EROS Data Center. These data were plotted on maps using the Generic Mapping Tool 3.0 (GMT) of Wessel and Smith (1995). To have an idea on the rate and direction of absolute and relative plate motions in the study area, we used the plate motion calculator of Kensaku Tamaki (http://manbow.ori.u-tokyo.ac.jp/tamaki-html/myhome.html) that is based on NUVEL-1 model. We also compiled heatflow data from previous workers (Anderson, 1980) and we used these in inferring the thermal regime of the subducting plates. In this study, we have an advantage over earlier writers in that we are looking at a bigger data set that covers a longer observation period. This will enable us to see a bigger picture of the problem and allow us to confidently resolve some of the controversies about the geometry of subducting slabs beneath northern Luzon.

4. Results and analyses

4.1. The seismicity and focal mechanisms of earthquakes

Fig. 5 shows the plot of seismicity for the northern Philippine region. The circles are scaled according to magnitude. The white circles represent shallow earthquake activity (0–65 km), light gray for moderate depths (65–150 km), dark gray for intermediate depths (150–300 km) and black for deep earthquakes (>300 km). The 0–65 km interval represents the shallow earthquakes found in the brittle part of the crust while earthquakes with depths greater than 65 km represents deformation along the subducted slabs. For earthquakes with hypocentral depths greater than 65 km, further subdivision were done based on typical focal mechanisms found at succeeding depth ranges. Earthquakes in the 65–150 km range usually exhibit extensional mechanisms that may be due to slab pull caused by the weight of the lower part of the subducted slab. The 150–300 km depth range represents a transition zone between the usual extensional mechanisms due to slab pull found at the 65–150 km depth range and the compressional mechanisms found at depths greater than 300 km. Earthquakes with depths greater than 300 km are those due to the weight of the overlying slab where its continued subduction is being resisted by the denser mantle.

Very dense clustering of shallow seismicity is observed along the northern segment of the Philippine Trench. In contrast, the area along the trenchline of the Manila Trench is characterized by relatively light to moderate shallow seismicity. In the overriding plate fronting the Manila Trench, a zone (about 100–150 km wide) of dense to moderate clustering of shallow epicenters can be observed starting from around 15 to around 22°N lat. in southern Taiwan. Much of the activities in the northern Luzon block are localized along the Philippine Fault and its splays. A noticeable relative seismic quiescence characterizes the Cagayan Valley region in the northeastern Luzon region. East of this region is a dense cluster of shallow to moderate activity which is related to subduction of the Philippine Sea plate along the East Luzon Trough. The cluster trends NNE starting at around 15–17.5°N lat. From this point, clustering tends to become very light northward. A linearly E–W-trending seismicity is observed connecting the southern terminus of the cluster related to the East Luzon Trough to the northern terminus of the dense cluster related to subduction along the Philippine Trench. This activity is due to an E–W-oriented sinistral transcurrent fault that transforms motion along the East Luzon Trough to the Philippine Trench.

In Mindoro, where the southern segment of the Manila Trench bends sharply to the east–southeast, dense clusters of shallow activity is observed. Dense clustering of deep seismicity is also observed in this area that extends up to a depth of about 300 km. This activity is due to the deformation of the subducted slab of the Eurasian plate beneath the Manila Trench. Southward beneath the Mindoro–Panay collision

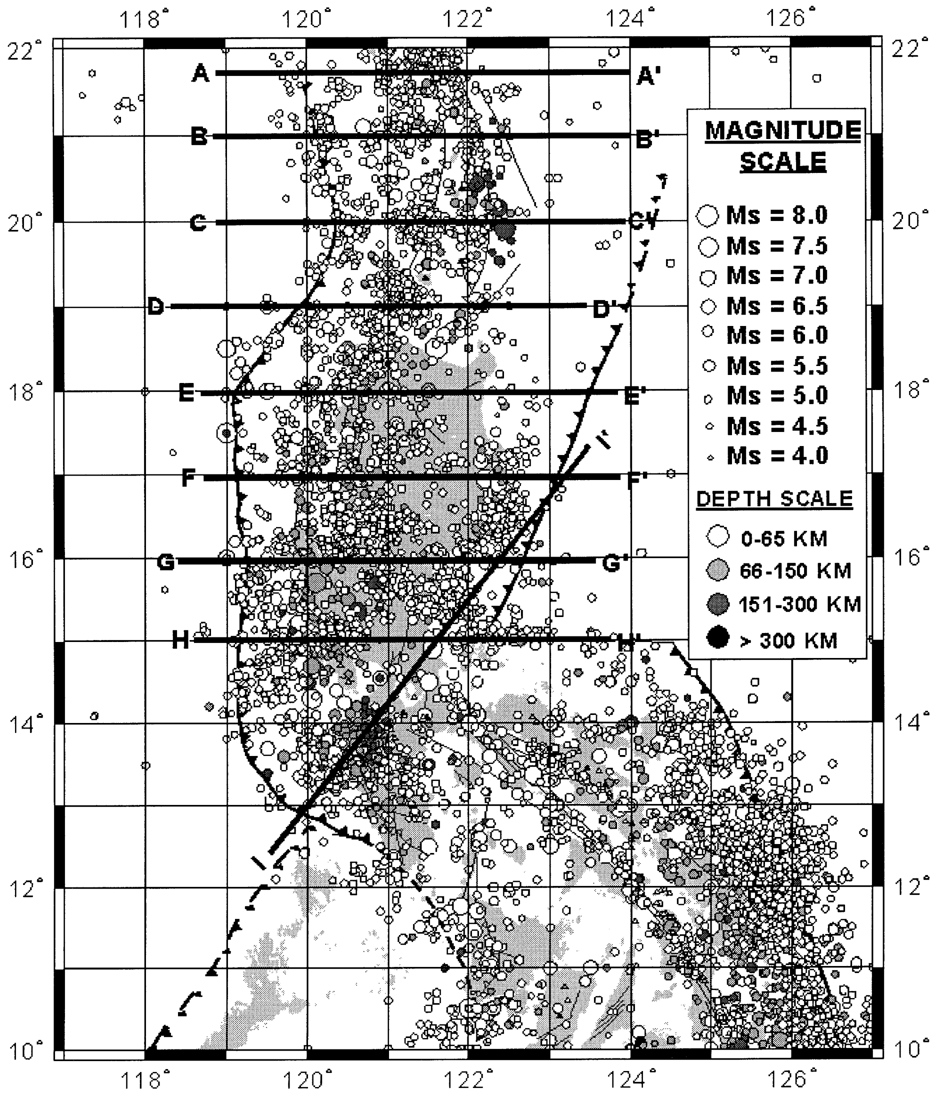

Fig. 5. Map showing the epicenters of earthquakes in northern Luzon from 1619 to 1997. Historical earthquake epicenters from 1619 to 1896 were derived from the work of Bautista and Oike (2000) while instrumental earthquake data from 1897 to 1997 were derived from the ISC and USGS-NEIC catalogs. Lines with capital letters (ex. A–A′) are the positions of seismicity profiles shown in Figs. 8–16.

zone, no trace of deep seismicity could be observed. It is possible that the subducted slab beneath this zone has heated up to the level of plastic deformation and is behaving aseismically or it is already melted and is assimilated into the mantle. North of 14°N lat. to around 14.5°N lat., a noticeable narrow gap in seismicity that trends in a northeasterly direction is observed. The exact tectonic significance of this narrow belt of seismicity that extends from the deeper part of the slab up to the surface at the trenchline at around 14°N lat. is not yet known. We would speculate that the aseismic character of this portion of the slab is caused by a tear, which resulted from sharp bending of the slab due to collision of a micro-continental plate with Mindoro and Panay islands.

Beneath Mt. Pinatubo at around 15°N lat., moderate clustering of deep seismicity is observable and continues to around 16°N lat. From this

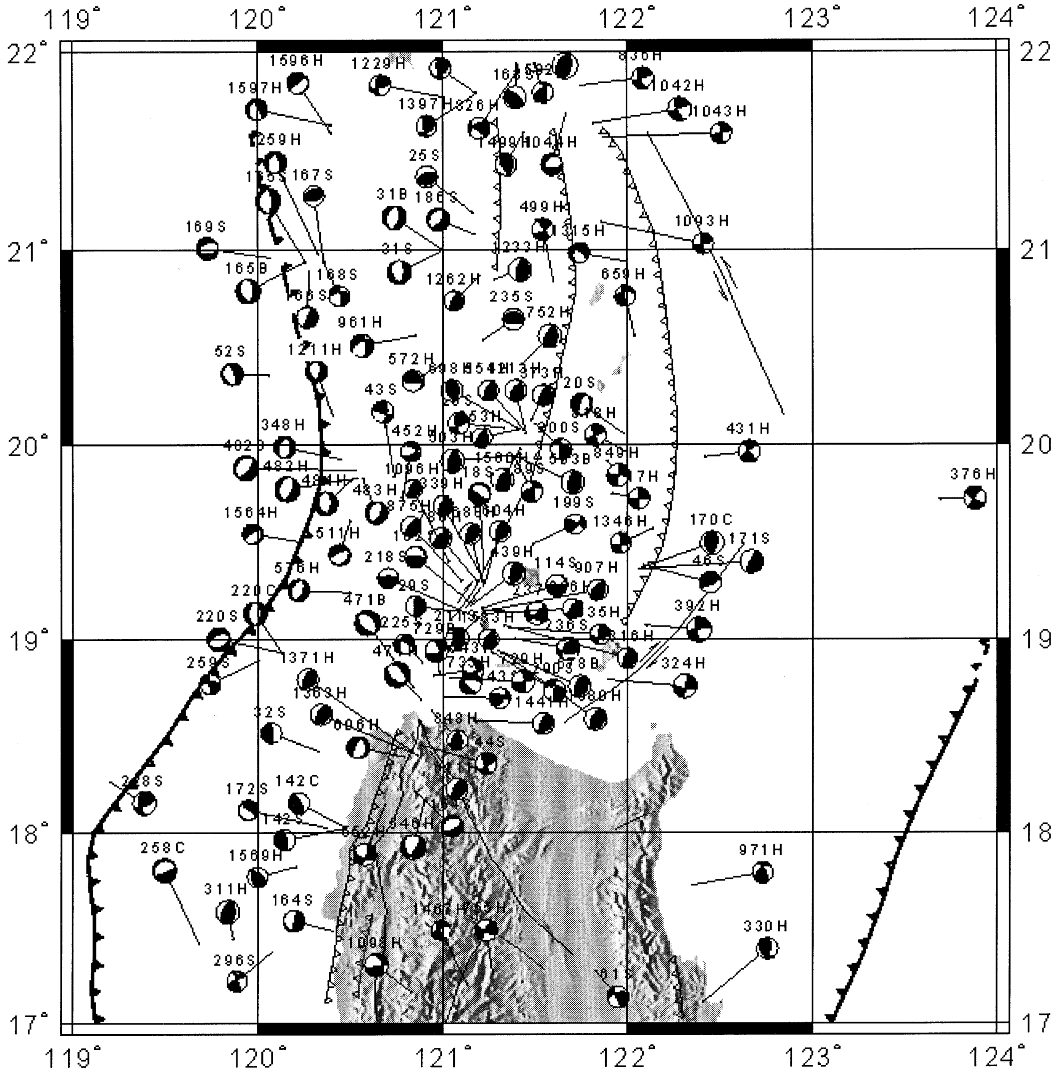

Fig. 6. Map showing focal mechanism solutions of shallow focus earthquakes (0–65 km) from 1963 to 1997 in the North Luzon Ridge region. Beachballs are lower hemisphere equal-area projections. Shaded parts represent compressional quadrants. Identification for each focal mechanism are described in the text.

point northwards, intermediate depth earthquakes disappeared and only very light clustering of small magnitude moderate depth earthquakes are seen in the seismicity map. This part of the slab from 17.5 to 18°N lat. appears to be aseismic at deeper levels. From 18°N lat. northward, moderate depth earthquakes start to increase again. Intermediate depth earthquakes begin to appear again north of 20°N lat. In this study, we will interpret the weak seismicity that characterizes the deep portion of the subducted slab starting at 17–18°N lat. as a manifestation of the presence of the subducted segment of an extinct MOR at depth. The high temperature in this portion of the slab is possibly causing seismicity to be weak. An eastward jump in seismicity is also observable starting at 18°N lat. northward.

In the North Luzon Ridge region, a 200-km-wide zone of dense shallow seismicity is observed. Figs. 6 and 7 show the plot of focal mechanism solutions for shallow earthquakes in the North Luzon Ridge and

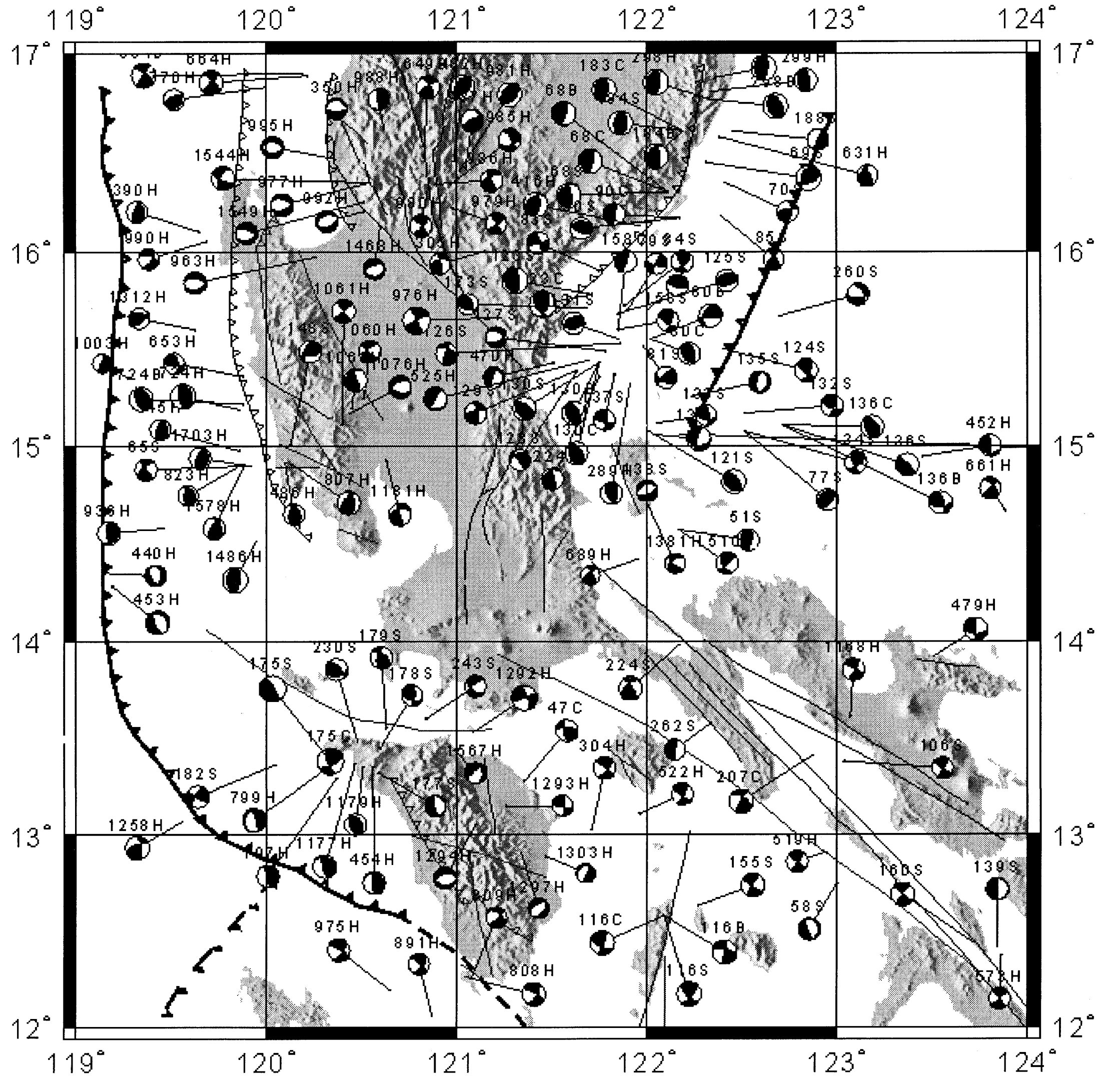

Fig. 7. Map showing focal mechanism solutions of shallow focus earthquakes (0–65 km) from 1963 to 1997 in the Central Luzon and Mindoro areas. (Descriptions same as in Fig. 6).

Northern Luzon regions. It can be discerned that the North Luzon Ridge region is characterized by a complicated deformation pattern as shown by the diverse and complex pattern of focal mechanism solutions. All types of mechanisms from extensional, compressional and shearing type are present in this area. We will argue later that this complicated pattern of deformation is influenced by the collision and partial subduction of a buoyant lithosphere west of the bend at 20°N lat. Meanwhile, we will evaluate the geometry and stress regime of the subducted slabs by examining the cross-sections of seismicity and focal mechanism solutions in the succeeding figures.

Section A–A′ in Fig. 8 shows the vertical distribution of seismicity across the overriding plate immediately south of Taiwan. A very dense cluster of seismicity is observed in the overriding plate that extends to a distance of around 300 km from the trench. The seismogenic part of the subducted slab

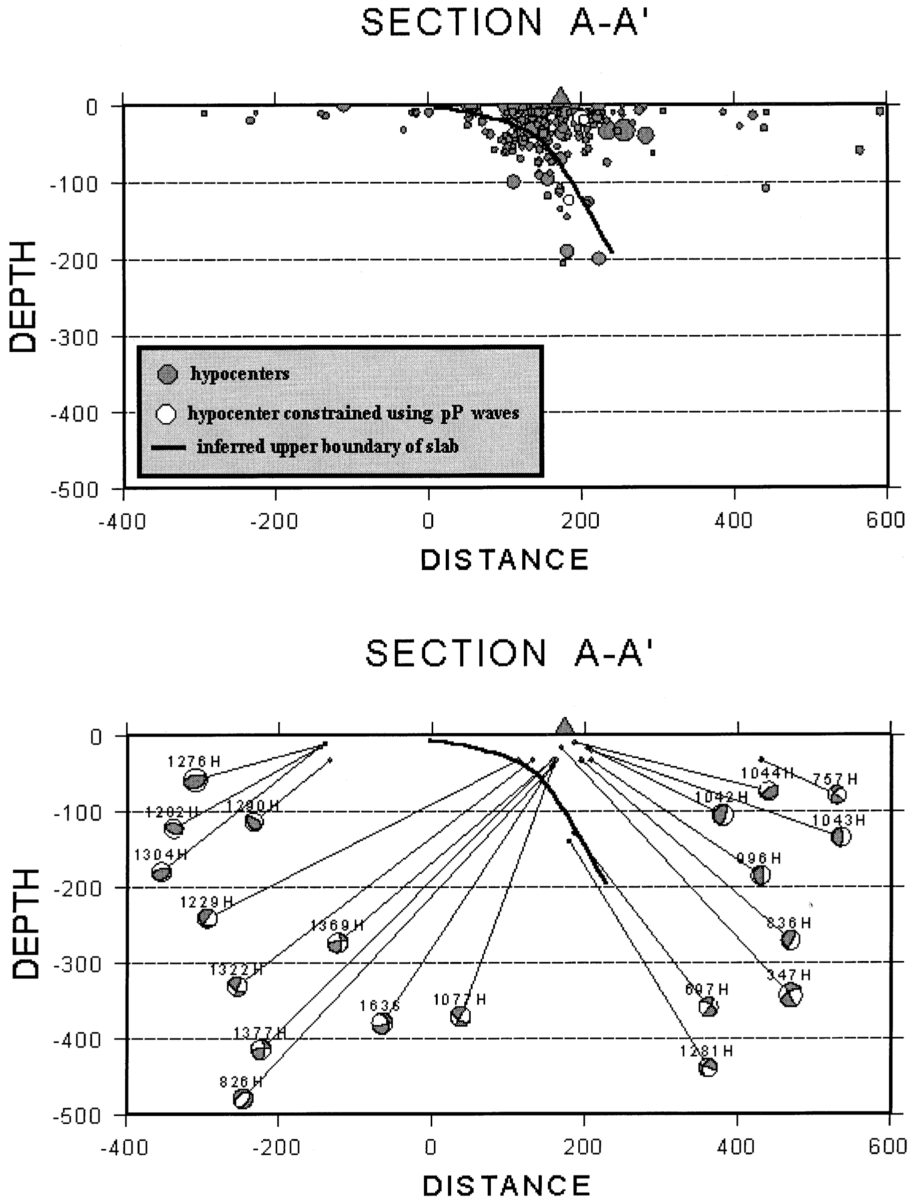

Fig. 8. Cross section along line A–A′ showing vertical distribution of seismicity and focal mechanism solutions. Hypocentral data from the ISC and USGS-NEIC. Well-constrained hypocentral depths using pP waves were done by the USGS-NEIC. Section width is 100 km (all earthquakes within the 50 km perpendicular distance from the section plane were projected). Dark colored triangles stand for active volcanoes while light colored triangles stand for inactive volcanoes. Beachballs are back hemisphere equal area projections with shaded parts representing compressional quadrant. The zero distance on the *X*-axis is the trench-axis of the Manila Trench.

extends to a depth of around 200 km. The slab dips eastward to about 20° at shallow depths while at below the 60–70 km depth, the dip steepens to around 45°. Event #1322H, which occurs very close to the inferred upper boundary of the slab, is interpreted to be an underthrusting earthquake as its shallow dipping nodal plane is roughly aligned parallel to the dip of the slab at this location. An inactive volcano is located on

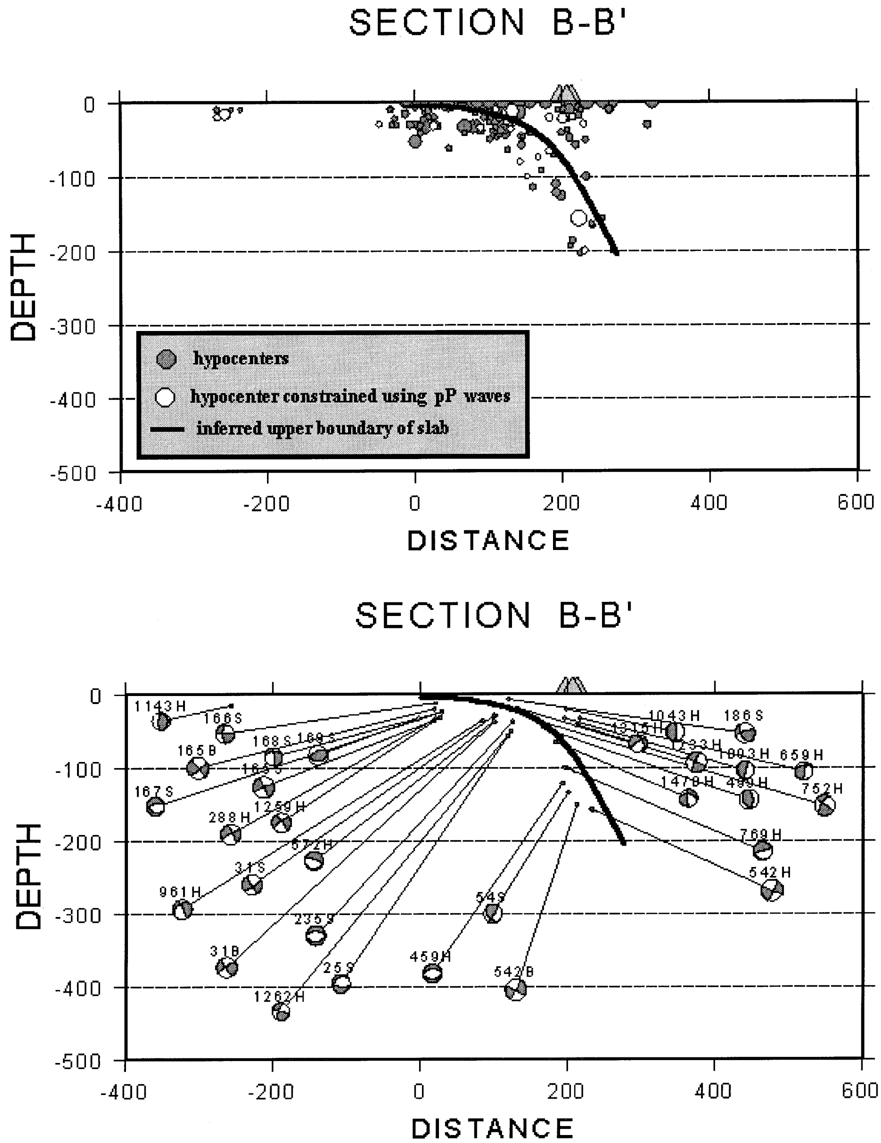

Fig. 9. Cross section along line B–B′ showing vertical distribution of seismicity and focal mechanism solutions. (Descriptions same as Fig. 8).

top of the slab shallower than the 100 km depth magma generation level. Events #347H, 1077H, 1377H, 1369H and 757H are shallow earthquakes with thrusting mechanism and are suggestive that the overriding plate is subjected to strong compressional forces. In section B–B′ (Fig. 9), several normal faulting mechanisms striking parallel to the trenchline are observed to occur in the upper layer of the slab close to the trench axis. Their positions in the slab suggest that the slab is being subjected to flexural bending as it subducts. These are events #165B, 165C, 288H, 1259H, 31S and 31B. On the other hand, events #752H and 1233H have shallow east-dipping nodal planes and are located close to the upper boundary of the slab. We interpret these to be due to interplate displacement. A slight shoaling of the dip of the slab is noticeable when compared to that of section A–A′. Below the three inactive volcanoes, the

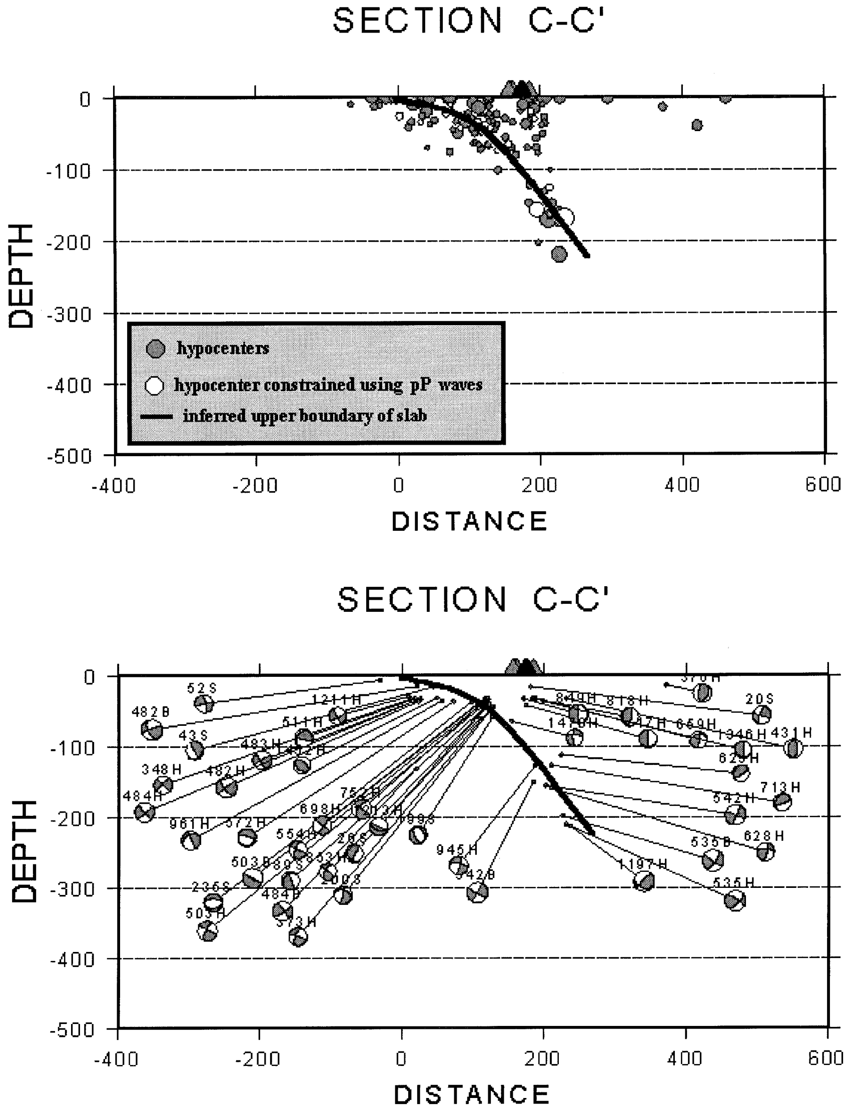

Fig. 10. Cross section along line C–C′ showing vertical distribution of seismicity and focal mechanism solutions. (Descriptions same as Fig. 8).

slab is above the 100 km magma generation level. In section C–C′ (Fig. 10), a further shoaling of the general dip of the slab is noticeable. Several flexural bending mechanisms (52S, 482B, 348H, 484H, 483H and 1211H) are also observed in front and behind the trench axis. Yang et al. (1996) proposed a tear in the subducted slab that is localized by the continental-to-oceanic boundary (marked as COB in Fig. 3). The COB appears to intersect the trenchline at around 20°N lat. If the tear is really present in the slab, we should see an abrupt jump in seismicity from section C–C′ (Fig. 10) to section D–D′ (Fig. 11). This means that the dip of the slab should change abruptly. The dip of the slab in section D–D′ showed only a minor shoaling of dip. It is still the same progressive gradual shoaling of dip we observed from section A–A′ to section C–C′. In section D–D′, the seismogenic part of the slab appears to have thickened. Two active volcanoes are approximately positioned above the 100 km magma generation level. Flexural bending

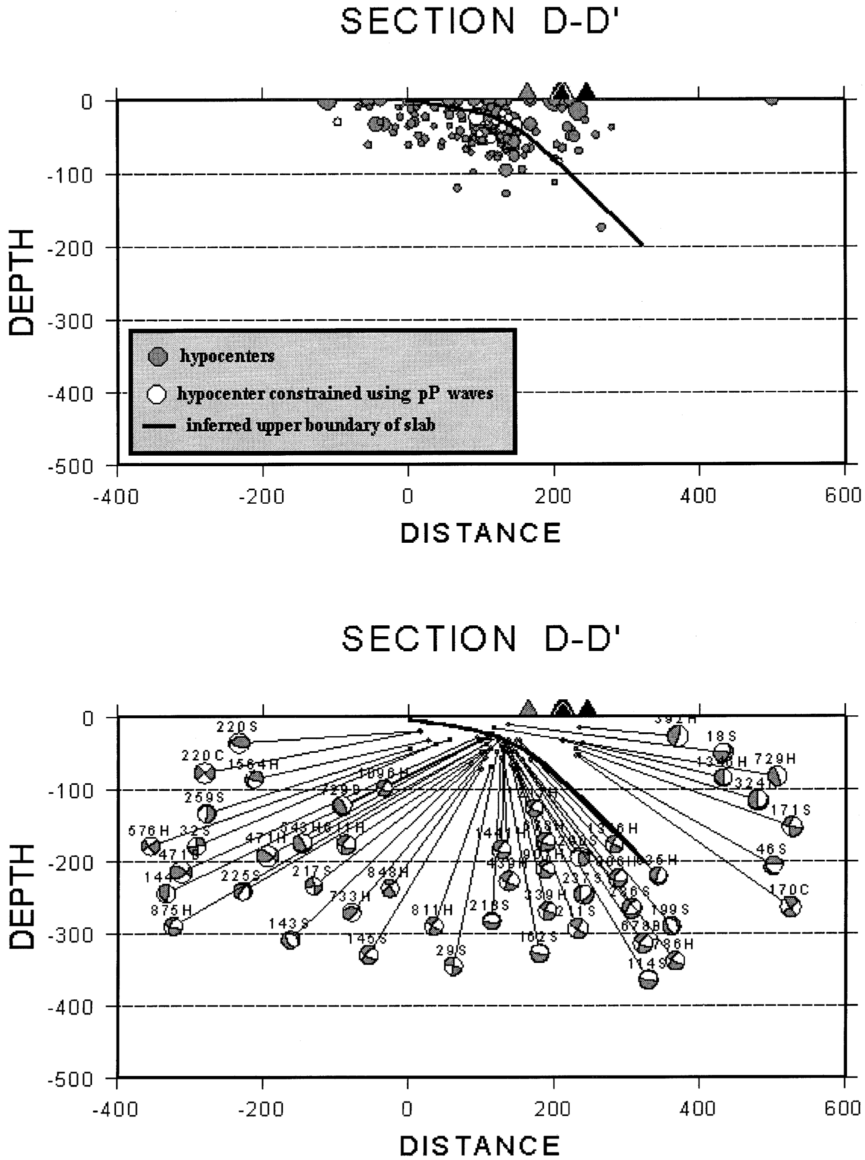

Fig. 11. Cross section along line D–D′ showing vertical distribution of seismicity and focal mechanism solutions. (Descriptions same as Fig. 8).

earthquakes are observed at a shallow depth close to the trench line (220C, 32S and 576H). Events #1441H, 339H, 1316H, 678B and 439H are interpreted to be underthrusting events based on their shallow east dipping nodal planes and their position on the slab. There are also shallow events in the section — (#171S, 1441H and 170C) — which show low angle thrusting mechanism and which can be considered as direct evidence for the ongoing process of plate shortening and thickening. In section E–E′ (Fig. 12), the slab appears to have attained its shallowest dip. As observed in section D–D′, the seismogenic layer is also observed to be very thick in this section. Events #1363H, 611H and 1371H are identified to be underthrusting earthquakes. From section E–E′ to F–F′ (Fig. 13), and abrupt change in dip from shallow to steep is observed. In section F–F′, the seismogenic layer is also observed to have

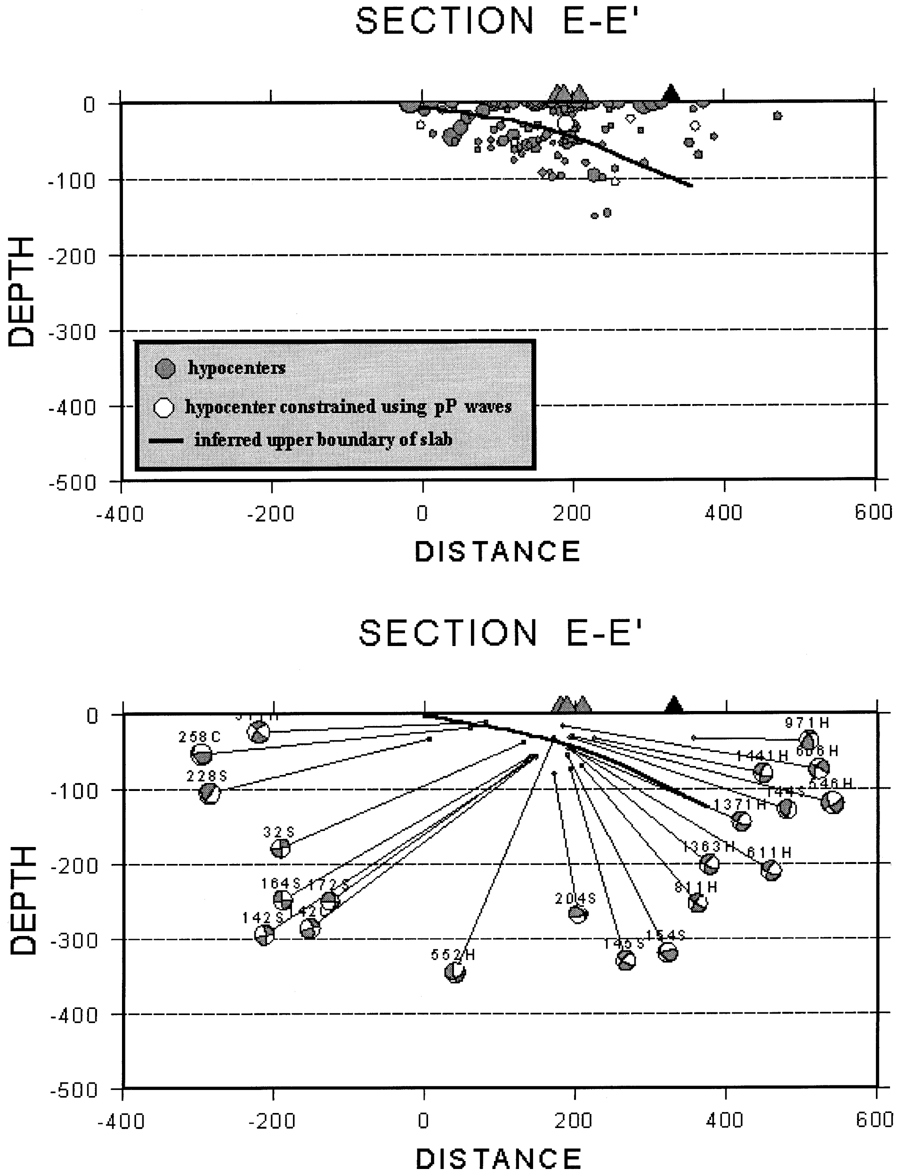

Fig. 12. Cross section along line E–E′ showing vertical distribution of seismicity and focal mechanism solutions. (Descriptions same as Fig. 8).

substantially decreased in thickness. A high-angle thrust fault mechanism (311H) is found in the thrust zone. From section F–F′ to G–G′ (Fig. 14), west-dipping cluster of dense seismicity related to subduction along the East Luzon Trough is visible. Several underthrusting mechanisms (events #631H, 310H, 298H, 183C, 330H in section F–F′ and events #123C, 130B, 90C and 88C in section G–G′) suggest active subduction along this structure. In section H–H′ (Fig. 15), Mt. Pinatubo, an active volcano which violently erupted in 1991 is located above the 100 km magma generation level. Active subduction is indicated by events #936H, 1003H, 545H, 724B, 406H and 807H that show underthrusting mechanisms. Section I–I′ (Fig. 16) is a NE-oriented section line that cuts across the southern terminus of the Manila

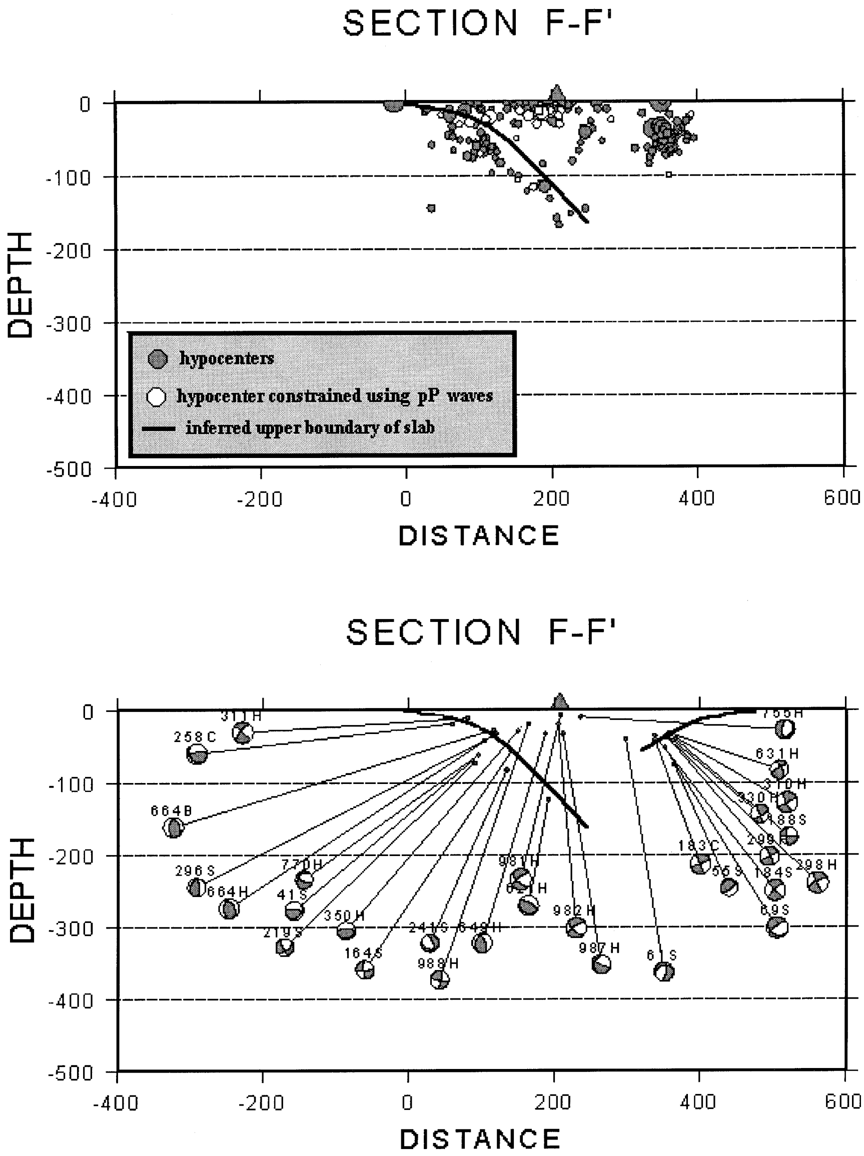

Fig. 13. Cross section along line F–F′ showing vertical distribution of seismicity and focal mechanism solutions. (Descriptions same as Fig. 8).

Trench at around 13°N lat. The seismogenic zone appears to have attained an almost vertical dip in this section. The steep dip of the slab is probably due the collision of a microcontinental fragment with the islands of Mindoro and Panay south of 13°N lat. Some active volcanoes are no longer above the 100 km magma generation level. Some authors had related magmatism of these volcanoes to rifting (Karig, 1983; Forster et al., 1990).

Some of the salient observations that we derived from the above analysis are summarized as follows: For the subducted slab along the northern segment of the Manila Trench, we observed a progressive gradual shoaling of slab dip southward starting from 22 to 18°N lat. From this point southward, rapid steepening of the slab dip is observed. A jump in seismicity appears to be present between 17 and 18°N lat. The upper

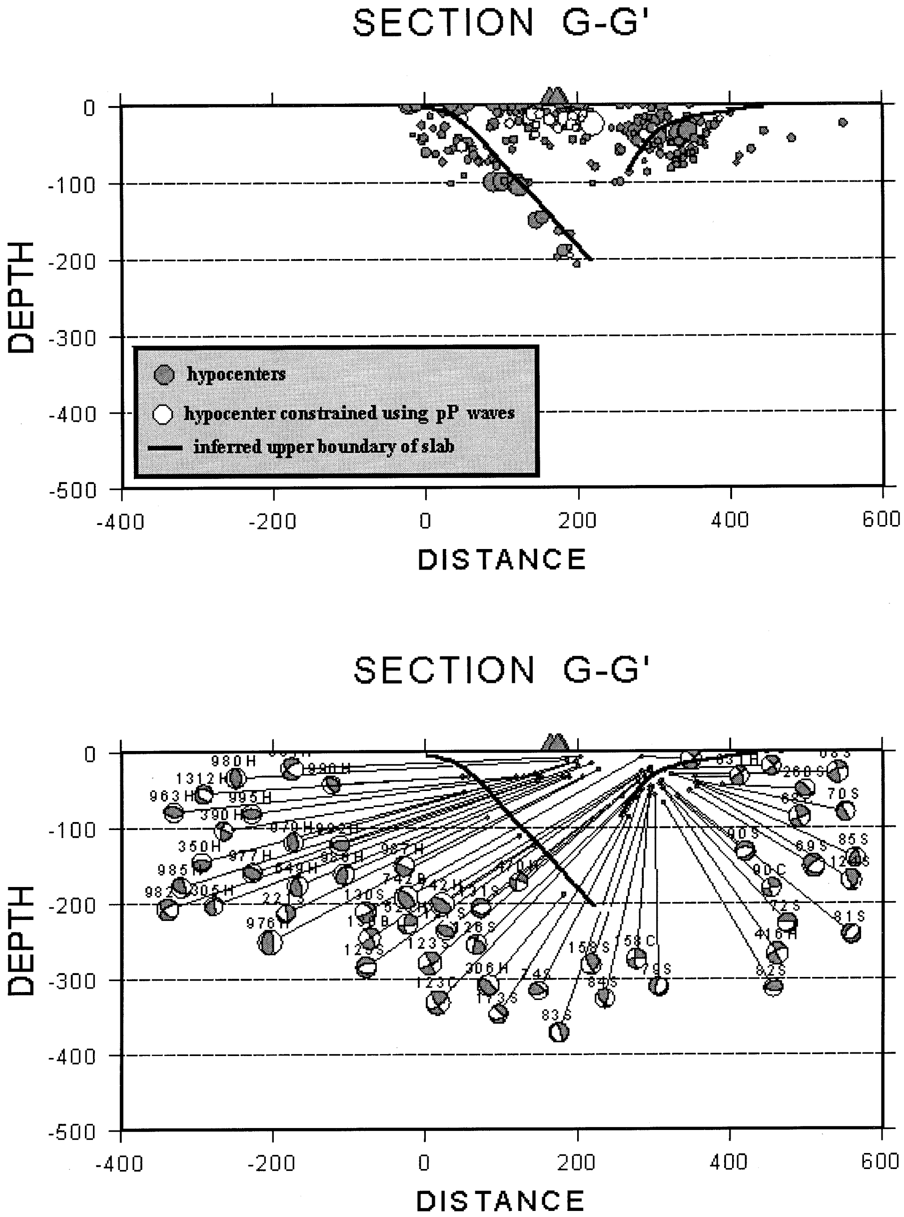

Fig. 14. Cross section along line G–G′ showing vertical distribution of seismicity and focal mechanism solutions. (Descriptions same as Fig. 8).

layer of the subducted slab close to the trench at around 20°N lat. is subjected to extensional stresses that indicate that a thick slab is being flexed as it subducts. Several underthrusting mechanisms were observed starting from 22 to 13°N lat., which means that subduction along the whole segment of the Manila Trench, is still very active. It is observed that most volcanoes are only active when they are above the part of the slab close to the 100 km magma generation level. Shallower and deeper than this level, volcanoes become extinct. Where the slab dip is shallowest, the seismogenic layer appears to be thicker. This observation is seen in sections D–D′ and E–E′ (Figs. 11 and 12).

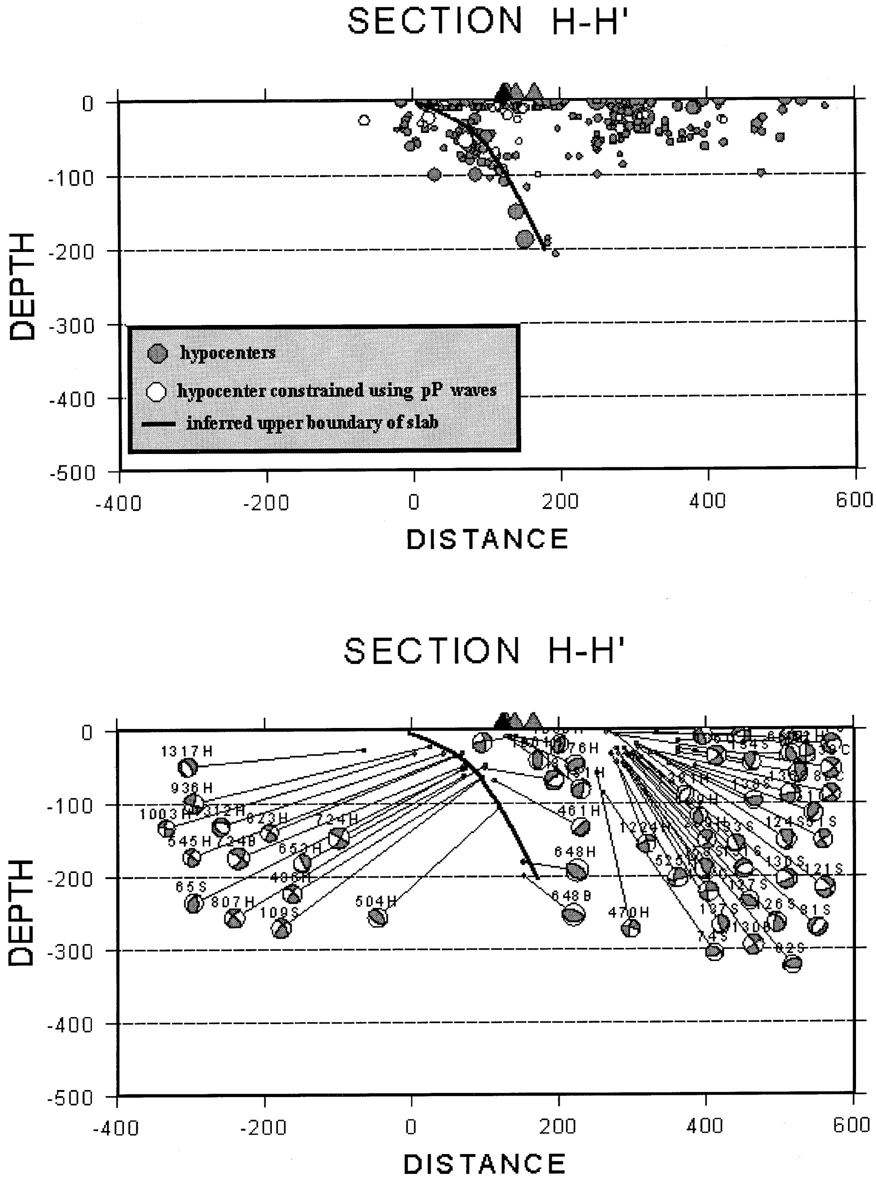

Fig. 15. Cross section along line H–H′ showing vertical distribution of seismicity and focal mechanism solutions. (Descriptions same as Fig. 8).

4.2. The distribution of seismic energy release

Along most of the trace of the Manila Trench, high energy release indicating strong seismic coupling is observed in the map showing strain energy release for shallow earthquakes (Fig. 17). A narrow zone along the trace of the trench from 16 to 17°N lat. shows low strain energy release indicating weak seismic coupling. The area in front of the bend at 20°N showed very high seismic energy release. On the other hand, in Fig. 18, which shows strain energy release of deep events, the subducted slab showed a discontinuous distribution of strain energy release. One noticeable feature in this map is the gap in the energy release at 17–18.5°N lat. This gap overlaps with the trajectory of the subducted MOR.

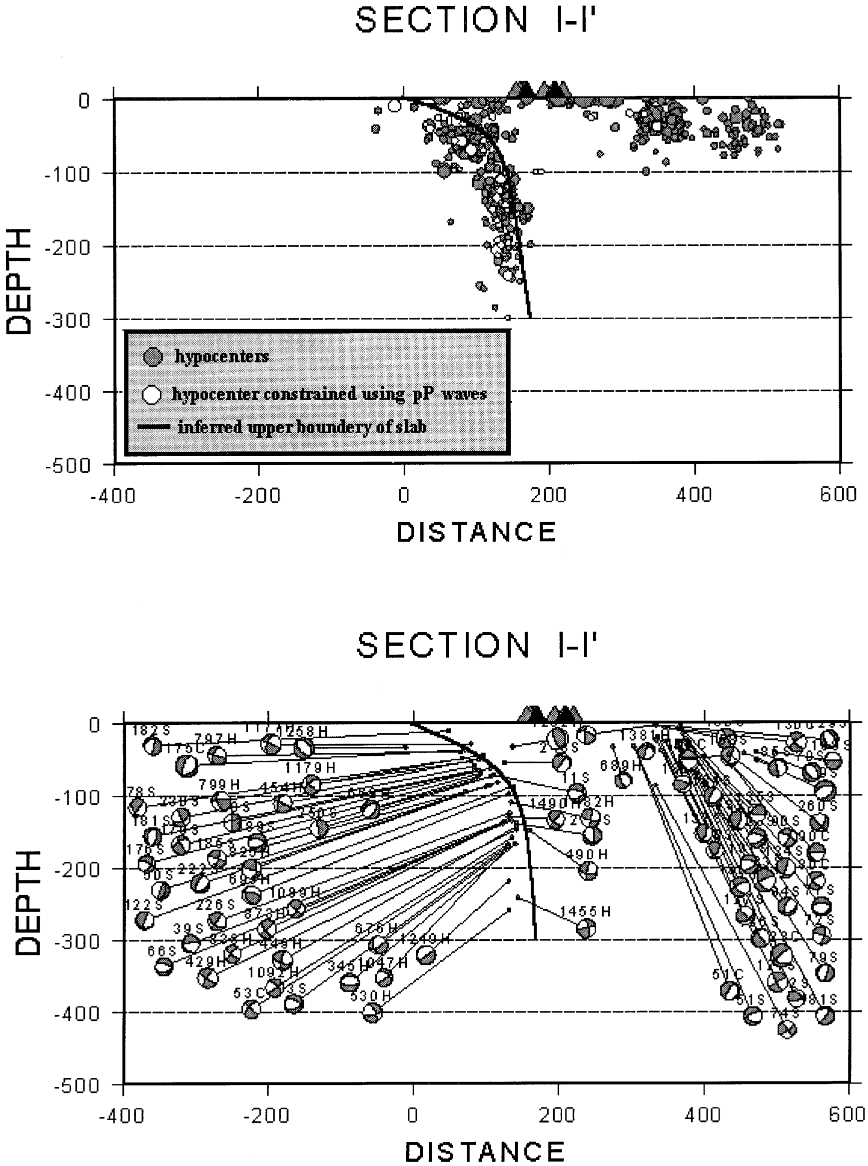

Fig. 16. Cross section along line I–I′ showing vertical distribution of seismicity and focal mechanism solutions. (Descriptions same as Fig. 8).

4.3. Observed features from bathymetric and topographic data

Fig. 19 shows the bathymetry of the study area. The most prominent is the N–S trending Manila Trench found west of Luzon Island. The Manila Trench is a 5 km deep bathymetric feature (Ludwig, 1970) extending from 13 to 21°N lat. (Lewis and Hayes, 1989). From 13 to 14°N lat., it trends northwestward and almost N–S from 14 to 17°N lat. From 17 to 21°N lat., trace of the trench is bent at an area where a buoyant mass seems to be abutting. From 20°N lat., it swerves back to the NW until it terminates north of Luzon in Taiwan, where the northern segment of the Luzon arc is believed to be colliding with the Eurasian plate. Deformed sediments can be found through

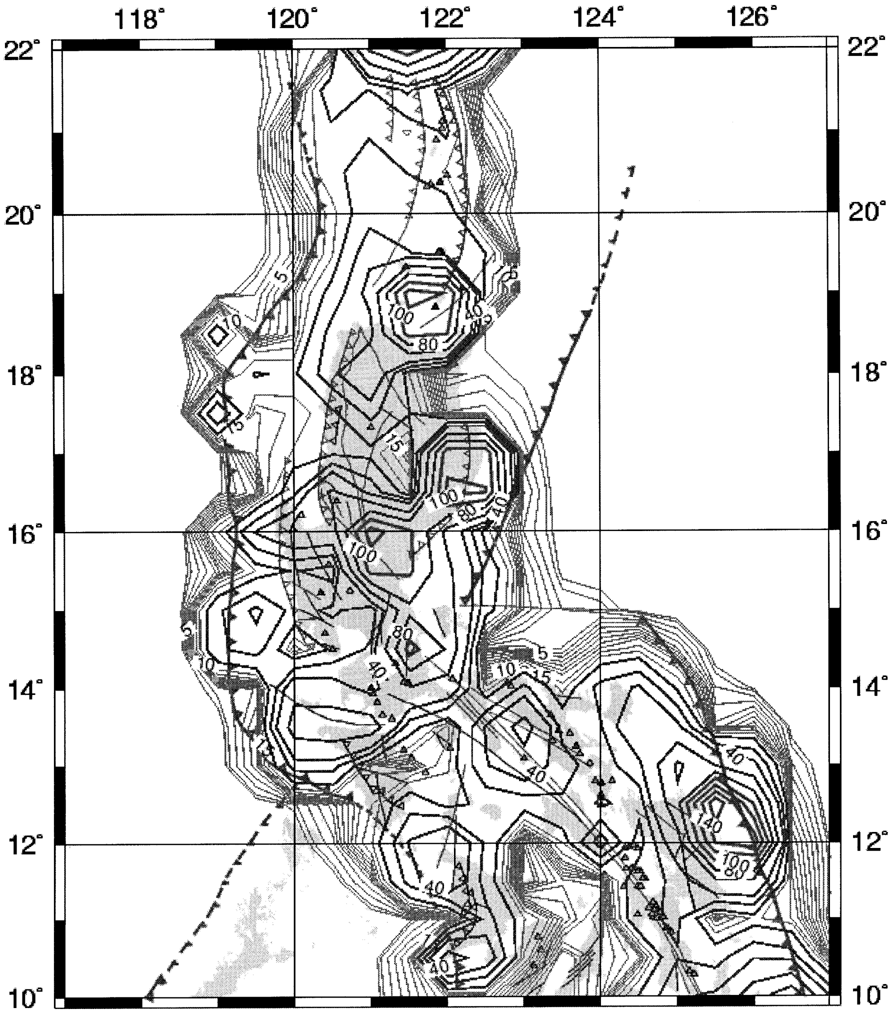

Fig. 17. Map showing the distribution of strain energy released per year from 1619 to 1997 by shallow depth earthquakes (0–65 km) in the northern Luzon region. Contours are in multiples of 1×10^9.

almost the entire stretch of the trench (Hayes and Lewis, 1984). Marine seismic profiles along the trench (Hayes and Lewis, 1984) show that the northern part, from 17 to 20°N lat., dips gently. It has two major sedimentary fore-arc basins called the West Luzon Trough (located south of Lingayen Gulf) and North Luzon Trough (located north of Lingayen Gulf). The West Luzon Trough is 2–3 km deep and is filled with 4.5 km thick sediment (Ludwig, 1970). Four-km of thick sediment is piled up on the North Luzon Trough. In between these two troughs is a 1500 m high, 150 km wide topographic high called Stewart Bank believed to be a piece of a subducted, NE-trending seamount chain traced from 115 to 119°N. This seamount chain called Scarborough Chain was interpreted by earlier writers like Ludwig (1970) and Pautot and Rangin (1989) as part of an extinct MOR that is presently being accreted or subducted beneath the Manila Trench at 16°N lat. This is the same MOR that we are referring to in this study. An E–W normal fault with two km of vertical displacement is seen in marine seismic profile along the southern flank of this topographic high (Lewis and Hayes, 1989).

At the bent part of the trench at 20°N lat., the

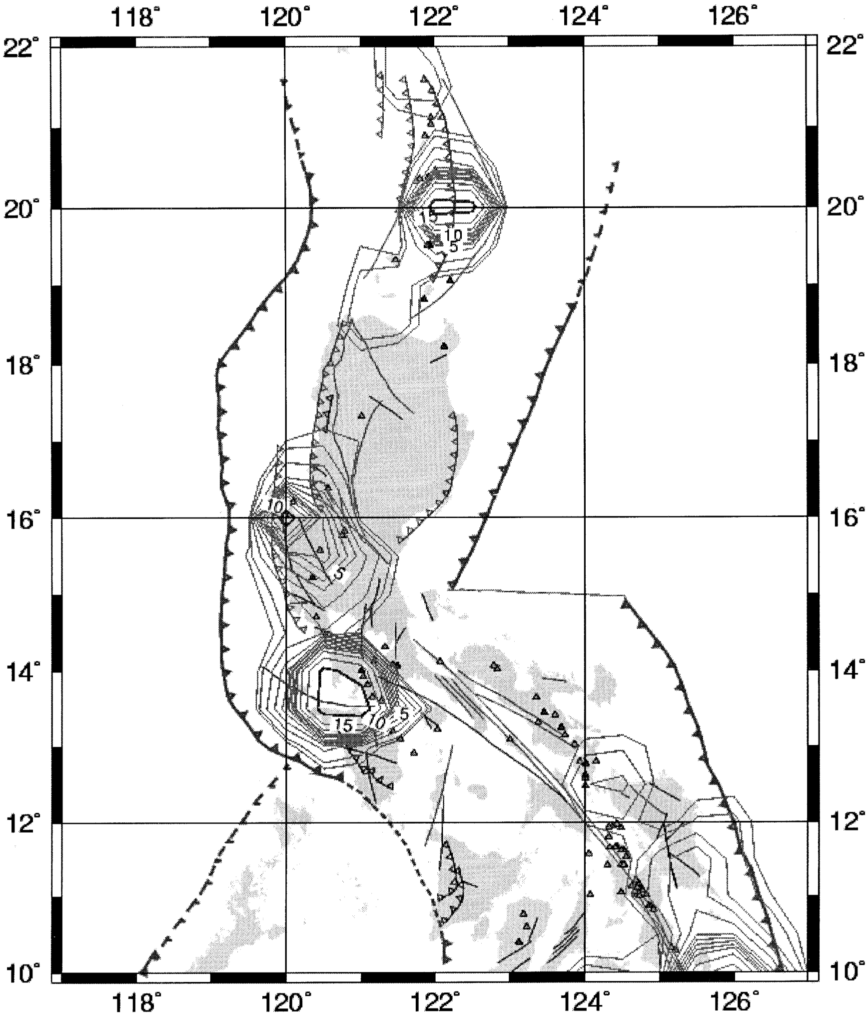

Fig. 18. Map showing the distribution of strain energy released per year from 1619 to 1997 by deep earthquakes (>65 km) in the northern Luzon region. Contours are in multiples of 1×10^9.

seafloor is characterized by the presence of a high-relief bathymetric feature, which is possibly a buoyant oceanic lithosphere that tends to impede the subduction of the Eurasian plate in this segment. Suppe (1988) earlier mentioned that in the western South China Sea, little true oceanic crust was formed. Instead, the continental crust was stretched by block faulting over a wide region giving rise to a number of microcontinental fragments. Meanwhile, geophysical studies made in the 1980s along the South China Sea had identified a magnetic quiet zone correlative to the continental-to-oceanic boundary. Taylor and Hayes (1980) have shown that the mass is a part of a magnetically quiet zone and represents a transition zone between a continental and oceanic zone and characterized by a negative free air gravity anomaly. Hence, it is possible that this bathymetric feature has sufficient buoyancy due to its composition and its resistance to subduction may have caused the segment of the trench line to lag behind at 20°N lat. while the rest of the Luzon block migrated westward. By observing the overall shape of the trench line and the shape and the position of the Luzon block, it would seem to suggest that the latter is dragging the former towards

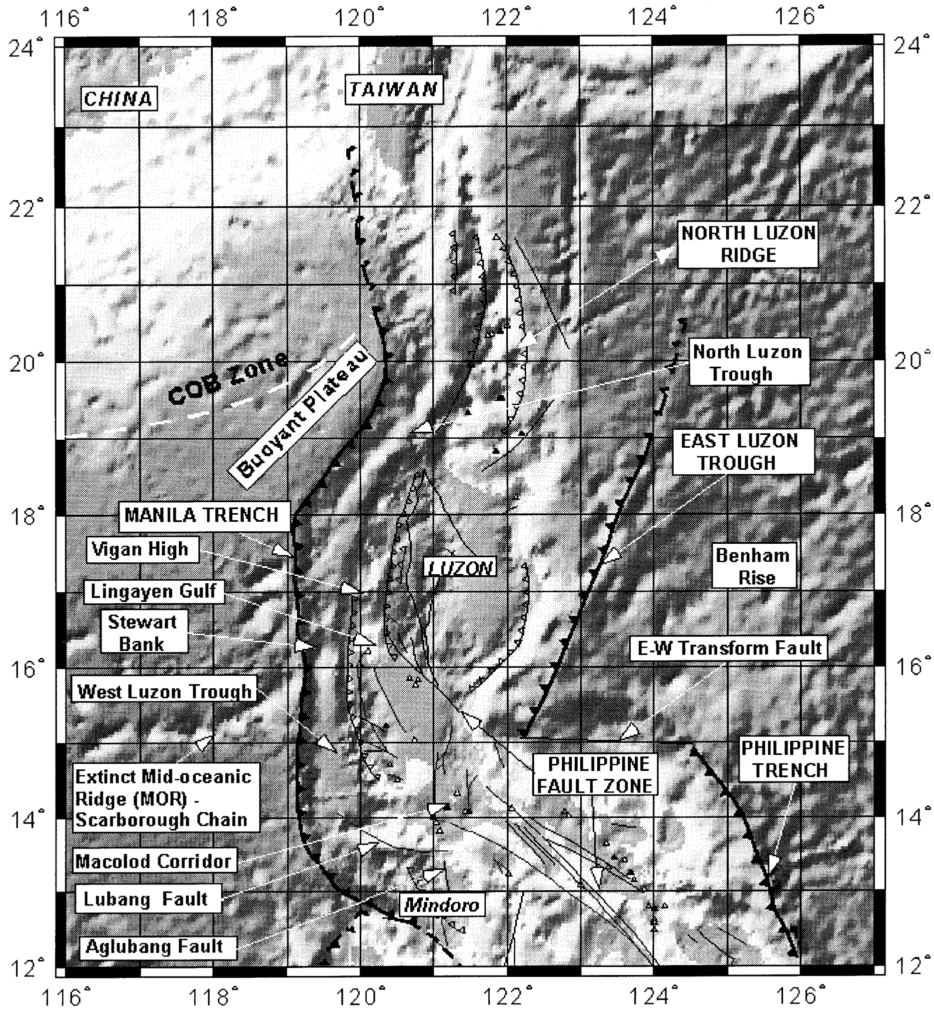

Fig. 19. Map showing the different bathymetric and topographic features in northern Luzon. Digital bathymetric data from the National Geophysics Data Center (NGDC) and digital elevation data from the USGS-EROS Data Center.

the west or WNW while being resisted at the buoyant bathymetric feature at 20°N lat. McGeary et al. (1985) had earlier suggested that a buoyant plateau may cause bends to form or may cause subduction to stop, or slow down, or plate boundaries to reorganize to accommodate continuing convergence.

East of this bend at 20°N lat. is the North Luzon Ridge area, characterized by a series of NE- and NNW-trending bathymetric ridges and troughs that extend into Northern Luzon Island. Bathymetric features indicating the presence of arc-shaped thrust faults have been identified.

In the Mindoro area at 13°N lat. where Manila Trench changes orientation from N–S to NW, the dip of the active seismic slab also steepens to almost vertical. This area is also a zone of active collision that extends southwards to western Panay and where no active subduction appears to be taking place (McCabe et al., 1982). Bathymetric and industry seismic survey results show that the zone south of Mindoro (referred to by earlier writers as the Mindoro Basin or Mindoro Strait) may be described as a pull-apart basin while the area to its southwest is marked by left-lateral strike-slip faults (Suppe, 1988). The strike-slip faults have left-lateral sense of movement and have similar orientation and sense with the NW-trending Philippine fault. The normal faults apparently form pull-apart basins. Marchadier and Rangin (1990) also identified a series of N50°W-trending normal faults having strike-slip components on seismic profiles along the strait where it meets the Manila Trench. These faults could be traced to onshore SW Mindoro.

East of Luzon is the East Luzon Trough, a recognizable 5 km deep, NE-trending bathymetric feature that may be traced from 15 to 18°N lat. (Lewis and Hayes, 1983; Rangin and Pubellier, 1990; Florendo, 1994). Marine seismic profiles show relict subduction zone features that were active in the Oligocene (Lewis and Hayes, 1983). The profiles also show that oceanic crust appears to be dipping westward at 5–10° angles (Lewis and Hayes, 1983). East of the East Luzon Trough is the Benham Rise, a basaltic portion of the west Philippine Sea Plate or probably a thickened oceanic crust that was probably produced by melting anomalies at the spreading ridges (Karig, 1975). He also noted the striking similarity of Benham Rise's shape to the sharp bend in the Luzon coastline, which according to him suggests a genetic relationship. Not much is known about this feature but SEASEE (1985) described this as composed of a series of basement ridges roughly parallel to the East Luzon Trough and appears to be a distinct tectonic feature from the East Luzon Trough-arc system. An E–W transform fault at 15°N lat. connects the East Luzon Trough with the Philippine Trench. Marine seismic profiles show a bathymetric trough at 15.5°N lat., which is a little northward of the fault trace determined from seismicity (Lewis and Hayes, 1983). The offset in the location of the fault and the bathymetric lines was interpreted as possibly due to the northward dip of the fault zone at depth or due to sediments, which have buried the transform fault (Lewis and Hayes, 1983).

4.4. Heatflow and magnetic data

We reviewed and compiled previous survey results and interpretations. Among the previous geophysical studies made on South China Sea basin were heatflow and magnetic measurements. Along the Manila Trench, heatflow values were found to be low (Taylor and Hayes, 1980) while one high heatflow value at the intersection of the MOR with the trench between 15 and 16°N lat. was identified. Anderson (1980) presented several heatflow values that he and other workers compiled along the back of the bent trenchline. At 20°N lat. where the maximum curve of the bend is found, values are 1.18, 1.48, 2.00, 2.38 and 2.46 (values in ucal/cm^2/s). The 2.46 value is the highest value among the readings in the South China Sea basin from 16°N lat. northward and is found right at the back of the bent trenchline. Farther from the sampling site of the 2.46 value, heatflow values are observed to decrease. North of the 2.46 site, the heatflow values are about half while to the south of the 2.46 reading, the heatflow values decreased to 2.0 in the southwest area and 2.38 in the south–southwest.

Meanwhile, the said back trench area from 18 to 20°N lat. was also described as thickly sedimented (Taylor and Hayes, 1980) based on sonobuoy data. They also identified a magnetically quiet zone in the area between the China continental slope and the South China Sea basin and which located immediately west of the bent trenchline area. They interpreted this as a transition zone between continentals to oceanic crust. The zone is also characterized by free-air gravity anomaly that was also identified morphologically in a previous study by Ludwig et al. in 1979 (Taylor and Hayes, 1980).

Two heatflow values are present along the Benham Rise-to-E–W transform fault boundary and their values are 2.19 and 2.12.

5. Discussions

Based on the foregoing results, we now propose an alternative model for the configuration of the subducted slab beneath Manila Trench (Fig. 20). The model suggests the collision and subsequent partial subduction of a buoyant mass at around 20°N lat. that caused the trench line to bend sharply at this latitude. This bent trenchline fronts the North Luzon Ridge where a 200 km wide band of diffuse shallow seismicity is found. As mentioned earlier, focal mechanism solutions of shallow events in this region give diverse patterns of mechanisms such as extensional, compressional and shearing type causing different authors to propose varying interpretations.

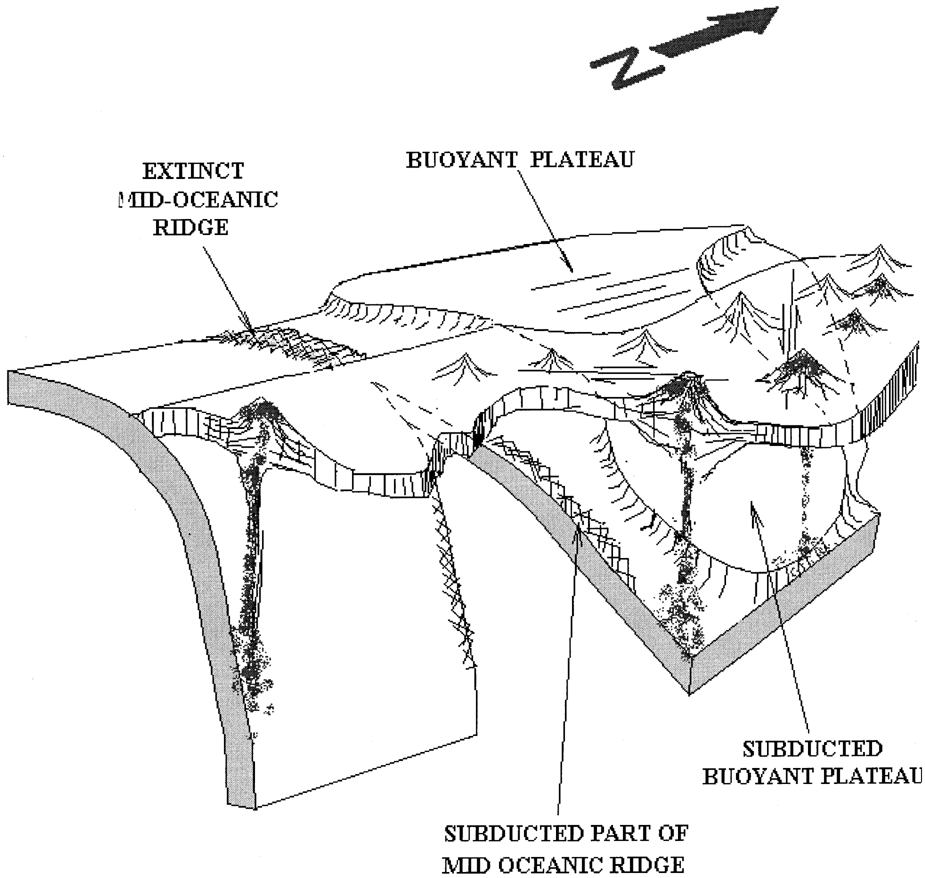

Fig. 20. Proposed model of the subducted slab of the Eurasian plate beneath northern Luzon.

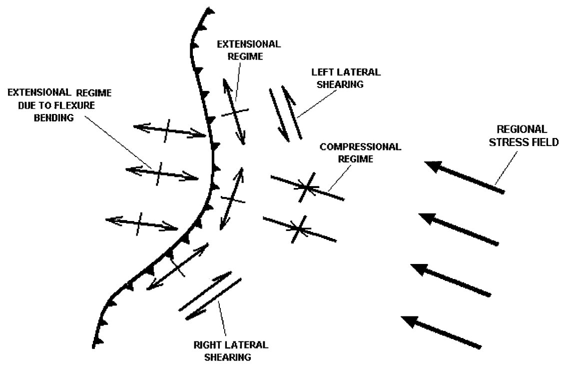

Fig. 21. Hypothetical model showing deformational pattern in the North Luzon Ridge region. The presence of the buoyant lithosphere west of the Manila Trench causes the trench line to bend giving rise to the complex pattern of deformation in the overriding plate. (Model after Bautista, 1996a).

None of the early works so far has explained the origin of the shallow extensional and compressional type of events that accompany strike-slip faulting.

Bautista (1996a) proposed a model (Fig. 21) that is based on a combination of crustal shortening, extension and shearing forces to explain the pattern of focal mechanisms in this region. This is close to the model proposed by Lewis and Hayes (1989) except that it is more elaborate and it explains the possible cause of shallow normal faulting mechanisms. In this model, compressive forces due to plate motion of the Philippine Sea Plate are believed to be directly transmitted in the region north of 18°N lat. as convergence along the East Luzon Trough terminates at around 18°N lat. based on the shoaling of the trench, the absence of deformed sediments and lack of seismicity. The buoyant bathymetric feature is shown to restrict subduction of the Eurasian Plate. With the continued

WNW-directed push induced by the motion of the Philippine Sea Plate and the presence of the bent trench line at 20°N lat., the area fronting the bend becomes more highly compressed compared to the unrestricted zone north and south of this buoyant mass. This causes left-lateral shearing along NW- to NNW-oriented faults in the area north of the bend and an opposite right-lateral shearing along NNE- to NE-oriented faults south of the same bend. In front of the bend, the rocks will be subjected to compressional stresses and deformation will be characterized by thrust faulting. The bending of the trench line will also cause extensional stresses within the overriding plate due to stretching and this could explain the shallow-focus earthquakes within the overriding plate which are characterized by normal faulting mechanisms and whose *T*-axes are roughly parallel to the trenchline. Another possibility is for the formation of pull-apart basins, which are also characterized by normal faulting events. Such is commonly observed along strike-slip zones. These shallow, normal faulting earthquakes discussed in this section are distinct from the normal faulting events, which are caused by flexural bending of the slab during the process of subduction.

We propose that prior to the abutment of this buoyant mass with the trench line, the WVC was already active. With the collision of this mass, the dip of the subducting slab from this buoyant mass became shallower due to buoyancy. Due to the change in dip, the position of the magma generation level shifted towards the east and may have led to the subsequent extinction of the WVC and the shift of active volcanism to the east. This observation is common to other areas where aseismic ridges or buoyant masses subduct. This phenomenon could cause bends or cusps to form, reverse arc polarity, cause slab and volcanic arc segmentation, cause anomalous seismicity, shear off of seamounts at the trench or may even inhibit back arc spreading (Vogt, 1973; Vogt et al., 1976).

At 16°N lat., on the other hand, an extinct MOR is presently subducting beneath the trench. Seismicity is characterized by not so large earthquakes and a gap in intermediate-depth earthquakes (65–300 km depth). Vogt et al. (1976) has proposed that the sites of subducting aseismic ridges are areas of weaknesses. Following this argument and to account for the gap in strain energy release of intermediate-depth earthquakes and the abrupt change in dip from shallow to steep south of 16°N lat., we propose that a tear in the slab is present at this latitude. The said gap in seismicity and strain energy release at around 17°N lat. may be used to infer the trajectory and location of the subducted extinct MOR. The aseismic behavior is probably because the subducted ridge is still hot and is deforming plastically. This is supported by heatflow data, which show high heatflow values along the extinct MOR. Vogt et al. (1976) noted that overall seismicity may be reduced by the subduction of an aseismic ridge or the plate containing the ridges may be hotter and deformation might be in the form of creep. The tear may also explain the cause of the abrupt termination of the eastern chain of volcanoes south of 20°N lat.

Yang et al. (1996) also showed that the geochemical characteristics of the WVC and the EVC are different. The EVC showed a more mantle-enriched geochemical characteristic with which they attributed to a tear at the subducted buoyant mass at 20°N lat. In this study, we propose that the geochemical difference between WVC and EVC is caused by the subduction of the buoyant mass with a composition intermediate to that of a continental and a real oceanic plate at around 20°N. We previously mentioned that this buoyant mass lies near a continental-to-oceanic boundary (Taylor and Hayes, 1980) while Suppe (1988) pointed out that there is little true oceanic crust along the western South China Sea due to the numerous continental fragments stretched out by block faulting over a wide region that gave rise to a number of microcontinental fragments. Therefore, we suggest that the subduction of this nearly continental buoyant mass was able to possibly affect the geochemistry of the EVC.

We also propose a change in the dip when this buoyant mass subducted as observed by seismicity. This change in dip resulted in the extinction of the volcanism associated with the WVC that fronts the buoyant mass at around 20°N lat. McGeary et al. (1985) has proposed that when a buoyant mass subducts and when its subduction angle becomes shallower, a gap in volcanism may result since the slab will not be dipping ideally for magma generation due to the absence of an asthenospheric wedge. Similarly, in Nankai Trough, there appears to be an apparent gap in volcanism probably since the subducting slab is too shallow to form an asthenospheric wedge for magma generation (McGeary et al., 1985). In this study, however, although the WVC became extinct, the asthenospheric wedge did not completely disappear but caused only an eastward shift of the 100 km magma generation level and developed a new chain known as the EVC.

Another buoyant mass east of East Luzon Trough, the Benham Rise, appears to play an equally important role in both present day-tectonics and past geodynamics of Luzon. Being a buoyant, thickened oceanic crust, it appears to be a distinct morphological unit that resists subduction and may have played a crucial role in the shaping the present configuration of northern Luzon and genesis of the E–W Transform Fault at 15°N lat. Although subduction is probably occurring along the East Luzon Trough, the process is possibly hindered by the presence of Benham Rise. Since plate motion of the Philippine Sea plate is faster with respect to the Eurasian plate, subduction along the East Luzon Trough probably occurs very slowly since the Benham Rise may be resistant to subduction. The present configuration of Luzon Island can give us an idea on the geodynamic history it underwent. Its shape would indicate that the whole landmass of the central and northern Luzon is being pushed up towards the Manila Trench by the compressive force induced by the WNW-drifting Philippine Sea plate. While it is being resisted at 20°N lat., the landmass of Luzon is being translated northwestward as a result of a collision with another buoyant landmass, the Benham Rise. Another area where subduction is being resisted is along the Mindoro–Panay area. Here, a microcontinental block has collided with the Mindoro and Panay islands and collision is presently going on.

In studies of configurations of other subduction zones, previous authors (Wu, 1978; Scholz and Campos, 1995) concluded that the trench line of subduction zones due to convergence of two plates tends to migrate in the direction of motion of the plate with higher velocity provided that the subducting plate is stationary or has a lower velocity than the overriding plate. As plate motion calculations have shown that the plate motion value for Eurasian plate is very small as compared to that of the Philippine Sea plate, we can therefore consider that the Eurasian plate is passive and the Luzon landmass is being pushed westward by the Philippine Sea plate. As a result, the trench line west of northern Luzon seems to have been dislocated westward relative to its continuation in the south, i.e. the Negros and the Cotabato Trenches. The present configuration of the Luzon landmass can be discerned by understanding the tectonic significance of the presence of the three buoyant masses — one at the back of the Manila Trench at 20°N lat., another is the Benham Rise east of East Luzon Trough and the third is the microcontinental plate colliding in Mindoro. The North Luzon landmass appears to have been shifted westward with respect to its continuation in southern Luzon.

For the above translation to occur, there must be a structure in Luzon that transforms the differential motion between northern and southern Luzon. There are three strike-slip faults that could be assuming this role: (1) the E–W transform fault at 15°N lat., (2) the NW-trending Philippine Fault and the (3) Sibuyan Sea Fault from Masbate to SW Luzon. The E–W Transform Fault appears to be connected to the NW-trending Luzon segment of the Philippine fault at Dingalan Bay. There is, however, no geological evidence landward to infer that this EW-transform fault cuts continuously through Luzon and connects to the Manila Trench. On the other hand, Sibuyan Sea Fault is being attributed by Bischke et al. (1990) to act as a transform fault for moving the Luzon block to its present position.

Another possible tectonic feature that could be transforming motion between northern and southern Luzon is the Macolod Corridor (Fig. 22). This region exhibits extensional tectonism. Plate extension is manifested by the presence of NE–SW-oriented down-faulting structures. The source of volcanism in this area is problematic since it cannot be related to simple subduction. Volcanoes are located too far from ideal magma generation depth. Some authors have proposed that volcanism may be related to rifting. The cause of rifting is also a controversial issue. For example, Karig (1983) proposed that Macolod Corridor formed as a pull-apart structure as a result of the shearing of the west Luzon boundary fault and the Philippine Fault. The west Luzon boundary fault transverses the western coast of Luzon in Zambales. However, Forster et al. (1990) disagreed and proposed that Macolod Corridor formed due to the shearing of

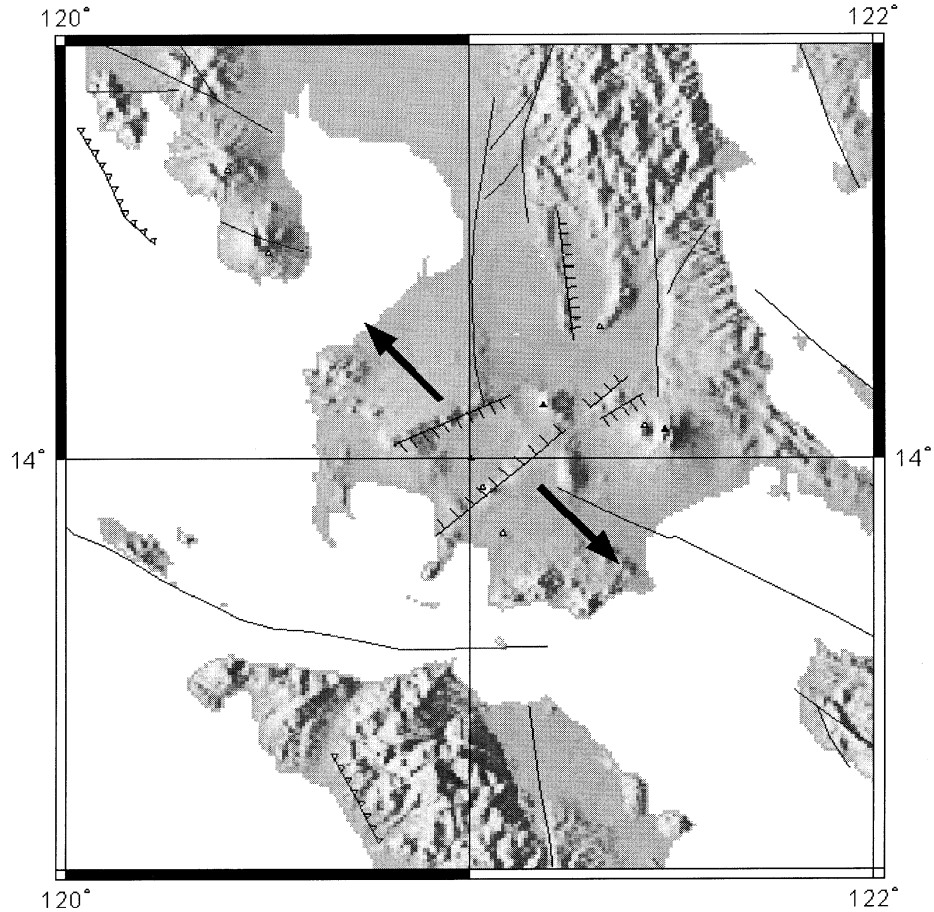

Fig. 22. Map showing the extensional structures in the Macolod Corridor area. The two diverging arrows represent the inferred direction of rifting.

the Manila Trench and Philippine Fault since the western boundary fault became inactive since the early Miocene while the Macolod Corridor was formed younger than Miocene. In this study, we are proposing that the westward motion of the northern Luzon block relative to southern Luzon is causing the extension along the Macolod Corridor.

With regards to the geodynamic timing of events, we agree with some of the dates established by Yang et al. (1996) particularly the time of cessation of volcanism along the WVC and the subsequent initiation of volcanism along the EVC. The cause of the 50 km gap in volcanism between the WVC and EVC is, however, problematic. Yang et al. (1996) attributed the gap to the cessation of subduction when the MOR was accreted to the trenchline. Yang et al. estimated the time of accretion by arguing that the 50 km gap in volcanism in the North Luzon Ridge region was caused by the cessation of subduction along the Manila Trench when the MOR collided. They estimated that subduction of the MOR occurred at 5.4–4.2 Ma. Their oldest dates for volcanoes in the EVC is about 3 Ma based on radiometric dating. Hence, a gap of 1 Ma between the time when the MOR subducted and the onset of volcanism in the EVC is suggested by their study. On the other hand, in this study, we do not agree that a narrow feature like the MOR has enough lithospheric strength to stop for a long period of time the subduction of a long stretch of the slab upon collision at the trenchline. We do not see any evidence like the presence of a large cusp or bend on the trenchline fronting the extinct MOR to suggest that subduction was once restricted. Instead, high relief bathymetric features (the Stewart Bank and the Vigan High) are found right in front of the subducting extinct MOR which we believe are parts or accumulation of decapitated seamounts from the MOR. This indicates that the extinct MOR is weak and easily subducts without much resistance. In this study, we propose that the cause of the 50 km gap in volcanism was due to the collision of a buoyant plateau at 20°N lat. We believe that this feature is broad enough and has sufficient lithospheric strength to initially resist subduction and cause a gap in volcanism in the area between the WVC and EVC. The presence of the large bend in the trenchline at 20°N lat. supports our arguments. We will use the timing determined by Yang et al. (1996) for the collision of the extinct MOR as the timing when the buoyant plateau collided with the trenchline. With regards to the timing of collision of the Benham Rise along the East Luzon Trough, we calculate that collision occurred at 3.2 Ma (Pliocene) based on the total displacement (about 240 km) along the E–W transform fault and the relative plate motion of the Philippine Sea plate with respect to the Eurasian plate. Since we associated rifting in the Macolod Corridor to the westward translation of the northern Luzon block, it also follows that the timing of the rifting began not earlier than Pliocene. This date conforms to the ages of volcanoes in the Macolod Corridor, which are all Quaternary (Forster et al., 1990). This also suggests that collision of a microcontinental block with Mindoro had already taken place on or before this date to prevent the translation of landmasses south of northern Luzon. The date of collision inferred by Karig (1975), which is towards the end of Miocene, agrees with our geodynamic model.

6. Conclusions

A new model of the subducted slab of the Eurasian plate beneath the Manila Trench is proposed in this study. The model suggests the collision and subsequent partial subduction of a buoyant plateau at around 20°N lat. to explain the sharp bend in the trench line, the complicated deformation pattern on the overriding plate fronting the bend and the shallow dip of the subducted slab beneath this zone. The shoaling of the dip of the slab may be due to the buoyancy effect of the subducted part of the buoyant plateau. The change in dip shifted the position of the magma generation level towards the east and may have led to the subsequent extinction of the western chain of volcanic centers and the eastward shift of active volcanism in the region. A tear in the slab is also inferred to be present as evidenced by the observed gap in strain energy release and the abrupt change in slab dip from shallow to steep south of 16°N lat. The gap in seismicity and strain energy release (65–300 km depth) at around 17°N lat. may be used to infer the trajectory and location of the subducted extinct MOR. The aseismic behavior is probably because the subducted ridge is still hot and is deforming plastically. This is supported by heatflow data, which shows high heatflow values along the extinct MOR. The subducted part of the MOR may serve as the weakest zone where this tear could be localized. The tear may also explain the cause of the abrupt termination of the eastern chain of volcanoes south of 18°N lat. The above model, which is a refinement of the model introduced by Yang et al. (1996), is consistent with the observed seismicity and deformation pattern, observed bathymetric features, spatial distribution and geochemical character of volcanism in northern Luzon.

A detailed seismic tomographic study will verify the plausibility of this slab model once a denser high-resolution seismic network is emplaced in northern Luzon while results of future GPS studies will test the deformation model that this study proposes.

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