CHAPTER 3

TECTONICS, SEISMICITY AND VOLCANISM OF LUZON

3.1 The Pacific Plate Region

The dynamic activity of the lithosphere is one of the most influential factors in the evolution of the surface of our planet. The earth's crust is composed of mobile plates of various shapes and sizes, which may be stationary for some time, or colliding, fracturing, spreading or diverging. Large plates are likely to be affected by some of these conditions at the same time.

The Pacific Plate (Fig. 3.1) is one of the most active, with high seismicity and significant volcanism around its periphery. About 80% of the world's active volcanoes as well as a considerable number of the yearly total of earthquakes are located along the Pacific Ring of Fire. The Plate is bordered by smaller crustal blocks: the Nazca and Coco Plates on the east, responsible for eastward subduction and high seismicity along the Chile-Peru-Central America Trench, and the northwestward-moving Philippine Sea Plate on the west, responsible for subduction beneath the Philippines (Fig. 3.2). The Archipelago, which is located at the convergence of the Eurasian and Philippine Sea Plates, forms part of a 4,000-km island arc stretching from the Kuril Basin in the north to Indonesia in the south.

According to Taylor and Hayes (1983) a phase of important crustal evolution affected the tectonic setting of the southwestern Pacific about 20 million years ago. A global plate rearrangement is thought to have taken place in that area during the middle to late Eocene (Appendix A), probably associated with the folding and uplifting of the Himalayan Belt. A fundamental contribution to the understanding of geodynamic processes in the western Pacific region and its present tectonic setting has been made by the studies conducted in recent years. Bathymetric variations, shallow and deep seismicity, vulcanism, seismic reflection profiles, gravimetric anomalies, surficial traces of faults and ocean floor geology have proved to be in good agreement with the plate tectonics scenario in the Philippines.

The double-sided reverse underthrusting of the ocean floor beneath the Country, the island-arc deformation, the associated high seismicity and volcanism are interrelated processes strongly affecting the environment of the Philippines. Due to the concentration of these phenomena in a relatively small part of the southwestern Pacific, the Archipelago is one of the planet's most disaster-prone areas.

3.2 Morpho-tectonic Units of Central and Northern Luzon

The Middle Miocene Philippine Fault, which was initially recognized more than a century ago, marks a strong physiographic contrast, separating the Central Luzon plain from mountainous northern Luzon. Six morpho-tectonic units can be recognized on the mid-northern part of the island (Fig. 3 3).

The N-S trending Cordillera Central, 300 km-long and 90 km wide, is the major tectonic unit; it runs along the western side of Luzon with maximum elevations of about 3,000 m. Acid plutonic rocks form the core of the chain, the outer shell of which consists of shallow- to deep-sea sedimentary rock formations with intercalated volcanics. The uplift of the Central Cordillera batholiths started dur-

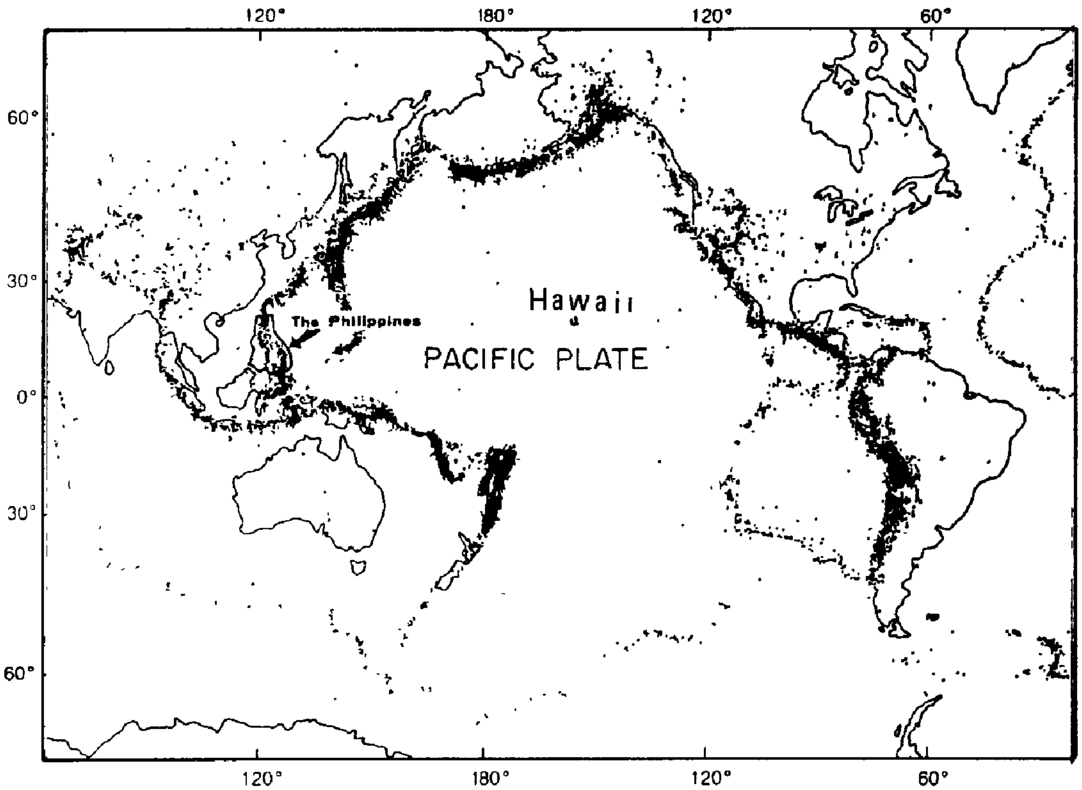

Fig. 3.1 – *Map showing earthquake distribution along the Pacific Plate margin during the period 1961-1967 (USGS). The periphery of the plate is also well known as the Pacific Ring of Fire due to the presence of numerous active volcanoes.*

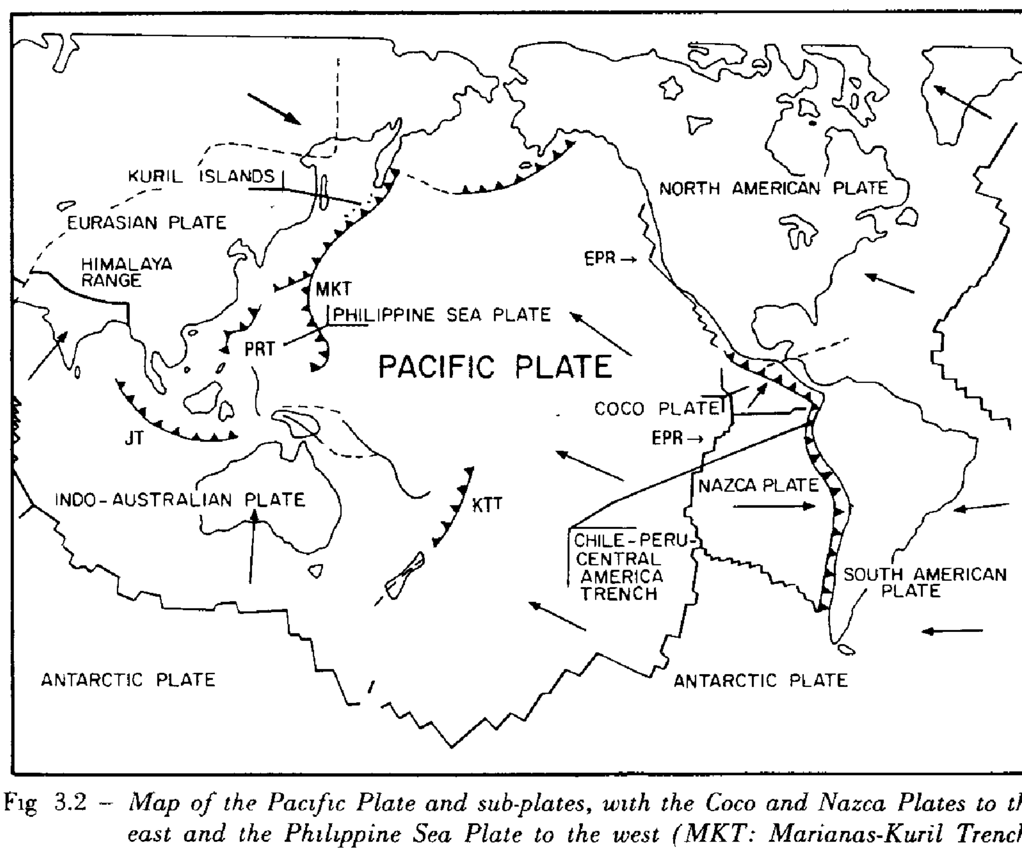

Fig 3.2 – *Map of the Pacific Plate and sub-plates, with the Coco and Nazca Plates to the east and the Philippine Sea Plate to the west (MKT: Marianas-Kuril Trench; PRT: Philippine-Ryukyu Trench, KTT. Kermadec-Tonga Trench, JT: Java Trench, EPR: East Pacific Rise).*

ing the Miocene. The Sierra Madre, which borders the entire eastern side of the island, has an overall length of 600 km and maximum elevations of 1,500 m. This Range, which also consists of acid intrusive bodies, is divided into a northern and a southern segment by the Philippine Fault near Dingalan Bay.

The connection between the southern zone of the Cordillera and the Sierra Madre is marked by the presence of a third morpho-tectonic unit, the Caraballo Mountains. With a Pre-Tertiary basement made of schists and tonalites unconformably overlain by sedimentary, volcanic and pyroclastic rocks, the Caraballo Range is a smaller unit with comparatively lower elevations.

These three units form the catchment basin of the fourth unit in Luzon, the N-S oriented Cagayan River Valley, which is the second largest expanse of flatland in the Philippines. The fault-bounded Cagayan archipelagic basin, 200 km long and over 50 km wide, is almost completely surrounded by these mountains, except on the northern side, and mainly consists of Oligocene to Quaternary clastic sediments.

The 200 km-long, 80 km-wide Central Plain (fifth unit) stretching from the Lingayen Gulf to Manila Bay is a N-S oriented depression forming the largest area of flatlands in the Philippines. Bounded to the northeast by the Philippine Fault and to the west by the Zambales Range, the Central Plain depression was filled with loose clastic sediments during Tertiary and Quaternary times. According to Bachman et al. (1983) a sedimentary sequence up to 14 km thick was identified through multichannel seismic reflection in the center of the Plain. Surficial deposits of sand along riverbanks, due to lahars (mudflows) deposited during the Quaternary, were recognized after the 1991 Mt. Pinatubo eruption. Isolated Quaternary volcanoes interrupt the otherwise unrelieved monotony of the plain; Mount Arayat (1,030 m), the most prominent item of relief midway between Manila and the Gulf of Lingayen, is one such example.

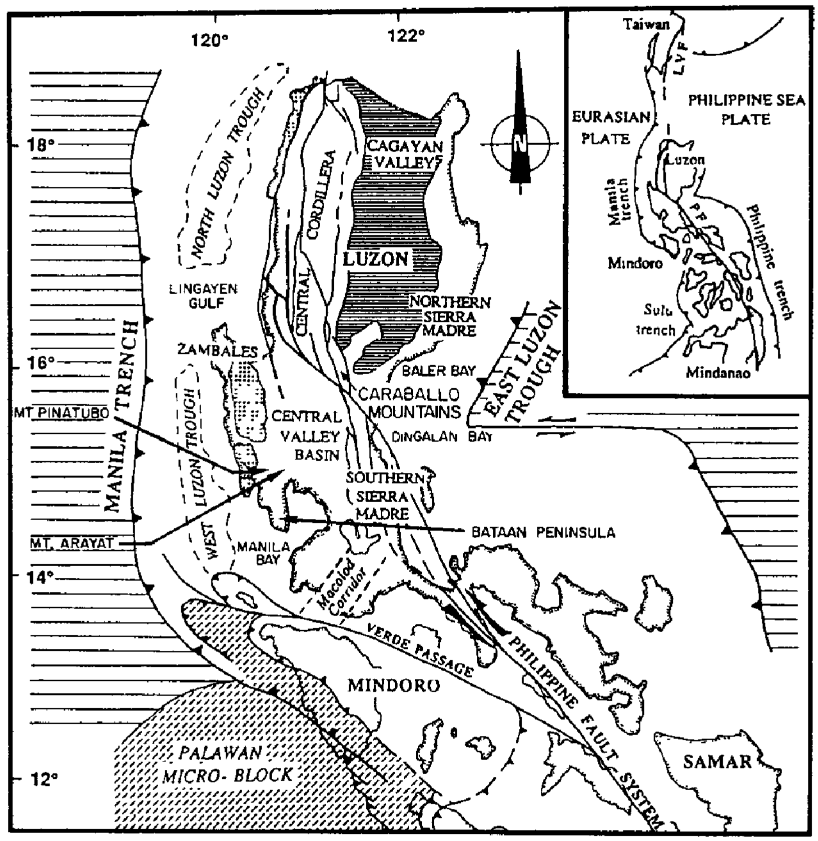

Fig. 3.3 – *Physiographic and tectonic features of Luzon Island (Pinet et al., 1990).*

West of the Central Plain lies the Zambales Mountain Range, the sixth unit, which extends southwards from the Lingayen Gulf for about 150 km. The range is composed of Tertiary ophiolitic rocks and its southeastern end is in contact with a sequence of Quaternary volcanoes known as the Bataan Orogen. Of the 27 vents forming the lineament, the most famous is Mt. Pinatubo, with its peak rising to 1, 732 m before the collapse of the crater after the 1991 eruption (Chapter 8).

3.3 Tectonic setting of Luzon

3.3.1 Lineaments and bathymetry

Luzon's major tectonic lineaments are the double-sided subduction due to the convergence of the Eurasian and Philippine Sea Plates and the horizontal slip motion along the Philippine Fault. Most researchers consider the left-lateral strike-slip motion along this several hundred km-long lineament to be the mechanism which accommodates part of the crustal shortening induced by the reverse polarity underthrusting of the ocean floor beneath the island. Relevant to this dynamic framework (Lewis & Hayes, 1983) are major sea-floor topographic features of the island arc (Fig. 3.4):

a) the 5,000 to 6,000 m deep Manila and Philippine Trenches located to the west and east of the Archipelago, respectively;

b) the flat-floored depression known as the East Luzon Trough;

c) the massive, basaltic Benham Rise, a topographic high, with a depth range of 2000-3,000 m locally ascending to a few dozen meters below sea level at Benham Bank, and

d) the South China Sea Plate west of the Archipelago.

The shape of the Philippine Island Arc has most probably been influenced by the presence of Benham Rise, which is a thickened portion of the Philippine Sea Plate oceanic crust. According to Ringenbach et al. (1991) the similarity of the shape of Benham Rise to the sharp bend in the Luzon coastline suggests that the resistance of the basaltic sea floor to subduction may be the reason for the bending of the Philippine Fault and the tangential shape of its splays.

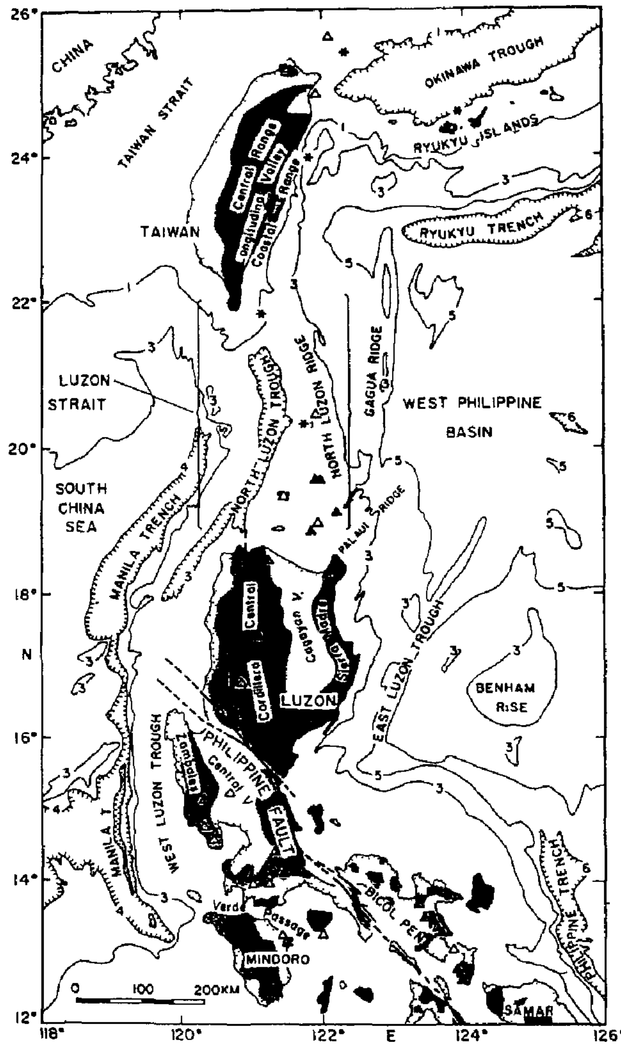

Fig. 3.4 – *Bathymetry of the Philippine Archipelago in thousands of meters (Hamburger et al., 1983). Reprinted by permisssion of the American Geophysical Union.*

3.3.2 Tectonics

Convergence of plates, the eastward subduction of the South China Sea Plate along the Manila Trench and the westward subduction of the Philippine Sea Plate along the Philippine-East Luzon Trench and, finally, the Philippine Fault are the most important tectonic elements of the Archipelago (Fig. 3.3). The Philippine Fault, a 1,300 km-long active lineament with left-lateral strike-slip motion, has played an important role since the start of the subduction.

With its seismicity, marked ground rupture features and evident morphologic contrasts, this fault, through a considerable regional deformation, absorbs part of the crustal shortening induced by the converging plates. The complex dynamics due to opposite trending subductions and the horizontal-slip along the Philippine Fault, subject subsurface stress fields to a continuous change in equilibrium, which results in countless minor tremors and frequent medium to strong earthquakes.

At the southern margin of the Caraballo Mountains, near Rizal City, the Philippine Fault splits into a number of northwestern then northern trending splays (Fig. 3.5), with a typical horse-tail pattern.

Due to this branchlike pattern of faults, the Central Cordillera is divided into a number of N-S trending structural units limited by the Coastal Thrust, the Pugo Fault, the Tuba and Abra River

Faults and the Digdig Fault. Philippine Fault splays are also interconnected by some transverse faults as for example the San Juan-Tebbo Lineament.

According to Pinet et al. (1990) and Ringenbach et al. (1992) the first Middle-Miocene movements along the Philippine Fault in Western Luzon were accommodated by strike-slip motion along the Abra River Fault. The Digdig Fault, which is connected to the Abra Fault by a NW trending segment near Baguio (Fig. 3.5), played a major role in the July 1990 earthquake.

In general, the division of the Philippine Fault into a number of subparallel lineaments suggests that strike-slip motion might have been channeled through different splays during Luzon's tectonic evolution. The core of the Cordillera Central (made of deep rooted batholiths) most probably reacted rigidly to the movement of the different blocks in the area, thus generating the splays as a sort of multiple-choice solution to the complex stress field.

The intricate fault pattern, which is well identified in Baguio-Lingayen Gulf region, is responsible for the local tectonic style and the destructive effects of the July 1990 and previous strong earthquakes.

Slip vectors of the Philippine Sea Plate region (Fig. 3.6) are NW oriented, while the motion of the South China Sea Plate is considered to be N to NE oriented.

Barrier et al. (1991) evaluate the northwestward displacement of the Philippine Sea Plate at 7.4 cm/year, while a slower rate of 2-3 cm/year is proposed by other researchers for the NE motion of the South China Sea plate. Since for the Philippine Fault a horizontal displacement rate of 2-3 cm year and an age of 2 to 4 million years are proposed, the overall displacement is estimated at between 40 and 120 km.

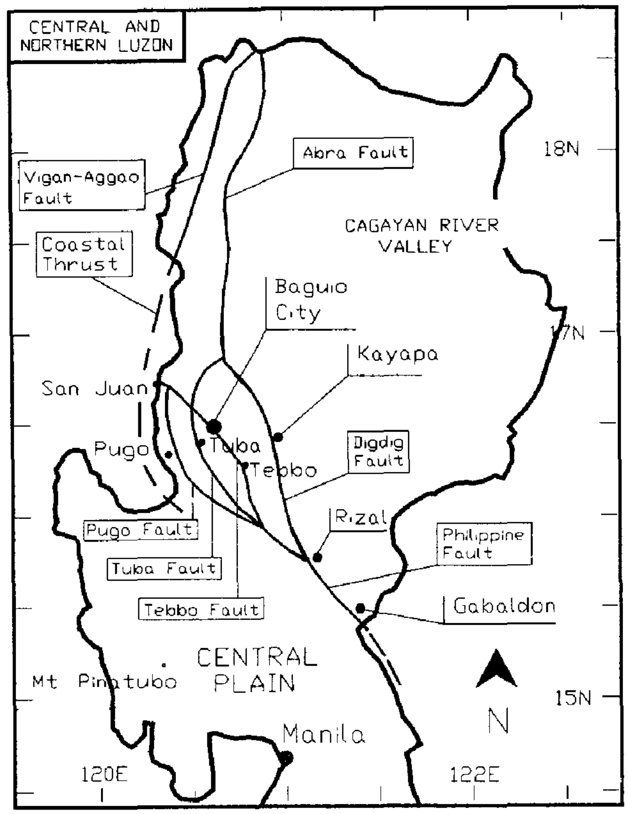

Fig. 3.5 – *Philippine Fault and Splays in Luzon.*

According to Seno (personal communication, October 1991, cited by Ringenbach, 1992) the crustal shortening, due to the convergence of Philippine and Eurasian plates, varies from 9.2 cm/year in Mindanao to 8 cm/year in Luzon. This considerable crustal reduction is thought to be partly compensated by the horizontal slip motion along the Philippine Fault and its splays, and partly converted into the uplift of the Central Cordillera.

By comparison, western and eastern parts of the Mid-Atlantic Ridge move apart at a speed of about one centimeter per year (Bonatti, 1994).

The uplift of the Central Cordillera is evident from the marked contrasts in elevation, youthful landform features, deeply incised steep-sided valleys, downcutting of streams and very active erosion. The rate of regional uplift during the Pleistocene is estimated at 1.5 mm/year by Ringenbach (1992), while the velocity of the convergence between the Philippine and Eurasian plates at Luzon's level is generally thought to be some 8 cm/year. About a quarter of it (2 cm/year or 2 m every 100 years) is compensated by the motion along the Philippine Fault during large earthquakes. Thus the July 16, 1990 quake with its maximum horizontal displacement of 6.2 m may have compensated about 310 years of cumulative crustal shortening. This timespan is quite close to the time elapsed since the previous strong earthquake which shook the same area in 1645 (SEASEE catalogue, 1985), i.e. 345 years before the Luzon quake (Fig. 4.9).

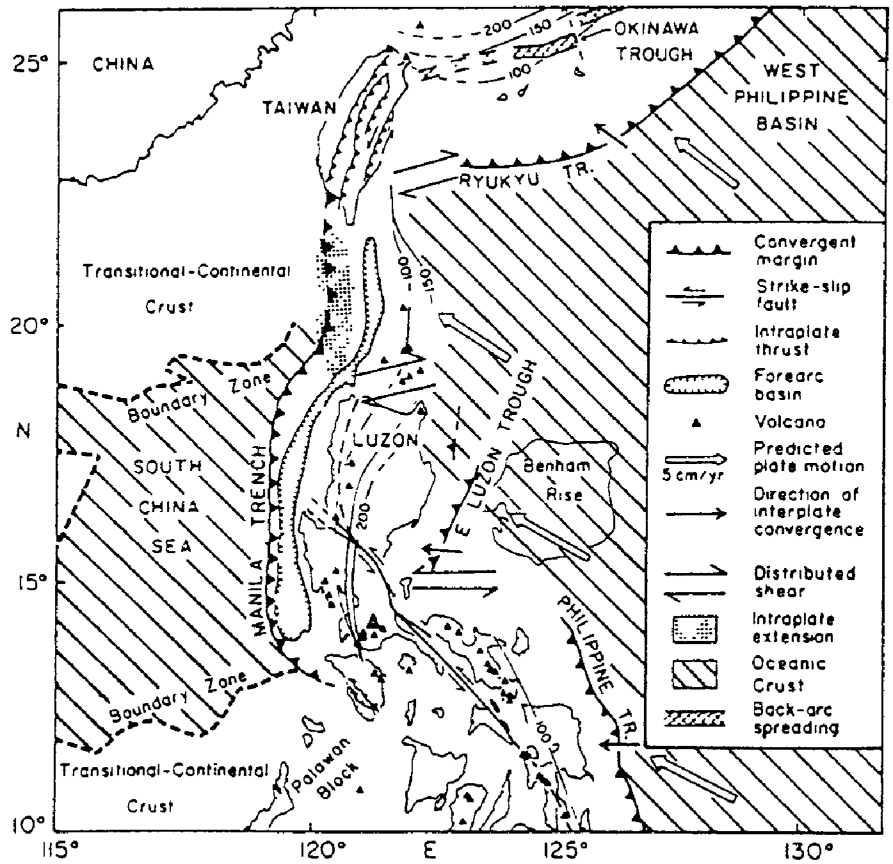

Fig. 3.6 – *Tectonic framework of the northern Philippine Island Arc (Hamburger et al., 1983) taken from Seno (1977); continent-ocean boundary zone from Taylor (1982), Okinawa Through from Lee et al. (1980). Reprinted by permission of the American Geophysical Union*

3.4 Geologic history

The description of Luzon geology (Fig. 3.7) is limited to the northern and central part of the island. since the remaining areas were only marginally affected by the events described in this book.

The beginning of the orogenesis, Late Eocene - Late Oligocene, was marked by the uplift of granodioritic bodies forming the core of the Cordillera. which was still beneath the sea at that time, though there were some emerging volcanic islands. Due to bathymetric variations of the sea-floor, deep and shallow marine sediments were deposited. The sequence rests unconformably on an ophiolitic Cretaceous - Middle Miocene basement, made of basalts, schists and cherts. The Sierra Madre Range, which is similarly made of granodioritic bodies. is considered to be of Eocene-Oligocene age.

During Late Oligocene to Early Miocene times the major uplift and the emergence of the Cordillera batholith occurred, accompanied by shallow-water sedimentation on its flanks and voluminous volcanic activity. Fracturing, folding and faulting of sediments forming the outer cover of batholiths is associated with this highly dynamic stage. The metamorphosed and intensely deformed rock formations, intruded by the pluton, originally formed the shell within which the magma slowly cooled and crystallized. During the orogenic stage this shattered shell became the ideal structure for future porphyry copper mineralizations.

The tectonic activity continued in Middle Miocene to Holocene times while conglomerates, sandstones and pelites with interbedded volcanics were deposited. Surrounded from west to south and east by the Cordillera Central, the Caraballo Mountains and the Sierra Madre lies the Cagayan River Val-

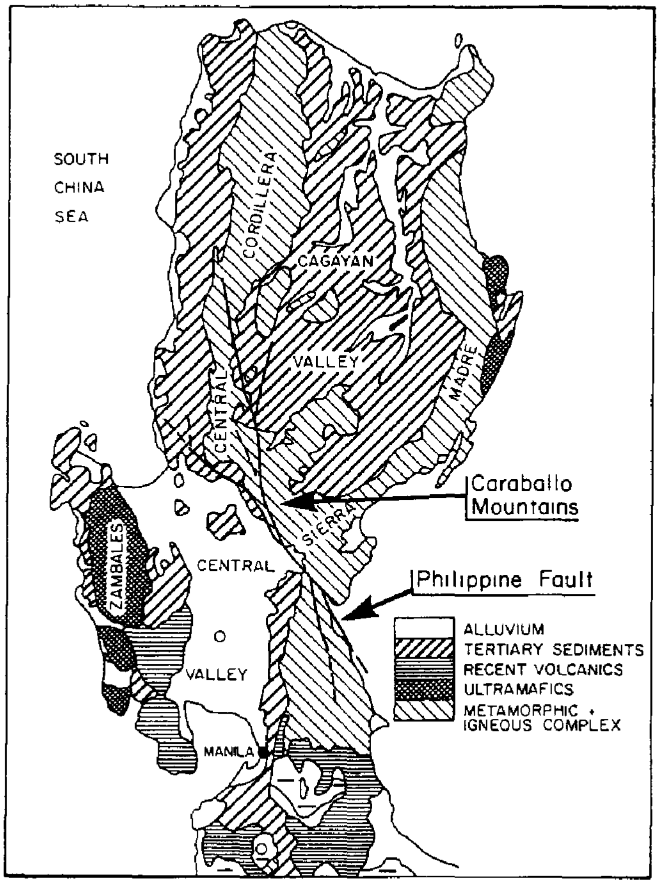

Fig. 3.7 – *Geologic reference map of Luzon and the location of the major morpho-tectonic units · Central Cordillera, Sierra Madre, Cagayan Valley, Caraballo Mountains, Central Valley and Zambales Range (Geary et al., 1983). Reprinted by permission of the American Geophysical Union.*

ley, a tectonic depression with a pre-Oligocene metamorphosed volcanic basement, filled with clastic sediments between the Oligocene and the Quaternary. The Caraballo Mountains, which rest on a pre-Cretaceous basement of schists and tonalites mainly consist of pyroclastic, volcanic and sedimentary rock formations ranging in age from Cretaceous to Eocene.

The Philippine Fault separates this part of Luzon from the Central Valley, a flat floored plain which was filled with loose sediments during the Tertiary and the Quaternary. Lastly, the Zambales Range, the most westerly unit in Central Luzon, is composed of a north trending assemblage of mafic-ultramafic rocks and basaltic to rhyodacitic volcanics. The emplacement of the Zambales ophiolite (Geary and Kay, 1983) took place during Middle to Late Oligocene times and is considered to mark the beginning of subduction along the Manila Trench.

3.5 Seismicity

Due to the active motion of plates in the archipelago numerous earthquakes are generated thus making the Philippines an area with a marked seismic hazard. The regional pattern of the seismicity shows a striking relationship with subduction dynamics. the inland and marine fault systems, major morpho-tectonic units in Luzon, and geophysical data. Clustering of seismicity. depth of hypocenters and focal mechanisms are also in agreement with this scenario.

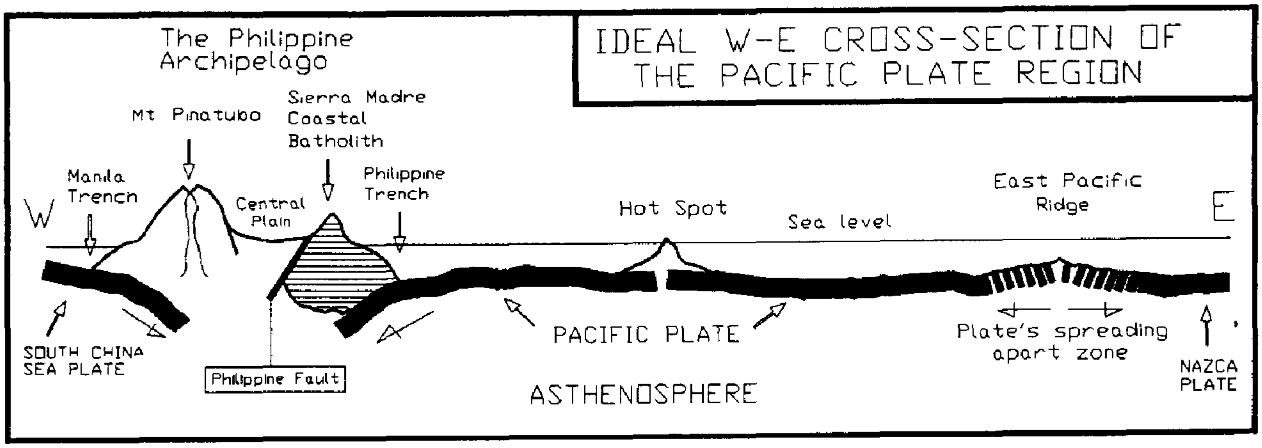

Fig 3.8 – *Idealized cross-section of the Pacific Plate from the Philippine Archipelago to Nazca Plate, showing the three types of volcanism: subduction zones (Pinatubo), hot spots (Hawaii) and oceanic ridges (East Pacific Rise).*

Numerous and often large earthquakes (SEASEE catalogue, 1985) hit the Philippines during the past four hundred years. The geologic history of Luzon suggests, however, that seismicity must have been consistent also during the most critical phases of the uplift of the Cordillera and certainly during the Quaternary.

According to Su (1988), 18 earthquake generators (source zones) are responsible for the high seismicity of the Philippines (Chapter 4). An important aspect of the converging motion of plates is the role of Benioff zones since numerous earthquake foci cluster along these dipping planes extending to a depth of over 200 km (Hamburger et al., 1983). A number of major earthquakes in the Archipelago are also located along the Philippine Fault.

3.6 Volcanism

3.6.1 Volcanic activity within the Pacific Plate

The Pacific Plate is well known for being surrounded by a Ring of Fire, which includes most of the world's active volcanoes; some activity, however, takes place within the plate as well. In a broad sense two basic conditions can occur: where the plate is thinned or is already spreading apart, hot basaltic magma quietly rises from the asthenosphere; in contrast, plate collision or underthrusting of one plate under another is generally associated with acid and explosive volcanism.

The Pacific Plate Region can be broadly divided into two parts by a line connecting the Kamchatka Peninsula to New Zealand through the Hawaii. The eastern portion (Figs. 3.1 and 3.2) is an unvaried huge depression about 5,000 meters deep, bounded to the E by the East-Pacific Ridge and marked by numerous parallel fractures. Along the thousands of kilometers of ridge the plate's margins diverge and crustal spreading takes place with the creation of new lithosphere as a consequence of the rise of molten basalt.

The western portion of the Plate, between Hawaii and the Philippines, is marked by submerged ridges, trenches, subduction zones and deep flat-floored areas. These morpho-structural variations of the ocean floor are indicative both of more complex tectonics in the Western Pacific Region and of the intricate dynamics of the asthenosphere underneath. Examples of this greater complexity are the basaltic magma being quietly extruded by volcanoes over hot spots along the Hawaiian Ridge, the explosive volcanism along the western margin of the Plate and the subduction of the ocean floor along the Marianas-Japan-Kuril Trench, the Philippine and Ryukyu Trenches and the Kermadek-Tonga Trench (Fig. 3.2)

Three types of volcanism (Fig. 3.8) are associated with the Pacific Plate dynamics: mantle plumes or hot spots (Hawaii); creation of new lithosphere where plates spread apart (East Pacific Ridge); and explosive activity where plates converge (Pacific and Eurasia collision zone).

In the first two cases non-explosive behavior and fluid basaltic magma characterize the activity. The volcanism along the Hawaiian Ridge occurs as mantle plumes or hot spots and is attributable to the presence of vents over plumes of heat rising through the upper mantle. Mostly thermal energy is released through this type of volcanism. A similar molten-rock rise, but related to a different tectonic setting occurs along the East Pacific Ridge, where the plate is separating after breaking apart. A quiet non-explosive upwelling of basaltic lavas from the asthenosphere takes place over several thousand kilometers along this fracture. This type corresponds to volcanism along mid-oceanic ridges and contributes greatly to the formation of new lithosphere.

By contrast, the third type of volcanism, widely represented in the Philippines, is characterized by explosive activity and occurs along converging plate boundaries. Along collision zones numerous earthquakes cluster and also Ocean floor is consumed through subduction and melting. As a result of this process the acid magma, which is generated at some depth, can intrude through the fissured zone into magmatic chambers near the surface during critical plate-motion episodes and produce the explosive type of volcanism. Most of the energy in this case is released as explosive kinetic energy.

In general a very different geological environment and diverse dynamics mark the evolution along the Pacific Plate margins, compared to other plate zones. Activity along plate boundary and subduction zones is mainly explosive, since the composition of the magma is granitic and thus has a degree of viscosity which favors explosive behavior. Besides, the rate of rise of viscous acid magmas is lower, compared to basaltic lavas, and so this type of molten rock can block chimney channels more easily. Once this happens gas pressure increases, the system reaches a critical condition and an explosive event takes place. The trigger of the explosion is often the compression of the magmatic chamber and underlying fractures, a consequence of the crustal movements with which earthquakes are associated. Explosive eruptions, however, can also take place in a mantle plume type of volcano if seawater penetrates the volcanic chamber, thus inducing a phreatomagmatic explosion, such as, for instance, the 1924 Kilauea eruption in Hawaii.

3.6.2 The volcanic environment of Mount Pinatubo

The explosive eruption of Mt. Pinatubo in 1991 belongs to the third volcanogenic environment: the volcano is located between the Manila Trench and the Philippine Fault (about 90 km west of it) which ruptured in July 1990. The Luzon earthquake was indirectly responsible for the awakening of the dormant Pinatubo: the actual triggering factor of the June 12, 1991 eruption was the subsurface block rearrangement which started after the 1990 quake and went on for months. The long reassemblage stage which took place during the aftershock period, modified the pre-existing equilibrium and affected the rock basement of the Central Valley, thus favoring magmatic injections into the Mt. Pinatubo chamber and the consequent awakening of the volcano. Mount Pinatubo is part of a sequence of vents parallel to the Manila Trench subduction zone and named the Bataan Lineament (Wolfe and Self, 1983).

The active and dangerous Taal Volcano, 60 km south of Manila, also warmed up during the beginning of 1991, as a result of the Luzon earthquake, and the central island in the caldera lake was later evacuated. Most likely due to the greater distance from the ground rupture zone and the related attenuation of subsurface movements in the area, the Taal volcanic chamber was marginally affected. After a few months of warming up and smoke emissions the danger gradually subsided. It is worthwhile to recall that in historic times ash from Taal eruptions reached Manila causing huge destruction (Hargrove, 1991). Recent news from PHIVOLCS confirm that Taal resumed activity again during 1994.