Crustal thickening in an active margin setting (Philippines): The whys and the hows

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A synthesis of crustal thickness estimates was made recently utilizing available field, geochemical, seismicity, shear wave velocity and gravity data in the Philippines. The results show that a significant portion of the Philippine archipelago is generally characterized by crust with a thickness of around 25 to 30 kilometers. However, two zones, which are made up of a thicker crust (from 30 to 65 km) have also been delineated. The Luzon Central Cordillera region is characterized by thick crust. Another belt of thickened crust is observed in the Bicol-Negros-Panay-Central Mindanao region. This paper examines the interplay of tectonic and magmatic processes and their role in modifying Philippine arc crust. The processes, which could account for the observed crustal thicknesses, are presented. The contributions of magmatic arcs as compared to the contribution of the emplacement and accretion of ophiolite complexes to crustal thickness are also discussed.

Introduction

The evolution of continental crust has been a problem of long standing interest to various geoscientists. In studies, which try to address the question of crustal growth, the addition of materials to the crust is attributed to several mechanisms. Juvenile crustal material is produced in island arcs and oceanic plateaus (Rudnick, 1995; Condie, 1998). These features eventually collide with and become sutured to continents thereby leading to the growth of continental crust. Contributions from magmatic underplating and overplating (Wilson, 1994; Rapp and Watson, 1995) as well as from the emplacement of ophiolites have also been recognized (Dewey and Windley, 1981). Processes such as arc magmatism, oceanic plateau accretion, intraplate volcanism, crustal underplating, accretion of ophiolites, sediment subduction, tectonic erosion and delamination may operate singly or in combination to contribute to crustal growth. In the Philippines, relatively few studies have looked closely into the problem of crustal growth. Crustal thickness estimates are limited to specific areas and are mostly derived from geochemical, seismicity, focal mechanism and gravity data (Bautista et al., 2001; Barretto et al., 2000). A recent compilation of geochemical, seismicity and gravity data to estimate crustal thickness in various parts of the Philippines show that a significant portion of the Philippine archipelago is characterized by crust with thicknesses ranging from 15 to 30 km. However, areas underlain by a thicker crust (from 30 to 65 km) have also been recognized from a recent compilation (Dimalanta & Yumul, 2003).

The complex geodynamic and tectonic setting of the Philippines necessitates an understanding of the role of tectonic and magmatic processes to crustal growth. The following questions need to be addressed. How much of the observed crustal thickening in some parts of the Philippines could be attributed to subduction processes? What is the effect of collision events on crustal growth? What other processes contribute to the thickened crust? This paper forwards an explanation on the different mechanisms and processes, which can account for the thickness of crust in the Philippines. This, hopefully, can help in our understanding of how crustal growth processes occur in an active margin setting.

Tectonic setting of the Philippine archipelago

The convergence of the Sundaland-Eurasian margin with the Philippine Sea Plate resulted in the different features that comprise the Philippine archipelago. These include magmatic arcs, subduction zones, collision zones and marginal basins. Based on seismicity and volcanism, the Philippine archipelago is divided into the seismically active Philippine Mobile Belt and the aseismic Palawan microcontinental block. The Philippines is bounded on the east by the westward-dipping East Luzon Trough — Philippine Trench along which the Philippine Sea Plate is obliquely subducting. NUVEL-1 measurements show that the Philippine Sea Plate, in the region northeast of Luzon, is moving northwest at a rate of approximately 7 cm per year. But southeast of Mindanao, the plate motion increases to ~ 9 cm per year (Bautista et al., 2001). Several marginal basins are found on the western portion of the archipelago. These include the South China Sea, Sulu Sea and Celebes Sea basins, which are subducting along the east-dipping Manila-Negros-Sulu-Cotabato trenches (Figure 1). The different ophiolite complexes, which can be found in various parts of the country, are believed to have originated from the marginal basins or their ancient counterparts surrounding the archipelago. The magmatic arcs associated with the subduction zones as well as the different ophiolite complexes are discussed in the succeeding sections. Excess stress resulting from the subduction of oceanic crusts along these subduction zones is absorbed by the Philippine Fault Zone and other related fault structures (Fitch, 1972).

Magmatic arcs

The Philippine island arc is built on oceanic crust, which had been modified by several episodes of magmatism (Figure 2a). Arc magmatic activity that characterized the evolution of the Philippines served to thicken the crust of this island arc system. The earliest volcanic activity recorded in arc volcanic rocks from the Philippine Mobile Belt commenced during the Cretaceous time (Wolfe, 1981; Deschamps and Lallemant, 2002). A record of this volcanic activity is preserved in arc rocks from Cebu, which yielded a late Early Cretaceous age (~108±1 Ma) (Walther et al., 1981). Evidence for this activity is also preserved in Catanuanes Island where an andesite sample gave a K-Ar age of 121.09±2.61 Ma (David, 1994). There is also a record of magmatism preserved in the Luzon Central Cordilleran region during the Late Cretaceous period (K-Ar dating of schist sample: 82.6±20.6 m.y.) (Wolfe, 1981). Ringenbach (1992) has also reported an Upper Cretaceous age (Cam-
A Late Cretaceous volcanic arc sequence was mapped in the Caramoan region in southeastern Luzon. 40Ar-39Ar dating of amphibole separates from a basaltic lava flow sample yielded an age of 91.1±0.5 Ma (David et al., 1997). Cretaceous magmatism is also recorded in Rapu-rapu where diorite intruding the ultramafic rocks yielded a 77.1±4.6 Ma age (David et al., 1996). Further south of that, three magmatic episodes have been recognized in the Southeastern Luzon volcanic arc. The oldest magmatism is recorded at 68.6 Ma in Balatan, which is in the central portion of the Southeastern Luzon volcanic arc. This age was based on the result of a K-Ar dating on a dioritic sample (Japan International Cooperation Agency—Metal Mining Agency of Japan, 1999). Andal (2002) suggested that this magmatic episode might be attributed to the subduction of the northern margin of the Indo-Australian Plate below the Philippine Sea Plate. In Central Philippines, the oldest dated rocks are found in Guimaras Island with an age of 59±2 Ma (Wolfe, 1981) (Figure 1).

The next most significant period of magmatism is represented by the Paleogene (Paleocene-Oligocene) and Neogene magmatic belts (Figure 2a) (Wolfe, 1981; Bureau of Mines and Geosciences, 1982; Yumul et al., 2003b). Most of the Paleogene magmatic belts are found in eastern Philippines (e.g. Sierra Madre, Bicol, Samar-Leyte and eastern Mindanao). Volcanism along eastern Philippines, from Bicol to Leyte, is mostly related to the westward subduction of the Philippine Sea Plate along the Philippine Trench (Divis, 1980). Oligo-Miocene magmatism, which are significant because of the gold deposits in the Philippines that are related to these intrusions, are represented by rocks in the Luzon Central Cordillera, eastern Negros—western Panay, Eastern Mindanao and Cotabato (Figure 2a) (Mitchell and Leach, 1991; Yumul et al., 2003a).
The Neogene magmatic arc from Tablas–Western Panay, which was interpreted by Mitchell and Leach (1991) to be a continuation of the Miocene Luzon arc, is deemed to be associated with the subduction of the South China Sea plate along the Manila-Negros Trench. In Cotabato, the Neogene magmatic belt is attributed to subduction of the Celebes Sea plate along the Cotabato Trench. Sajona (1995) proposed that volcanoes in central Mindanao, which cannot be attributed to any active subduction zone, may be explained as the products of partial melting of a detached slab beneath Mindanao.

Holocene magmatic belts are noted north of Luzon in the Batanes islands, Zambales-Bataan-Mindoro and Negros-Zamboanga-Western Mindanao (Figure 2a). The Holocene volcanism in Luzon is attributed to the subduction of the South China Sea oceanic lithosphere along the east-dipping Manila Trench (Yumul et al., 2003b). The volcanoes in eastern Negros have been proposed to be related to the subduction of the Sulu Sea basin along the Negros Trench (Mitchell and Leach, 1991). The Zamboanga-Western Mindanao arc is explained by subduction along the Sulu Trench (Aurelio, 2000).

These different episodes of magmatic activities commencing from the Cretaceous to Recent have produced a considerable volume of materials (1.85 × 10^7±256,000 km^3). This translates to arc magmatic addition rates ranging from 30 to 95 km^3/km/m.y. (Dimalanta and Yumul, 2003).

**Ophiolites and ophiolitic complexes**

Another mechanism that results into crustal addition, aside from arc magmatism, is the emplacement of ophiolites (Figure 3a). The presence of ophiolite and ophiolitic complexes has been reported by workers in various parts of the Philippine archipelago (e.g. Balce et al., 1976; Yumul et al., 1997; Tamayo, 2001; Dimalanta and Yumul, 2003). These exposed oceanic lithospheres make up a large part of the basement lithologies in these areas. Ophiolite complexes are believed to have been emplaced and accreted through onramping, upwending, compression and faulting (Figure 3a) (e.g. Moores, 1982; Cannat, 1993; Hacker et al., 1996).

Balce et al. (1976) presented a zonation of ophiolite complexes based on the geographic distribution of these ophiolite units. Recent data, however, has led to the grouping of the ophiolites, on the basis of their ages as well as other characteristic features (e.g. presence of associated metamorphic sole; related to mélanges; manner of emplacement mechanism). The ophiolites are grouped into the following belts: Eastern Philippines, Central Philippines, Zambales, Panay-Mindoro, Palawan-Zamboanga (Figure 2b). This latest zonation suggests a progressive younging of the ophiolites in a westward direction (Yumul, 2003).

Despite the presence of numerous ophiolites and ophiolitic complexes in different parts of the archipelago, the volume of material resulting from the emplacement of these ophiolites (724,000 ± 106±256,000 km^3) (Dimalanta and Yumul, 2003). This is understandable considering that not all of the materials become accreted or emplaced. Some crustal subtraction takes place when a certain portion of the materials becomes destroyed or lost as a result of subduction, tectonic erosion or subduction kneading (e.g. Charvet and Ogawa, 1994; Clift et al., 2003).

The simplified computation of the volume of material related to ophiolite and ophiolitic complexes yielded ophiolite accretion rates ranging from 2 to 19 km^3/km/m.y. (Dimalanta and Yumul, 2003). These rates are lower compared to the few rates that are available elsewhere. Godfrey and Klemperer (1998) derived an ophiolite accretion rate of 50 km^3/km/m.y. for the Great Valley ophiolite in California. Although arc magmatic processes dominate crustal growth in the Philippines, present available data demonstrate the critical role played by magmatic crustal growth processes, that is, the accretion of ophiolites. This is made more significant considering the fact that the Philippine island arc system is made up of several collision and suture zones. These areas are, almost always, characterized by the presence of ophiolites and, to a certain extent, mélanges.

### Crustal growth by magmatic and tectonic processes

Available field, geophysical (e.g. seismicity, gravity, seismic refraction) and geochemical data (e.g. CaO 6.0 and Na_2O 6.0) were utilized to estimate crustal thickness in various parts of the Philippine archipelago. The resulting values were subsequently used to obtain arc magmatic addition as well as ophiolite accretion rates. This kind of work had not been done previously for the entire Philippines. The results reveal that certain portions of the Philippines are underlain by thickened crust (>30 km) (Dimalanta and Yumul, 2003). From the observed crustal thicknesses, this paper presents and examines the various mechanisms responsible for the thickening of the crust in the archipelago.

Figure 2c shows that a zone of thickened crust characterizes the Luzon Central Cordillera region. The oldest magmatic activity in this region began during the Late Cretaceous period. Substantial thickening of the crust was brought about by subsequent magmatic episodes from the Paleocene to Upper Miocene, which are recorded among the various sedimentary and igneous rocks in this region (Dimalanta, 1996). Such multiple phases of magmatism concentrated along linear belts corresponding to magmatic arcs can explain...
why there is a thickening of the crust in this part of the Philippines. This mechanism may also account for the thickened crust that can be observed in other parts of the Philippines like the central Mindanao region.

The significantly thickened crust in Bicol, southeastern Luzon may be accounted for by the numerous episodes of arc magmatism, both ancient and recent, which the region had experienced (Figure 3b). This area is also characterized by the presence of several ophiolite complexes. The emplacement of these ophiolite complexes has further served to increase the thickness of the crust in this part of the archipelago.

It is interesting to note that in the zonation of the Philippines based on crustal thickness, central Philippines (i.e. Negros, Panay, Cebu and Bohol) is shown to be made up of thick crust (30–65 km) (Figure 2c). One of the magmatic belts passes through this region. The islands are also characterized by the presence of ophiolite suites. In eastern Central Philippines, Leyte is characterized by Neogene volcanism but no ancient magmatic activity has been reported for the island. Hence, the crust here is only less than 30 kilometers thick. Although Leyte is also floored by an ophiolite basement, this has not caused a substantial increase in the thickness of the crust.

It would, thus, appear that crustal thickening in the Philippines is the result of the various episodes of arc magmatism occurring in almost the same region or belt, which modified the crust. In addition, the emplacement of ophiolites through various mechanisms has put in a considerable amount of material to cause crustal thickening. However, based on present available rates, it is apparent that the addition of materials by arc magmatism is more substantial compared to those added during the accretion and emplacement of ophiolites.

The boundary between the thick and thin crustal regions coincides with recognized sutures (e.g. Siayan-Sindangan Suture Zone in western Mindanao) or major faults (e.g. the Philippine Fault Zone) in some places (Figure 4). In areas where a physical boundary between the thin and thick crustal regions is not observed, this might be attributed to the complex history involving magmatic, structural and sedimentation processes which makes the boundary not readily observable. This is a subject that can be looked into in future research work.

The collision between the Palawan microcontinental block and the Philippine Mobile Belt during the Early Miocene is one of the more significant events in the evolution of the Philippines (Bellon and Yumul, 2000). Hence, it may be worthwhile to consider whether the collision event had any effect on the thickening of the crust. In the crustal thickness zonation map, the Mindoro-Romblon region, which is supposedly the site of collision (Yumul et al., 2003c), does not show any significant thickening of the crust. The material being "crumpled" as a result of the collision has not sufficiently thickened or stacked up to cause a significant increase in the thickness of the crust in the area surrounding the collision zone. Current studies are being undertaken to investigate what processes are responsible for this result. However, some initial models to explain the absence of crustal thickening from collision are proposed here. This could be due to the fact that although the collision is still in progress, the resulting crustal thickening has not been readily registered. Another possibility is that the plates that are colliding are initially thin, thus, although considerable thickening of the collided portions occurred, with respect to the surrounding plates, they do not manifest anomalous thickness. Although accretion can result from collision, mechanisms such as delamination, subduction erosion and other related processes might also explain the observed result (Figure 3c). This will have to be addressed by future work.

Conclusions

The most recent estimates of arc magmatic addition rates in the Philippines reveal values from 25 to 60 km³/km²/m.y. Ophiolite accretion rates have been estimated to range from 2 to 19 km³/km²/m.y., which are considerably higher compared to rates obtained elsewhere. From the volumes of crustal material produced by arc magmatism, it would seem that crustal growth in the Philippines has been dominated by arc magmatism. However, contributions from the emplacement and accretion of ophiolites are quite significant. The combination of these processes might also explain the occurrence of thickened crust in certain portions of the archipelago (i.e. Luzon Central Cordillera and the Bicol-Panay-Masbate areas). The "crumpling" effect caused by the collision event between the Palawan microcontinental block and the Philippine Mobile Belt has not resulted in thickening of the collided crusts. The manner in which island arcs evolved, as presented here, through magmatic and amagmatic processes may help us understand their ultimate fate of being accreted to the continents.

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