NORTHERN PHILIPPINE OPHIOLITES: MODERN ANALOGUES TO PRECAMBRIAN OPHIOLITES?

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The northern Philippines is a possible modern analogue for some Precambrian greenstone belts. It has a ∼150 Myr history of multiple and overlapping periods of oceanic crust generation, arc volcanism, sedimentation, and deformation dominated by wrench tectonics. At least five ophiolite complexes of distinct ages make up most of the basement—all having a distinct suprasubduction zone signature. Arc plutons are predominantly of the diorite-tonalite series with minor alkali-feldspar bearing rocks. Sedimentary basins probably floored by oceanic crust are dominated by immature sediments and volcaniclastics and are locally up to ∼10 km thick. The whole arc and ophiolitic complex is in the process of being accreted to Eurasia, where it may be preserved in a broad “suture zone” between Eurasia and Australia and/or the Americas.

1. INTRODUCTION

The Philippine islands constitute a mature island arc complex comprised mainly of ophiolites, island arc plutons, volcanics and volcaniclastics, and thick sedimentary basins filled with immature sediments. The term “island arc complex” is used because what is now the Philippines is a composite of more than one arc magmatic belt due to a long history of subduction whose polarity has probably changed more than once along the western and eastern side of the islands (in the current reference frame). However, the available evidence does not support the presence of any suture within the Philippines east of the Manila-Negros trench collision, at least in the northern part of the islands. Hence, the various arc volcano-plutonic belts on the islands were probably not juxtaposed by arc collisions, but rather were generated above the same suprasubduction zone setting by inward subduction from the western and eastern sides. These magmatic belts are built on a basement of oceanic crust (ophiolites) that is itself composite. Based on good biostratigraphic ages on overlying sedimentary rocks and modern dating techniques (zircon U-Pb and 40Ar-39Ar dating), it has been shown that there are at least five generations of ophiolitic basement in the northern Philippines spanning an age range of ∼150 Myr. Based on areas that have been mapped in more detail, it appears that the ophiolites are not allochthonous slices that have been tectonically amalgamated. A model consistent with the field relations is one where

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Table 1.

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<tr>
<th>Name and label in Fig. 1</th>
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<td>c Dibut Bay ophiolite</td>
<td>Billedo et al. (1996), Hashimoto et al. (1978), Tejada and Castillo (2002)</td>
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List of ophiolites labeled on Fig. 1 and references pertaining to them.

each episode of oceanic crust generation occurs adjacent to or within older basement as forearc, backarc, or intraarc seafloor spreading type process.

It has been pointed out that the Philippine island arc complex is “reminiscent of Precambrian greenstone belts” (e.g., Hall, 1996). In this paper, I outline some of the more salient features of the northern Philippines and its ophiolitic basement. I focus on the northern Philippines because it has been studied in more detail and is, therefore, more well-known. However, there are no known fundamental differences between the northern and southern Philippines, therefore the broad outline of the geology presented here is probably applicable to the south as well. For a more detailed discussion of each individual ophiolite terrane, the reader is referred to the original papers (see Table 1) and to a recent review paper focusing on the details of each individual ophiolite and their relationships to each other (Encarnación, in press).

2. REGIONAL TECTONIC SETTING

The Philippines is located in Southeast Asia in the western Pacific at the juncture of the Philippine Sea plate and Eurasian plate (Rangin, 1991). It is a mature island arc that is in the process of being accreted to the Eurasian margin by subduction-related convergence along the east-dipping Manila and Negros trenches. Subduction along the western side of
2. Regional Tectonic Setting

Fig. 1. Present tectonic setting of the Philippines. Rectangle outlines the location of Fig. 2. PF—Philippine Fault; MN—Mindanao; M—Mindoro; P—Panay; LZ—Luzon; NPB—North Palawan Block.

the northern Philippines is generating the Luzon volcanic arc, which consists of the stratovolcanoes in the southern Zambales range (where Mt. Pintubo is located) and volcanic centers running northward along the east side of the Central Cordillera to small islands north of Luzon and into Taiwan. The Luzon arc has collided with the Eurasian margin in Taiwan and in the central Philippines along the islands of Mindoro and Panay (Fig. 1) (McCabe et al., 1982). Presumably as a result of this collision, subduction may be waning on the west side of the Philippines and convergence between the Philippine Sea plate and the Eurasian plate may be increasingly taken up along the west dipping Philippine trench and East Luzon trough (Cardwell et al., 1980; Hamilton, 1979; Lewis and Hayes, 1983;
Fig. 2. General geology of the northern Philippines. See Fig. 1 for location. Main ophiolite exposure: a—Lagonoy ophiolite; b—Calaguas Islands ophiolite; c—Dibut Bay ophiolite; d—Casiguran ophiolite; e—Montalban ophiolite; f—Zambales and Angat ophiolites; g—Itogon ophiolite. CTVB—Central Valley Basin; CAVB—Cagayan Valley Basin; MB—Marinduque Basin; CSC—Cordon syenite complex. Adapted from (Anonymous, 1963, 1977, 1981, 1991; Letouzey and Sage, 1988).
Rangin, 1991). An active arc in southeast Luzon has formed due to subduction along the Philippine trench; no volcanic arc has yet developed from underthrusting at the East Luzon trough. The latter appears to be exploiting an old subduction zone because there is a mature accretionary prism and Eocene plutons and arc volcanics in the northern Sierra Madre as shown in Fig. 2 (Lewis and Hayes, 1983). Oblique northwest convergence of the Philippine Sea plate is being accommodated partly by sinistral wrench faulting along the Philippine Fault system (Aurelio et al., 1991). The Marinduque basin (Fig. 2) is a pull apart basin associated with wrench faulting and is floored by young oceanic crust (Sarewitz and Lewis, 1991). It formed by seafloor spreading type processes reflected in symmetric magnetic anomalies. It is a good actualistic example of formation of younger ophiolitic basement within older ophiolitic and arc basement.

3. MAJOR GEOLOGIC ELEMENTS OF THE NORTHERN PHILIPPINES AND THEIR CHARACTERISTICS

Ophiolites are scattered throughout the northern Philippines as shown in Fig. 2. Many of them have been disrupted mainly by wrench faulting. All of the ophiolites variably preserve residual mantle peridotite (in the form of partly serpentinized harzburgite), gabbroic rocks and ultramafic cumulates, sheeted dikes or dike swarms, pillow lavas and pillow breccias. Modern dating by the zircon U-Pb and \(^{40}\)Ar-\(^{39}\)Ar techniques coupled with traditional biostratigraphic work has shown that there are at least five generations of ophiolite preserved in the northern Philippines. The oldest is the Lagonoy ophiolite in southeast Luzon (Fig. 2), which has a minimum age of Jurassic (Geary et al., 1988). It comprises the oldest basement known in the Philippines east of the Manila trench-Negros trench convergent margin. It has a distinct suprasubduction zone signature and may be a primitive island arc. The Calaguas Islands, Dibut Bay, Casiguran, and Montalban ophiolites are constrained as pre-Late Cretaceous or Early Cretaceous (see Table 1 for references). Together they may comprise a large section of Early Cretaceous oceanic crust that may have formed as backarc basin lithosphere associated with the Jurassic Lagonoy ophiolite/primitive arc. An interesting relationship established by careful mapping and biostratigraphy in the Northern Sierra Madre is the occurrence of a sequence of pillow lavas of Late Cretaceous age with a distinct arc signature overlying the Early Cretaceous back-arc basin-like pillow lavas of the Casiguran ophiolite (Billedo et al., 1996) (Fig. 2).

The Eocene Zambales ophiolite, in western Luzon (Fig. 2) has been the most intensely studied and is the largest exposed ophiolite in the Philippines. It has a distinct suprasubduction zone signature with boninites, MORB-like crust and transitional arc like crust (Hawkins and Evans, 1983). The Zambales ophiolite may be a part of a much larger Eocene ophiolitic basement that most likely extends eastward underneath the Central Valley of Luzon and into the Southern Sierra Madre where it crops out again as the Eocene Angat ophiolite. Fig. 3 is a cross section across central Luzon that shows the probable geometry of the basement and the known geology in the Zambales range and western side of the Southern Sierra Madre. The Eocene ophiolitic basement may also extend northward into
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Fig. 3. East-West section across Luzon from the Zambales Mountains, across the Central Valley Basin and into the Southern Sierra Madre (compare with Fig. 1). It is inferred that most of the section is underlain by an ophiolitic basement that crops out as the Zambales ophiolite in the west and the Angat ophiolite in the east. Section is based on data from several sources (Arcilla et al., 1989; Bachman et al., 1983; Encarnación et al., 1993; Haeck, 1987; Hawkins and Evans, 1983).

northern Luzon. Fig. 4 shows the inferred extend of the various ophiolitic basement in Luzon. A detailed discussion for the basis of this model is discussed elsewhere (Encarnación, in press).

The Itogon ophiolite in the Central Cordillera is Oligocene in age and is thought to have been generated during intraarc rifting (Florendo, 1994). Oligocene and Miocene alkaline plutons and volcanics in the Cordon Syenite Complex (CSC, Fig. 2), are thought to have been related to the same intraarc rifting event. Some of the lavas and dikes associated with the Itogon complex are similar to magmatic rocks in the Sumisu Rift (Florendo, 1994).

Geochemical data for the various ophiolites is of variable quality and coverage. As mentioned earlier, the Zambales ophiolite has been studied the most and has a wide variety of data available. Although clearly a single slab of oceanic lithosphere, it contains MORB-like, transitional arc tholeiite, and boninitic rocks typical of a suprasubduction zone setting. A detailed discussion of all the available geochemical data from all the ophiolites in the northern Philippines can be found in Encarnación (in press). Not surprisingly, all of the ophiolites have evidence for a suprasubduction zone origin (e.g., Hawkins and Florendo, 1992) primarily in the form of variable enrichment of large ion lithophile elements and depletion in high field strength elements.

Overlying and intruding many of the ophiolites are arc volcanics/volcaniclastics and arc plutons, respectively (Figs. 2 and 5). Abundant Cretaceous arc volcanics and volcaniclastics of andesitic and dacitic composition are the first major manifestation of arc volcanism in the northern Philippines. Eocene and Oligocene volcanics are also widespread and abundant. Many of these arc rocks are metamorphosed to lower greenschist facies assemblages. They are largely submarine and along with the volcanic sections of the ophiolites have been mapped as “Cretaceous-Paleogene metavolcanics” in the older maps and literature. The large batholiths exposed in the Central Cordillera and Northern Sierra Madre and to
Fig. 4. Possible extent of ophiolitic basement in the northern Philippines. Dashed lines—outline of northern Philippines. Solid lines—inferrred location of contacts between ophiolites of various ages. Compare with Fig. 2. The extrapolation of ophiolitic basement beyond the main exposures shown in Fig. 2 is based on isolated smaller exposures, structural, isotopic, and seismic data (Encarnación, in press). The contacts between the ophiolites are probably “intrusive” (i.e., younger ophiolites form by extension adjacent to, or within older ophiolite basement), although possibly modified by later wrench faulting (Encarnación, in press; Encarnación et al., 1993; Karig, 1983; Karig et al., 1986). The dominant ophiolitic basement is intruded by arc plutons, partly covered by volcanics and volcaniclastics, and downfaulted or downwarped into deep sedimentary basins that are filled with sediments and volcaniclastics.

a lesser extent, the Southern Sierra Madre, are largely hornblende diorites, quartz diorites and tonalites. These plutons are poorly studied and few of them have any published chemical analyses. Although dominated by diorite-tonalite series plutons, minor syenites, granodiorites, monzonites and lamprophyres have also been described. Most of these more alkali rich rocks are found in the southern Central Cordillera.

4. ANALOG FOR ARCHEAN AND PROTEROZOIC SYSTEMS?

The key characteristics of the northern Philippines that may be relevant to Precambrian ophiolites and greenstone belts are summarized in Fig. 5. Petrologically, the crust is dominated by ophiolitic lithologies that would be classified as “greenstones”. Much of the arc volcanics and volcaniclastics that overly the ophiolitic basement may be difficult to differentiate from the ophiolitic volcanic section and indeed they may certainly be transitional in space and time. In some areas, a significant portion of the crust is made up of
diarrhoea, e.g. de Wit and Ashwal, 1997). The thick ophiolite-floored sedimentary basins are also another key feature and because of their thickness, are likely to be preserved in the geologic record.

The span of geologic activity preserved in the Philippines, covering 150 Myr is comparable to the span of activity recorded in some greenstone belts (de Wit and Ashwal, 1997; Kusky and Polat, 1999). Ophiolite generation, arc magmatism, and sedimentary deposition all spanned this ~ 150 Myr period and occurred in various places in northern Luzon at various times. If this complex package were preserved in an ancient mountain belt, any attempt to understand the geology in terms of a “layer cake” stratigraphy would lead to erroneous conclusions. Interpretation of structural relationships of volcano-sedimentary belts in Archean greenstone terranes might benefit from a more realistic, albeit more complex, model based on modern analogues (e.g., Kusky and Vearncombe, 1997).

In order to use the Philippine ophiolitic terranes as analogues for Precambrian greenstone belts, we need to project current plate motions and kinematics forward in time and predict what the geometry of the major units will be upon final accretion to the Eurasian margin. The Philippines has already partly collided with Eurasia along the Mindoro and Panay area. Convergence continues with eastward subduction of the South China Sea basin and Sulu Sea basin. Once these two small marginal basins are completely consumed by subduction, the Philippine arc complex will have been completely accreted to the Eurasian margin. The final stages of collision may likely be a bit more complex because westward subduction along the Philippine trench has started and the central part of the Philippines is already locked along the North Palawan Block margin. Hence, the final stages of collision
will probably require opening up of extensional basins, with possible formation of oceanic crust to accommodate heterogeneous strain. For example, Pubellier et al. (1996) suggested that the Philippines is undergoing ‘escape tectonics’ which allow the archipelago to deform. The formation of the oceanic Marinduque basin (Sarewitz and Lewis, 1991) is partly related to this intradocking deformation phase.

As the westward subduction on the east side of the Philippines develops further, the northern Philippines will be intruded by yet another suite of plutons and will be blanketed by young arc volcanics. If closure of the Pacific ocean continues, the whole assemblage will be incorporated in a broad suture zone between Eurasia and Australia and/or the Americas. It will then be presumably overprinted by compressional structures and perhaps finally intruded by a post-orogenic intrusive suite. Its overall petrological, structural, and sedimentological characteristics would then be quite evocative of some Precambrian granite-greenstone belts.

REFERENCES


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