Zircon U-Pb Geochronology of the Zambales and Angat Ophiolites, Luzon, Philippines: Evidence for an Eocene Arc-Back Arc Pair

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Two basement terranes, the Zambales ophiolite in the west, and the Angat ophiolite in the east, are exposed on the island of Luzon, separated by a circa 10 km thick and circa 100 km wide sedimentary basin. The structural and age relationships between the two ophiolitic blocks are central to understanding the geologic and tectonic development of the northern Philippines and evaluating models of tectonic evolution proposed for this area of the western Pacific. We analyzed zircons from the Zambales and Angat terranes to better constrain their origin. Two zircon fractions from tonalite in the Acoje block of the Zambales ophiolite give concordant U-Pb ages at 44.2 ± (0.9) Ma. Two zircon fractions from plagiogranite and one fraction from diorite in the Coto block of the Zambales ophiolite give concordant U-Pb ages of 45.1 ± (0.6) Ma. These results provide a Middle Eocene age for the Zambales ophiolite, in agreement with the minimum Late Eocene age of the overlying Aksitero Formation. No age difference is discerned between the arc-like Acoje block and MORB-like Coto block of the Zambales ophiolite. Four zircon fractions from two sample sites in the Angat ophiolite give concordant ages of 48.1 ± (0.5) Ma. This age is considerably younger than the Late Cretaceous age based on radiolarian fauna derived from a sheeted dike-pillow lava-sediment sequence south-southeast of the main ophiolite. The small age difference between the Zambales and Angat ophiolites suggests a common origin and obviates the need for a major structural discontinuity west of the Southern Sierra Madre beneath the Central Valley of Luzon. The Cretaceous biostratigraphic ages of the ophiolitic rocks southeast of the Eocene Angat ophiolite implies that there are two ophiolitic basements exposed in the Southern Sierra Madre. The relationship between the two ophiolites is constrained by the overlying stratigraphic relations which indicate that an Eocene volcanic arc and associated volcaniclastic apron was built on both the Eocene and Cretaceous ophiolitic basement. This suggests that the Zambales-Angat ophiolite represents a preserved Eocene back-arc basin that opened behind an Eocene arc that developed within Cretaceous oceanic basement. In this model, the Zambales-Angat ophiolites are therefore not allochthonous terranes but part of a single plate, generated in situ, forming part of the autochthonous basement of Luzon.

INTRODUCTION

The Philippine archipelago is widely recognized as a natural laboratory in which to study tectonic processes occurring during the evolution of terranes prior to their accretion to continental margins. However, the lack of well-constrained isotopic ages on Philippine pre-Neogene igneous and metamorphic rocks commonly assigned to "basement," has been a continuing problem in Philippine geology. A knowledge of precise ages is critical for evaluating models of the tectonic evolution of the Philippines and the complex western Pacific region. Most isotopic ages reported from the Philippines are poorly documented K-Ar ages making it difficult to evaluate their integrity [Wolfé, 1981]. Paleontological dates of sedimentary rocks in the terranes provide only minimum ages of the underlying ophiolites and these rocks commonly have uncertain relationships with adjacent formations. Furthermore, many reported paleontological ages lack the precision to resolve events especially in a complex orogenic area like the Philippines.

A few well-documented isotopic studies have placed important constraints on the origin of some basement areas in the Philippines. For example, using the known variation of ^{87}Sr/^{86}Sr in seawater over time, Knittel and Daniels [1987] demonstrated that marbles in northern Mindoro (Figure 1), on the Eurasian side of the Philippines, must have formed in pre-Early Permian time. They also reported a Rb-Sr whole rock model age of at least 180 Ma (Jurassic) from a granite in the same area. This established the Paleozoic age of the northern Mindoro metamorphic complex and thus its probable Eurasian affinity [Hamilton, 1979] which had been questioned by some workers [Karig, 1983; Taylor and Hayes, 1983; McCabe et al., 1985]. In a well-documented study of ophiolitic rocks exposed on the east side of the Bicol peninsula, southeastern Luzon (Figure 1), Geary et al. [1988] used the ^{40}Ar/^{39}Ar stepwise degassing method on several hornblende separates from diabase and gabbro and derived Jurassic plateau ages (circa 156 and 151 Ma) demonstrating the existence of pre-Cretaceous ophiolitic basement in the easternmost Philippines. These studies therefore establish that pre-Late Cretaceous crust exists in some places on either side of the Philippine archipelago.

Here we report zircon U-Pb ages from the Zambales and Angat ophiolites, the two most studied and perhaps most fundamental suspect terranes in Luzon, and attempt to establish their origin and relationship. The results have important bearing on the nature of the basement between the older terranes recognized in the west and east as discussed above and place constraints on the evolution of the Philippine island arc complex as a whole.
Fig. 1. Major tectonic elements of the Philippines and physiography of central Luzon showing locations of figures 2 to 5 (numbered boxes).
The Zambales Ophiolite

Hawkins and Evans [1983], using geological and geochemical data, demonstrated that the Acoje block at the northern end of the Zambales ophiolite (Figure 1) exhibits arc-like features and the Coto block to the south has mid-ocean ridge (MOR)-like characteristics. These broad differences between the two blocks has largely been born out by subsequent work [e.g., Geary et al., 1989; Yumul et al., 1990; Florendo and Hawkins, 1991]. The San Antonio massif at the southern end of the ophiolite (Figure 1) has not been studied as extensively as the northern area, but recent work suggests that the San Antonio massif is also arc-like [Yumul et al., 1990].

The lack of any coarse arc-derived material in the overlying Akstero Formation [Corby, 1951] contributed partly to the idea that the Zambales ophiolite was allochthonous and derived far from any arc [Schweller et al., 1983]. Because the Late Eocene Akstero formation provides only a minimum age, there has been much latitude in age assignments which has partly led to the disparate tectonic models involving the ophiolite [Zanoria et al., 1989; Tamesis et al., 1982; Bachman et al., 1983; Schweller et al., 1983; Karig, 1983; Stéphan et al., 1986; Mitchell et al., 1986].

A number of K-Ar ages have been attempted on the Zambales ophiolite, many of which are summarized by Wolfe [1981]. The reported ages range from 12 Ma to 62 Ma with quoted errors of 0.8 to 30 Ma. Many of these samples came from diabase dikes and Wolfe [1981] concluded that a "sequence of intrusions" had occurred not earlier than mid-Oligocene. These did not provide any new constraints on the age of the ophiolite since the minimum age obtained from the overlying sediments is late Eocene. More recently, in a paleomagnetic study, Fuller et al. [1989] reported the following whole rock K-Ar ages with quoted errors: 44 (+3.5) Ma from a "granodioritic phase" and 44.1 (+3.0) Ma from a sill in pillow lava from northern Zambales; 46.6 (+5.1) Ma from a dike in gabbro at the Coto mine in central Zambales. They adopted an Eocene age for the ophiolite but noted that "more refined ages are needed." The caution was warranted since whole rock K-Ar ages may record a cooling age, a later thermal event, or may be geologically meaningless if the system acquires excess Ar or experiences partial Ar loss. The U-Pb system in zircon, however, is capable of recording crystallization ages on account of its high blocking temperature for Pb (>750°C [Heaman and Parrish, 1991]). For example, K-Ar ages from the sheeted dikes and pillows of the Troodos ophiolite are 6 to 16 Ma younger than the zircon U-Pb ages derived from plagiogranites [Mukasa and Ludhen, 1987].

The Angat ophiolite

Karig [1983] first drew attention to the existence of an ophiolitic sequence in the Southern Sierra Madre east of the Zambales range which he named the Angat ophiolite (Figure 1). Based on the presence of Late Cretaceous strata in close proximity to the ophiolite he inferred a Late Cretaceous age for the Angat. Partly because of the large apparent age difference between the Zambales and Angat terranes, he proposed that the two ophiolites are allochthonous, with a major suture beneath the Central Valley Basin of Luzon (Figure 1). He also suggested that the two terranes amalgamated chiefly by strike-slip displacement [Karig, 1983; Karig et al., 1986].

However, subsequent studies by Haack [1987], Arcilla et al. [1989], and our own field investigations, have revealed more complex relationships between the various stratigraphic elements in the Southern Sierra Madre. Arcilla et al. [1989] questioned the age of the Angat ophiolite by pointing out that the presumed age is based on sediments resting on pillow lava separated from the main ophiolite mass by younger sedimentary packets along major fault slices. They also called for a reevaluation of the age of the Zambales ophiolite because of the possible presence of an unconformity between the overlying Eocene sediments and the ophiolite.

Samples

A total of 11 samples ranging from 20 to 50 kg were taken from the Zambales and Angat ophiolites, but only six yielded enough zircon to be useful and are therefore the only ones described here. Intermediate to silicic plutons were searched for since these generally yield abundant zircon. Several small silicic plutons and plugs of late Tertiary to Pleistocene age occur on the eastern side of the Zambales range, and maps published by the Philippine Bureau of Mines indicate sporadic exposures of diorite and quartz diorite of possible Oligocene age within the ophiolite. Similar Oligocene plutons are also reported within the Angat ophiolite. Because these igneous bodies might be mistakenly sampled as part of the ophiolites, we made a careful effort to take samples from plutons that had contact relations indicating penecontemporaneous formation with the dominant basin magma associated with ophiolite generation.

Zambales Ophiolite Samples

Acoje block. Our sample from the Acoje Block is a tonalite (ZA9101-4) from the northwest side of the range along the North Balincoguin River at latitude 15°52.5' and longitude 119°59' (Figure 2). Although contact relations were not observed, the general position of this body between the gabbros and basalt-diabase horizon suggests that it is a part of the upper plutonic section of the ophiolite. The sample is a member of a suite of intermediate to silicic plutonic and volcanic rocks analyzed by Hawkins and Evans [1983] that are arc-like in terms of their major and trace element characteristics. The Pb-isotopic composition of the sample is also arc-like (work in progress). This sample therefore provides the timing of arc-like magmatism (or at least a part of it) in the Acoje block and not some mid-ocean ridge or back-arc basin basement upon which the arc might have been built, i.e., the Coto block.

Coto block. Two samples were collected from the Camiling River which drains eastward on the eastern flank of the ophiolite at about latitude 15°33' (Figure 3). The first sample (ZA9101-10) comes from the transition between the diabase dike complex and gabbros as mapped by the Philippine Bureau of Mines and Geosciences (PBMG) [1983a]. The sample is a leucocratic tonalite occurring as a small pod a few meters wide that has mutually intrusive relations with multiple phases of gabbro. At some borders the leucocratic material has not been observed, the general position of this body between the gabbros and basalt-diabase horizon suggests that it is a part of the upper plutonic section of the ophiolite. The sample is a member of a suite of intermediate to silicic plutonic and volcanic rocks. These field relations indicate that the tonalite formed coevally with the gabbroic magmas, and therefore the age of this sample records the time of crystallization of this section of the ophiolite.

The second sample from the Coto block is a hornblende quartz diorite (ZA9101-12) taken approximately 2 km upstream of the first sample (Figure 3). This rock type occurs as two exposures
Fig. 2. General geology of Dasol area, northern Zambales mountains, showing location of sample ZA9101-4. The tonalite has yielded an age of 44.4 (±0.7 Ma). See Figure 1 for location. (Modified from Hawkins and Evans [1983].)

Fig. 3. General geology of the Camiling River area showing sites of samples ZA9101-10 and ZA9101-12. ZA9101-10 is an unmappable pod in the diabase-gabbro transition zone. Both sites give the same age of 45.1 (±0.6 Ma). See Figure 1 for location. (Modified from PBMG [1983a].)
mapped as Oligocene diorite [PBMG, 1983a], also near the
dike-gabbro transition. No lateral contacts were observed at the
site. The diorite contains numerous angular xenoliths of fine-
grained gabbro and diabase several centimeters in diameter.
While its field occurrence does not rule out the possibility of an
age younger than that of the ophiolite, its zircon U-Pb
systematics yield an age indistinguishable from the first sample.

San Antonio massif. A sample of quartz hornblende gabbro
(ZA9101-13) from the gabbro-sheeted dike transition was taken
from the southern area of the Zambales range along a roadcut in
the Subic area (longitude 120°14', latitude 14°52'; Figure 4).
Several diabase dikes cut through the gabbro. The outcrop
exhibits some deformation along several northeast trending
decimeter to meter wide shear zones with development of
 breccia and gouge, the sample being taken from a meter scale,
relatively fresh, undeformed area from within the shear zone.
The Pb-isotopic composition of this sample is similar to the
Acoje sample mentioned above and therefore also dates the
timing of arc-like magmatism.

Angat Ophiolite Samples

Two samples have been obtained from the Angat ophiolite at
latitude 14°47.5', longitude 121°11' taken along the Hanginan
River, one of the northern tributaries of the Montalban River
(Figure 5). The Hanginan River section exposes upper level
isotropic gabbros and portions of the sheeted dike horizon which
are contiguous to the main exposure of the ophiolite just north
(Figures 1 and 5). The age derived from these samples therefore
dates the main exposure of the Angat ophiolite.

The first sample (ANG9007-2) was taken from an irregular
dike/pod of tonalite with similar contact relations as described
above for ZA9101-10 from the Coto block of Zambales. The
second sample (ANG9101-2) was taken about 1 km upstream
and is a leucocratic dike about 1.5 m wide within a section of
sheeted diabase dikes. The dike is structurally concordant with
the diabase dikes and one contact shows chilling of diabase
against the leucocratic dike. In thin section the sample appears
highly altered with abundant epidote, chlorite, albited
plagioclase and Fe-Ti oxides. Zircons analyzed from the first
sample, ANG9007-2, were pristine and euhedral ones whereas
those from ANG9101-2 were anhedral, reddish, partly opaque or
turbid varieties. However, both samples give the same internally
and externally concordant ages as discussed below.

Nonophiolite Plutons

We have results from two plutons that are unrelated to the
ophiolites but are pertinent to this study. One sample is a quartz

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Fig. 4. General geology of the San Antonio massif at the southern end of the Zambales ophiolite. Sample ZA9101-13 is a quartz
hornblende gabbro taken from a roadcut along the Olongapo-Subic national road. The age of this sample is 43.7 (±0.9 Ma).
(Modified from Yumul et al. [1990] and PBMG [1981].)
Eocene radiolaria found with pillow lava at base of these Eocene volcaniclastics

EOCENE ANGAT OPHIOLITE
48.1 (±0.5) Ma

Cretaceous (undifferentiated) radiolaria with pillow basalt

Late Cretaceous (Turonian-Coniacian) radiolaria with pillow basalt at base of Eocene volcaniclastics

Fig. 5. Geologic map of Montalban area where the southern end of Angat ophiolite is exposed (modified from Arcilia, 1991). The locations of critical geochronologic sample sites are shown. All rectilinear solid lines are faults except for syncline axis at upper right.
diorite, the Antipolo-Teresa diorite (ANT90-1), from the Southern Sierra Madre taken about 15 km south of the Angat ophiolite samples at latitude 14°35', longitude 121°13' (see Figure 5). It is a part of a suite of north-south trending dioritotonalitic plutons exposed along the Sierra Madre. The other sample is quartz diorite (BG9101-7) of the Agno batholith, from the Central Cordillera, taken east of Baguio city (see Figure 1) at latitude 16°25' approximately 2 km west of the Agno river. This sample is part of a series of rocks that has recently been interpreted as the upper portions of a pre-Eocene ophiolite sequence (United Nations Development Programme, Geology and mineralization in the Baguio area, northern Luzon, unpublished technical report, Manila, 1987) (hereinafter referred to as UNDP [1987]). However, as discussed below, this is not borne out by the age relations.

**ANALYTICAL TECHNIQUES**

The rock samples were washed in water and brushed clean to remove dust, grit and other surface contamination. Samples were then jaw-crushed and pulverized and run over a Gemini table to concentrate heavy minerals. Zircon was concentrated further by using heavy liquids and a Frantz magnetic separator. Mineral identification was aided by a scanning electron microscope (SEM) with energy dispersive system (EDS) capability.

The zircon concentrate was sieved into several size fractions and further magnetic separation on each size fraction was done when possible. Final hand picking under a binocular microscope removed remaining impurities, which for most samples consisted of titanite and some pyrite. Almost all the zircons contained some inclusions which were predominantly apatite. The latter probably contributed to the relatively low 206Pb/204Pb ratios. The final zircon separates were washed in dilute, warm, nitric acid in an ultrasound bath for ~30-40 minutes and rinsed several times with ultrapure water. The amount of zircon dissolved ranged from less than 0.1 mg to 19 mg but most were less than 5 mg. Feldspars for common lead analyses were sequentially leached in warm HCl-HNO₃ and diluted HF then rinsed several times in ultra pure water prior to dissolution.

Zircons (and titanite for one sample) were spiked with a mixed 206Pb/204Pb tracer and bombarded for at least 60 hours at 240°C in concentrated HF and nitric acid using micro capsules similar to those described by Parrish [1987]. Column chemistry is similar to that described by Parrish et al. [1987]. All zircon fractions were processed with the HCl procedure except sample ZA9101-4 and the zircon-titanite composite of sample ANG9101-2 which went through HBr chemistry. Total procedural blanks for zircon varied over the course of this study, earlier blanks being circa 100-250 pg (one as high as 2 ng, though). Later blanks settled to values of about 70 pg. The amount of Pb in the feldspars made blanks for the common Pb determination insignificant. The initial lead and blank composition correction was important for almost all zircon samples on account of the relatively low 206Pb/204Pb ratios. Assigned initial Pb compositions were measured on co-genetic feldspar for each sample except ANG9101-2, which used the common lead isotopic composition of ANG9007-2. Two blank isotopic compositions were measured, each based on a composite of four total procedural blanks.

All lead ratios were corrected for mass discrimination at 0.10% per amu based on replicate analyses of standard NBS-SRM 981. Uranium ratios were corrected at 0.2% per amu based on replicate analyses of NBS-SRM U500. Analyses were done on a VG Sector multicollector mass spectrometer equipped with six faraday cups and a Daly detector at the Radiogenic Isotope Geochemistry Laboratory at the University of Michigan. Most analyses were run in static multicollector mode with 206Pb and small signals of 205Pb collected with the Daly detector. Lead was run on single rhenium filaments using the phosphoric acid-silica gel technique [Cameron et al., 1967]; uranium was run as the metal with phosphoric acid and graphite. Data were reduced, and errors calculated, using the method of Ludwig [1980, 1982] and the decay constants recommended by the International Union of Geological Sciences [Steiger and Jäger, 1977]. The errors in 206Pb/238U and 207Pb/235U ages reported here are 2σ standard errors which include the following: (1) uncertainty in U and Pb fractionation factors = ± 0.04% and 0.3%, respectively, (2) uncertainty in blank composition (absolute) = ± 0.6 on both 206Pb/204Pb and 207Pb/204Pb, (3) uncertainty in initial lead composition (absolute) = ±0.1 on both 206Pb/204Pb and 207Pb/204Pb, (4) uncertainty in blank amount = ± 60%, (5) uncertainty in U and Pb concentration of spike = ± 0.1%, (6) nonfractionation run-to-run variation in measured 206Pb/204Pb and 207Pb/206Pb are 0.5% and 0.06%, respectively, and (7) within run errors on isotopic ratios (most less than 0.1%).

**RESULTS**

The analytical results and calculated ages are given in Table 1. Errors in 207Pb/206Pb ages for young zircons similar to those reported here are large and are therefore not included [Matinsson, 1987]. Our criterion in evaluating lead loss (or inheritance from a reservoir along the young linear segment of concordia) is the concordance between U-Pb ages of a number of fractions of different size or magnetic susceptibility. The 206Pb/238U ages of these young samples are more accurate and precise because of the greater enrichment in 206Pb and hence the lower sensitivity of that age to blank and initial Pb corrections. However, most 207Pb/235U ages are in agreement with their corresponding 206Pb/238U ages within errors. The slight internal discordance of U-Pb ages of ZA9101-12 (100-140 μm) and slight external discordance of 207Pb/235U ages of ZA9101-13 is most likely due to error in the common lead correction affecting the 207Pb/235U age rather than discordance due to Pb loss or inheritance. Because of the better precisions of the 206Pb/238U ages, we take the mean of those ages from a sample as the age of that sample.

The following ages are adopted: Acojc block is 44.2 (±0.9) Ma, Coto block is 45.1 (±0.6) Ma, San Antonio massif is 43.7 (±0.8) Ma, Angat ophiolite is 48.1 (±0.5) Ma. Agno batholith (Baguio region) is 26.8 (±0.4) Ma, Teresa diorite is 33.4 (±0.5) Ma. The uncertainties are based on the maximum and minimum ages of the set of zircon fractions from the said areas.

**DISCUSSION**

**Central Valley Suture**

The age determined for the main exposure of the Angat ophiolite is significantly younger than the previously quoted Late Cretaceous age, based on radiolarian fauna derived from inter pillow sediments southeast of our sample sites (Figure 5). The 3 Ma age difference between the Zambales and Angat ophiolites does not require any major structural discontinuity
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* Size range in microns; n, nonmagnetic; m, magnetic; side tilt of chute in degrees. All currents for magnetic splits, 1.5 amps, except ZA9101-4 (0.5 amps).
** Zircon (~60%) and titanite composite.
between the two bodies [Karig, 1983], a result which suggests that the Central Valley Basin is, most likely, completely underlain by Eocene ophiolitic basement. However, the Cretaceous biostratigraphic age is also well-constrained [Haeck, 1987; Arcilla et al., 1989] and this immediately implies the presence of both Eocene and Cretaceous ophiolitic basement in the Southern Sierra Madre. This important finding merits a reexamination of the geology and stratigraphy of the area to determine the relationship between the two ophiolites.

**Relationship Between the Two Southern Sierra Madre Ophiolites**

Although several north-south possible strike-slip faults cut through the Southern Sierra Madre, complicating stratigraphic analyses of the region [Haeck and Karig, 1985; Haeck, 1987; Arcilla et al. 1989; Arcilla, 1991], a few critical sections exist that allow important conclusions to be drawn regarding the relationship between the Eocene and Cretaceous ophiolitic basements in the Southern Sierra Madre.

The Cretaceous biostratigraphic ages of ophiolitic basement come from three sites [Haeck, 1987; Arcilla et al., 1989] as indicated in Figure 5. The presence of a significant age difference between any of these sites (Turonian or Coniacian versus Maastrichtian) and the occurrence of a Turonian through Early Maastrichtian limestone formation free of volcanic input a few kilometers east of Figure 5 (Kinabuan Formation; see Haeck [1987]) suggests that the Cretaceous basement is composite in nature. It is in these units that pre-Eocene strike slip faulting may have juxtaposed allochthonous slices [e.g., Karig et al., 1986]. However, by Eocene time when the Zambales-Anagat ophiolite was being generated and widespread submarine volcanoclastic were being deposited (Maybangain Formation), all the Cretaceous units had already "amalgamated" since they form part of the basin for or are reworked into the Eocene volcanoclastics.

A nearly continuous stratigraphic section occurs along the Tayabasan River (Figure 5) where the pillow lava-radiolarite unit of Turonian or Coniacian age, is directly overlain by a south-southwest plunging syncline of dominantly volcanoclastic sediment of the upper Paleocene - upper Eocene Maybangain Formation [Arcilla et al., 1989]. In a detailed sedimentological study of this section, Siringan [1988] verified the Eocene age of the volcanoclastics and concluded that they had been deposited in a deep, arc-related basin. The apparent age gap between the Late Cretaceous chert-basalt basin and the Late Paleocene - Eocene volcanoclastics may be due to a biostratigraphic sampling artifact or to a real disconformity between the two sections. In either case, the Eocene volcanoclastic are clearly in depositional contact with the underlying Cretaceous basalts.

The stratigraphic relations outlined above demonstrate that the Eocene volcanic arc was in close enough proximity to the Cretaceous basin to have shed its pyroclastic apron upon it. Although the volcanic section of the Eocene Angat ophiolite is apparently not exposed in the area of Figure 5, the wedge of Maybangain volcanoclastics 3 km west of our sample sites contains a few kilometers north, and Haeck [1987, p. 189] reports that at "the base [?] of this sequence of MVM (Maybangain Volcanoclastic Member) equivalents...red siliceous mudstones intercalated with pillowd and massive basalt in upper Sapang Anguinan (~5 km NE of Angat Dam) contain a radiolarian fauna yielding Paleocene (?Eocene) and Eocene (probably middle Eocene) ages." It seems likely that the section described represents the pillow lava-volcanic section of the Eocene Angat ophiolite, the exposures being just a few kilometers north of our sampling sites. This demonstrates that the Eocene volcanoclastic apron was deposited on both the Eocene ophiolitic basement and the Cretaceous ophiolitic basement. The Eocene Angat ophiolite was therefore probably generated as back arc crust adjacent to the Eocene arc represented by the Maybangain formation, and both formed in proximity to Cretaceous oceanic crust.

In the area mapped by Arcilla et al. [1989], where the 48-Ma Angat samples were taken (Figure 5), the contact between the Eocene ophiolite and the Cretaceous ophiolitic rocks is a high angle fault characterized by a zone of gouge and brecciation that has been traced for at least 10 km (the "East Marikina Fault" [Arcilla et al., 1989; Tamesis, 1991]). However, the full "contact" may be distributed over a wide zone of high angle faults and possible thrusts east of Figure 5 in which up to kilometer-wide slices of both Cretaceous and Eocene sedimentary packets have been juxtaposed in complex relationships [Haeck and Karig, 1985; Haeck, 1987]. The amount of displacement along these faults is unknown, but the presence of the same Eocene volcanoclastics on either side of the faults implies that transport has not been sufficient to juxtapose disparate sedimentary facies at least since the Eocene.

**Tectonic Model and Paleogeography**

A model (Figure 6) is suggested wherein westward subduction (in the current reference frame) within Cretaceous lithosphere (eastern Cretaceous ophiolitic basement) in perhaps Middle to Late Paleocene time led to the development of a late Paleocene - Eocene island arc. The late Eocene-early Oligocene [International Union of Geological Sciences, 1989] Antipolo diorite (Figure 5) and several possible Eocene plutons further north in the central Sierra Madre [Wolfe, 1981] may represent the subvolcanic section of the arc. Arc generation is soon accompanied by back-arc spreading which forms the Eocene Angat and Zambales ophiolites. The arc sheds volcanoclastic turbidites onto the back arc basin and onto the Cretaceous "foundation." A similar paleogeography was suggested by Stéphan et al. [1986, Figure 3a] although they did not provide any basis for their reconstruction.

Subduction was possibly accompanied by oblique convergence with concomitant wrench tectonics in the upper plate [Beck, 1983] giving rise to the structural features in the Southern Sierra Madre [Haeck and Karig, 1985; Haeck, 1987]. Duyanen [1988] described several massive, up to several kilometer long, gravity slides and slump deposits of Cretaceous deep marine limestone (Kinabuan formation) incorporated in Eocene volcanoclastics east of Figure 5. Widespread reworking of Cretaceous - Paleocene components into younger Eocene strata was also documented by Haeck [1987]. These features may have been caused by gravitational instabilities resulting from the generation of dynamic topography on the seafloor as a result of the said wrench tectonics. The apparent widespread Paleocene unconformity in the Southern Sierra Madre [Hashimoto, 1981; Haeck, 1987] might also be explained by this oblique subduction event.

The presence of a spreading ridge west of the Angat ophiolite would be consistent with the slightly younger age of the Zambales area. The circa 3-Ma age difference between the two areas can be accounted for by reasonable half spreading rates of the order of a few centimeters per year. Karig [1983] suggested a NNW-SSE spreading direction for the Zambales ophiolite.
Fig. 6. Model for the origin of the Zambales and Angat ophiolites, ~44 Ma B.P. The ophiolites probably formed as back arc basin crust associated with an Eocene arc in the Southern Sierra Madre. This arc-back arc pair developed within Cretaceous lithosphere. This model differs from previous models wherein most of Luzon consists of allochthonous terranes derived either from the Philippine Sea Plate or the Eurasian Plate.
based on dike directions and aeromagnetic anomalies. Dike and sill strike orientations in the subvolcanic zone of the Zambales ophiolite are actually variable but a detailed study along one river section showed a slight maximum at NE directions [Hawkins and Evans, 1983]. Dikes of the Eocene Angat ophiolite show N and NNW orientations based on a few exposures from a relatively small area. If the Angat data are representative, then the apparent discrepancy between the Zambales and Eocene Angat dike directions may be due to relative rotations along faults (e.g., West Marikina Fault, Figure 5) or variations in the maximum tensile stress direction in space and/or time.

One argument that might be invoked against the proposed paleogeography is the difference between the sedimentary cover of the Zambales and Angat ophiolites. The east side of the Zambales is overlain by the Eocene-Oligocene basinal Aksitero formation consisting primarily of pelagic carbonates [Schweller et al., 1983; Bachman et al., 1983]. However, the pelagic carbonates contain 10-30% volcanic material [Garrison et al., 1986; Hashimoto, 1981]. The lack of volcaniclastic turbidites in the lower Eocene Aksitero may be due to those areas being a basement high [e.g., Schweller et al., 1983]. Heavy mineral separates from an exploratory oil well in the median area of the Central Valley that penetrated probable Eocene sediments below well-dated Oligocene sediments, have yielded abundant silt to sand-sized pyroxene, brown hornblende and Fe-Ti oxides [Marqueda and Tamesis, 1991], all of which lack any exsolution textures resolvable on the SEM, indicating rapid cooling and hence a volcanic origin (J. P. Encarnación, unpublished data, 1992). This suggests that the volcaniclastic apron sourced from the east may have already been making its way westward across the proto Central Valley Basin in Eocene time prior to the recorded influx of volcanic detritus on the east flank of Zambales in mid to late Oligocene time [Schweller et al., 1983]. The timing and scales involved in this paleogeographic reconstruction are broadly consistent with models for sedimentation in marginal basins [Karig and Moore, 1975],

In summary, the ages of ophiolitic basement, the regional facies distribution of the overlying sediments, volcaniclastics and plutons, and the apparent lack of major disturbances in the subsurface structure of the Central Valley (see Tamesis et al. [1982] and Bachman et al. [1983] for seismic sections) are all consistent with a continuous Eocene back arc basin crust beneath the Central Valley coupled to an upper Paleocene - Eocene volcano-plutonic arc in the east.

Extent of Eocene Ophiolitic Basement

The large-scale processes proposed above immediately raise the question of whether the regions north and south of the central Luzon transect are consistent with the proposed scenario. Eocene volcaniclastics are widespread in the Philippines [Philippine Bureau of Mines, 1963; Hashimoto, 1981], and therefore it is not unreasonable to suggest that Eocene back arc basin basement may be widespread as well. The geology of the adjacent regions may be used to test the model.

Central Cordillera. The Central Cordillera is separated from the central Luzon area by the left-lateral Philippine Fault (Figure 1). However, the Philippine Fault is a fairly young feature [Aurelio et al., 1991; Barrier et al., 1991; Ringenbach et al., 1993] with a probable maximum displacement of ~100 km and therefore does not preclude correlations across it. The basement of the Central Cordillera, in northern Luzon has been commonly mapped as "Cretaceous-Paleogene metavolcanics." In the Baguio region of the Cordillera (Figure 1), early workers assigned various foliated greenschist facies rocks to the basement but it has been concluded that these rocks are simply deformed facies of the Pugo Formation along the margins of younger intrusions [Balce et al., 1980]. The Pugo Formation consists of weakly metamorphosed mafic to andesitic flows and pyroclastics with some spilitic pillow lava facies. Balce et al. [1980] assigned part of the formation a late Oligocene to early Miocene age but noted that other portions of the formation might be as old as Eocene since abundant reworked Eocene fossils occur in the younger Kennon limestone with the Pugo Formation as the most likely source. Preliminary results from trace element analyses of the Pugo Formation by Diomampo et al. [1991] indicate that these rocks exhibit transitional MORB-island arc tholeiite characteristics which, they suggested, indicates the Central Cordillera is built on marginal basin crustal basement.

Further north in the Cervantes area (circa 80 km north of Baguio), Ringenbach et al. [1990] described several exposures of spilitic pillow lavas associated with radiolarian chert. Some pillow lava sections are cut by basaltic dikes that are also spilitic in character, typical of seafloor hydrothermal metamorphism. They cited a pre-Late Eocene age for these basement rocks based on the late Eocene-early Oligocene age of the overlying Balili formation, the lower portion of which consists largely of fine-grained deep marine volcaniclastic material. In the Ilocos foothills of northwestern Luzon, Pinet and Stephan [1990] described graywacke, conglomerate, tuffs and volcanic flows with local exposures of Late Eocene limestone, and to the east of this sequence, Eocene to Middle Miocene volcaniclastics associated with andesitic and basaltic flows.

Some of the rock sequences in the Baguio region have been interpreted as the upper levels of an inferred Cretaceous ophiolite sequence (UNDP, 1987). An important aspect of this interpretation is the inclusion of a part of the Agno Batholith as the upper level gabbro section of the proposed ophiolite. A sample of this pluton yielded a well-constrained age of 26.8 ±0.5 Ma (Table 1) which is younger than nearby basement. The Agno batholith is therefore a later intrusion that is likely associated with the N-S trending group of plutons along the axis of the Central Cordillera [Balce et al., 1980].

In view of the broad similarities between the metavolcanic sequences in the Central Cordillera and Southern Sierra Madre, the absence of ages older than Eocene from the Central Cordillera, and the presence of Eocene basement not far to the south in the Central Valley, it seems likely that the basement of the Central Cordillera is Eocene and correlatable to the Zambales-Angat Ophiolite.

Northern Sierra Madre. The northern Sierra Madre is one of the least studied areas in Luzon. However, in a stratigraphic study of the sedimentary basin between the Central Cordillera and the Northern Sierra Madre (Cagayan Valley Basin), Cuacusan [1980] mentioned sporadic exposures of Eocene basement in the Northern Sierra Madre and Central Cordillera consisting of "pyroclastics and wackes." He differentiated this younger basement from the Cretaceous ophiolitic basement in the east that is probably the northern extension of the Cretaceous basement in the Southern Sierra Madre. The gross similarities of the regional geology in the Northern Sierra Madre and the Southern Sierra Madre together with the consistent mid to late Eocene K-Ar ages reported from several dioritic plutons
in the Northern Sierra Madre [Wolfe, 1981] strongly suggests that the Eocene arc-back arc pair may extend to the northeast. The structure and stratigraphy of the northern Sierra Madre is currently being studied in more detail (E. Billedo, personal communication, 1992) and these ideas may be tested soon. We have sampled some of the said plutons and better ages on the northern plutons are also forthcoming.

Excluding the Sierra Madre, the only Cretaceous ages reported from northern Luzon are from radiolarian cherts incorporated in a north-south shear zone exposed locally along the western side of Luzon ("West Luzon Shear Zone" [Karig, 1983]). The origin of this shear zone is not certain but Karig [1983] interprets it as a major zone of strike-slip displacement. However, the age of the chert cannot be used to constrain the age of any basement and is consistent with the model presented here which predicts the former presence of Cretaceous lithosphere west of Luzon.

Central and southern Philippines. In a study of terranes in the central Philippines, McCabe et al. [1985] described the "Central Philippine Arc Terrane (CPAT)" as the arc-volcano-plutonic terrane extending from the Molucca Sea to the eastern portion of Taiwan. They suggested that it consisted of a younger (mid to late Tertiary) arc built along the margin of an older (Cretaceous) core. The relationships demonstrated on Luzon are broadly consistent with this suggestion; however, the ages of terranes in the central Philippines need to be better constrained before this model can be extended to the south, since tectonic configurations may change significantly with latitude. For example, south of Mindanao, in the Molucca Sea, the tectonic regime has been established as the collision of two inwardly facing arcs, the Sangihe arc and Halmahera arc [Silver and Moore, 1978] yet the possible extension of this collision zone under Mindanao is uncertain [Hawkins et al., 1991; Pubellier et al., 1991]. Some of the problems encountered in understanding the paleotectonics of the southern Philippines are those that have hampered our understanding of past tectonics on Luzon, i.e., the age of basement on either side of the proposed sutures are unknown or poorly known and the purported sutures are inaccessible for examination beneath thick sedimentary basins (the Agusan-Davao basin and the Cotabato basin).

Implications

The proposed model explains several problematic aspects of Luzon geology. The Acoje block and San Antonio Massif of the Zambales ophiolite exhibit several features which indicate that they are arc related [Hawkins and Evans, 1983; Yumul et al., 1990] but neither built a large volcanic edifice with an associated volcaniclastic apron [Florendo and Hawkins, 1991]. The paleogeography suggested by the presence of the Eocene volcanoclastic and plutons in the east indicates that the Acoje and San Antonio areas were spatially separated from the main arc axis during their generation and thus probably saw only the marginal effects of arc magmatism. The presence of an arc signature in back arc basins is not unexpected in view of their supra subduction zone position. For example, recent work in the Lau Basin has demonstrated the occurrence of lavas with an arc affinity in the back arc [Hawkins et al., 1991; Parson et al., 1991] including boninitic lavas [Faloon et al., 1992]. This is also consistent with the observations of Geary et al. [1989] who showed that although the Coto volcanic and subvolcanic section formed as dominantly N-MORB crust, effects of arc magmatism were subsequently imprinted on the trace element signature.

If the Zambales-Angat ophiolite formed the eastern half of a back arc basin formed behind an east facing Eocene arc, this implies that more Eocene oceanic crust must have existed "west" of Luzon. The demise of this Eocene oceanic crust might have some bearing on the origin of the calc-alkaline batholiths forming the axis of the Central Cordillera of Luzon. The plutons could not have formed by the current subduction of South China Sea lithosphere at the Manila trench because the plutons were already forming in the mid-Oligocene [Wolfe, 1981; this work], prior to the opening of the South China Sea [Taylor and Hayes, 1983; Wolfe, 1988]. Wolfe [1988] suggested that the Central Cordillera plutonic arc formed as a result of westward subduction beneath eastern Luzon rather than eastward subduction in western Luzon as proposed by Balce et al. [1980]. Eastward subduction of the proposed Eocene crust west of Luzon prior to the subduction of South China Sea crust is a possible solution to this dilemma. Furthermore, if the Eocene arc-back arc pair developed within Cretaceous oceanic lithosphere, pre-Eocene crust must also have existed outboard of Eocene crust. This may explain the occurrence of Cretaceous radiolarian chert incorporated into the mélangé/shear zone on the western margin of Luzon [Karig, 1983] and the presence of Jurassic-Cretaceous and Eocene ophiolitic fragments in Panay [McCabe et al., 1982; Mitchell et al., 1986].

Finally, this model implies that the Eocene arc-back arc pair preserved on Luzon may have been an independent lithospheric plate since it must have been bounded by a subduction zone in the east and a spreading ridge to the west. Initiation of eastward subduction on the western side of Luzon trapped the Zambales-Angat ophiolite. Much of Luzon might therefore be a coherent terrane formed in situ rather than an amalgamation of crustal fragments sourced from either the Eurasian plate or the Philippine Sea plate [e.g., Rangin, 1991].

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