Geoscience Frontiers 11 (2020) 23–36

Contents lists available at ScienceDirect

China University of Geosciences (Beijing)

Geoscience Frontiers

journal homepage: www.elsevier.com/locate/gsf

Research Paper

Slab rollback and microcontinent subduction in the evolution of the Zambales Ophiolite Complex (Philippines): A review

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ARTICLE INFO

Article history:
Received 21 April 2018
Received in revised form
3 November 2018
Accepted 19 December 2018
Available online 22 February 2019

Keywords:
Ophiolite
Slab rollback
Radiolarians
Subduction
Zambales
Philippines

ABSTRACT

New radiolarian ages show that the island arc-related Acoje block of the Zambales Ophiolite Complex is possibly of Late Jurassic to Early Cretaceous age. Radiometric dating of its plutonic and volcanic-hypabyssal rocks yielded middle Eocene ages. On the other hand, the paleontological dating of the sedimentary carapace of the transitional mid-ocean ridge – island arc affiliated Coto block of the ophiolite complex, together with isotopic age datings of its dikes and mafic cumulate rocks, also yielded Eocene ages. This offers the possibility that the Zambales Ophiolite Complex could have: (1) evolved from a Mesozoic arc (Acoje block) that split to form a Cenozoic back-arc basin (Coto block), (2) through faulting, structurally juxtaposed a Mesozoic oceanic crust with a younger Cenozoic lithospheric fragment or (3) through the interplay of slab rollback, slab break-off and, at a later time, collision with a micro-continent fragment, caused the formation of an island arc-related ophiolite block (Acoje) that migrated trench-ward resulting into the generation of a back-arc basin (Coto block) with a limited subduction signature. This Meso-Cenozoic ophiolite complex is compared with the other oceanic lithosphere fragments along the western seaboard of the Philippines in the context of their evolution in terms of their recognized environments of generation.

1. Introduction

Ophiolites that formed in mid-ocean ridge settings and exposed along suture zones as a consequence of basin closure are recognized and reported (e.g. Varne et al., 2000; Wang et al., 2012; Zhang et al., 2013). Nonetheless, ophiolites formed in intra-oceanic subduction zone environment resulting into the generation of supra-subduction zone ophiolites appear to be the more dominant mode of formation (Pearce et al., 1984; Pearce, 2003; Dimalanta and Yumul, 2006; Zhou et al., 2014; Xiong et al., 2017). Although some authors consider ophiolites to be mid-oceanic fragments that have tapped subduction-modified upper mantle sources (e.g. Moores et al., 2000), several lines of evidence show that a direct comparison of ophiolite generation to that of ocean crust formation along mid-ocean ridges is not directly feasible (Metcalf and Shervais, 2008). Sheeted dike complexes, as mapped in the Troodos and Oman ophiolites, are utilized as direct evidence that the mode of

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Peer-review under responsibility of China University of Geosciences (Beijing).

https://doi.org/10.1016/j.gsf.2018.12.008

spreading involving mid-ocean ridge oceanic crusts and ophiolites are similar. However, Robinson et al. (2008) concluded that sheeted dike complexes represent a balance between an extensional regime and the corresponding magmatism which is normally found in a mid-ocean ridge setting; the same cannot always be said for supra-subduction zone settings which led them to conclude that ophiolite generation cannot be directly compared to mid-ocean ridge processes. Metcalf and Shervais (2008) listed several reasons why formation along convergence zone among ophiolites is more of the norm. These reasons include, among others: (1) the involvement of hydrous magmas in the generation of ophiolites as indicated by their mineral chemistry, crystallization order and whole rock geochemistry (e.g. Pearce et al., 1984), (2) field evidence wherein crust-mantle sequences have better chances of being emplaced intact when they are in the overriding plate of a convergence zone (e.g. Dilek and Furnes, 2011; Draut and Clift, 2013) and (3) overlying sediments of mid-ocean crusts are mostly devoid of volcanic materials compared to sediments on top of supra-subduction zone ophiolites which would have volcanic ash as a component (e.g. Schweller et al., 1983, 1984; Dimalanta et al., 2015). Thus, although evidence point to the present-day existence of island arc geochemical signatures, mostly inherited or brought about by slab window magmatism within mid-ocean ridge settings, they cannot fully account for the field and geochemical characteristics exhibited by supra-subduction zone ophiolites. Applying the concept of uniformitarianism, Shervais (2001) concluded that the typical cycle of supra-subduction zone ophiolite generation from birth, through youth, maturity, to death and resurrection involves a major role by subduction accompanied by multi-stage and differing degrees of partial melting, varying fluid and melt influx and changing tectonic settings (e.g. Shervais et al., 2004; Dimalanta et al., 2006; Ozawa et al., 2015; Dilek and Yang, 2018).

Ophiolites within the Western Pacific region mostly fit into the cycle of generation as expounded by Shervais (2001). The Zambales Ophiolite Complex, a complete ophiolite sequence, exposed along the western seaboard of the island of Luzon and a supra-subduction zone ophiolite is a good example (e.g. Stoll, 1958; Hawkins and Evans, 1983; Rossman et al., 1989; Encarnacion, 2004) (Fig. 1A and B). This ophiolite complex, made up of the Acoje and Coto blocks, is considered as an arc-back arc pair, and has been dated as Eocene (e.g. Amato, 1964; Schweller et al., 1983; Encarnacion et al., 1993). However, recent radiolarian dating of chert olistoliths sampled from the Acoje block gave a Late Jurassic to Early Cretaceous age for this ophiolite complex (e.g. Ishida et al., 2012; Queaño et al., 2017a). The implication of this new age dating is reviewed together with what is already known which can further constrain our understanding on the origin and evolution of the Zambales Ophiolite Complex. This is then extended to the other oceanic lithosphere fragments exposed along the western side of the Philippine archipelago (Fig. 1A). An understanding of how the Zambales Ophiolite Complex and the other oceanic lithosphere fragments exposed along the western seaboard of the Philippines evolved can contribute in comprehending how this part of the Philippine island arc system had changed through time.

2. Geology and geochemistry of the Zambales Ophiolite Complex

2.1. *Regional setting*

The Zambales Ophiolite Complex is exposed for about 160-km along the western portion of Central Luzon (Hawkins and Evans, 1983; Yumul, 1989). This ophiolite sequence is within the Philippine Mobile Belt (PMB), an actively deforming region bounded by subduction zones that consume the marginal basins of the Eurasian Plate and the Philippine Sea Plate (Fig. 1A). In Central Philippines, active tectonics is marked by the collision between the PMB and the Palawan Continental Block (PCB). The PCB is a terrane of Eurasian affinity that originated from the southeastern margin of Asia prior to the opening of the South China Sea (e.g. Taylor and Hayes, 1980; Suzuki et al., 2000; Suggate et al., 2014). The Zambales Ophiolite Complex is tilted towards the east with the volcanic members mostly exposed at the eastern portion and the mantle peridotites outcropping at the western side. Several models have been

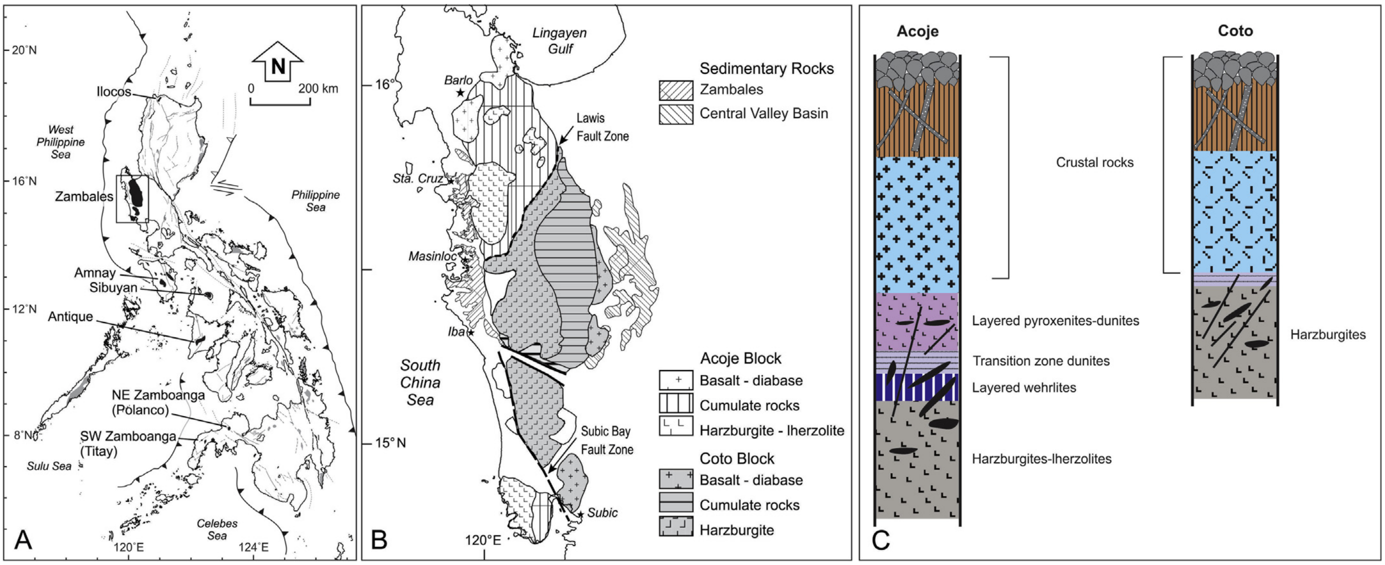

Figure 1. (A) Map showing the ophiolites exposed along the western seaboard of the Philippine archipelago (black shaded areas). Polanco and Titay would correspond to NE and SW Zamboanga complexes as discussed in the text. (B) The Zambales Ophiolite Complex occupies three fault-bounded massifs in the Zambales Range (from north to south) — Masinloc, Cabangan and San Antonio. These massifs are further subdivided into the Acoje and Coto blocks on the basis of field and geochemical characteristics (modified from Yumul et al., 1998a). The northern part of the Masinloc Massif is occupied by the Acoje block whereas its southern portion exposes the Coto block. Field and geochemical characteristics show that the Acoje block in the Masinloc Massif and the San Antonio Massif are similar. The same can be said for the Coto block and the Cabangan Massif. See text for discussion. (C) Stratigraphic logs showing the differences between the ophiolite sequences from the Acoje and Coto blocks.

forwarded to account for the geology, geochemistry, mineralization and tectonic evolution of this ophiolite complex (e.g. Hawkins and Evans, 1983; Fuller et al., 1989; Geary et al., 1989; Rossman et al., 1989; Zhou et al., 2000).

2.2. Geological comparison of the Acoje and Coto blocks

The Zambales Ophiolite Complex is made up of three massifs from north to south: Masinloc, Cabangan and San Antonio (Fig. 1B). The Masinloc Massif, in turn, is divided into two blocks with different petrological and geochemical signatures – Acoje and Coto. The Cabangan Massif has geochemical affinity with the Coto block, whereas the San Antonio Massif exhibits similar geology and geochemistry with that of the Acoje block (e.g. Hawkins and Evans, 1983; Yumul, 1989). With the presence of a well-developed cumulate sequence and volcanic-hypabyssal section, the Zambales Ophiolite Complex is deduced to have formed in a fast-spreading center. Unlike ophiolites formed in slow spreading centers whose extension is due to amagmatic processes and marked by listric faults with cherts overlying peridotites, the Zambales Ophiolite Complex follows the Penrose Conference-defined layered cake model of an ophiolite sequence (Anonymous, 1972; Yumul et al., 2008; Dilek and Furnes, 2011) (Fig. 1C). Pillow lavas, sheeted dike complex, massive gabbros, layered mafic and ultramafic cumulate rocks, transition zone dunites and residual peridotites typify the ophiolite (Fig. 2A–E). The boundary between the Acoje and Coto blocks was previously thought to be intrusive, transitional or faulted (e.g. Hawkins and Evans, 1983; Abrajano et al., 1989; Rossman et al., 1989). Recent geophysical work, however, had shown that a structural boundary exists between the Acoje and Coto blocks (Salapare et al., 2015). This boundary, the Lawis Fault, separates the relatively lower gravity anomalies over the Acoje block (<250 mGal) from the relatively higher anomalies in the Coto block (in excess of 300 mGal) (Fig. 3). The gravity anomalies were used by Salapare et al. (2015) to indicate that the Acoje block has a thicker crust in contrast to the Coto block, which is modelled to have a thinner crustal structure typical of a marginal basin.

Whole rock geochemistry shows the Acoje block is represented by island arc tholeiites with associated boninitic rocks. The cumulate sequence defines a crystallization order of olivine ± spinel → pyroxene → plagioclase. Aside from having a well-defined ultramafic cumulate sequence composed of wehrlite, websterite, clinopyroxenite, dunite and harzburgite, the mafic cumulate sequence is defined by gabbro, norite, gabbronorite, and anorthosite. Metallurgical chromitites (chromian spinel with spinel Cr# $[=\mathrm{Cr}/(\mathrm{Cr}+\mathrm{Al})] \geq 0.6$) associated with nickel sulfides and platinum-group of elements are present in the Acoje block (e.g. Abrajano and Pasteris, 1989; Abrajano et al., 1989; Bacuta and Lipin, 1990; Manjoorsa and Yumul, 1996). The mantle sequence of the Acoje block has an underlying lherzolite with very aluminian spinel overlain by harzburgite (Yumul, 1989). The mantle and cumulate sequence of the Acoje block is cut by clinopyroxenite dikes and rare gabbro dikes. Cyprus-type volcanogenic massive sulphides, hosted by island arc tholeiites and boninites, have been mined in the Barlo mine located at the northern part of the Acoje block.

The Coto block, on the other hand, has volcanic rocks defined by transitional mid-ocean ridge basalt - island arc tholeiite geochemical signatures. The crystallization order of the Coto cumulate is olivine ± spinel → plagioclase → pyroxene. The plagioclases of the Coto cumulate rocks are less calcic compared to that of the Acoje cumulate rocks. The ultramafic cumulate sequence of the Coto block is thin and made up of the transition zone dunite. The mafic cumulate sequence is dominated by troctolite, olivine gabbro and gabbro. Refractory chromitites (aluminian spinel with spinel Cr# ≤ 0.6) are present in the Coto block. The harzburgite mantle sequence is intruded by numerous arc-related diabase dikes (Hawkins and Evans, 1983; Yumul et al., 1998a). The range of models for the transition zone dunites in the Acoje and Coto blocks includes residual, cumulate or replacive in origin (e.g. Abrajano et al., 1989; Yumul, 2004; Payot et al., 2013).

Evans et al. (1991) showed that as the Sm/Nd ratios in basaltic rocks of the Zambales Ophiolite Complex decrease from north (Acoje) to south (Coto), it is matched by an accompanying decrease in $^{143}\mathrm{Nd}/^{144}\mathrm{Nd}$. The Sr isotopic range for the two blocks is high ($^{87}\mathrm{Sr}/^{86}\mathrm{Sr} = 0.7035–0.7040$). The study on whole rock and mineral separates by Encarnacion et al. (1999) yielded the same results as those of Evans et al. (1991) in terms of Nd, but has also conclusively shown elevated $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ and $^{207}\mathrm{Pb}/^{204}\mathrm{Pb}$ for the Acoje block compared to the Coto block. The rare earth element patterns of the Acoje block volcanic rocks are extremely depleted in light rare earth elements (LREE) whereas the Coto block volcanic rocks are slightly LREE depleted (e.g. Geary et al., 1989; Evans et al., 1991; Yumul, 1996). These indicate that subduction inputs are more significant in the formation of the Acoje block than the Coto block.

The Acoje chromitites are metallurgical and chromian while the Coto chromitites are refractory and aluminian (e.g. Hock et al., 1986; Rossman et al., 1989; Yumul, 1992; Payot et al., 2013). Petrofabric directions show a vertical orientation for the Acoje mantle rocks in contrast to the horizontal orientation of the Coto peridotites; the Cr-rich chromitites are found in the deeper lherzolite-harzburgite region compared to the Al-rich chromitites which are distributed within the harzburgite-dunite transition (Nicolas and Violette, 1982; Leblanc and Violette, 1983). Both the Acoje and Coto chromitites have similar Pt and Pd although the former is characterized by higher Cu, Ir, Ru and Rh compared to the latter. In addition to this, the PGE-normalized patterns of the Acoje dunites exhibit flatter patterns with respect to the Coto dunites that display depleted Pt trends (Zhou et al., 2000). The PGE patterns of the chromitites and dunites clearly show that the Acoje and Coto blocks have different source regions that have undergone multi-stage partial melting processes. Furthermore, they have been influenced by the introduction of variable melt or fluid compositions, as has been suggested by other previous studies (e.g. Evans and Hawkins, 1989; Bacuta and Lipin, 1990; Manjoorsa and Yumul, 1996; Zhou et al., 2000). As such, the Acoje block is regarded as a product of higher degrees of partial melting compared to the Coto block. This also led to the general conclusion that the Zambales Ophiolite Complex is a paired ophiolite belt formed in an island arc and back-arc basin environment. However, recent radiolarian age dating, as will be presented in the succeeding section, negates this possibility.

2.3. Reported ages

The reported Eocene age of the Zambales Ophiolite Complex is based on the fossil assemblages from the overlying pelagic Aksitero Formation. This formation consists of tuffaceous and calcareous sediments exposed at the eastern foothills of the southern Zambales Range (Amato, 1964). Additional ages for the ophiolite were obtained with K–Ar methods (46.6–44 Ma) performed on diabase and granodiorite dikes (Fuller et al., 1989). Encarnacion et al. (1993), on the other hand, using zircon U–Pb dating on tonalite dikes, plagiogranites and diorites (Table 1), suggested a Middle Eocene age for both the Acoje and Coto blocks. They concluded that there is not much difference between the ages of two blocks. Whole rock K–Ar dating of diabase dikes intruded into the Coto mantle rocks gave Late Oligocene (25 ± 7 Ma) to Late Eocene (36 ± 5 Ma) ages (De Boer et al., 1980). All of these age datings, most of which are within the Coto block, have since relegated the Zambales Ophiolite Complex as Cenozoic.

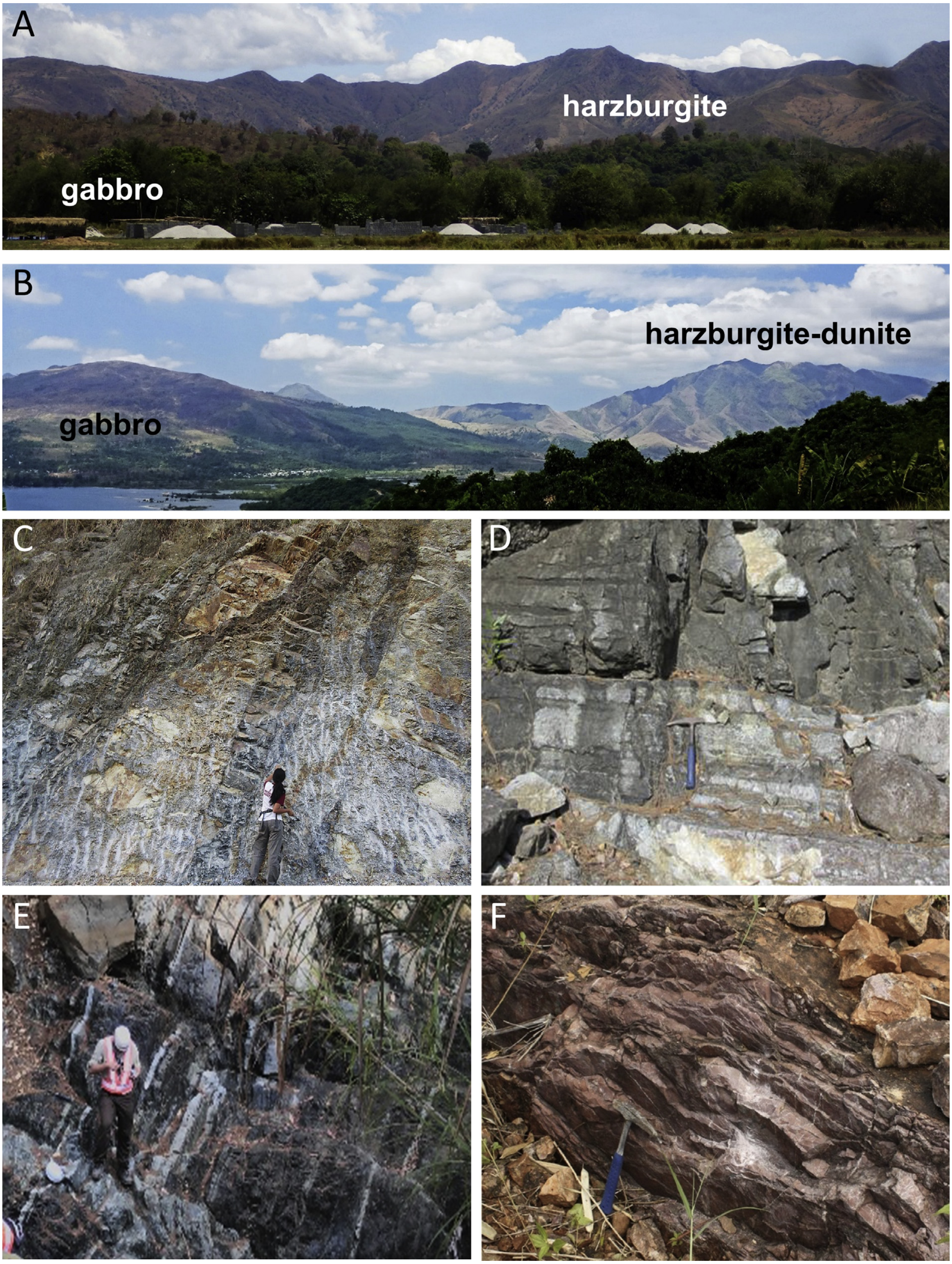

Figure 2. (A) View of the Cabangan Massif looking east with the gabbro on the left and the harzburgite on the right; (B) the San Antonio Massif with the gabbro unit on the left and harzburgite-dunite on the right (looking southwest); (C) Coto block-affiliated sheeted dike complex at Subic, Zambales; (D) layered troctolite-gabbro from the Coto block; (E) layered mafic (light bands) - ultramafic (dark bands) sequence in the Acoje block; (F) chert from the Acoje block that occurs as olistoliths in the Cabaluan Formation.

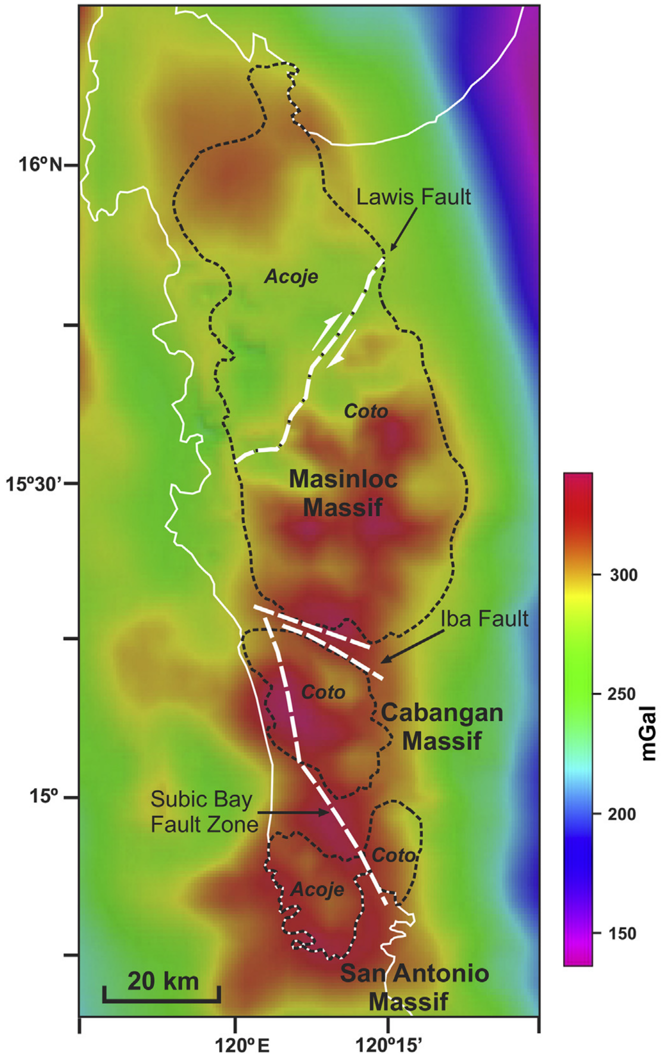

Figure 3. Bouguer anomaly map of the Zambales Ophiolite Complex. The Lawis Fault, a right-lateral fault based on field evidence, was defined by the difference in the gravity anomalies exhibited by the Acoje block (less than 250 mGal) compared to the higher gravity anomalies (>300 mGal) in the Coto block. Gravity data is compiled from the Bureau Gravimetrique Internationale (BGI) (Bonvalot et al., 2012) and ground gravity data from Salapare et al. (2015).

Recently, a Late Jurassic to Early Cretaceous age was obtained from radiolarian dating of chert within the Cabaluan Formation (e.g. Ishida et al., 2012; Queaño et al., 2017a). This formational unit consists mostly of conglomerates that directly overlie the Acoje block in northern Zambales range. As a note, the conglomerates are mostly with peridotite fragments and few chert fragments, some of which occur as huge olistolith blocks within the formation (Queaño et al., 2017a). The cherts were likely derived from the sedimentary cover of the Acoje block (Queaño et al., 2017a). Fig. 4 provides a summary of the stratigraphy of the Central Valley Basin and the Zambales Range.

2.4. Possible evolutionary paths

The Zambales Ophiolite Complex, a supra-subduction zone ophiolite, is thought to be an allochthonous lithospheric fragment made up of two blocks – the Acoje block with island arc geochemical characteristics, and the Coto block with transitional arc-mid-ocean ridge geochemical signatures (e.g. Fuller et al., 1983; Yumul, 1989, 1994; Tamayo et al., 2004; Dimalanta et al., 2015). The mode of tectonic emplacement ranges from obduction, through large-scale strike-slip faulting or onramping (e.g. Karig, 1983; Rossman et al., 1989; Yumul et al., 2003). Previous models on how the ophiolite formed include: (1) formation of an arc (Acoje block) which, through continued subduction, resulted into arc splitting and back-arc basin formation (Coto block), (2) formation of a marginal basin crust (Coto block) followed by subduction resulting into arc generation (Acoje block) and (3) trench-parallel marginal basin associated with an arc edifice that opened in a scissor-like manner wherein the ocean crust-forming seafloor spreading (Coto block) is propagating in a zip-like manner towards the arc edifice (Acoje block) (e.g. Schweller et al., 1984; Geary et al., 1989; Yumul, 1994). Although several oceanic basins were identified as possible source of the ophiolite, it appears that the best progenitor would be the Eocene Celebes Basin (Fuller et al., 1989). Encarnacion (2004) and his co-workers (1993, 1999), on the other hand, forwarded the notion that the Zambales Ophiolite Complex and some of the ophiolites in northern Luzon are actually autochthonous in origin. Recent studies, nonetheless, considered the ophiolite to have been derived from Mesozoic oceanic crusts such as the proto-South China Sea or the East Asian Sea plate (e.g. Queaño et al., 2007; Perez et al., 2018).

Regardless of the discrepancies in ideas related to the different models of formation, there is general agreement that the Zambales Ophiolite Complex was emplaced, exposed, and eroded by the Early to Late Miocene as evidenced by the first appearance of ophiolitic clasts within the Moriones Formation exposed east of the ophiolite (Fig. 4). This and younger overlying sediments suggest continuous uplift from a deeper oceanic setting, as exemplified by the pelagic Aksitero Limestone capping the Coto block, to a shallow environment as shown by the Cabaluan and Sta. Cruz formations exposed immediately west of the ophiolite and the Moriones and Malinta formations on its eastern side (e.g. Amato, 1964; Bachman et al., 1983; Schweller et al., 1984; Karig, 1986; Geary et al., 1989; Dimalanta et al., 2015; Queaño et al., 2017a) (Fig. 4). As mentioned, the ophiolite is tilted to the east with its volcanic rocks mostly exposed along the northern, eastern and southern parts and the mantle sequence exposed along the western side of the Zambales range. Post-emplacement faulting caused the San Antonio Massif (present-day southernmost part of the Zambales Ophiolite Complex) to be translated southward, along the Subic Bay Fault Zone, to its present position (Yumul and Dimalanta, 1997; Yumul et al., 1998b) (Fig. 1B).

2.5. Radiolarian data

Cherts were recently sampled in the Acoje block from which radiolarians were extracted. The cherts occur as olistoliths and also as clasts within the late Early to early Middle Miocene Cabaluan Formation (Fig. 2F). Radiolarian dating of these cherts showed the presence of *Pseudodictyomitra okamurai* Mizutani, *Archaeospongoprunum* sp., *Crytamphorella* sp., *Stichocapsa* sp., *Diacanthocapsa* sp. and *Zhamoidellum ventricosum* Dumitrica (Fig. 5) (e.g. Baumgartner et al., 1995). Queaño et al. (2017a) also previously reported the presence of *Eucyrtidiellum* sp., *Wrangellium* sp., *Crucella* sp., *Triactoma* sp., *Striatojaponocapsa conexa* Matsuoka and *Cenosphaera* sp. These results are in addition to the ages previously reported for the Zambales Ophiolite Complex (Table 1). These radiolarian ages give a Late Jurassic to Early Cretaceous age for the Acoje block. With this Mesozoic age for the Acoje block, there is now a higher possibility that the Acoje and Coto blocks do not represent a simple island arc-back-arc basin pair, as forwarded by Queaño et al. (2017a). This is expounded in a later section in this paper.

Table 1
Compilation of the ages, geochemical affinity and tectonic setting of the ophiolites along the western seaboard of the Philippine archipelago.

Ophiolite	Age	References	Geochemical affinity	Tectonic setting	References
Zambales	Radiolarians from chert: Late Jurassic–Early Cretaceous (Acoje block) K–Ar dating of sill among the pillow lavas near Barlo Mine (Acoje block): 44.1 ± 3.0 Ma U–Pb dating of tonalite (Acoje block): 44.4 ± 0.7 Ma	Suzuki et al. (2011) Ishida et al. (2012) Queaño et al. (2017a) Fuller et al. (1989) Encarnacion et al. (1993)	Mid-oceanic ridge basalt (MORB) – island arc tholeiite (IAT) (dominantly IAT)	Paired arc – back-arc; marginal basin	Hawkins and Evans (1983) Geary et al. (1989), Yumul et al. (1998a)
	K–Ar dating of diabase dike intruding gabbro (Coto Mine): 46.6 ± 5.1 Ma (Eocene) U–Pb dating of leucocratic tonalite and hornblende quartz diorite (Coto block): 45.1 ± 0.6 Ma	Fuller et al. (1989) Encarnacion et al. (1993)	Transitional MORB-IAT	Paired arc – back-arc; marginal basin	Hawkins and Evans (1983) Geary et al. (1989), Yumul et al. (1998a)
Amnay	Foraminifera in siltstone intercalated with pillow basalts: Middle Oligocene U–Pb dating of troctolite in Paluan: 23.2 Ma and 23.4 Ma U–Pb dating of gabbro in Paluan: 33.4 Ma and 34.3 Ma	Rangin et al. (1985) Yu, pers. comm.	Normal mid-oceanic ridge basalt (N-MORB), enriched mid-oceanic ridge basalt (E-MORB) and ocean island basalt (OIB)	Marginal basin	Jumawan et al. (1998), Perez et al. (2013)
Antique	Radiolarians from chert: Early Cretaceous	Rangin et al. (1991)	Transitional MORB-IAT, N-MORB, IAT and E-MORB	Mixed fore-arc marginal basin	McCabe et al. (1985), Tamayo et al. (2001, 2004)
Sibuyan	Radiolarians from chert: Jurassic to Cretaceous K–Ar dating of diorite (plagiogranite): 43.2 ± 2.5 Ma	Maac and Ylade (1988) Dimalanta et al. (2009)	MORB	Mid-oceanic ridge	Payot (2009) Payot et al. (2009, 2011)
NE Zamboanga	Calcarenite in sedimentary mélange: Late Oligocene to early Middle Miocene	Tamayo et al. (2004)	Transitional MORB-IAT, IAT, calc-alkaline (CA)	Mixed fore-arc, arc and marginal basin	Pubellier et al. (2004) Tamayo et al. (2004) Yumul et al. (2004)
SW Zamboanga	Regional correlation: Late Cretaceous (?)	Tamayo et al. (2004)	N-MORB	Back-arc basin	Tamayo et al. (2004)

2.6. *Oceanic lithospheric fragments along the Philippine western seaboard*

Several ophiolite and ophiolitic complexes are exposed along the western seaboard of the Philippines (Fig. 1A) (e.g. Arai et al., 1997; Jumawan et al., 1998; Tamayo et al., 2000, 2001, 2004; Tamayo, 2001; Yumul et al., 2004; Yumul, 2007; Payot, 2009; Perez et al., 2013; Gabo et al., 2015; Padrones et al., 2017). The Zambales Ophiolite Complex is compared with these lithospheric fragments using published representative data. These lithospheric fragments include the ophiolitic rocks in Ilocos (Arai et al., 1997; Tamayo, 2001), Amnay Ophiolite in Mindoro island (Jumawan, 1999; Perez et al., 2013), the Antique Ophiolite in Panay island (Tamayo et al., 2001), Sibuyan Ophiolite in the Romblon Island Group (Payot, 2009; Payot et al., 2009, 2013), and the NE (Polanco) and SW (Titay) Zamboanga crust-mantle fragments in the Zamboanga peninsula in Mindanao (Tamayo et al., 2000, 2004). Fig. 6A–C shows the spinel Cr# vs. Mg# of the peridotites from the different ophiolites. The peridotites of the Acoje and Coto blocks of the Zambales Ophiolite Complex fall within the abyssal and forearc fields. The peridotites from the other ophiolites also show variable spinel Cr# (=Cr/[Cr + Al]) vs. Mg# (=Mg/[Mg + Fe^{2+}]) typical of abyssal and forearc peridotites. Plotting representative spinel chemistry in the olivine-spinel mantle array (OSMA) of Arai (1987) shows that the Acoje harzburgites (olivine 100 × Mg# = 90–92; spinel Cr# = 0.10–0.55) and dunites (olivine 100 × Mg# = 90–92; spinel Cr# = 0.65–0.80) fall within the OSMA (Fig. 6D). The same can be said for Ilocos (lherzolite olivine 100 × Mg# = 90; spinel Cr# = 0.19–0.20), Amnay (lherzolite olivine 100 × Mg# = 89–93; spinel Cr# < 0.20), Antique (harzburgite olivine 100 × Mg# = 90–92; spinel Cr# = 0.25–0.65; dunite olivine 100 × Mg# = 91–92; spinel Cr# = 0.60), Sibuyan (lherzolite and harzburgite olivine 100 × Mg# = 91; spinel Cr# = 0.20–0.55) and NE (harzburgite olivine 100 × Mg# = 90–92; spinel Cr# = 0.25–0.80) and SW Zamboanga (harzburgite olivine 100 × Mg# = 90–92; spinel Cr# = 0.40–0.55) although there is a wide range of spinel Cr# values compared to the limited olivine forsterite content (Fig. 6D–F). The Al_2O_3 vs. TiO_2 plots of Kamenetsky et al. (2001) for the different crust-mantle sequences reveal a range of composition from MORB to SSZ peridotites (Fig. 7A–C). The Acoje harzburgite and lherzolite plot in the MORB peridotite field whereas the dunite and chromitite plot in the SSZ peridotite field. The harzburgite and dunite of Coto plot in the overlapping field of MORB and SSZ peridotite fields. The Amnay ultramafic rocks define two distinct populations of MORB and SSZ peridotites. The same can be said for the Antique, Sibuyan and NE and SW Zamboanga peridotites which show a full range of MORB and SSZ spinel chemistry (Fig. 7A–C). The spinel Cr–Al–Fe^{3+} shows the full range of spinel chemistry from aluminian (mostly lherzolites) to chromian character (mostly dunites and chromitites) with the harzburgites plotting in between the fertile lherzolites and refractory dunites and chromitites (Fig. 8A–C).

3. Discussion

3.1. *Zambales Ophiolite Complex: age and geochemical considerations*

From the new data provided by the radiolarian dating of cherts, the Acoje block is considered Late Jurassic to Early Cretaceous in age, with the Coto block having a minimum age of Eocene on the basis of the Aksitero Formation found on top of its pillow lavas. As stated before, this led Queaño et al. (2017a) to suggest that this ophiolite complex can be divided into two distinct ophiolite blocks,

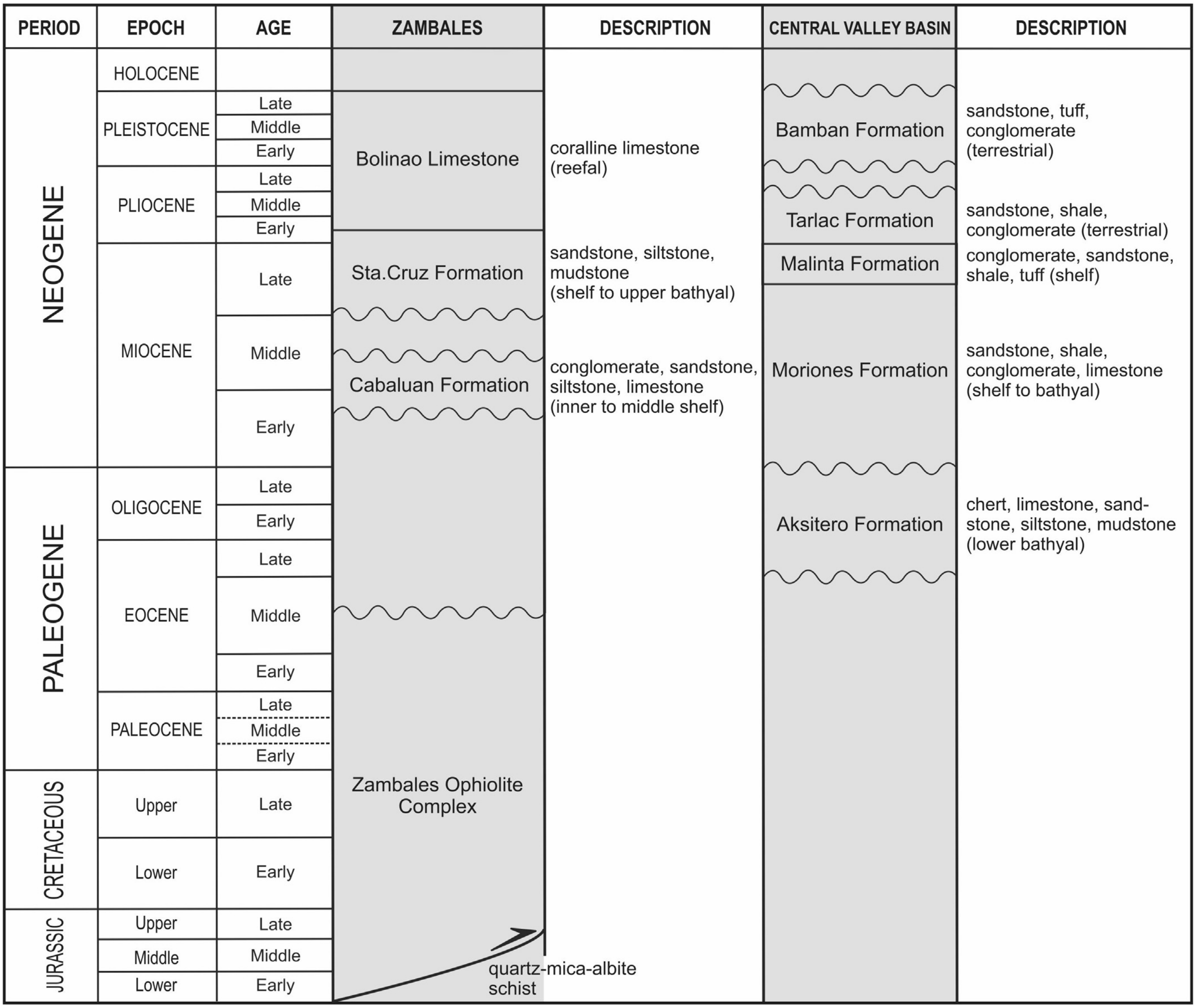

Figure 4. Stratigraphic column showing the sedimentary units west and east of the Zambales Ophiolite Complex which suggest the shallowing of the depositional environment of the overlying sedimentary units. The Central Valley Basin is a sedimentary basin that bounds the Zambales Ophiolite Complex to the east (e.g. Bachman et al., 1983; Schweller et al., 1984).

a Late Jurassic to Early Cretaceous Acoje Ophiolite and Eocene Coto Ophiolite, which does not define a paired island arc-back arc basin. Nonetheless, previous age dating of igneous rocks from the Acoje and Coto blocks actually show an almost similar Eocene age; some of the island arc-related diabase dikes intruded into the Coto harzburgites are of Oligocene age (Fuller et al., 1983). These age datings cannot be ignored and a reconciliation needs to be achieved.

Field data for the Acoje block show that the lowermost part of the exposed mantle sequence in the Acoje chromitite mine is made up of lherzolites (Yumul, 1989). The fertile lherzolites (spinel Cr# ≤ 0.3) are overlain by harzburgites (spinel Cr# ≥ 0.6), transition zone dunites, layered pyroxenites and gabbronorites, sheeted diabase dike complex and mostly low-Ti pillow lavas and boninitic rocks. The same mantle-cumulate sequence relationship is also observed in the southward-displaced San Antonio Massif (Yumul and Dimalanta, 1997). The lherzolites and some of the harzburgites manifest mid-ocean ridge peridotite characteristics although the majority of the ultramafic to mafic cumulate rocks, diabase dike and volcanic rock complex exhibit island arc geochemical signatures. The cherts sampled and analyzed occur as olistoliths within the areas where the Acoje lherzolites are exposed and are not found in any other part of the ophiolite. The Early to Middle Miocene Cabaluan Formation that directly overlies the Acoje block mantle sequence contains serpentinites, gabbronorites and cherts (Fig. 4). The chert then could have been confined within the Acoje block only or as even forwarded by Queaño et al. (2017a), specifically within the Acoje lherzolite area. Ophiolites formed in slow spreading centers are known to be characterized by lherzolites with chert capping these mantle materials (e.g. Dilek, 2003; Andal et al., 2005; Yumul et al., 2008). This suggests the probability that the Acoje block was initially generated in a slow spreading center associated with low degrees of partial melting. This can explain the presence of both lherzolite and chert within the Acoje block. The idea of a slow-spreading ridge origin was previously forwarded by Hawkins and Evans (1983) on the basis of the observed sill complex in the mafic suite of the Acoje block. Post-Mesozoic events characterized by a more dominant participation of subduction resulted

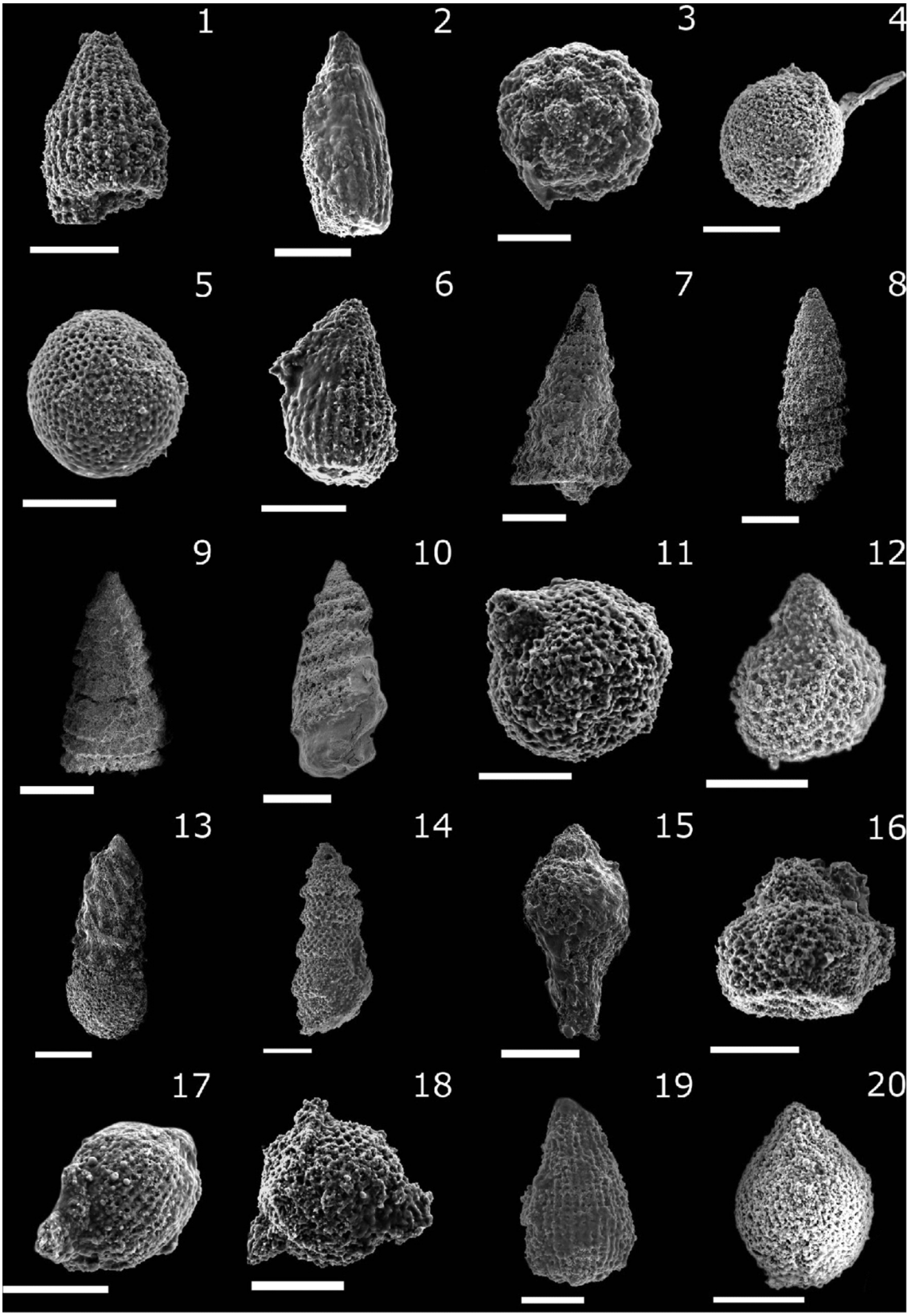

Figure 5. Radiolarians extracted from the cherts that yielded a Middle Jurassic to Early Cretaceous age include: (1) *Thanarla brouweri* Tan Sin Hok, (2) *Thanarla* sp., (3) *Praeconosphaera sphaeraconus Rüst,* (4) *Archaeospongoprunum* sp., (5) *Holocryptocanium barbui* Dumitrica, (6) *Dictyomitra* sp., (7) *Pseudodictyomitra carpatica* Lozyniak, (8) *Wrangellium* sp., (9) *Pseudodictyomitra* sp., (10) *Pseudodictyomitra okamurai* Mizutani, (11) *Williriedellum carpathicum* Dumitrica, (12) *Hiscocapsa* sp., (13) *Pseudoristola* sp., (14) *Parvicingula* sp., (15) *Podobursa* sp., (16) ?*Eucyrtidiellum* sp., (17) *Striatojaponocapsa conexa* Matsuoka, (18) *Triactoma* sp., (19) *Parashuum* sp., (20) *Stichocapsa* sp. (Baumgartner et al., 1995). Scale bar = 100 μm.

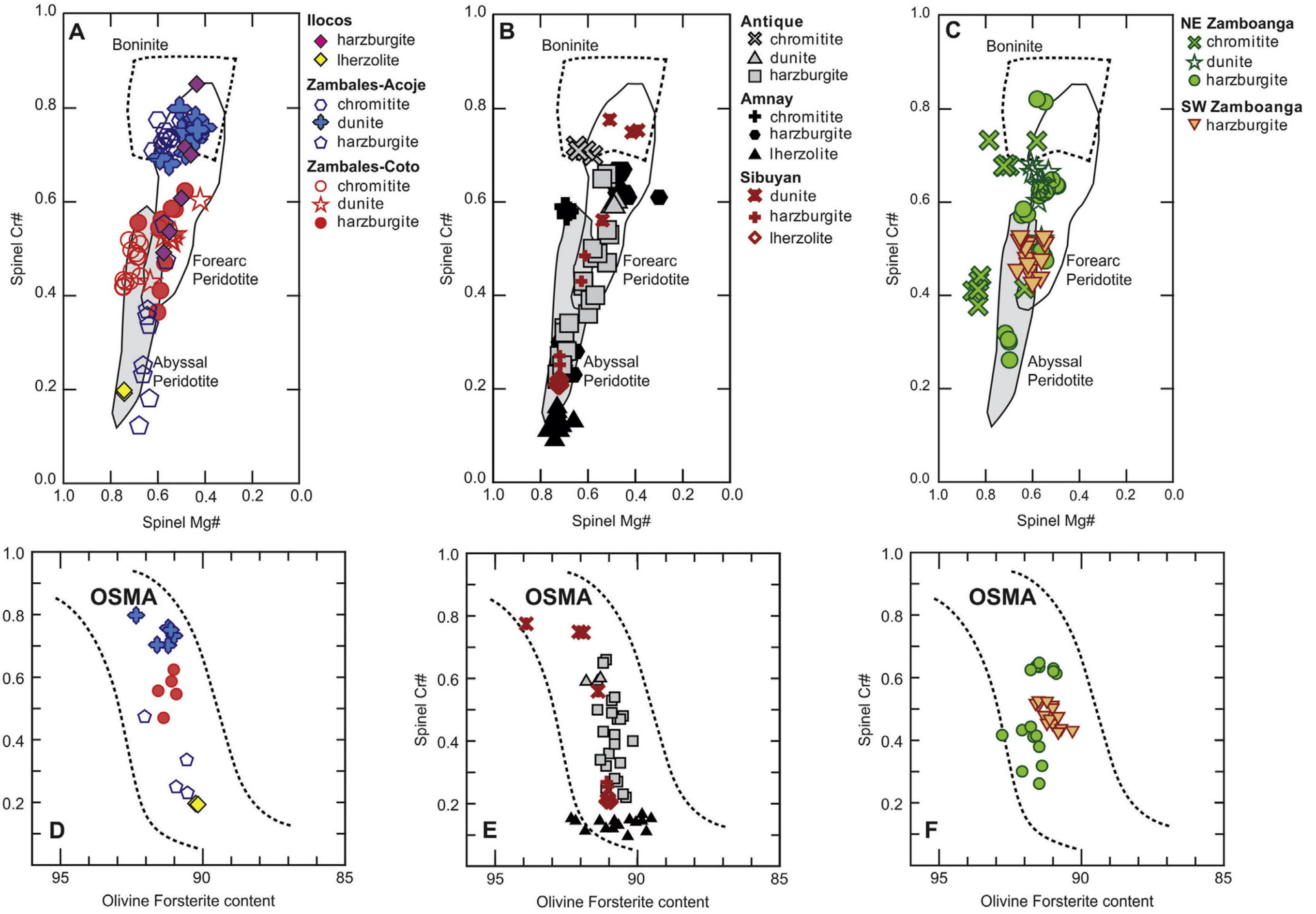

Figure 6. Spinel Cr# vs. Mg# for peridotites from (A) Zambales, (B) Antique, Amnay, Sibuyan and (C) NE and SW Zamboanga ophiolites. (D–F) Olivine forsterite content vs. spinel Cr# in peridotites from the same ophiolites. Diagrams and fields were modified from Dick and Bullen (1984), Van der Laan et al. (1992) and Arai (1994).

into an elevated degree of partial melting which, coupled with the presence of magmatic water, led to the formation of Acoje block lithologies with distinct island arc signatures (e.g. more siliceous melt associated with boninites, presence of clinopyroxene and orthopyroxene-rich cumulate rocks, calcic plagioclase in the mafic cumulate sequence, presence of PGEs indicative of second-stage melts and chromium-rich chromitites). This is consistent with the formation of a stunted arc edifice on top of the lherzolite platform. Considering that several hypabyssal and mafic cumulate rocks have been dated Middle Eocene in the Acoje block, this would suggest that the generation and evolution progressed from Middle Jurassic to the Eocene time. This observation is not exclusive to the Zambales Ophiolite Complex as multiple ages within an ultramafic-mafic complex have been recognized in other ophiolites (e.g. Palawan; Isabela; Angat) in the Philippines (e.g. Yumul, 1993; Billedo, 1994; Tamayo et al., 2004; Dimalanta and Yumul, 2006). It is clear then that the presence of a Late Jurassic to Early Cretaceous chert associated with the Acoje lherzolites can be reconciled with the dominantly Eocene age derived from the Acoje block. How then did the Zambales Ophiolite Complex evolve?

3.2. Role of subduction, slab rollback and microcontinent subduction

Subduction initiation, slab rollback resulting to hinge retreat and back-arc opening followed by partial subduction of a continental crust can account for the evolution of the Zambales Ophiolite Complex. During the Late Jurassic to Early Cretaceous, chert was deposited over exposed lherzolites possibly in a slow-spreading ridge environment (Fig. 9A). This can account for the fertile character of the lherzolites that subsequently served as the mantle platform for the subdued arc edifice formed in the later history of the Acoje block. The Mesozoic chert deposition was followed by intra-oceanic subduction initiation during the Eocene that led to the formation of the Eocene Acoje block formed on top of a Mesozoic Acoje block platform (Fig. 9B). The subduction can account for: (1) the island arc tholeiite-hosted volcanogenic massive sulphides and sheeted dike-sill complex in the Acoje block, (2) boninites within the Acoje block volcanic section, and (3) a lithospheric crust-mantle sequence composed of harzburgite, transition zone dunites, cumulate rocks and volcanic-hypabyssal rocks exhibiting arc geochemistry. The presence of boninites has been associated with rapid spreading in forearc settings as noted in the Coast Range Ophiolite and other ophiolite complexes (e.g. Shervais et al., 2004; Zhou et al., 2014; Zhang et al., 2016; Zaeimnia et al., 2017).

After the generation of the Acoje block possibly in a forearc setting, subduction was followed by slab rollback (e.g. Dilek and Flower, 2004) (Fig. 9C). Nakakuki and Mura (2013) had recognized a "stagnant slab formation" or "vertical slab anchoring" as two possible mechanisms that can generate slab rollback. Flows either around the lateral edges of the slab (toroidal component)

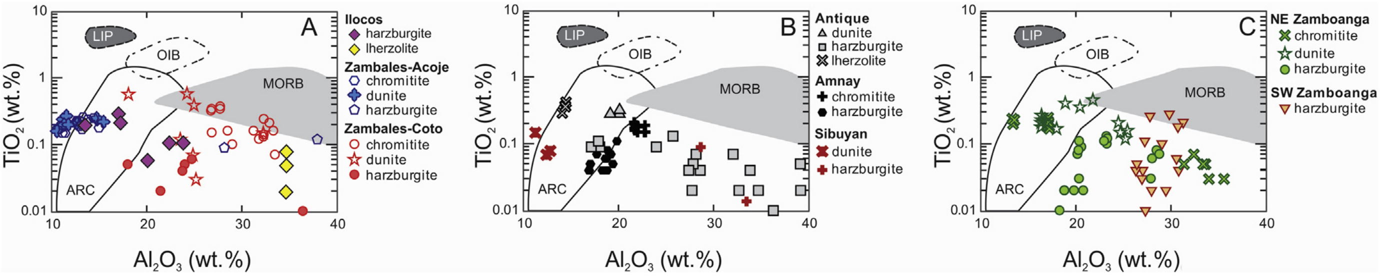

Figure 7. Spinel Al_2O_3 vs. TiO_2 for peridotites from (A) Zambales, (B) Antique, Amnay, Sibuyan and (C) NE and SW Zamboanga ophiolites. Diagram after Kamenetsky et al. (2001).

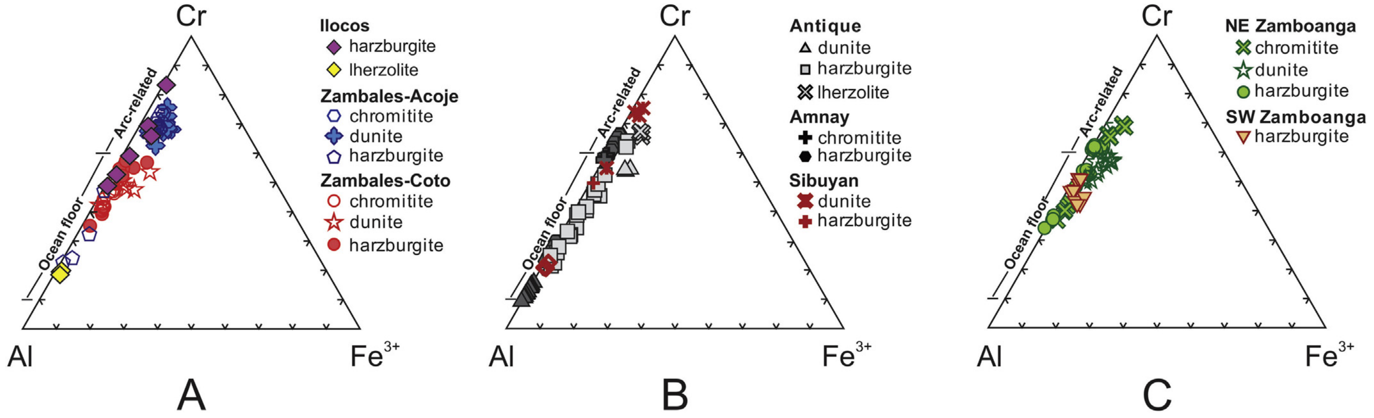

Figure 8. Ternary diagrams showing Cr–Al–Fe^{3+} content in spinels of the peridotites from (A) Zambales, (B) Antique, Amnay, Sibuyan and (C) NE and SW Zamboanga ophiolites. Symbols as in Fig. 7. Compositional range of arc-related and ocean floor peridotites from Dick and Bullen (1984). See text for details.

or flows underneath the slab tip (poloidal component) occur during slab rollbacks (Stegman et al., 2006; Yamato et al., 2009). Slab rollback, rather than the overriding plate, is believed to be the main mechanism controlling the rheology of the overriding plate (e.g. Schellart, 2008; Rey and Müller, 2010; Spakman and Hall, 2010; Butterworth et al., 2012). With slab rollback, the hinge retreats causing the migration of the overriding plate towards the trench side. Attenuation of the ocean crust at the back-arc side with the diminishing influence of subduction led to ocean floor rifting and spreading. This could correspond to the formation of the Coto block, which has more mid-ocean ridge/back-arc basin affinity, compared to the Acoje block. The subduction, slab rollback and basin opening would have happened in a relatively short time to explain the almost similar age of the Acoje and Coto blocks (Fig. 9C).

Hawkins and Evans (1983) recognized the presence of quartz-albite-mica schist beneath the peridotite of the Acoje block leading them to conclude that a continental crustal fragment serves as basement of the Acoje block. Queaño et al. (2007), in their reconstruction, believed that during the southward translation of the Palawan microcontinental block, a fragment of this block was subducted along the Manila Trench and was left beneath the Zambales Ophiolite Complex. Consistent with this model, the offshore seismic survey results reported by Arfai et al. (2011) suggest that continental crust underlies the southern portion of the Zambales Ophiolite Complex. These onland field data, offshore geophysical results and palinspathic reconstruction are consistent with the model that slab rollback was followed by the subduction of the leading oceanic edge of a microcontinental fragment, an oceanic bathymetric high. With gravitational instability and negative buoyancy, the steep-angled, rolled-back slab could have broken off (Fig. 9C and D). The subsequent arrival of the microcontinental fragment into the trench led to the flattening of the subduction angle of the slab (Fig. 9D). Continued subduction of the oceanic bathymetric high resulted into the emplacement of the ophiolite over the microcontinental fragment.

The Zambales Ophiolite Complex was previously classified as a Tethyan ophiolite (Yumul et al., 1997). Following Dilek (2003), this ophiolite complex, in spite of its being polygenetic and previously classified as Sierran-type, can be classified as Mediterranean-type, with a complete oceanic crust-mantle sequence emplaced on top of a continental fragment similar to what is recognized elsewhere (e.g. Dilek, 2004; Robertson et al., 2012). The Miocene period saw the Zambales Ophiolite Complex continuously uplifted and eroded. This was followed by the southward translation of the Acoje block-related San Antonio Massif resulting to the present-day configuration of the ophiolite.

3.3. A western Mesozoic ophiolite belt for the Philippines

The eastern seaboard of the Philippines is recognized to be underlain by Mesozoic ultramafic-mafic complexes (e.g. Faustino et al., 2003, 2006; Pubellier et al., 2004; Tamayo et al., 2004; Suerte et al., 2005; Balmater et al., 2015; Guotana et al., 2018). These Mesozoic complexes have been modelled to be derived from the proto-Philippine Sea Plate or Indo-Australian plate. The possibility of the western seaboard being underlain by Mesozoic lithospheric fragments is a distinct possibility (Tamayo et al., 2000, 2001; Dimalanta et al., 2006; Queaño et al., 2007, 2017a; Yumul, 2007). The Zambales Ophiolite Complex has been assigned a Late

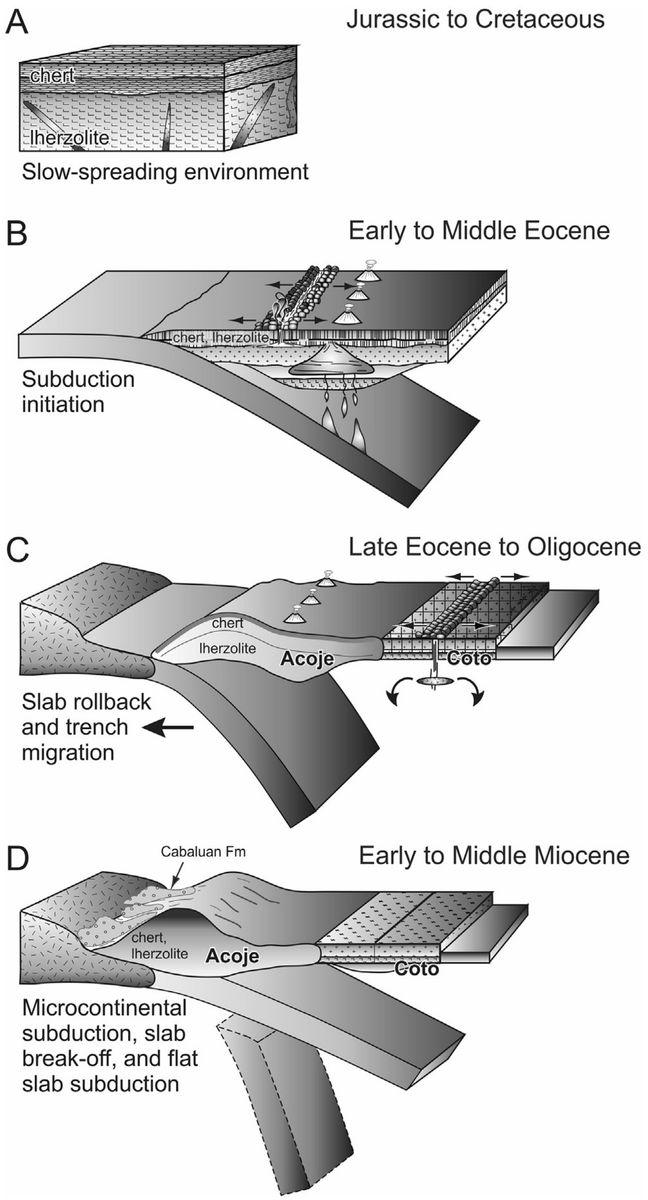

Figure 9. Proposed model regarding the evolution of the Zambales Ophiolite Complex. (A) Chert was deposited during the Mesozoic over the exposed mantle fragments of the Acoje block possibly in a slow-spreading environment. (B) Intra-oceanic subduction initiation took place during the Early to Middle Eocene and led to the formation of the Eocene Acoje block. (C) Slab rollback ensued leading to a steepening of the angle of the subduction. The Acoje block migrated trenchward and the Coto block started to form. (D) Slab rollback during the Eocene–Oligocene was followed by slab break-off (marked by dashed line). With the subduction of the leading edge of the microcontinental fragment at the trench, flat-slab subduction ensued. See text for discussion.

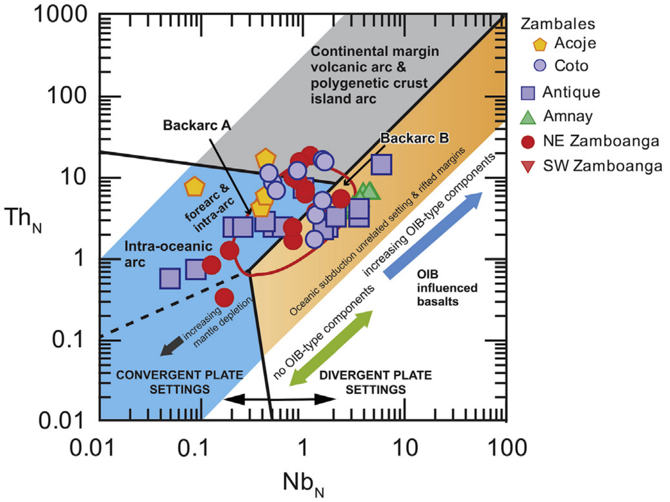

Figure 10. Th vs. Nb plot (after Saccani, 2015) of the volcanic sections of the Zambales, Antique, Amnay, and NE and SW Zamboanga ophiolites. See text for discussion.

Jurassic–Early Cretaceous to Eocene age. The ophiolitic rocks in the Ilocos region in northwestern Luzon were assigned an uppermost Jurassic to lower Cretaceous age based on the radiolarian assemblage obtained from the chert samples (Queaño et al., 2017b). The Amnay Ophiolite is of Middle Oligocene age (Rangin et al., 1985; Jumawan et al., 1998). The Antique Ophiolite in Panay island, Central Philippines has an age ranging from Jurassic to Eocene. The Sibuyan Ophiolite is said to be Jurassic to Cretaceous in age whereas the Zamboanga complexes have been dated pre-Miocene (Maac and Ylade, 1988; Tamayo et al., 2004). Almost all of the reported Mesozoic ophiolites and the Zamboanga Peninsula complexes have been derived from oceanic lithospheric fragments formed during the subduction-related rifting of mainland Asia (Tamayo et al., 2004; Yumul et al., 2004; Zamoras et al., 2008; Dimalanta et al., 2009; Yan et al., 2018). Most of the ultramafic-mafic sequences along the western seaboard exhibit supra-subduction zone signatures. The younger mid-Oligocene Amnay Ophiolite, aside from a transitional arc-mid-ocean ridge geochemistry also exhibits E-MORB-like character. It is clear that, through time, subduction and rifting was operative in the formation of these crust-mantle sequences with the participation of plume magmatism during the Cenozoic period. Available volcanic rock geochemistry also manifests the transitional island arc – mid-ocean ridge character of the rocks (Fig. 10), consistent with subduction-related extensional regimes (forearc or back-arc) similar to other reported ophiolite complexes (e.g. Xiong et al., 2017; Dey et al., 2018). These lithospheric fragments all appear to be allochthonous in origin.

4. Conclusions

Cherts collected from the Acoje block of the Zambales Ophiolite Complex yielded Late Jurassic to Early Cretaceous radiolarian ages. Isotope age dating of the mafic cumulate and volcanic-hypabyssal rocks of the Acoje block yielded middle Eocene age. This is consistent with the Eocene age provided by paleontological studies on the overlying sediments of the Coto block and isotope age datings from its plutonic and extrusive rocks. The Acoje block is believed to have formed first followed by the Coto block. The tectonic setting is envisioned to have evolved from a subduction-related forearc setting that migrated trenchward leading to the rifting and extension of a back-arc basin. Subduction followed by slab rollback, slab break-off and microcontinental fragment subduction beneath the ophiolite can explain the field, geochemical and geophysical features of this crust-mantle sequence. The Zambales Ophiolite Complex typifies a Mediterranean-type crust-mantle sequence emplaced on a microcontinental fragment. Available field data shows that this lithospheric fragment evolved from a slow-spreading to a fast-spreading ridge environment. Lastly, the western seaboard of the Philippines is characterized by supra-subduction zone ophiolites that are of allochthonous origin derived from the rifted oceanic basins that formed through subduction-related extensions that occurred along the fringes of mainland Asia from the pre-Mesozoic through the Cenozoic periods.

Acknowledgments

Field and logistic support from the University of the Philippines-National Institute of Geological Sciences and financial support from the Department of Science and Technology through the years are acknowledged with thanks. The authors also acknowledge the assistance of M.P. Sanchez during the radiolarian biostratigraphic studies and the participation of the 2010 Field Mapping Class of Adamson University during one of the field campaigns. Discussions with other members of the Rushurgent Working Group are appreciated. Comments made by J. Shervais and an anonymous reviewer helped improve our paper. The authors declare that they have no relevant financial interests that relate to the research described in this paper.

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