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Mesozoic rock suites along western Philippines: Exposed proto-South China Sea fragments?

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A B S T R A C T

An ancient oceanic crustal leading edge east of mainland Asia, the proto-South China Sea crust, must have existed during the Mesozoic based on tectonic reconstructions that accounted for the presence of subducted slabs in the lower mantle and the exposed oceanic lithospheric fragments strewn in the Philippine and Bornean regions. Along the western seaboard of the Philippine archipelago, numerous Mesozoic ophiolites and associated lithologies do not appear to be genetically associated with the younger Paleogene-Neogene ocean basins that currently surround the islands. New sedimentological, paleomagnetic, paleontological, and isotopic age data that we generated are presented here, in combination with our previous results and those of others, to reassess the geological make-up of the western Philippine island arc system. We believe that the oceanic lithospheric fragments, associated melanges, and sedimentary rocks in this region are exhumed slivers of the proto-South China Sea ocean plate.

1. Introduction

Tectonic reconstructions of ocean – island arc – continental plate interactions have always taken into consideration the opening and subsequent closure of oceanic basins. Piercing points, magnetic lineation direction of spreading, rate of spreading and regional correlations involving rock suites and ophiolite complexes have been used conventionally in palinspastic restorations (Pubellier et al., 2003; Keenan et al., 2016). Recently, images brought about by P-wave mantle tomography and unfolded subducted slabs, together with computer-based reconstruction programs, have also been utilized in coming up with models on the possible original configuration of areas being studied (Rangin et al., 1999a; Zahirovic et al., 2014). Several works, of similar nature, have been applied to the Philippine island arc system and its surrounding areas (e.g. Rangin, 1991; Queaño et al., 2007a, 2007b; Suzuki et al., 2016; Hall, 2018).

The geological evolution of the Philippine island arc system is intertwined with the opening of the Oligocene to Miocene South China Sea and the drifting of the Palawan micro-continental block (e.g. Taylor and Hayes, 1980; Briais et al., 1993; Cullen et al., 2010). The Palawan Microcontinental Block collision with the seismically-active Philippine Mobile Belt has resulted into geological features typically expected of such interaction (e.g. rotated islands, rifting, emplaced ophiolites) (e.g. McCabe et al., 1987; Concepcion et al., 2011; Manalo et al., 2015) (Fig. 1A). However, there are several geological attributes (Mesozoic sedimentary rock suites, ophiolites, Mesozoic to Oligocene magmatic plutons) that could not be accounted by the subduction of the Oligocene to Miocene South China Sea plate or any other surrounding oceanic plate underneath the Philippine Mobile Belt (Fig. 1B and 1C). It has been realized before that an older oceanic basin has to be responsible for these. The existence and interaction of Mesozoic oceanic plates (e.g. proto-Mesozoic Huatung Basin, paleo-Pacific Plate, proto-Philippine Sea Plate) have been forwarded to possibly account for the observed Mesozoic sedimentary, igneous and metamorphic complexes exposed especially in the central and eastern seaboard of the Philippine island arc system (e.g. Huang et al., 2019; Zhang et al., 2019; Dimalanta et al.,

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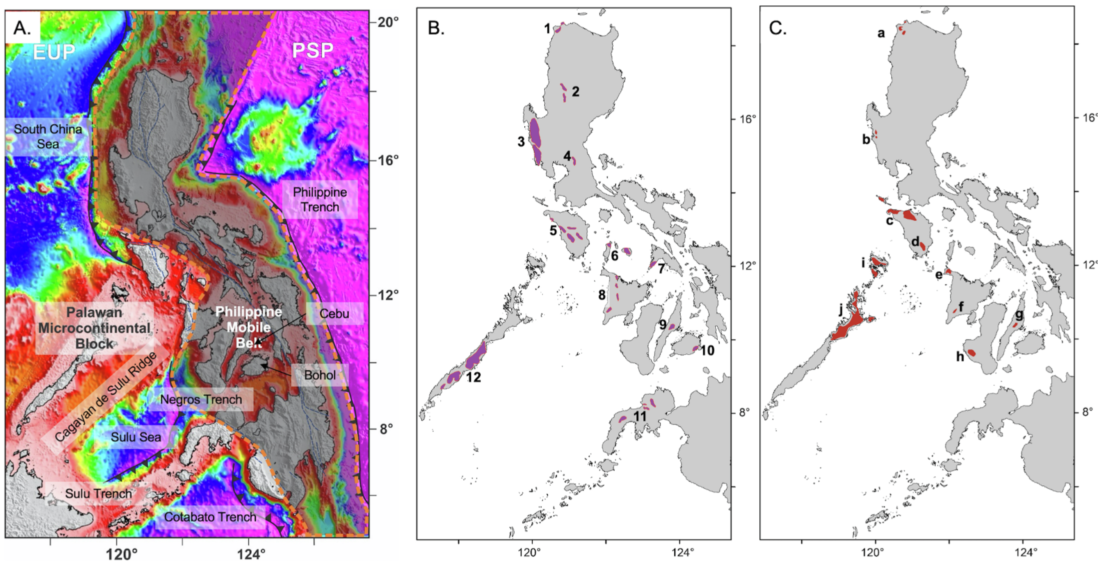

1: Ilocos Norte Ophiolitic Complex, 2: Baguio-Mankayan Ophiolite, 3: Zambales Ophiolite complex, 4: Angat Ophiolite, 5: Mangyan Ophiolite complex, 6: Sibuyan Ophiolite, 7: Balud Ophiolitic Complex, 8: Antique Ophiolite, 9: Lutopan/Cebu, 10: Southeast Bohol Ophiolite Complex, 11:Titay Ophiolitic Complex, 12: Palawan Ophiolite

a: Dos Hermanos Melange, b: Cabaluan Formation, c: Halcon Metamorphics, d: Mansalay Formation, e: Buruanga Peninsula, f: Paniciuan, g: Pandan, h: Southwest Negros, i: Busuanga-Calamian, j: North Palawan

Fig. 1. A. Tectonic map of the Philippines showing the surrounding marginal basins and geological features produced by the collision of the Palawan Microcontinental Block and the Philippine Mobile Belt. Legend: PSP = Philippine Sea Plate, EUP = Sundaland-Eurasian Plate. B. Map showing the ophiolites and ophiolitic complexes (purple shaded areas) exposed along the western seaboard of the Philippines. Numbers correspond to the different ophiolitic units indicated in the figure. C. Map showing the mélanges and sedimentary units (orange shaded areas) which yielded Mesozoic ages. Letters represent the location of the sedimentary units discussed.

2020).

Recent studies have looked into the oceanic plate offshore and east of Mainland Asia that preceded the formation of the Oligocene to Miocene South China Sea plate (e.g. Rangin et al., 1999b; Hall and Spakman, 2015; Wei et al., 2015). This ancient oceanic plate, considered as the proto-South China Sea, has long been consumed along subduction zones (Wu et al., 2016; Fan et al., 2017; Pubellier et al., 2018). Its existence has mostly been deduced from inferred subducted slabs recognized mainly through mantle tomography and by palinspastic reconstruction aided by modeled unfolded slabs. Interestingly, several ultramafic-mafic sequences and Mesozoic sedimentary packages are exposed along the western seaboard of the Philippine island arc system (Fig. 1B and 1C). These complexes are not correlatable with any of the surrounding present-day oceanic marginal basins. Although there is the possibility of these rock suites coming from a paleo-Pacific, proto-Philippine Sea or Mesozoic Australian plate, these Mesozoic fragments may actually owe their origin from the proto-South China Sea plate. If indeed these are part of the proto-South China Sea plate, this can help in elucidating and constraining the geological evolution of the Philippines, in particular, and this lost ancient oceanic plate, in general.

2. Methods

Available geological information on the different Mesozoic ophiolites, related oceanic and arc fragments and sedimentary sequences were compiled and presented (Tables 1, 2 & 3). The geology of three Cretaceous oceanic lithospheres (Angat Ophiolitic Complex in Luzon, Balud Ophiolitic Complex in Masbate, Southeast Bohol Ophiolite Complex in Bohol) and Cretaceous sedimentary complex (Pandan Formation), volcanic arc (Cansi Volcanics) and pluton (Lutopan Diorite) were also looked into (Fig. 1). The interest in this comes from the fact that their locations along the central part of the Philippine Mobile Belt make it difficult to determine from what oceanic basin or magmatic arc they could have come from. The possibility that they were actually part of the proto-South China Sea plate was investigated.

Data on available paleomagnetic results were also compiled and reanalyzed. Obtaining paleomagnetic data for tectonic reconstruction from Mesozoic ultramafic to mafic rock complexes and associated sediments on the western seaboard of the Philippine archipelago have met with limited success. We are presenting the most reliable published pre-Cenozoic paleomagnetic data with the hope that it can help in elucidating, to a certain extent, the evolutionary path/s the different complexes in this part of the Philippines had undergone.

3. Results

3.1. Geology

3.1.1. Proto-South China Sea

The existence of a Mesozoic oceanic crust ahead of the formation of the Oligocene – Miocene South China Sea crust has been reported before (Holloway, 1981; Sarewitz and Karig, 1986; Faure et al., 1989; Hinz et al., 1991; Faure and Natalin, 1992; Tamayo et al., 2004; Sun, 2016). However, it was only very recently that the study of the evolution of this ancient oceanic plate has taken root as shown by the preponderance of published literatures. Wu et al. (2016), in their paper, had concluded that several geological facets of the Philippine Sea and East Asian region can be explained fully with the presence of two oceanic plates, the proto-South China Sea and East Asian Sea, both of which are now fully consumed. An Eocene age has been opined by Wu and Suppe (2017) for the proto-South China Sea plate. In their reconstruction, involving mapped and unfolded slabs, this ancient oceanic plate basin extended below the Luzon island in the east and beneath the Borneo area in the south. Double-sided subductions involving northward direction underneath the Dangerous Grounds at 450 to 700 km depth and southward plunge underneath Borneo at 750 to

Table 1
Compilation of geochemical characteristics of western Philippine ophiolites.

Location	Spinel Cr#	Ol Fo%	Volcanic Rocks	Tectonic Setting	Crystallization Order	Age of Intrusives (Ma)	Age of sed carapace	References
Ilocos Norte/ Dos Hermanos (mélange)	Lz: 0.17–0.24 Hz: 0.47–0.52	Lz: 88–90 Hz: 89-91 Tr: 81-82 Gab: 66–80		Mid-ocean ridge - island arc	Mafic clasts: ol-plag-cpx		Late Jurassic to Early Cretaceous: radiolarians from chert	Queaño et al., 2017a; Pasco et al., 2019
Zambales: Acoje Block	Hz: 0.1–0.55 Dun: 0.65–0.80	Restite: 90-92 Cumulate: 80–90.5	MORB-IAT	Paired arc-backarc marginal basin	Hz: ol-sp-opx-cpx Dun: ol-sp-minor opx&cpx	44.1 ± 3.0 (K-Ar of sill in pillow basalt); 44.4 ± 0.7 (U-Pb of tonalite)	Late Jurassic to Early Cretaceous: radiolarians from chert	Fuller et al., 1989; Encarnacion et al., 1993; Queaño et al., 2017b
Zambales: Coto Block	Cr: < 0.6	Residual hz: 90-92 Cumulate: 89–84	Transitional MORB-IAT	Paired arc-backarc marginal basin	Dun-hz: ol-sp-opx Ol gab: ol-plag-cpx Gab: plag-cpx	45.1 ± 0.6 (U-Pb of tonalite & hbl qtz diorite); 46.6 ± 5.1 (K-Ar of diabase dike)		Hawkins & Evans, 1983; Fuller et al., 1989; Encarnacion et al., 1993
Angat			MORB, IAT	Back-arc basin		48.1 ± 0.5 (U-Pb of tonalite dike)	Cretaceous: radiolarians from radiolarite	Arcilla et al., 1989; Encarnacion et al., 1993; Yumul, 1993
Amnay	Lz: 0.10–0.20 Cr: 0.6 Hz: > 0.6 & < 0.3	Lz: 90–94	N-MORB, E-MORB, OIB; calc-alkaline, sub-alkaline, minor tholeiitic	Marginal basin		23.2 & 23.4 (U-Pb of troctolite); 33.4 & 34.3 (U-Pb of gabbro)	Middle Oligocene: foraminifera in siltstone	Rangin et al., 1985; Jumawan et al., 1998 ; Yumul et al., 2009
Palawan	Hz: 0.50–0.75 Cr: 0.38–0.90	Web: 80.7 Wehr: 82.2 Lz: 90 Hz: 91-92 Dun: 85–92	MORB to MORB-IAT (Central Palawan); IAT, OIB (South Palawan)	Back-arc basin		34.1 ± 0.1 (U-Pb of plagiogranite, C. Palawan)	Early Cretaceous: nannoplanktons from deep sea sediments; Cretaceous: radiolarians from chert	Raschka et al., 1985; Claveria & Fischer, 1991; Muller, 1991; Tamayo et al., 2004; Yumul et al., 2009; Keenan et al., 2016
Antique	Hz: 0.22–0.66 Dun: 0.6	Hz: 90-92 Dun: 91–92	Transitional MORB-IAT, N-MORB	Mixed forearc - marginal basin			Late Cretaceous: radiolarians from chert	Rangin et al., 1991; Tamayo et al., 2001, 2004; Yumul et al., 2020
Balud			Subalkaline tholeiitic basalts	Transitional MORB-like to IAT			Early to Late Cretaceous: radiolarians from chert	Manalo et al., 2015
SE Bohol	Hz: 0.24–0.49 Dun: 0.37–0.4; 0.78–0.80 Lz & Wehr: 0.16–0.18	Hz: 90–91.5 Lz: 90.4 Dun: 91	Boninitic, MORB-like, calc-alkaline, high-Mg andesite	Supra-subduction zone	Gab: plag-cpx; Nor: cpx-opx-plag			De Jesus et al., 2000; Faustino et al., 2003; Yumul et al., 2001
Titay, Zamboanga Peninsula	Hz: 0.40–0.55	Hz: 90–92	N-MORB	Back-arc basin			Late Cretaceous(?): regional correlation	Tamayo et al., 2004; Yumul et al., 2020

Legend:
Hz = harzburgite; Lz = lherzolite; Dun = dunite; Wehr = wehrlite; Web = websterite; Cr = chromitite; Gab = gabbro; Ol gab = olivine gabbro; Tr = troctolite.
Cpx = clinopyroxene; Opx = orthopyroxene; Ol = olivine; Plag = plagioclase; Sp = spinel.
MORB = mid-ocean ridge basalt (N = normal; E = enriched); IAT = island arc tholeiite; OIB = ocean island basalt.
Cr# = Cr/(Cr + Al).
Fo% = Mg/(Mg + Fe^{2+}).

Table 2
Comparison of characteristics of Mesozoic arc rocks in the western portion of the Philippines.

Location	Rock Type	Geochemical Affinity	Tectonic Setting	Age	References
Basak Fm (SW Negros)	Basalt; agglomerate		Arc	Cretaceous to Eocene	Bobis & Comia, 1987; Maglambayan et al., 1998
Daroctan Granite (Palawan)	Granite	Arc-related	Arc	87.3 ± 4.9 Ma and 85.7 ± 8.2 Ma (U-Th-total Pb of monazite)	Padrones et al., 2017a
Lutopan and Cansi Diorite (Cebu)	Diorite	Adakitic	Intra-oceanic island arc	107.10 ± 0.5 Ma – 109.01 ± 0.47 Ma (U-Pb of zircons)	Deng et al., 2019
Cansi Basalt (Cebu)	Basalt	Calc-alkaline	Arc	118.5 ± 1.2 Ma (pyroclastics); 126.2 ± 2.4 Ma (porphyritic andesite)	Deng et al., 2015

900 km depth have been modelled (Wu and Suppe, 2017; Lin et al., 2020). The Dangerous Ground and Borneo ultimately collided at 20-15 Ma (Early to Middle Miocene) (Ding and Li, 2016; Wu and Suppe, 2017). On the other hand, Hall and Breitfeld (2017), following the study of Hall and Spakman (2015), think that the proto-South China Sea had occupied the same areas occupied by the Oligocene to Miocene South China Sea. Aside from being Mesozoic in age, they proposed that this oceanic basin was consumed solely by southward subduction underneath Borneo, Cagayan arc and parts of the western Philippines (Figure 8a of Hall and Breitfeld, 2017). In addition to this, it was proposed that a portion of the proto-South China Sea is still present in the north of the Sulu Sea, associated with the ophiolitic fragments in Palawan (Rangin et al., 1999; Pubellier et al., 2018). Subduction is thought to have occurred during the Eocene to early Miocene (e.g. Tongkul, 1997; Hall and Breitfeld, 2017). The extent of the north proto-South China Sea plate that subducted beneath the Dangerous Ground, following Wu and Suppe's (2017), is beneath the whole of Luzon and northern part of the Visayas in Central Philippines (Figure 5b of Wu and Suppe, 2017). On the other hand, based on P-wave velocity tomography, Fan et al. (2017) think that the proto-South China Sea plate can only be observed beneath the Visayas in Central Philippines (Figure 9 of Fan et al., 2017). These differences in interpretations highlight the fact that there are still a lot of things to know to understand this old oceanic plate. Paleo-biogeographic reconstruction of areas thought to be associated with the proto-South China Sea ocean basin revealed that during the mid-Triassic, Tethyan and Pacific-derived radiolarians abound in this basin. A dominant Pacific source of radiolarians characterized the mid-Jurassic. The Late Cretaceous proto-South China Sea basin was a closed one as suggested by the minimal Tethyan and Pacific-sourced radiolarians (Zheng et al., 2019).

3.1.2. Western Philippines

Mesozoic ophiolites, dismembered lithospheric fragments and mélanges are exposed along the western sides of Luzon, the Visayas and Mindanao in the Philippines. The Cretaceous ophiolite and ophiolitic complexes exposed in Luzon include the Ilocos Norte, the Acoje block of the Zambales Ophiolite Complex, Mangyan Ophiolite, the Cretaceous Southern Palawan Ophiolite in Palawan; the Antique Ophiolite in Panay island and the reported Cretaceous-Paleogene volcanic rocks in southwest Negros (Table 2) are exposures along the western part of the Visayas whereas the Titay Ophiolitic Complex is exposed in southwest Zamboanga Peninsula in Mindanao island (Fig. 1B) (e.g. Canto et al., 2012; Claveria and Fischer, 1991; Queaño et al., 2017b, 2017a; Rammlmair et al., 1987; Tamayo et al., 2001; Yumul et al., 2020). Mesozoic sedimentary rock suites and melanges, which include exotic chert blocks, limestone and volcanic rocks (e.g. Isozaki et al., 1988; Wakita and Metcalfe, 2005), are also evident along the western part of the Philippines. These include the Dos Hermanos Mélange, chert carapace of the Acoje block, Zambales Ophiolite, Mesozoic sedimentary formations in Halcon and Mansalay both in Mindoro, north Palawan, Busuanga – Calamian and Buruanga Peninsula (e.g. Hashimoto and Sato, 1968; 1973; Faure and Ishida, 1990; Suzuki et al., 2000; Zamoras and Matsuoka, 2004; Gabo et al., 2009; Queaño et al., 2017b; Pasco et al., 2019) (Fig. 1C). A description of each follows (Tables 1–3).

3.1.2.1. Ophiolite and ophiolitic complexes

3.1.2.1.1. Ilocos Norte Ophiolitic complex. The northwest part of Ilocos Norte province was previously mapped to comprise of an ophiolite basement albeit incomplete due to the absence of a gabbro section (e.g. Pubellier et al., 2004; Tamayo et al., 2004). Smith (1907) first reported the presence of variably serpentinized pyroxenites, which occur with reddish radiolarian chert, in Baruyen River, Pasuquin and Bangui, Ilocos Norte (Fig. 2A). Pinet and Stephan (1990) mapped serpentinite bodies within north-south to northeast-trending deformation zones. They also reported the presence of gabbros within the serpentinites. Arai et al. (1997) observed pebbles of harzburgite, troctolite, olivine gabbro, gabbro and pegmatitic hornblende gabbro in the Tulnagan River. They noted that some of the ultramafic and mafic rocks have been metamorphosed to greenschists and amphibolites. The spinel Cr# [Cr/(Cr + Al)] of the Ilocos harzburgite varies from 0.4 to 0.8, higher than that of abyssal peridotites (Cr# < 0.6), which indicates a supra-subduction zone origin (e.g. Arai et al., 1997). The Ilocos Norte ophiolitic complex was previously assigned a Late Jurassic to Early Cretaceous age based on radiolarians extracted from associated chert samples (e.g. Tamayo et al., 2004).

3.1.2.1.2. Acoje Block, Zambales Ophiolite complex. The Acoje Block is one of two blocks that make up the Masinloc Massif of the Zambales Ophiolite Complex. It is the northernmost block in the north-south trending ophiolite complex (Fig. 3A). The Acoje Block manifests field, petrographic and geochemical characteristics which are distinct from the Coto Block. The former is made up of very fertile lherzolites, harzburgites, transition zone dunites, layered ultramafic cumulate rocks (websterites, wehrlites, clinopyroxenites), mafic cumulate rocks (gabbronorites, norites, gabbros), sheeted diabase-dike sill complex and pillow basalts. In contrast, the Coto Block consists of residual harzburgites, a thin transition zone dunites, cumulate gabbros and troctolites. The Coto Block lacks a well-developed layered ultramafic cumulate sequence. The ultramafic cumulate rocks from the Acoje Block are characterized by spinel Cr# > 0.60 in contrast to the spinel Cr# < 0.60 of samples from the Coto Block. Whole rock and mineral chemistry of the volcanic and ultramafic rocks indicate formation of the Acoje Block in an island arc setting (e.g. Perez et al., 2018; Yumul et al., 2020). The Zambales Ophiolite Complex was previously assigned an Eocene age (44–47 Ma) based on whole rock K-Ar and zircon U-Pb dating of diabase, granodiorite and tonalite dikes (e.g. Fuller et al., 1989; Encarnacion et al., 1993). The Late Jurassic – Early Cretaceous age obtained recently from the chert blocks and clasts within the Cabaluan Formation overlying the Acoje Block led to the thinking that this block could be a Mesozoic ophiolite fragment within the Zambales Range Complex (e.g. Ishida et al., 2012; Queaño et al., 2017b).

3.1.2.1.3. Mangyan Ophiolite, Mindoro island. Earlier models on the tectonic makeup of Mindoro island is that it is composed of three terranes, from southwest to northeast as: the North Palawan Block, the Mindoro Suture Zone, and the Mindoro Block (Sarewitz and Karig,

Table 3
Mesozoic sedimentary and mélange units in western Philippines and their characteristics.

Lithologic Unit	Location	Age	Basis	Description	Environment of Deposition	References
Dos Hermanos Mélange	Ilocos Norte	Late Jurassic to Early Cretaceous	Radiolarian assemblage	Pebble to cobble sized serpentinized peridotite, greenschist, quartz-mica schist, gabbro and chert clasts set in a highly sheared sandy matrix; cherts are red, ribbon-bedded knockers within the serpentinite matrix of the mélange	Accretionary prism	Queaño et al., 2017a; Pasco et al., 2019
Cabaluan Fm.	Acoje, Zambales	Late Jurassic to Early Cretaceous (chert clasts); late Early to early Middle Miocene	Radiolarian assemblage; Foraminiferal assemblage	Thick conglomerate beds with few intervening thin to thick sandstone-siltstone-mudstone beds; clasts of peridotites and minor gabbros and chert set in poorly sorted coarse sand matrix	Inner to middle neritic zone	Queaño et al., 2017b
Abra de Ilog Fm.	Mindoro	Late Cretaceous	Foraminiferal assemblage	Graywacke-chert-shale sequence with intercalated spilitic basalt flows	Marine	Hashimoto, 1981; Karig, 1983
Mansalay Fm.	Mindoro	late Middle Jurassic to early Late Jurassic	Ammonite	Thin to thickly bedded sandstones, shale, and mudstones; sandstones mostly epiclastic lithic and arkosic arenites	Non-marine, tidal, shallow marine	Andal et al., 1968; Sarewitz & Karig, 1986; Sato et al., 2012
Unidos Fm.	Buruanga Peninsula, Panay	early Middle Jurassic	Radiolarian assemblage	Thin to thick beds of complexly folded bedded chert	Pelagic	Zamoras et al., 2008
Gibon Fm.		early Middle Jurassic	Correlation with Unidos Fm.	Indurated, thin to thickly bedded pelagic limestone, lime mudstone and wackestone; with gray chert nodules/lenses	Pelagic	Zamoras et al., 2008
Saboncogon Fm.		late Middle Jurassic to early Late Jurassic	Radiolarian assemblage	Siliceous mudstones and terrigenous mudstone-sandstone-shale interbeds	Pelagic	Zamoras et al., 2008; Gabo et al., 2009
Paniciuan Melange	Antique, Panay	Early Cretaceous	Radiolarian assemblage	Deformed clasts of serpentinized peridotites, gabbros, sandstones and chert in silty matrix	Accretionary prism	Tamayo et al., 2001; this study
Minilog Limestone	North Palawan & Busuanga-Calamian Group of Islands	Late Permian to Middle Triassic	Foraminiferal assemblage	Micritic, massive to partly bedded, partly recrystallized, oolitic limestone; some dolomite present	Accretionary prism	Wolfart et al., 1986
		Middle to Late Permian (Lower); Early to Middle Triassic (Upper)	Fusulinid assemblage (lower); Conodont assemblage (upper)	Recrystallized limestone, partly bedded and oolitic; partly oolitic lower horizon and massive, bituminous upper horizon		Zamoras & Matsuoka, 2001
Coron Limestone		Triassic to Late Jurassic	Fossil assemblage	Massive, jointed limestone with local interbeds of arkosic to quartzose sandstone and silty to muddy shale; crystalline, reefal, and in places oolitic and conglomeratic	Open marine; Accretionary prism	Wolfart et al., 1986
		late Late Triassic	Occurrence of pelecypod *Paramegalodus*	Massive to bedded, light to dark gray, crystalline, reefal, oolitic or conglomeratic		Zamoras & Matsuoka, 2001
Liminangcong Fm.		Late Permian to Late Jurassic		Hematite-bearing chert with slate and bedded tuff; with interbedded manganese ore layers	Accretionary prism	Hashimoto & Sato, 1973; Fontaine, 1979; Wolfart et al., 1986
		Middle Permian to Late Jurassic	Radiolarian assemblage	Bedded chert sequences of highly varying characteristics, commonly intercalated with clayey layers, distributed in the northern part of Palawan Island and Calamian islands		Zamoras & Matsuoka, 2001; Marquez et al., 2006
Guinlo Fm.		Late Jurassic to Early Cretaceous	Stratigraphic position	Weakly metamorphosed, cross-stratified coarse sandstone with minor conglomerate interbeds containing clasts of quartz and siliceous rocks	Accretionary prism	Hashimoto & Sato, 1973
		Middle Jurassic to Early Cretaceous	Radiolarian assemblage	Siliceous mudstone and terrigenous interbeds of mudstone, sandstone, and conglomerate		Zamoras & Matsuoka, 2001; Marquez et al., 2006
Bicatan Melange				Poorly layered melange of indurated micritic limestone, basalt and bedded chert in mudstone matrix	Accretionary prism	Zamoras & Matsuoka, 2001
Pandan Fm.	Cebu	middle to late Late Cretaceous	Foraminiferal assemblage	Highly indurated and deformed sandstones, shales and conglomerates	Pelagic to partly turbiditic	Porth et al., 1989; Rodrigo et al., 2020

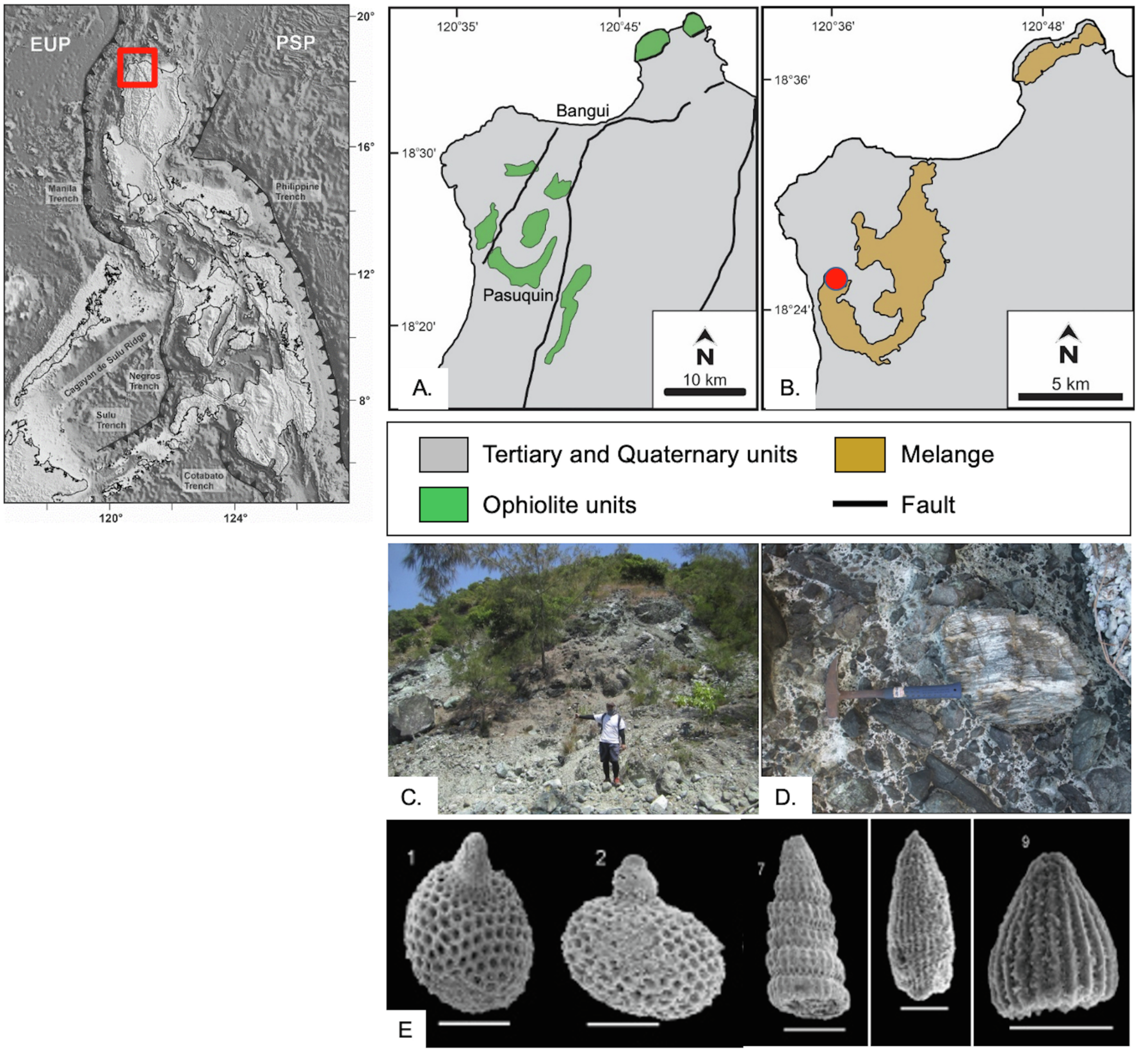

Fig. 2. A. Ultramafic and mafic units in Pasuquin and Bangui, Ilocos Norte previously believed to form part of an ophiolitic sequence (green areas). B. Ultramafic units enclosed within the Dos Hermanos Melange (brown areas) based on recent mapping. Red circle shows where the outcrop photos in C and D were taken. C. Photo of the Dos Hermanos Melange as observed at Pasuquin Hills (N18°22′44″, E120°42′13″). D. Close-up view of clasts of peridotite, chert and schist within a serpentinized matrix (N18°38′21.3″, E120°51′23.1″). E. Radiolarians extracted from the chert samples (from left to right): *Hiscocapsa asseni* (Tan), *Hiscocapsa* sp. cf. *H. asseni* (Tan), *Pseudodictyomitra carpatica* (Lozyniak), *Archaeodictyomitra* sp. and *Thanarla brouweri* (Tan). The white lines correspond to a length of 100 µm.

1986). Within the Mindoro Suture Zone, the Lubang-Puerto Galera ophiolite is floored by a broken formation that is thought to correlate with the Eocene Zambales Ophiolite Complex (Karig, 1983; Yumul et al., 2009). Also distributed NW-SE are small, isolated blocks of ultramafic lithologies that were previously referred to as the Mangyan Meta-ophiolite (Rangin et al., 1985). Ages from the sedimentary carapace associated with the volcanic units of this ophiolite provided the basis for the Cretaceous age assignment (Hashimoto, 1981). The *meta*-ophiolite was later renamed as the Mangyan Ophiolite based on the less fragmented southeastern extension exposed along the central mountain range of the island (Karig, 1983; Rangin et al., 1985) (Fig. 4A).

Other models consider Mindoro island as made up of only two terranes. One model suggests the combination of a Central Range terrane and a San Jose Platform (Fig. 2 of Canto et al., 2012), and another describes the island to consist of a northern block of Philippine Mobile Belt affinity and a southern block of Palawan Microcontinental Block affinity (Fig. 1 in Yumul et al., 2009). The latter model accounts for a northern section with the basal pre-Cretaceous Halcon Metamorphics and the Mangyan Ophiolite, and overlain by the Lasala Formation; and a southern block floored by the Jurassic sedimentary Mansalay Formation, overthrust by the Middle Oligocene Amnay Ophiolite (Yumul et al., 2009) (Fig. 4A–B). Canto et al. (2012) suggested that the Mangyan Ophiolite occurs as fragmented blocks within the metamorphic units of the Central Range and are composed of extremely sheared and pervasively serpentinized harzburgites, isotropic gabbros, dikes and pillow basalts. The Cretaceous age of these enclosed disrupted bodies are taken to indicate the minimum age for the interaction between mainland Asia and the oceanic lithosphere from which the blocks were derived. Our recent mapping resulted in the identification of several distinct lithologic units that, when taken together, constitutes a near-complete ophiolite sequence. Zahirovic et al. (2014) suggest that these lithospheric fragments represent sections of the proto-South China Sea that were emplaced via subduction-related processes.

3.1.2.1.4. Southern Palawan Ophiolite, Palawan. West of the Ulugan Bay Fault, the Southern Palawan Block comprises of Eocene and Cretaceous ophiolites (Fig. 5A-B). The Palawan Ophiolite exposed in central Palawan is composed of a mantle section dominated by harzburgites and dunites with chromitites, isotropic gabbros and pillow basalts with associated cherts (Raschka et al., 1985). The ophiolite lacks a sheeted dike complex. Radiometric dating of gabbros and metamorphic rocks in central Palawan yielded an Eocene age

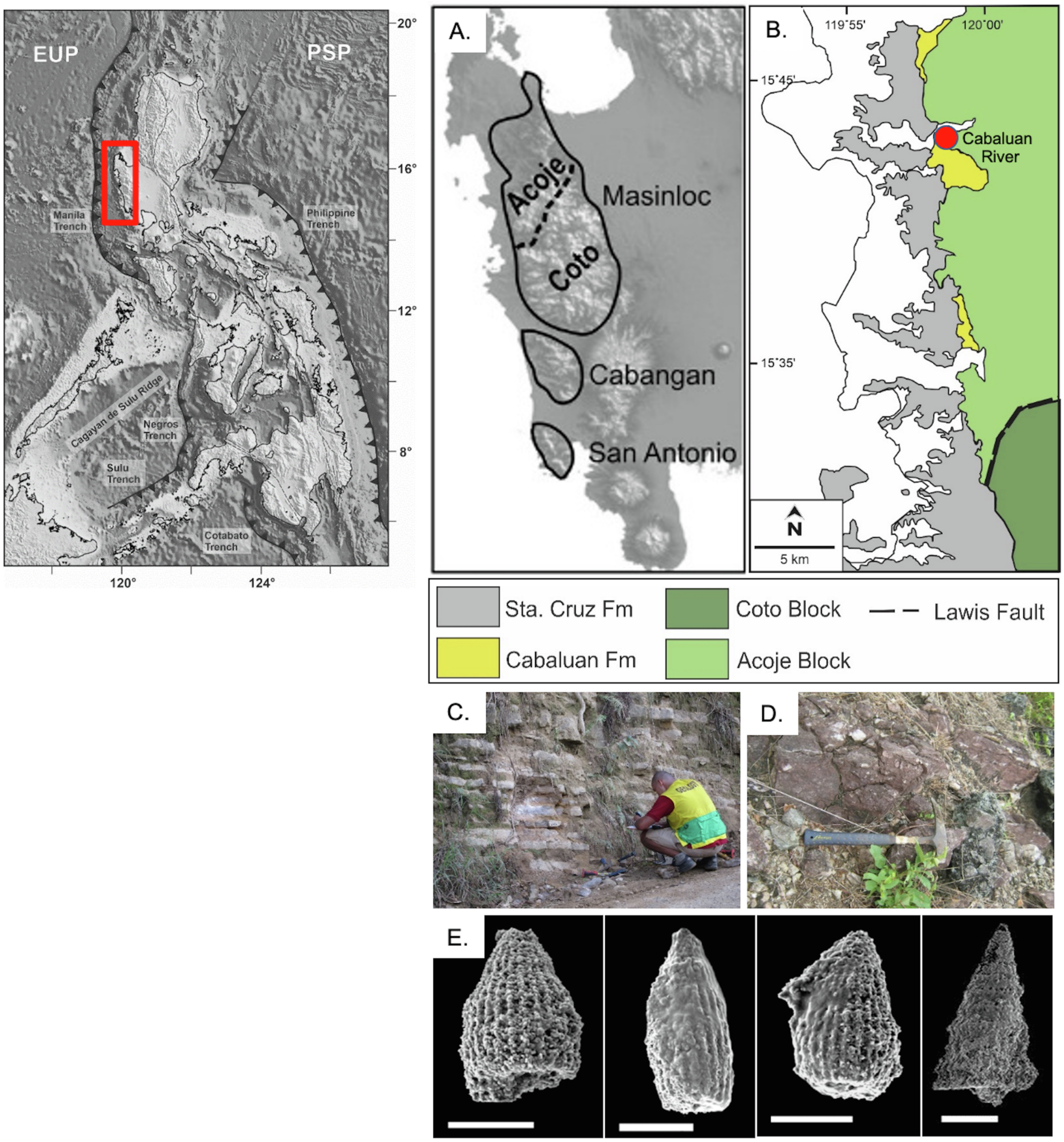

Fig. 3. A. Masinloc, Cabangan and San Antonio Massifs comprising the Zambales Ophiolite Complex in western Luzon. The Masinloc Massif is further divided into the Acoje and Coto Blocks. B. The Cabaluan Formation, best exposed along the Cabaluan River, unconformably overlying the Acoje Block. Red circle shows where the outcrop photos in C and D were taken. C. Interbeds of sandstone-siltstone-mudstone near the Cabaluan River (N15°41′19.5″, E119°56′7.5″). D. Chert blocks found within the Cabaluan Formation (N15°42′41.5″, E119°54′36.5″). E. Radiolarians from the chert blocks include (from left to right): *Thanarla brouweri*, *Thanarla* sp., *Pseudodictyomitra* sp. and *Pseudodictyomitra carpatica*. The white lines correspond to a length of 100 µm.

(Encarnacion et al., 1995; Keenan et al., 2016). Chromitites in central Palawan contain spinel Cr# of 0.38 to 0.90 (Rammlmair et al., 1987; Claveria and Fischer, 1991). Santos (1997), on the other hand, established that the chromitites in Palawan are compositionally heterogenous and formed from melt-rock interaction and fractional crystallization. The crustal section of the Palawan Ophiolite exhibits tholeiitic to calc-alkaline signatures, and mid-ocean ridge basalt (MORB) to transitional MOR – island arc tholeiite (IAT) affinities (Raschka et al., 1985). Fernandez (2001) reported low to medium K and tholeiitic signatures for basalts and diabase in central Palawan. Mantle peridotites and basalts are also exposed in southern Palawan (Fig. 5C–D). Previous works correlate these rocks with the ophiolitic lithologies in central Palawan. However, paleontological dating using calcareous nannoplankton assemblages from deep sea sediments yielded an Early Cretaceous age for the southern Palawan Ophiolite (Muller, 1991). Almasco et al. (2000) referred to the ophiolitic lithologies in south Palawan as the “Calatuigas Ophiolite”. Paleomagnetic studies on basalts and andesites of the Calatuigas Ophiolite reveal that the ophiolite was obducted from the south and rotated counterclockwise during its northward translation (Almasco et al., 2000). The Southern Palawan Ophiolite is thought to be a trapped oceanic lithosphere emplaced onto the continental North Palawan Continental Terrane (Mitchell et al., 1986). The thrusting of this denser oceanic lithosphere during the Early Miocene is attributed to the collision of Palawan with the Cagayan de Sulu Arc (e.g. Raschka et al., 1985; Keenan et al., 2016). It has to be noted, though, that there is another school of thought that states that the Palawan Ophiolite has to be rooted on the northern side along the South China Block which would be in agreement with the observed intrusion of Cretaceous plutons and structural analyses (e.g. Faure and Natalin, 1992; Wei

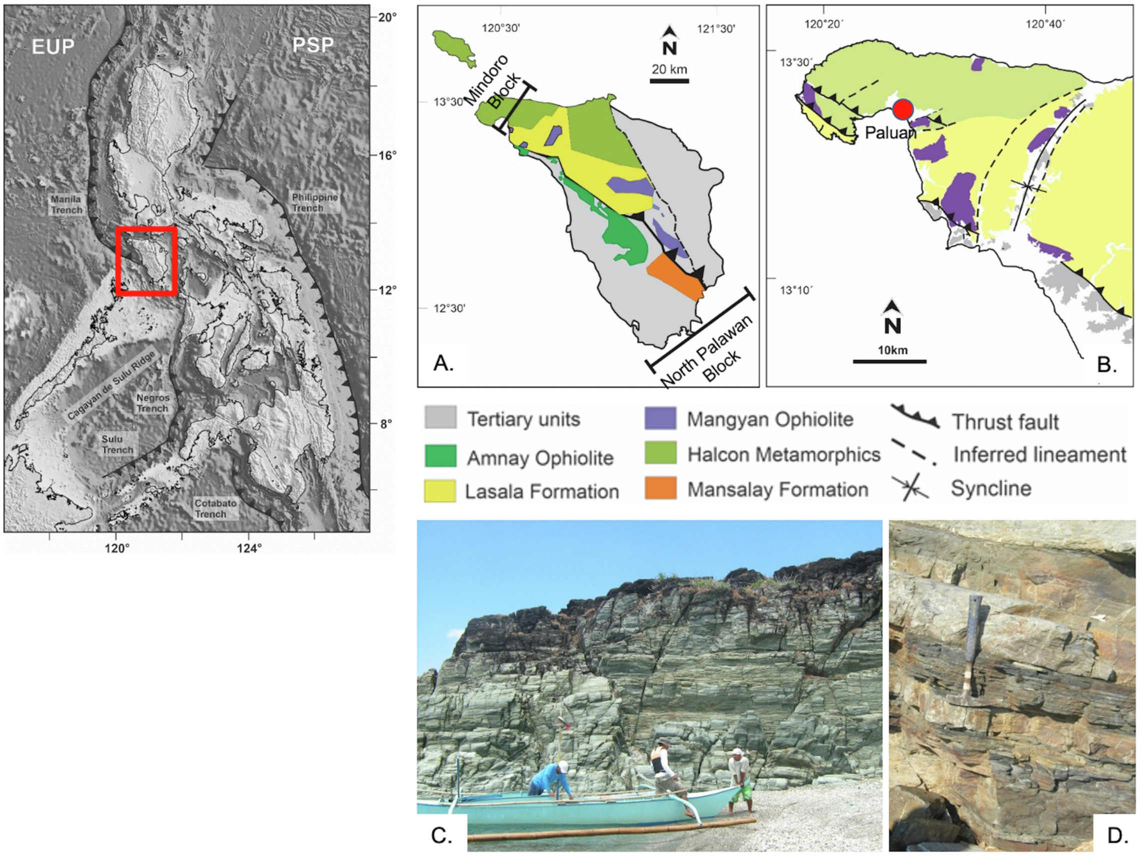

Fig. 4. A. Mindoro island underlain by the Jurassic Mansalay Formation, pre-Cretaceous Halcon Metamorphics, Eocene Lasala Formation and the Oligocene Amnay Ophiolite. B. Northwest Mindoro underlain by the Halcon Metamorphics, Mangyan Ophiolite, Lasala Formation and Amnay Ophiolite. Red circle shows where the outcrop photos in C and D were taken. C. Outcrop of Halcon Metamorphics along the Paluan coast (N13°24′49.3″, E120°23′51″). D. Close-up view of the Halcon Metamorphics.

et al., 2015). The presence and near juxtapositioning of the Cretaceous southern Palawan Ophiolite and Eocene central Palawan Ophiolite is similar to what is recognized elsewhere in the Philippines.

3.1.2.1.5. Antique Ophiolite, Panay island. Northeast and north-south trending ophiolite bodies occupy the Antique Range in western Panay particularly along Sibalom River (Fig. 6A). The Antique Ophiolite is also closely associated with the Paniciuan Mélange (Fig. 7A-B). The ophiolite is made up of serpentinites, serpentinized harzburgites, layered mafic rocks with thin dunite layers, sheeted dikes, basaltic sheet flows and pillow basalts conformably overlain by chert beds (Tamayo et al., 2001). Serpentinized dunites, harzburgites and lherzolites have also been mapped in Bugtong Bato in the northern part of western Panay (Zamoras et al., 2008) (Fig. 6B–C). The rare earth element (REE) patterns displayed by the Antique ultramafic rocks (slight enrichment in HREE and LREE with respect to the MREE) are similar to those seen in the Izu-Bonin-Marianas fore-arc peridotites (Tamayo et al., 2001). Mineral chemistry analysis of the harzburgites shows that the olivine and orthopyroxene are highly magnesian (olivine Mg# [Mg/(Mg + Fe^{2+})] = 0.91–0.92 and orthopyroxene Mg# 0.91-0.97, respectively). A wide range of Cr# is noted for the spinels from harzburgites (Cr# = 0.22–0.66) with the majority of the spinels showing Cr# < 0.60 (Tamayo et al., 2001; Yumul et al., 2013). The volcanic sequence made up of basalts and diabases are mostly olivine tholeiites and display transitional (T)-MORB, normal (N)-MORB and intermediate MORB-IAT geochemical signatures (Tamayo et al., 2001). A Barremian-Aptian age (Late Cretaceous) was assigned to this ophiolite based on radiolarians extracted from chert samples (Rangin and Silver, 1991; Rangin et al., 1991).

3.1.2.1.6. Titay Ophiolitic Complex, Zamboanga Peninsula. The Zamboanga Peninsula consists of two contrasting geologic terranes separated by the northwest-trending Siayan-Sindangan suture zone: the northeast block consisting of an ophiolitic suite with metamorphic, volcanic and sedimentary rocks (Yumul et al., 2004) and the southwest block which consists of quartz-rich metamorphic rocks believed to be of continental affinity (Tamayo et al., 2000) (Fig. 8A). The northeast block is underlain by the Late Oligocene to Early Miocene Polanco Ophiolite Complex, a northwest-trending, complete crust-mantle sequence (Yumul et al., 2004). This ophiolite complex has transitional MORB-IAT and calc-alkaline affinities whereas its dunites and harzburgites are similar to forearc and abyssal peridotites (Tamayo et al., 2004). Along the central portion of the Zamboanga Peninsula, which is part of the southwest block, is the Late Cretaceous Titay ophiolitic sequence (Tamayo et al., 2004) (Fig. 8B–D). This, we believe, is equivalent to the Labason Ophiolite reported by Pubellier et al. (1991) in the Zamboanga Peninsula. The Titay Ophiolitic Complex harzburgites (Fig. 8D) are characterized by transitional abyssal to forearc peridotite geochemical characteristics possibly formed in a back-arc basin setting (Tamayo et al., 2004). This oceanic fragment is thrusted over the Dansalan Metamorphics (Tamayo et al., 2000; Yumul et al., 2004). The characteristics of the crust-mantle sequences in Zamboanga prompted previous workers to infer that the peninsula could be part of Borneo or it could represent the southernmost part of the Palawan Microcontinental Block (Tamayo et al., 2000; Yumul et al., 2004).

3.1.2.2. Volcanic and intrusive rocks

3.1.2.2.1. SW Negros volcanic rocks, Negros island. Southwest Negros was reported to be underlain by Upper (?) Cretaceous sandstone, shale, spilite and pillow basalt (Hamilton, 1979) (Fig. 1C).

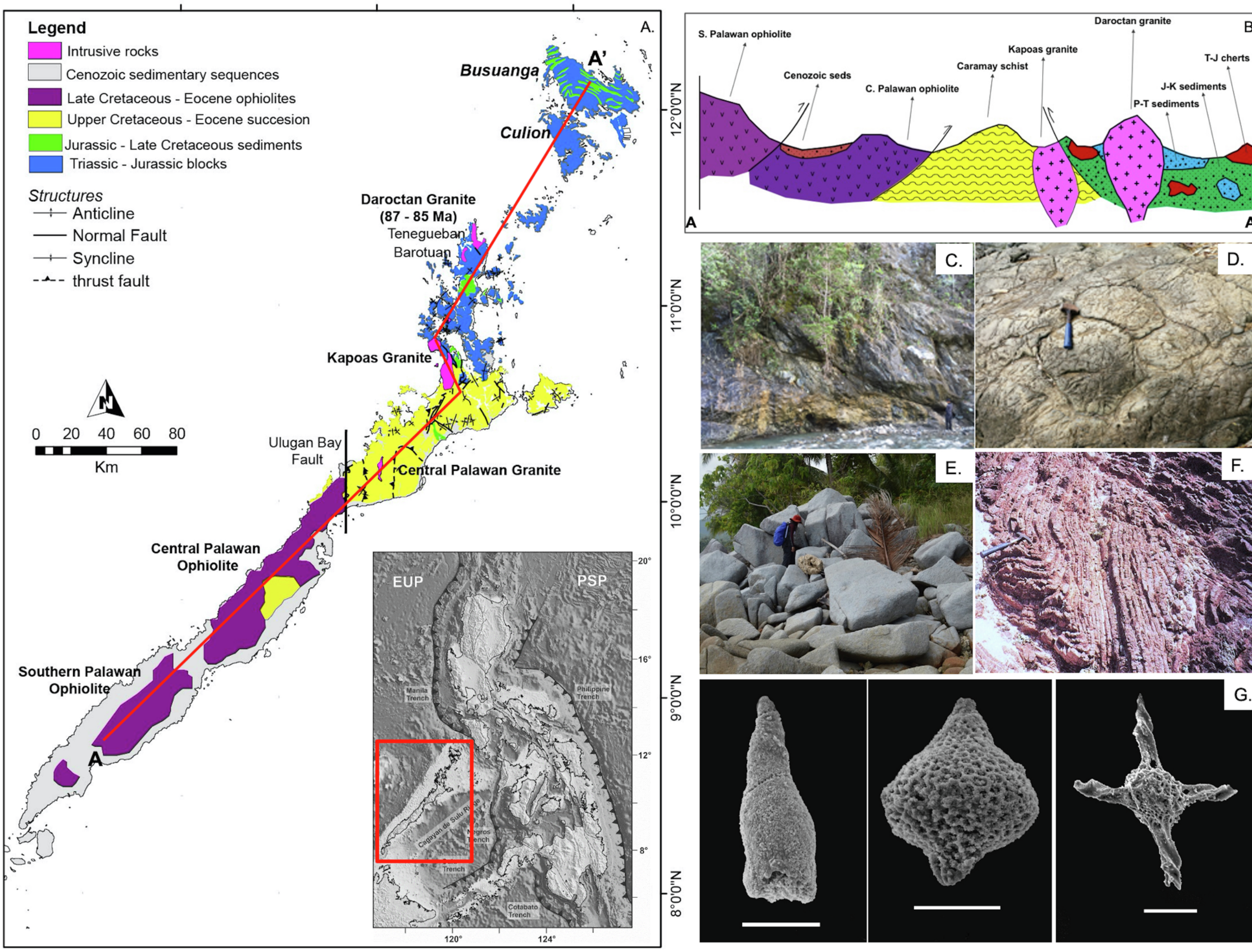

Fig. 5. A. Palawan island characterized by a northern oceanic plate stratigraphy (OPS) and sedimentary-metamorphic successions with the southern portion dominated by ophiolite fragments. B. Schematic cross-section of the island showing Palawan Ophiolite thrusted onto the schist in the central portion and the intrusive units cutting the *meta*-sedimentary rocks in the northern portion and in the Busuanga island group. C and D. Sheared serpentinized harzburgites (C) (N8°57′1.1″, E117°53′29″) and pillow lavas (D) (N8°51′42.6″, E117°47′48.23″) of the Southern Palawan Ophiolite. E. Floats of the granites along the coast of Bgy. Tenegueban in El Nido (N11°22′19.7″, E119°30′23.8″). F. Steeply-dipping bedded cherts of the Liminangcong Formation exposed in western Busuanga island (N12°6′11.2″, E119°50′47.1″). G. The cherts yielded Middle Triassic (upper Anisian-Ladinian) radiolarians (from left to right): *Follicucullus porrectus* (Rudenko), *Katroma westermanni* (Whalen and Carter) and *Plafkerium abboti* (Pessagno). The white lines correspond to a length of 100 µm.

Subsequent works assigned the name Basak Formation, comprising of amygdaloidal basalt and agglomerate with andesitic and basaltic clasts. It is intercalated with tuff and thin beds of metamorphosed conglomerate, sandstone, siltstone and shale. This formation was assigned a Cretaceous to Eocene age (Burton, 1983; Bobis and Comia, 1987 in Maglambayan et al., 1998; Peña, 2008). It is intruded by the Pangatban Batholith, a quartz diorite intrusive body. Radiometric dating (K-Ar) of biotite from the batholith samples yielded ages from 38.4 to 25.1 Ma (Late Eocene to Late Oligocene) (Burton, 1983; Santos and Velasquez, 1987 in Maglambayan et al., 1998).

3.1.2.2.2. Daroctan Granite, Palawan island. The Late Cretaceous plutons of the Daroctan Granite are observed in Barotuan and Tenegueban in El Nido, Palawan (Padrones et al., 2017a) (Fig. 5A). It intruded the lower member of the Mesozoic mélange particularly the middle Permian Bacuit rocks (Metal Mining Agency of Japan – Japan International Cooperation Agency (MMAJ- JICA), 1988) (Fig. 5B). This unit was previously recognized as part of the Middle Miocene Kapoas Granite (Peña, 2008). However, recent age dating from the Tenegueban pluton yielded Late Cretaceous ages with peak ages at 87.3 ± 4.9 Ma and 85.7 ± 8.2 Ma. The granodiorite enclave yielded Late Cretaceous age (peak age at 87.3 ± 4.9 Ma) suggesting a co-magmatic origin with the host rock (Padrones et al., 2017a). The Daroctan Granite is composed of medium-grained biotite granite. The Barotuan pluton is abundant in biotite but does not contain inclusions while the Tenegueban pluton (Fig. 5E) contains quartz xenocrysts, granodiorite enclaves, and *meta*-sedimentary xenoliths (Padrones et al., 2017a). The Daroctan Granite samples are holocrystalline with subhedral to anhedral crystals of quartz, plagioclase, K-feldspar, and biotite (Padrones et al., 2017b). The enclaves show similar mineralogical composition with the granite host rock but contain more opaque minerals such as ilmenite and cassiterite (Padrones et al., 2017a,b). Both plutons are classified as ilmenite-series type of granite (Ishihara and Chappell, 2010) based on their magnetic susceptibility values ($< 3.0 \times 10^{-3}$SI) (Padrones et al., 2017b).

3.1.2.2.3. Cebu intrusive rocks. Cebu island intrusive rocks range in age from late Early Cretaceous to early Late Cretaceous (Lutopan Diorite and Cansi Diorite) to late Middle Miocene (Talamban Diorite) (Walther et al., 1981; MMAJ-JICA, 1990) (Fig. 1B). The Lutopan Diorite is composed of diorite, quartz diorite, andesite, dacite, and gabbro that occur as stocks and dikes in the central part of Cebu. Age dating yielded an Early Cretaceous age (101–108 Ma) from K-Ar dating and 107 Ma from Rb-Sr dating (Walther et al., 1981). This unit intruded the Cansi Basalt and is considered to have brought the mineralization associated with the oldest porphyry copper deposit in the Philippines, the Atlas

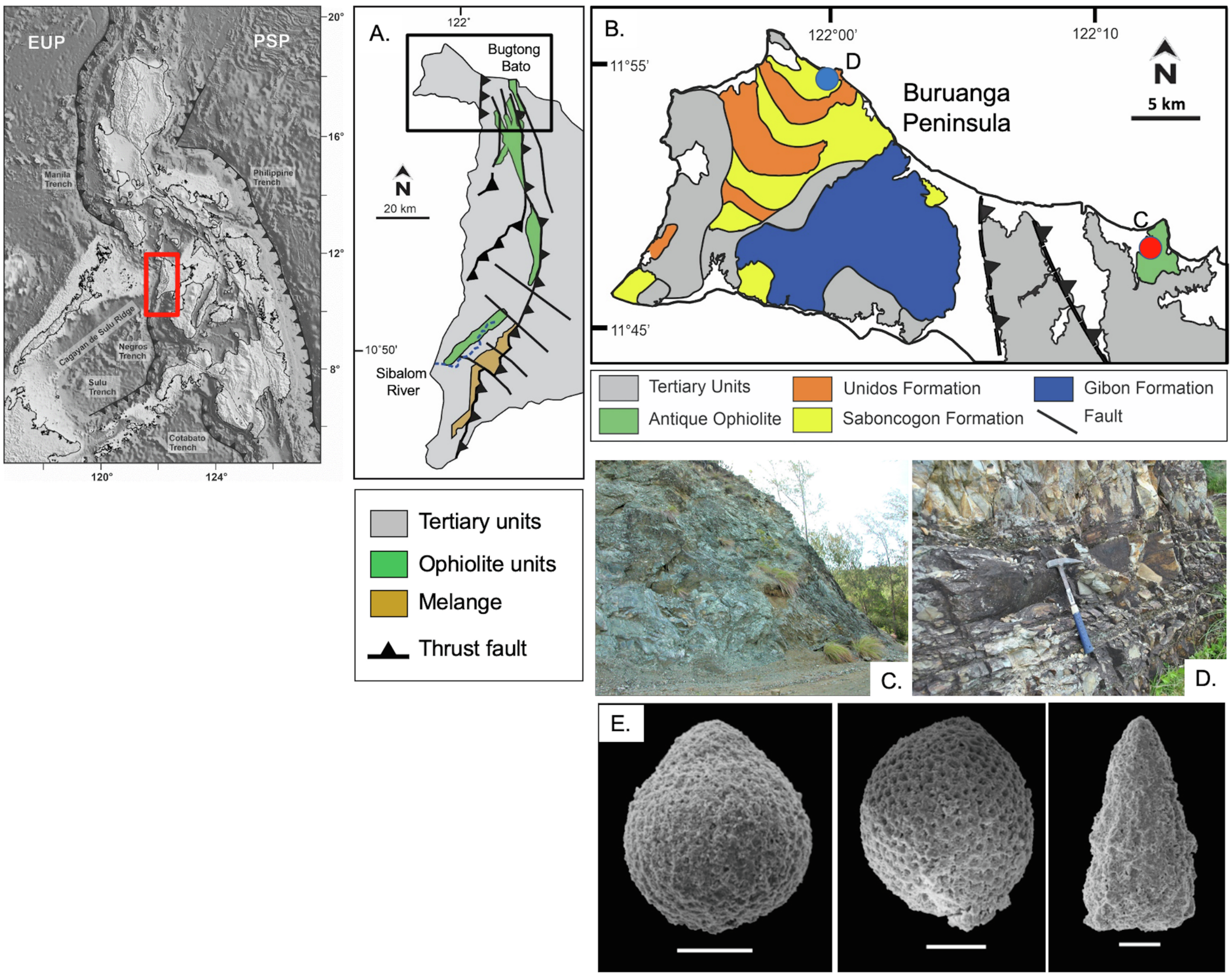

Fig. 6. A. The western part of Panay Island underlain by the Antique Ophiolite in the south and the Mesozoic sedimentary sequence in Buruanga Peninsula (boxed area). B. Map of northwestern Panay showing the location of serpentinized peridotites of the Antique Ophiolite exposed in Bugtong Bato. Chert-clastic-limestone sequence representing an oceanic plate stratigraphy also observed in the Buruanga Peninsula. The dots correspond to locations of outcrops in C and D. C. Outcrop of serpentinized peridotite in Bugtong Bato (red circle in B) (N11°48′13.8″, E122°13′14.4″). D. Siliceous mudstone-sandstone-shale interbeds of the Saboncogon Formation (blue circle in B) (N11°54′43.8″, E121°59′58.8″). E. Radiolarians from the siliceous mudstone which include (from left to right): *Tricolocapsa* sp., *Stichocapsa* sp. and *Transhuum* sp. The white lines correspond to a length of 100 µm.

deposit (Walther et al., 1981). Southwest of the Atlas deposit, the Cansi Diorite intruded the Mananga Group volcanics (Deng et al., 2017). The Talamban Diorite, on the other hand, is an intrusive unit that is in fault contact with the Tunlob Schist (MMAJ-JICA, 1990). Recent field mapping showed that it also intruded the Late Cretaceous Pandan Formation (Rodrigo et al., 2020). The Talamban Diorite is composed of diorite and quartz monzonite which occur as small stocks located east of central Cebu island.

3.1.2.3. Sedimentary packages and melanges

3.1.2.3.1. Dos Hermanos Melange, Ilocos Norte. Peridotites which were previously mapped to comprise part of the Ilocos Norte Ophiolite Complex have instead been recently reported to occur as blocks or fragments within the Dos Hermanos Mélange. This tectonic mélange is best exposed in the Dos Hermanos islands, Bangui and Pagudpud, Ilocos Norte (Fig. 2B). It consists of pebble- to cobble-sized clasts of peridotites, gabbros, cherts, greenschists and mica schists set in a highly-sheared serpentinite matrix (Fig. 2C-D). This mélange has previously been identified by Pinet and Stephan (1990). It has been assigned a Late Jurassic to Early Cretaceous age based on the radiolarian assemblage extracted from the cherts (Queaño et al., 2017a; Pasco et al., 2019). Radiolarian faunas include *Eucyrtidiellum pyramis* (Aita), *Hiscocapsa acuta* (Hull), *Archaeodictyomitra montisserei* (Squinabol), *Hiscocapsa asseni* (Tan), *Pseudodictyomitra carpactica* (Lozyniak) (Fig. 2E). Lherzolite, harzburgite, dunite and chromitite clasts exhibit deformation features such as kink banding and bent lamellae. The spinel Cr# in the lherzolite and dunite clasts (0.17–0.60) is consistent with residual mantle peridotites, some of which are relatively fertile. The low Al_2O_3 (1.0–2.77 wt%) and high Mg# (0.92–0.94) of clinopyroxene in the harzburgite clasts are similar to those displayed by forearc peridotites (Pasco et al., 2019). The gabbroic clasts include troctolites, gabbros and olivine gabbros. Olivines in the troctolites have higher forsterite content (Fo = 80–81) compared to those in the olivine gabbros and gabbros (Fo = 66–80). The characteristics of the troctolite clasts suggest formation in a mid-oceanic ridge setting whereas the gabbro and olivine gabbro clasts show similarities with arc-related gabbros (Pasco et al., 2019).

3.1.2.3.2. Chert carapace of the Acoje Block, Zambales Ophiolite complex. The Cabaluan Formation, best exposed along the Cabaluan River and Acoje Road in Santa Cruz, Zambales, is divided into a lower clastic member and an upper limestone member (Fig. 3B). It unconformably overlies the serpentinized peridotites of the Acoje

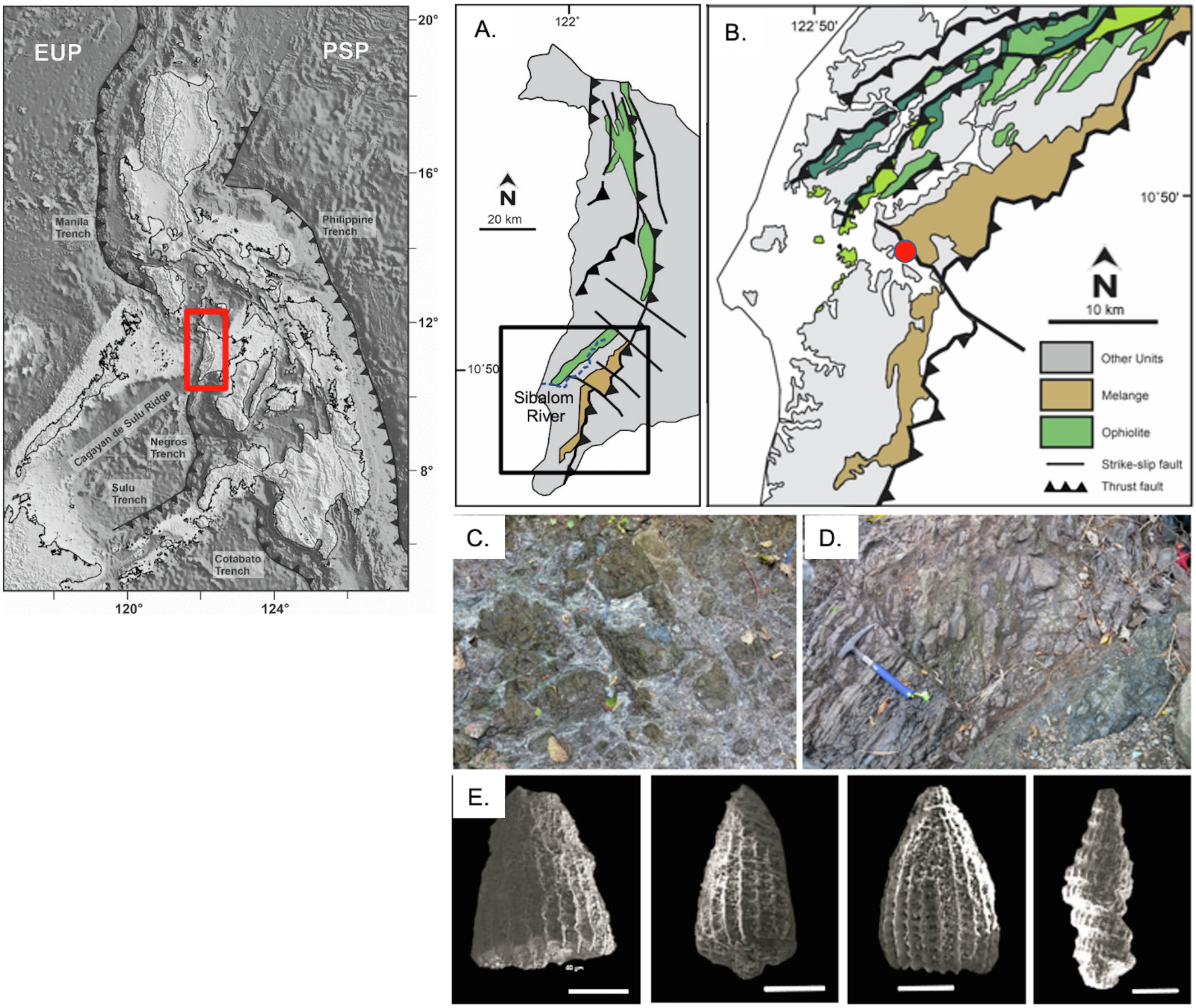

Fig. 7. A. Index map showing the southern part of Panay island. B. Southern Panay island underlain by units of the Antique Ophiolite as well as the Paniciuan Melange (modified from Tamayo et al., 2001). C. The Paniciuan Mélange along the San Joaquin River (marked by the red circle) (N10°32′41.8″, E122°5′6.5″) consists of blocks of highly deformed serpentinized peridotites, gabbros, sandstones. D. Chert blocks are embedded in a greenish silty matrix. E. Radiolarian fauna from the chert samples include (from left to right): *Archaeodictyomitra* sp., *Archaeodictyomitra* sp., *Thanarla* sp. and *Pseudodictyomitra* sp. The white lines correspond to a length of 100 μm.

Block. The clastic member is composed of thick conglomerate beds with some intervening beds of sandstone-siltstone-mudstone (Fig. 3C). The conglomerates and medium-grained lithic sandstones are made up of clasts of serpentinized peridotites, serpentinites, minor gabbros and cherts (Fig. 3D). Radiolarian faunas extracted from the chert samples include *Archaeodictyomitra* spp., *Mictyoditra* spp., *Xitus* spp., *Pseudodictyomitra* spp., *Pseudoeucyrtis* spp. (Fig. 3E). These suggest a Late Jurassic to Early Cretaceous age (Ishida et al., 2012; Queaño et al., 2017b).

3.1.2.3.3. Halcon Metamorphics, Mindoro island. The metamorphic rocks that underlie the island of Mindoro have been described differently by various authors. The Mindoro Metamorphic Complex (Teves, 1954) is described as regionally metamorphosed, lower greenschist facies with protoliths of laminated mafic and intermediate tuffs, interstratified with laminated limestone, subquartzose volcaniclastic sandstones and shales, massive marbles, and tonalitic plutonic rocks (Caagusan, 1966; Sarewitz and Karig, 1986). Sarewitz and Karig (1986) have also reported the occurrence of small tectonic slices of serpentinites inter-sheared with the metasediments, which led them to conclude an accretionary complex origin for the suite. Peña (2008) used the name Halcon Metamorphics to designate metamorphic units of the island as well. However, "Halcon Metamorphics" was originally introduced by the Metal Mining Agency of Japan – Japan International Cooperation Agency (MMAJ-JICA) (1983) which exclusively only accounts for higher grade metamorphic rocks. The same work maintained that the lower grade metamorphic rocks correlate more with the Jurasssic Mansalay Formation. However, such an association is not substantiated by the fact that the Mansalay Formation is generally not metamorphosed (Sarewitz and Karig, 1986; Canto et al., 2012; Concepcion et al., 2011). Variably metamorphosed pelitic and intrusive lithologies dominate the Halcon Metamorphics terrane in Mindoro island (Fig. 4C–D). As mentioned earlier, occasional fragments of various ophiolitic rocks enclosed within this metamorphic unit are collectively referred to as the Cretaceous Mangyan Ophiolite (Canto et al., 2012). The southeastern extension of the terrane towards east-central Mindoro (e.g., Ogos, Balete and Bongabong) exposes large ultramafic units that are in tectonic contact with the metamorphic rocks. The margins between the contrasting lithologies are marked by

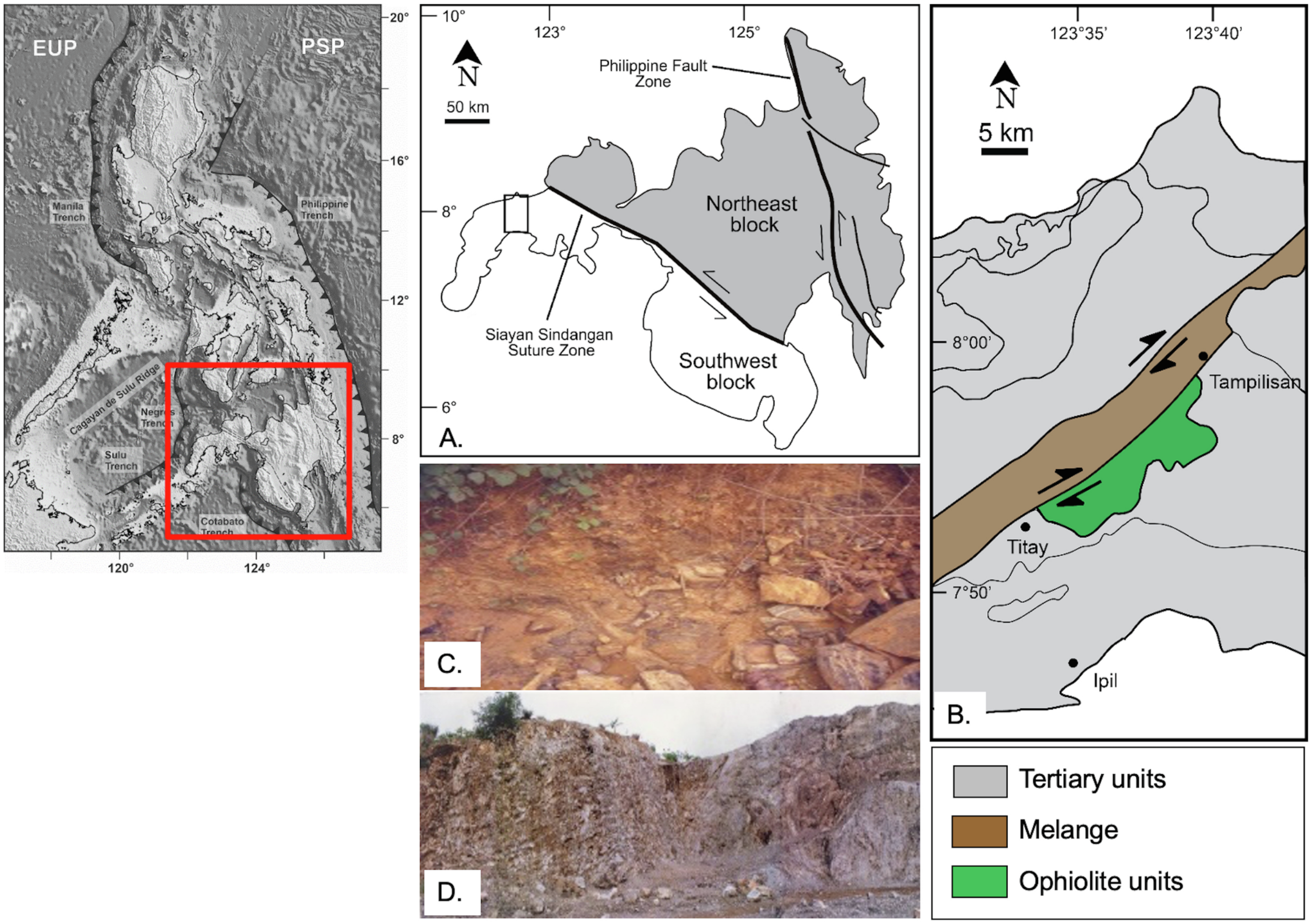

Fig. 8. A. The Titay Ophiolitic Complex (boxed area) is located in the continental southwest block of the Zamboanga Peninsula. B. Melange and ophiolite units exposed in the Titay-Tampilisan area closely associated with faults. C. Gabbronorite exposure in the Ipil-Liloy Road in Titay. D. Harzburgite unit of the Titay Ophiolitic Complex exposed in the Zamboanga del Norte Agricultural College campus in Titay.

amphibolites (Metal Mining Agency of Japan – Japan International Cooperation Agency (MMAJ-JICA), 1983). The age of metamorphism was found to be 59 Ma based on K-Ar analysis of amphibole separates (Faure et al., 1989). Episodes of Permian to Cretaceous magmatic events that produced some of the protoliths of the Halcon Metamorphics are evidenced by U-Pb geochronologic data (Knittel et al., 2010, Knittel et al., 2017). These ages for the Halcon Metamorphics, alongside the late Carboniferous age of the Puerto Galera marbles (Knittel and Daniels, 1987; Knittel et al., 2017), and the Middle to Late Jurassic age of the Mansalay Formation (Andal et al., 1968; Sato et al., 2012) strongly support a Mesozoic basement for the entire island of Mindoro. In northwestern Mindoro, between the towns of Mamburao and Abra de Ilog, the Halcon Metamorphics is overlain by submarine volcanic rocks (Sarewitz and Karig, 1986). The same units have been referred to as the Mamburao basalts (Metal Mining Agency of Japan – Japan International Cooperation Agency (MMAJ-JICA), 1983) and the Abra de Ilog Formation (Mines and Geosciences Bureau, 2010). Late Cretaceous foraminifera extracted from their interpillow limestones (Hashimoto, 1981; Karig, 1983) indicate a close temporal association with the rest of the Mangyan Ophiolite slivers. These pillow basalts and the metamorphic basement are unconformably overlain by the Late Eocene-Early Oligocene Lasala Formation (Concepcion et al., 2011).

3.1.2.3.4. Mansalay Formation, Mindoro island. Mansalay Formation was first described by Feliciano and Basco (1947) for outcrops in southeastern Mindoro, between the coastal towns of Pinamalayan and Naujan, and in Bulalacao at the southern terminus of the island (Fig. 4A). Most exposures of the formation are composed of dark-colored fossiliferous beds containing ammonite remains and dated as Jurassic (e.g. Hashimoto, 1981; Sato et al., 2012). Subsequent mapping works revealed the formation to be truly widely exposed in southern Mindoro, and that it is composed of a thick (> 2,500 m) sequence of fluvial, tidal, and shallow marine clastic rocks, with minor carbonate interbeds (Andal et al., 1968; Sarewitz and Karig, 1986). Sandstone units record volcanic inputs (abundant albite and lithic volcanic fragments) despite a generally subquartzose constitution (Sarewitz and Karig, 1986). The Mansalay Formation is in tectonic contact (Sarewitz and Karig, 1986) with the Eocene to lower Oligocene Caguray Formation (Hashimoto, 1981). Unconformable contacts with overlying Eocene rocks have also been reportedly observed from drill well data (Sarewitz and Karig, 1986). Paleomagnetic studies on five sites drilled through clastic rocks of the Mansalay Formation yielded a mean paleolatitude of ~ 20° (Dec = 75.7°; Inc = 27.7°; α_{95} = 19.4°) which is consistent with a North Palawan Block affinity (McCabe et al., 1987). This, in combination with the mean paleolatitudes derived from the Late Cretaceous cherts of Busuanga and northern Palawan (Almasco et al., 2000), support a northerly paleo-position for the Palawan Microcontinental Block (Holloway, 1981; Faure et al., 1989; Faure and Ishida, 1990).

3.1.2.3.5. Unidos, Saboncogon and Gibon Formations, Buruanga Peninsula, Panay island. The Buruanga Peninsula in northwest Panay dominantly consists of highly folded Mesozoic chert-clastic-limestone sequences with associated metamorphic rocks that are distinct from the rest of Panay island (Zamoras et al., 2008; Gabo et al., 2009; 2015) (Fig. 6B). The complexly folded chert beds of the early Middle Jurassic Unidos Formation comprise the oldest sedimentary unit observed in the north-central portion of the peninsula. The cherts are intercalated with the bedded pelagic limestone of the Gibon Formation, which dominates the southwestern portion of the Buruanga Peninsula. The folded and highly faulted limestone beds also contain chert nodules or lenses in other areas. The Unidos Formation is conformably overlain by the steeply dipping siliceous mudstone-sandstone-shale interbeds of the late Middle Jurassic to early Late Jurassic Saboncogon Formation (Fig. 6D) also found in the north-central portion of the peninsula. Moderately to well-preserved radiolarians from the chert and siliceous mudstones include species such as *Tricolocapsa conexa* Matsuoka, *Stichocapsa robusta* Matsuoka, *Archaeodictyomitra* sp., *Transhuum* sp. and *Stylocapsa* sp. (Fig. 6E). Separating the chert-clastic sequences of the Unidos and Saboncogon Formations with the pelagic limestone of the Gibon Formation is a 2-km zone of slate, phyllite and quartz-sericite schist. The whole-rock geochemical compositions of the Saboncogon Formation clastic rocks are characterized by silicic sources attributed to a continental margin composition consistent with the setting of the Palawan Microcontinental Block (Gabo et al., 2009). The rock units in the Buruanga peninsula are part of the Mesozoic accretionary complex that can be correlated to the sedimentary sequences of Busuanga island in north Palawan (Zamoras et al., 2008). Moreover, data from U-Pb dating of zircons from sedimentary units in Buruanga, as well as those from the rest of the Palawan Microcontinental Block, indicate correlation with rocks in Taiwan and South China which reveal sources of Cathaysian origin (Dimalanta et al., 2018).

3.1.2.3.6. Paniciuan Mélange, Antique, Panay island. The Paniciuan Mélange is well-exposed along the San Joaquin River, west of Iloilo City (Fig. 7A-B). Blocks of highly deformed serpentinized peridotites, gabbros, sandstones and ribbon chert are embedded in a greenish silty matrix (Fig. 7C-D). The age of exhumation of the ophiolite is dated Middle Miocene, based on the nannofossils found in the matrix of the mélange (e.g. Tamayo et al., 2001). Early Cretaceous radiolarians were extracted from the chert blocks in the mélange. These include *Archaeodictyomitra* spp., *Thanarla* spp., *Pseudodictyomitra* sp., and *Pseudodictyomitra* sp. (Fig. 7E). Some of these Mesozoic radiolarians are similar to those found in the Dos Hermanos Mélange in Ilocos Norte as well as from the chert samples in the Acoje Block of the Zambales Ophiolite Complex.

3.1.2.3.7. Pandan Formation, Cebu island. The Pandan Formation consists of interbedded and intercalated siliceous sandstone, siltstone, shale, limestone and conglomerate overlying the Cansi Basalt in Central Cebu (Corby et al., 1951; Rodrigo et al., 2020) (Fig. 1C). This formation was interpreted to have formed in a pelagic to turbiditic depositional setting. Age dating from foraminifera and calcareous nannoplankton assigned a late Santonian to late Maastrichtian age (Porth et al., 1989; Rodrigo et al., 2020). The Pandan Formation is considered as one of the oldest sedimentary sequences in the Philippines and the only Cretaceous clastic unit in central Philippines. Recent work by Rodrigo et al. (2020) interpreted this clastic sequence to have originated from erosion at the oceanic edge of the Australian Plate related to the subduction of the paleo-Pacific Plate.

3.1.2.3.8. North Palawan Cretaceous sedimentary rocks. The lithologic units in the northern part of Palawan are composed of a Mesozoic mélange and the Late Cretaceous to Eocene sedimentary and *meta*-sedimentary rocks (Hashimoto and Sato, 1973; Faure and Ishida, 1990; Suzuki et al., 2000) (Fig. 5A–B). The Mesozoic mélange (also called Malampaya Sound Group by Hashimoto and Sato, 1973) is composed of olistoliths with varying ages set in a Middle Jurassic to Early Cretaceous Guinlo Formation (Zamoras and Matsuoka, 2001; Yokoyama et al., 2012; Padrones et al., 2017a). The oldest olistostrome unit is the Middle to Late Permian Bacuit Formation composed of interbedded fine to coarse-grained sandstones, pebbly mudstones, and siliceous sediments (Hashimoto and Sato, 1973; Metal Mining Agency of Japan – Japan International Cooperation Agency (MMAJ- JICA), 1988). The Bacuit Formation is overlain by the olistolith of the Minilog Limestone (formerly Minilog Formation by Hashimoto and Sato 1973) which yielded Late Permian to Middle Triassic ages based on foraminiferal assemblage (Wolfart et al., 1986 in Mines and Geosciences Bureau, 2010) and Middle Permian to Middle Triassic based on fusulinid and conodont assemblages (Zamoras and Matsuoka, 2001). This olistolith is composed of partly recrystallized micritic to oolitic limestones. The Minilog Limestone is juxtaposed with the Middle Triassic to Late Jurassic Liminangcong Formation composed of bedded chert intercalated with slate and tuffaceous sediments (Hashimoto and Sato, 1973; Zamoras and Matsuoka, 2001). The Guinlo Formation, interpreted to be the matrix of the Mesozoic mélange, is composed of a sequence of tuffaceous shale and coarse-grained sandstone intercalated with tuff and minor thinly-bedded chert (Hashimoto and Sato, 1973; Faure and Ishida, 1990; Zamoras and Matsuoka, 2001). This formation, although barren of fossils at Guinlo Point in Taytay (Hashimoto and Sato, 1973), contains Middle Jurassic to Early Cretaceous radiolarian fossil assemblage in the exposures in Busuanga island (Zamoras and Matsuoka, 2001). Moreover, Yokoyama et al. (2012) reported Jurassic to Early Cretaceous (125 Ma) detrital monazite ages from sandstones in Busuanga island while Padrones et al. (2017a) yielded Late Jurassic to Early Cretaceous (108 to 152 Ma) zircon ages. To the south of the Guinlo and Liminangcong Formations, extensive outcrops of the Tumarbong Semi-schists (equivalent to the Concepcion Pebbly Phyllite of Suzuki et al., 2000) are exposed. Recent monazite and zircon dating (Padrones et al., 2017a) of river sediments from the tributaries in Roxas area yielded Early Cretaceous to Late Cretaceous maximum age of deposition. To note, previous studies of Walia et al. (2013) and Suggate et al. (2014) reported Late Cretaceous maximum ages for the Caramay Schist, Tumarbong Semi-schist, and the Babuyan River Turbidites. Suzuki et al. (2000) interpreted this sequence as a contiguous unit stratigraphically arranged with the Caramay Schist as the bottom unit. The succession is composed of phyllite and low-grade schist (i.e. graphite and mica schists) of the Caramay Schists, slate, phyllite, quartz semi-schists, and psammitic schists of the Tumarbong Semi-schist, and the sandstone, shale, and mudstone sequences of Babuyan River Turbidite (United Nations Development Programme (UNDP), 1985). The lower members were affected by very low to low-grade regional metamorphism (Suzuki et al., 2000). The protoliths are composed of mudstone, interbedded sandstone and mudstone, sandstone and pebbly mudstone (Suzuki et al., 2000). Analysis of the detrital minerals in the Tumarbong Semi-schists suggests granitic sources probably from the Daroctan Granite (Padrones et al., 2017a). The depositional environment of this sequence is in deep-sea submarine fans and basinal plains located in a continental margin to ocean basin (Suzuki et al., 2000).

3.1.2.3.9. Busuanga – Calamian Group of Islands accretionary complex, Northern Palawan. Zamoras and Matsuoka (2001) provided the most recent modifications on the stratigraphy of northern Palawan based on their mapping surveys and detailed radiolarian biostratigraphy. Marquez et al. (2006) also provided significant inputs in expanding the known geographic extent of the Paleozoic to Mesozoic sections in Busuanga island and in refining stratigraphic ages of the units in northern Palawan. Generally, the stratigraphy of Busuanga and adjoining islands consists of the Middle Jurassic to Lower Cretaceous Guinlo Formation consisting of siliceous mudstone, sandstone and conglomerate (Zamoras and Matsuoka, 2001) (Fig. 5A). The bedded Guinlo Formation either conformably overlies or is in thrust fault contact with the Liminangcong Formation (Zamoras and Matsuoka, 2001). Middle Triassic radiolarians extracted from the cherts of the Liminangcong Formation (Fig. 5F) include *Follicucullus porrectus* (Rudenko), *Katroma westermanni* (Whalen and Carter), *Plafkerium abboti* (Pessagno) and *Stichocapsa* sp. (Fig. 5G). Previous workers (e.g. Hashimoto and Sato, 1973; Wolfart et al., 1986; Zamoras and Matsuoka, 2001; Marquez et al., 2006) also reported limestone bodies of different ages (Middle Permian to Late Jurassic) that are scattered around the Calamian group of islands. These limestone bodies, along with the Liminangcong and Guinlo Formations, comprise the

Malampaya Sound Group. Minor mélange bodies made up of either limestone-basalt-chert or sandstone-chert-mudstone fragments were also identified (Zamoras and Matsuoka, 2001). Zamoras and Matsuoka (2001) interpreted the stratigraphic units in Busuanga island and neighboring islands in northern Palawan as defining an old accretionary complex. They delineated three accretionary belts in the Calamian Group of Islands based on chert to clastic transitions from different stratigraphic sequences. In addition, they correlated these units with those found in Togano Group of the southern Chichibu Terrane of SW Japan based on the work of Matsuoka (1984) and Aita (1987). Such correlation suggests that the terrane of Busuanga and the neighboring islands in northern Palawan is a southern extension of the Mesozoic accretionary complex of the East Asian margin and NE-SW Japan (Faure and Natalin, 1992; Zamoras and Matsuoka, 2001).

4. Discussion

4.1. Visualizing a lost ocean basin: Exposed evidence along western Philippines

Most of the oceanic lithospheres and exposed sedimentary rocks in the western portion of the Philippines are Cretaceous in age. For the oceanic lithospheres, in some instances, Eocene ophiolites are closely related (e.g. Zambales, Angat, Palawan) (e.g. Encarnacion et al., 1993; Queaño et al., 2017b; Labis et al., 2020) (Fig. 1B). The geochemistry of the ophiolites, based on whole rock and mineral chemistry, reveal transitional MOR to IA affinity, mostly indicative of a marginal basin setting (Table 1). The Mesozoic sedimentary rocks are mostly deep-water limestones and cherts with associated clastic sediments that are exposed either as fragments within mélanges or part of uplifted accretionary prisms. Some of the older formations (e.g. Mansalay Formation in Mindoro, Guinlo Formation and related formations as exposed in mainland Palawan, Busuanga – Calamian group of islands and Buruanga Peninsula, Panay) support their Mainland Asian affinity different from that of the Philippine Mobile Belt (e.g. Holloway, 1981; Yumul et al., 2003; Knittel et al., 2010). Subduction upwedging, large scale-strike slip faulting and back-thrusting were responsible for the emplacement of these rock formations.

The Mesozoic rocks observed from Ilocos Norte through Palawan and Panay to the Zamboanga Peninsula define a belt of Mesozoic ophiolitic nappes obducted on top of continent-derived fragments belonging to the Palawan Microcontinental Block which was termed as West Philippines Microcontinent by Faure and Natalin (1992). The presence of Mesozoic fragments of complete to dismembered ophiolites and mélanges along the western side of the Philippines need to be explained (Fig. 1B-C). None of the nearby ocean basins (Early Oligocene to Early Miocene South China Sea ocean basin for Luzon and Early to Middle Miocene SE Sulu Sea ocean basin for Panay island in the Visayas and Zamboanga Peninsula in Mindanao) can account for these older lithologies (Fig. 1). It is imperative for an older oceanic basin to have existed that can serve as the provenance of these Mesozoic rock suites. The existence of the proto-South China Sea plate can actually account for these Mesozoic rock fragments. Although two different ages, Eocene and Mesozoic, have been considered for this lost basin, the age discrepancy can be easily reconciled (Hall and Breitfeld, 2017; Wu and Suppe, 2017). The ocean plate can in fact be Eocene to Mesozoic in age. Additionally, its subduction need not only be southward but also north-northeastward (present-day geographic setting). The proto-South China Sea plate has been reported to be beneath the Visayan region only but the presence of Mesozoic rock fragments along western Luzon is suggestive that the ancient oceanic plate also subducted beneath what is now Luzon (e.g. Fan et al., 2017; Hall and Breitfeld, 2017; Wu and Suppe, 2017). Tectonic reconstruction and modeling of East Asia showed that the proto-South China Sea occupied most of the present-day South China Sea, extending southwards at subequatorial latitudes underneath northern Borneo – Zamboanga Peninsula and beneath northern and central Philippines (e.g. Tongkul, 1997; Tamayo et al., 2004; Wu et al., 2016; Wu and Suppe, 2017). Consistent to this, Chien et al. (2019) reported that the 47 ± 2 to 42.5 ± 0.3 Ma (zircon U-Pb ages in gabbros) Telupid Ophiolite in northern Borneo may be related to the Palawan Ophiolites and could be exhumed proto-South China Sea fragments. This reconstruction of the proto-South China Sea provides an attractive source for the ophiolitic fragments and mélanges that define the Mesozoic belt of western Philippines, especially given the sub-equatorial paleolatitude of the ophiolitic rocks in western Philippines. Most of these oceanic lithosphere fragments are thrusted over or in fault contact with accretionary prism deposits, related sedimentary and metamorphic rocks which are part of the Palawan Microcontinental Block. Considered as the leading edge of the Palawan Microcontinental Block, some of the proto-South China Sea lithosphere would have also obducted onto the western Philippines as tectonic slivers. Their accretion follows the clockwise rotation of the Philippine Mobile Belt from the subequatorial region in the early Cenozoic (Queaño et al., 2007a, 2007b; Wu et al., 2016).

Zheng et al. (2019) had reported that the Triassic to Cretaceous cherts and limestone exposed in the Calamian group of islands in Palawan could be part of the proto-South China Sea plate. The Buruanga Peninsula in Panay island also exhibits chert – clastic sequences associated with limestone blocks similar to an ocean plate stratigraphy that would have been emplaced in an accretionary prism. These rocks are correlative with those exposed at the Busuanga - Calamian group of islands (e.g. Marquez et al., 2006; Zamoras et al., 2008; Gabo et al., 2009). Paleomagnetic data from Guinlo and Busuanga show a high latitude (> 20°) origin consistent with a Mainland Asia and possibly proto-South China Sea affinity (Almasco et al., 2000) (Fig. 9A-B). Paleomagnetic evidence of the Jurassic Mansalay Formation observed in southeast Mindoro show that this formation also originated from the northern hemisphere (Fig. 9A-B). Previous workers had forwarded the model that a Western Philippines Microcontinent collided with the South China Block during the Mesozoic (e.g. Faure and Natalin, 1992; Wei et al., 2015). The above Mesozoic accretionary prism deposits and related lithologies could then be considered part of this microcontinental block that collided with China. With the subsequent rifting and separation of the Western Philippines Microcontinent (equivalent to the North Palawan Block) from the South China Block, this microcontinental block acted as the trailing edge of the proto-South China Sea ocean plate that has moved southward. This would be in agreement with the observations that oceanic fragments believed to be of proto-South China Sea origin are thrusted over microcontinental blocks (equivalent to the North Palawan Block). The collision followed by subsequent rifting of microcontinental blocks from a continental massif has been recognized in other parts of Asia (e.g. Hall, 2002; Metcalfe, 2011, Metcalfe, 2014). The possibility though that these Mesozoic accretionary prism deposits and lithologies could have their origin not entirely related to the North Palawan Block but also with the generation of the proto-South China Sea plate should not be negated. Future studies may bear this out.

The Acoje Block of the Zambales Ophiolite Complex in Luzon, the Mangyan Ophiolite in Mindoro, the Southern Palawan Ophiolite, the Antique Ophiolite in Panay island, the SW Negros Cretaceous volcanic rock exposures and the Titay Ophiolitic Complex in the Zamboanga Peninsula have all been dated as Cretaceous based on fossils, mostly radiolarians, and stratigraphic relationships. The few paleomagnetic results available for these Mesozoic fragments is not inconsistent with a Mainland Asia – possibly proto-South China Sea plate origin. Geochemically, the exposed Mesozoic oceanic fragments exhibit transitional MORB-IAT affinity indicative of spreading and subduction contributions in their formation (Table 1). In particular, the peridotites of the ophiolites along western Philippines show a wide range of spinel Cr# values (Fig. 10A), but most of them fall within the olivine-spinel mantle array (OSMA; Arai, 1994) (Fig. 10B) indicating mantle origin. A marginal basin setting influenced by subduction or having tapped a

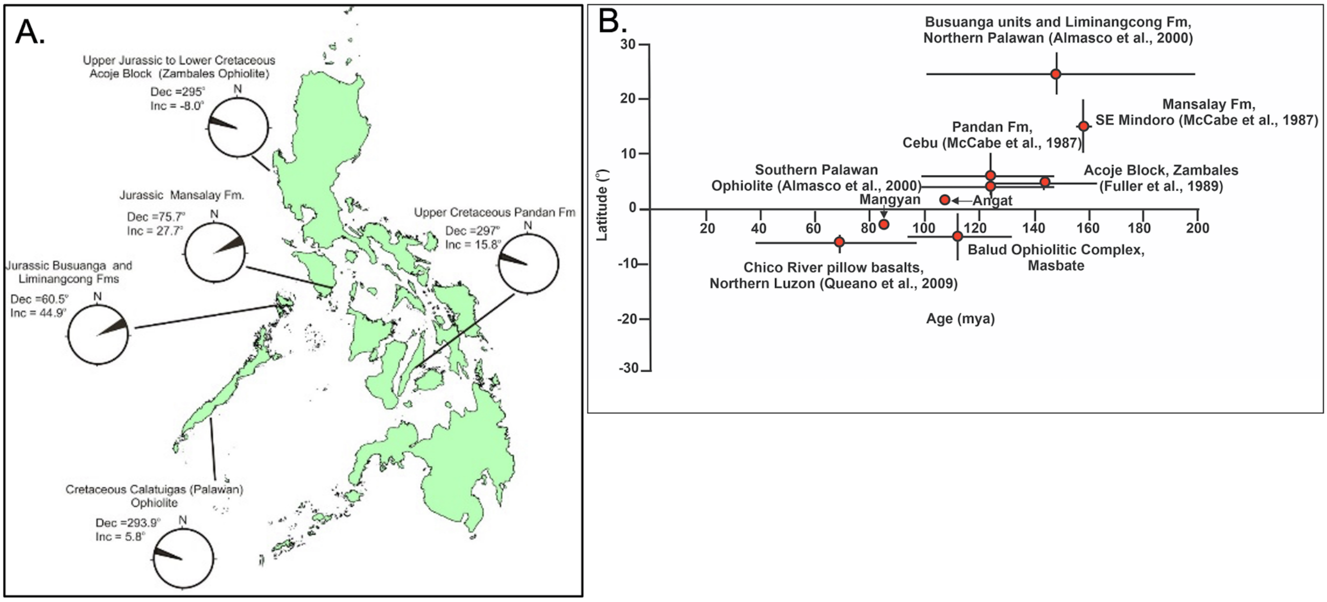

Fig. 9. A. Map showing location of paleomagnetic results from Mesozoic rocks, which indicate the paleolatitude of specific rocks at a given time. Small circles show the direction of magnetic declination values, with the wedge size corresponding to α95. Data from McCabe et al., 1987; Fuller et al., 1989; Almasco et al., 2000. B. Plot of the paleolatitude of the different western Philippine ophiolites and ophiolitic complexes versus age with corresponding error bars. References for each site are shown in parentheses. Note that the paleolatitudes of Balud, Mangyan and Angat are from our preliminary paleomagnetic data.

mantle source region with inherited island arc components can account for the geochemistry. If correct, this provides a glimpse on how the proto-South China Sea plate was generated.

The important role played by subduction is also highlighted by the presence of the Late Cretaceous Daroctan Granite in northern Palawan. This is the first time that a well-constrained Mesozoic granitic pluton is reported from mainland Palawan island (Fig. 11A-C). Most Mesozoic granites associated with the Andean subduction beneath Mainland Asia were only recognized and previously reported in mainland and offshore China, Vietnam and Borneo (e.g. Pearl River Mouth Basin, Xisha Block, Dangerous Ground, Schwaner Mountains) (e.g. Faure & Natalin, 1992; Knittel, 2010; Wei et al., 2015; Wang et al., 2020). The blocks from SE China that bear Mesozoic granitic plutons, as mentioned, served part of the trailing edge of the proto-South China Sea plate that rifted from Mainland Asia.

4.2. *Centrally-located Philippine Mesozoic rocks: Edge of the obducted proto-South China Sea plate*

The Cretaceous-Paleogene basement rocks of the Baguio and

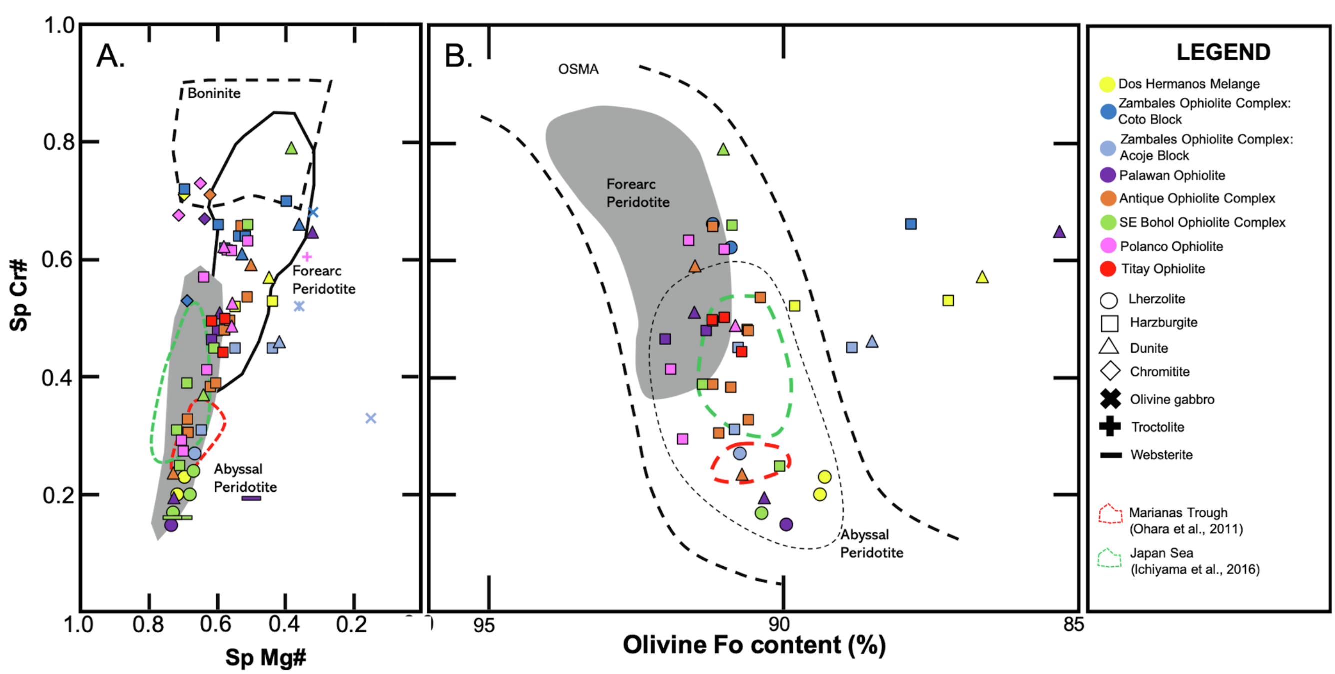

Fig. 10. A. Spinel Cr# vs Mg# for the peridotites from various ophiolites in the western portion of the Philippines. B. Olivine forsterite content vs spinel Cr# (Arai, 1994) in the peridotites from the ophiolite mantle sequences in western Philippines. Diagrams and fields were modified from Dick and Bullen (1984) and Van der Laan et al. (1992). The Japan Sea Basin and Marianas Trough Sea were plotted for comparison.

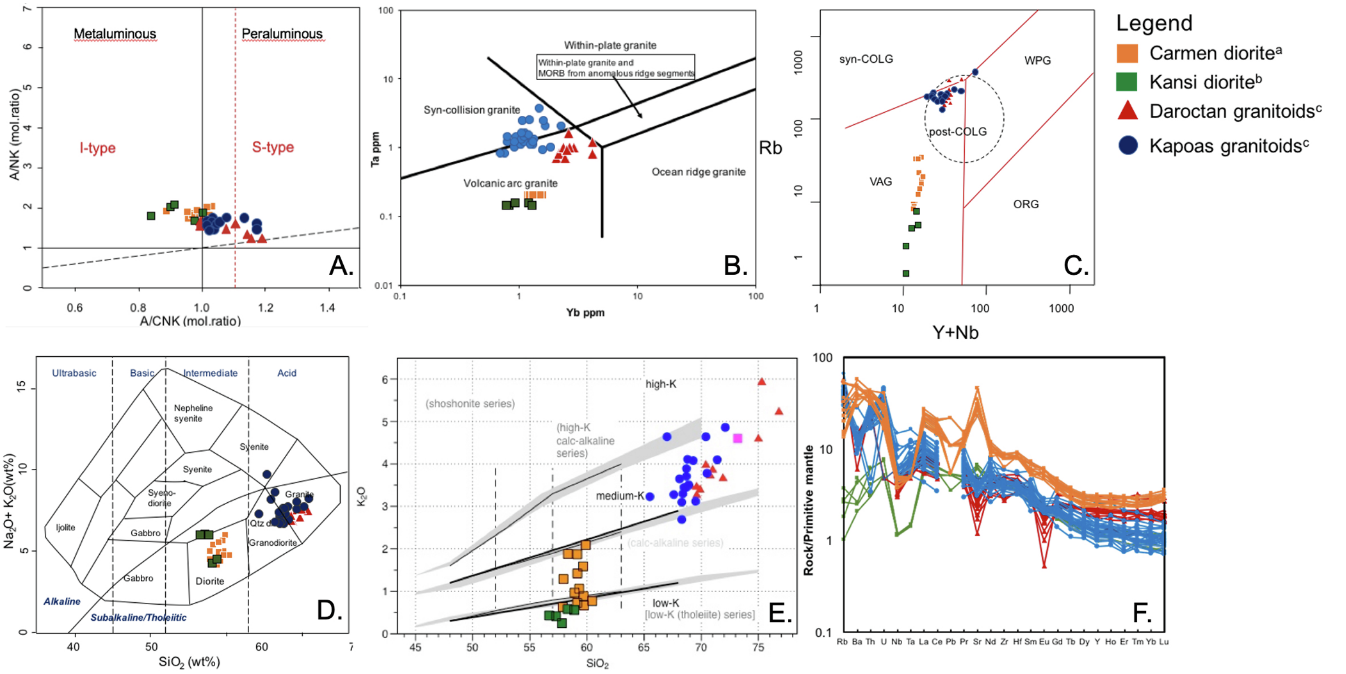

Fig. 11. A. Cebu intrusives classified as I-type and metaluminous while Palawan intrusives are intermediate I- and S-type, and peraluminous (Shand, 1943; Chappell and White, 1974). B-C. Carmen and Kansi diorites formed in volcanic arc granite (VAG) setting similar to Daroctan granite while Kapoas granitoids formed in VAG and *syn*-collisional settings (Pearce et al., 1984). D. Major elements discrimination diagrams for the intrusives of Palawan (Kapoas and Daroctan Granite) and Cebu (Carmen and Kansi diorites) showing intermediate type for the Cebu intrusives and acid compositions for the Palawan intrusives. E. Cebu intrusives classified as low-K tholeiite and calc-alkaline while Palawan plutons are high K calc-alkaline (Peccerillo and Taylor, 1976). F. Plots showing primitive mantle normalized trace elements for all intrusive units (Sun and McDonough, 1989).

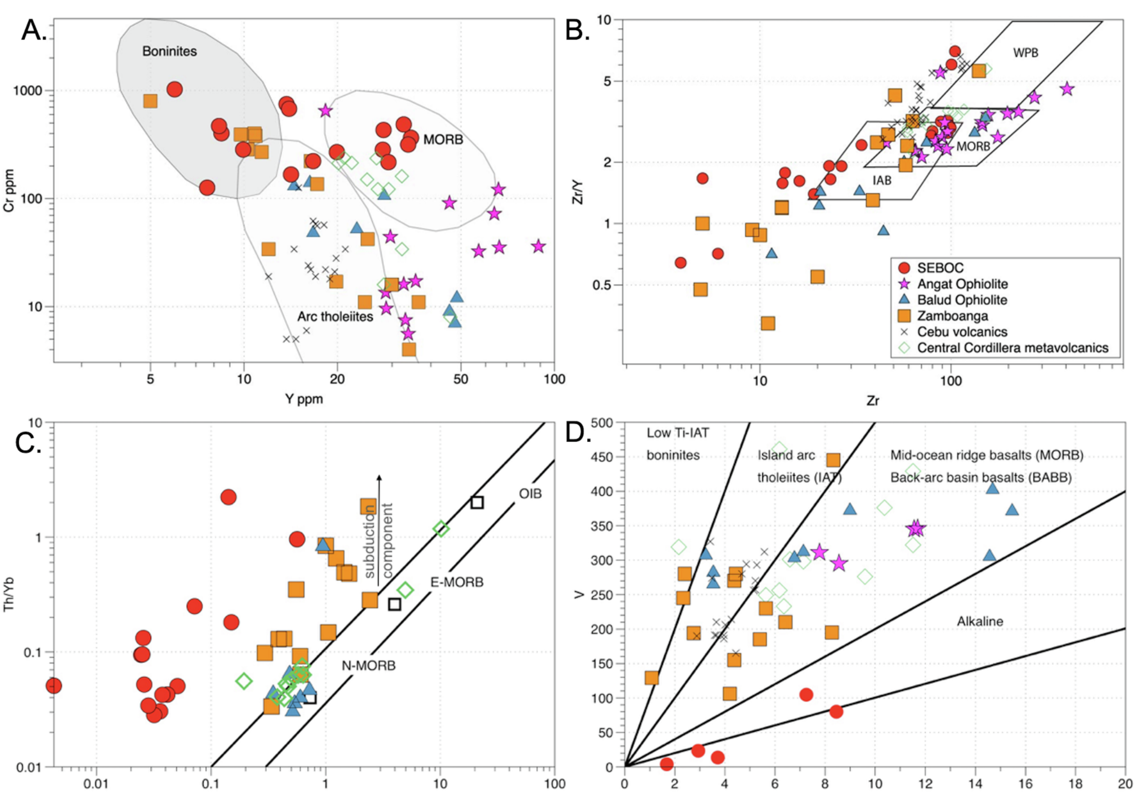

Fig. 12. Tectonic discrimination diagrams for the Cretaceous – Paleogene basement rocks in the western portion of the Philippines: A. Y vs. Cr plot (Pearce, 1982); B. Zr vs. Zr/Y plot (Pearce and Norry, 1979); C. Nb/Yb vs. Th/Yb (Saccani, 2015); and D. Ti/1000 vs. V (Shervais, 1982).

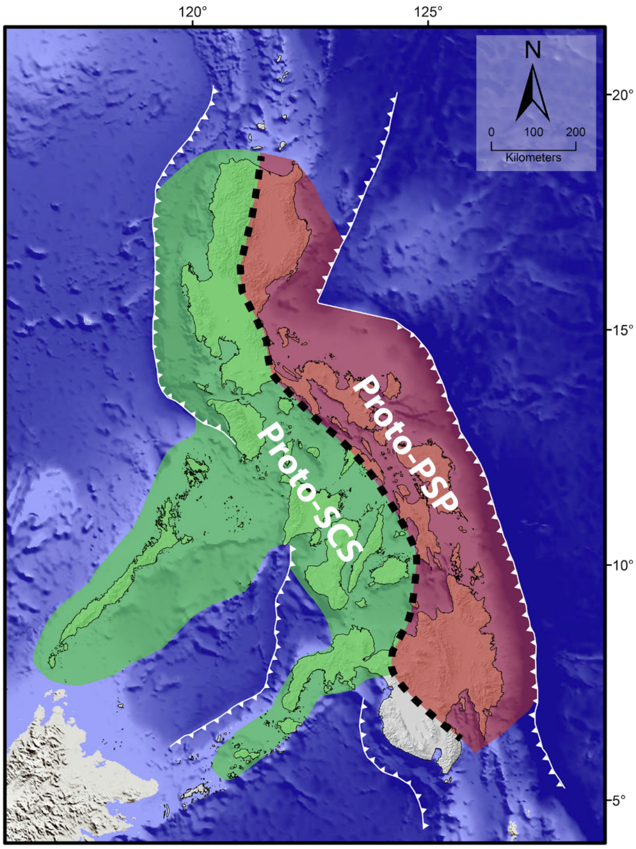

Fig. 13. A schematic representation of where the preserved remnants, mostly oceanic lithospheric fragments and associated melanges, of the proto-South China Sea (proto-SCS) can possibly be found in the Philippines (which is shown in green) and the proto-Philippine Sea Plate (proto-PSP) represented in red. Take note that the continental substratum of the areas where the proto-South China Sea fragments are expected to be present are affiliated with the North Palawan Block (e.g. Taylor and Hayes, 1980; Holloway, 1981) or West Philippines Microcontinent (e.g. Faure et al., 1989; Faure and Natalin, 1992). The white lines refer to the trenches surrounding the Philippine island arc.

Mankayan Mineral Districts in northern Luzon exhibit transitional MORB-IAT signatures (Fig. 12A-D) and are considered part of the Philippine Sea Plate (e.g. Queaño et al., 2008; Lagmay et al., 2009). Huang et al. (2019), on the other hand, based on studies done in Taiwan, the Huatung basin and northern Luzon concluded that the Mesozoic complexes exposed in these areas are part of the Early Cretaceous (131–119 Ma) Huatung Basin plate (Queaño et al., 2013). South of the Baguio-Mankayan basement rock suite is the Late Cretaceous Angat Ophiolitic Complex which exhibits back-arc basin geochemical affinity (Arcilla et al., 1989; Yumul, 1993). Earlier work by Encarnacion et al. (1993) reported an Eocene age for the Angat Ophiolitic Complex based on U-Pb age dating result. In line with this, they concluded that this Eocene ophiolitic complex is related to the Eocene Zambales Ophiolite and that the Zambales-Angat ophiolites are part of a single plate, generated in situ, and now comprising Luzon's basement. Recent studies, however, showed that the arc-related Acoje Block of the Zambales Ophiolite Complex is Middle Jurassic to Early Cretaceous in age (Ishida et al., 2012; Queaño et al., 2017b). The Cretaceous Acoje Block is closely associated with the Eocene part of the Zambales Ophiolite Complex. The presence of Eocene ophiolites associated with Cretaceous oceanic lithospheres, as in the case of Angat and Zambales, suggests the presence of a Mesozoic basement that served as substratum on which Eocene oceanic crusts have been obducted (e.g. Yumul et al., 2020). Yumul (2007) previously referred to the proto-Philippine Sea plate as the possible source of these Mesozoic complexes.

The Sibuyan Ophiolite Complex is characterized by dismembered units in east-verging thrust faults in the Romblon Island Group (Dimalanta et al., 2009). Its age is reported as Jurassic to Cretaceous from radiolarians in the cherts intercalated with the pillow lavas (Maac and Ylade, 1988). Studies on the mineral chemistry of the dunite from the mantle section of the ophiolite indicate formation from high degree of partial melting below a mid-oceanic ridge (Payot et al., 2009). The metamorphic rocks associated with the ophiolite revealed an Early Miocene emplacement related to the collision of the Palawan Microcontinental Block and the Philippine Mobile Belt.

Towards the south, in the Visayas, the early Cretaceous (126–117 Ma) Cansi Volcanic arc, the late Cretaceous sedimentary Pandan Formation and the Cretaceous (102–109 Ma) Lutopan Diorite pluton are exposed in Cebu island (e.g. Wolfe, 1995; Deng et al., 2015; Rodrigo et al., 2020). Deng et al. (2015) reported that the Cretaceous volcanic arcs in Cebu could be products of the melting of the sub-arc mantle with contributions from the subducted slab and minor sediments of the proto-Pacific plate. The Cretaceous adakitic plutons (i.e. Carmen and Kansi diorites) (Fig. 11D-F) were interpreted to be slab-melting products by Deng et al. (2019) whereas Zhang et al. (2019) preferred the derivation of these plutons from the melting of the lower continental crust or interaction between asthenospheric and lower crust melts. Subduction of the proto-Pacific Plate beneath the proto-Philippine Sea plate or India-Australia plate in the early Cretaceous was invoked upon (Zhang et al., 2019; Rodrigo et al., 2020). Southeast of Cebu island is Bohol island. An early Cretaceous ophiolitic complex, the Southeast Bohol Ophiolitic Complex, is exposed which exhibits supra-subduction zone geochemical characteristics (Faustino et al., 2003). The Cretaceous Southeast Bohol Ophiolite Complex and the magmatic arc in Cebu island were previously thought of as a forearc – volcanic arc pair related to the north-northwestward (present geographic setting) subduction of a Mesozoic oceanic plate along the proto-Southeast Bohol Trench. The origin of the ophiolitic complex has also been attributed with the proto-Philippine Sea plate (Dimalanta et al., 2020).

The above lithological suites, as presented, have been attributed to the proto-Philippine Sea plate, proto-Pacific plate or even the Australian margin. Considering their distribution and chemistry, the paleo-tectonic setting of these plutonic – oceanic fragments could have been along the edge of an oceanic plate and near a zone of accretion (Dimalanta and Yumul, 2006; Yumul, 2007). These Mesozoic complexes may actually represent the edge of the obducted parts of the proto-South China Sea plate. The proto-South China Sea oceanic plate subduction-related marginal basin setting would be consistent with the supra-subduction zone geochemistry of the ophiolite complexes. Although available data will suggest that this is a far-fetched idea, considering that the location of the ophiolitic and arc suites are along the "transition area" between two Mesozoic oceans (proto-South China Sea and proto-Philippine Sea), future studies may bear this idea possible.

The completely subducted proto-South China Sea slab is identified as a high velocity anomaly and is stagnant at around 1000 km below the South China Sea (Wu et al., 2016). Unfolding of the subducted slabs, P-wave velocity tomography and other subsurface geophysical data showed the extent of the supposed proto-South China Sea plate beneath Palawan, Sulu, Luzon and the Visayas (e.g. Rangin et al., 1999; Pubellier et al. 2003; Fig. 5 of Wu and Suppe (2017); Fig. 9 of Fan et al. (2017)). Regional geological correlation suggests that ophiolitic fragments along the Borneo – Zamboanga Peninsula could be related to the proto-South China Sea (e.g. Tongkul, 1997; Tamayo et al., 2004; Chien et al., 2019). What was once considered a lost plate, with limited expanse, may actually have extensive preserved remnants as suggested by these onland exposures of Mesozoic formations in the Philippines (Fig. 13).

5. Crustal thickness: Amagmatic Mesozoic rock contributions

Based on crustal thickness estimation of western Philippines, the

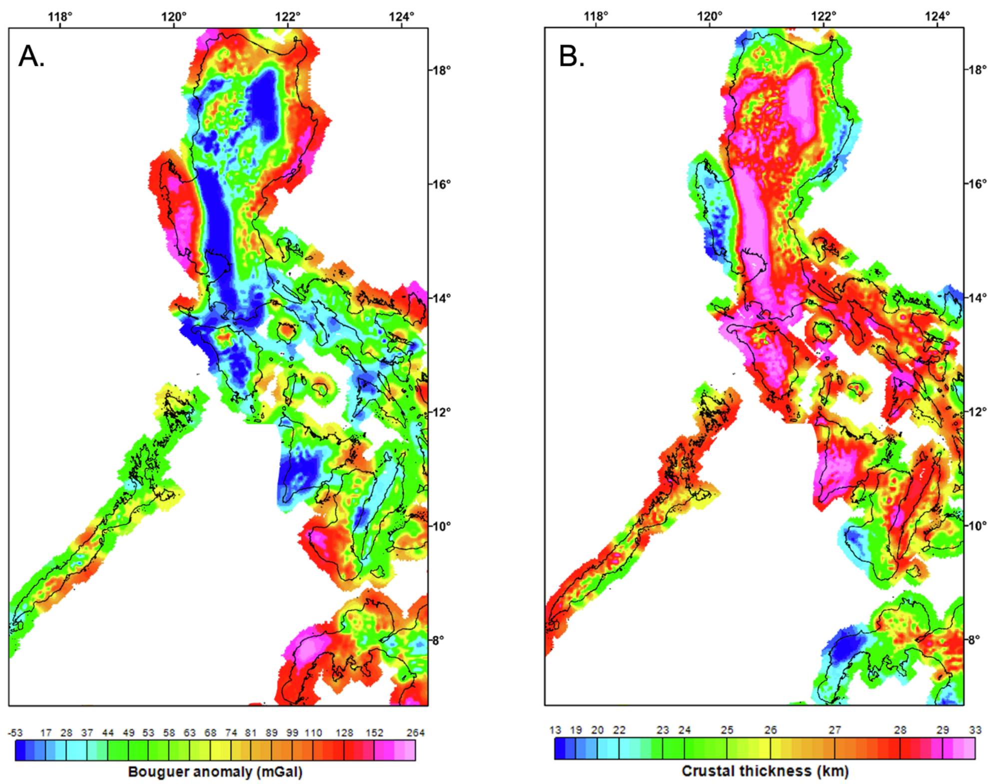

Fig. 14. A. Bouguer anomaly map of western Philippines. Low Bouguer anomaly values (-53 mGal to 58 mGal) characterize sedimentary basins while high Bouguer anomaly values (128 to 264 mGal) characterize arc and ophiolite regions. B. Crustal thickness map of western Philippines. Thickness values range from 13 km to 33 km.

areas proximal to the Mesozoic ophiolitic terranes are mostly characterized by crustal formations (e.g. Zambales, Ilocos Norte, Baguio, Angat, Mindoro, Sibuyan, Antique, North Palawan, and South Palawan ophiolitic complexes) where extensive ophiolitic units, continent-derived materials and associated mélanges are observed. These ophiolitic terranes are generally expressed as intermediate to high Bouguer anomaly values reflecting the higher densities of the oceanic fragments emplaced in these areas (Fig. 14A). Based on established stratigraphy in the ophiolitic units, the occurrence of continent-derived materials and the nature of the basement over which the oceanic lithosphere fragments were obducted, contrasting trends in the Bouguer anomalies are observed for the different oceanic lithospheres. The highest Bouguer anomaly values are observed where the ophiolite is emplaced over an assumed oceanic island arc (e.g. Zambales, Angat, Ilocos Norte, Sibuyan). Lower values, however, characterize ophiolites associated with thick continent-derived materials (e.g. Mindoro and Antique). Crustal thickness along western Philippines where Mesozoic fragments and rocks suites were accreted range from 13 to 33 km (Fig. 14B). The relatively thickened crust along western Philippines is attributed to crustal addition from amagmatic contributions. These include the arc-continent collision in Central Philippines which led to the emplacement and accretion of ophiolitic materials (Dimalanta and Yumul, 2006).

CRediT authorship contribution statement

Graciano P. Yumul: Conceptualization, Writing - original draft, Writing - review & editing. **Carla B. Dimalanta:** Writing - original draft, Writing - review & editing. **Jillian A. Gabo-Ratio:** Writing - original draft, Writing - review & editing. **Karlo L. Queaño:** Writing - original draft, Writing - review & editing. **Leo T. Armada:** Formal analysis, Investigation, Writing - original draft. **Jenielyn T. Padrones:** Writing - original draft. **Decibel V. Faustino-Eslava:** Writing - original draft. **Betchaida D. Payot:** Writing - original draft. **Edanjarlo J. Marquez:** Writing - original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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