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Graciano P. Yumul Jr

Edanjarlo J. Marquez

Jillian Aira Gabo-Ratio

Betchaida D. Payot

See next page for additional authors

Authors

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Consumed tectonic plates in Southeast Asia: Markers from the Mesozoic to early Cenozoic stratigraphic units in the northern and central Philippines

Karlo L. Queaño[a,*], Graciano P. Yumul Jr.[b], Edanjarlo J. Marquez[c], Jillian A. Gabo-Ratio[d], Betchaida D. Payot[d], Carla B. Dimalanta[d]

[a] Department of Environmental Science, School of Science and Engineering, Ateneo de Manila University, Quezon City, Philippines
[b] Cordillera Exploration Company, Inc., Bonifacio Global City, Taguig, Metro Manila, Philippines
[c] GAEA Research Laboratory, Department of Physical Sciences and Mathematics, University of the Philippines, Manila, Padre Faura, Manila, Philippines
[d] Rushurgent Working Group, National Institute of Geological Sciences, College of Science, University of the Philippines, Diliman, Quezon City, Philippines

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ABSTRACT

Tectonic reconstruction models of Southeast Asia all invoke in the early Cenozoic the collision of Mesozoic oceanic plates, which have been fragmented, consumed along subduction zones or emplaced onto the overriding plate. However, with marked variations in these models, we reinvestigate the tectonic evolutionary landscape of Southeast Asia through the lens of Philippine geology. In particular, we present revisions to the more recent models by adopting the unique approach of integrating data that we have gathered for the past 17 years from the Upper Mesozoic to Lower Cenozoic stratigraphic formations in northern and central Philippines. These formations, which resulted mainly from submarine mass transport processes, evolved in response to early arc-related processes of oblique subduction, frontal wedge deformation, terrane accretion and strike slip faulting. Additional key constraints for the revisions include: (1) the timing of early Cenozoic magmatism in eastern Luzon; (2) the spatial distribution of the Upper Mesozoic to Lower Cenozoic sedimentary formations with respect to other key features (e.g. distribution of Mesozoic ophiolite fragment and continent-derived rocks) in the Philippine arc; (3) the paleolatitudinal position of Luzon and surrounding regions and; (4) the movement of the surrounding plates since the Late Mesozoic.

In revising previous models, a subduction zone (proto-East Luzon Trough) separating Benham Plateau and the Philippine arc was placed to explain the spatial distribution of Eocene arc-related formational units and Mesozoic ophiolite materials comprising the accretionary complex east of Luzon at ~40 Ma period. During this time, Luzon was modeled at the southern margin of the East Asia Sea or the proto-Philippine Sea Plate. Mesozoic ophiolitic complexes that line the eastern Philippine arc as well as the ophiolitic and pelagic limestone and chert fragments included in the arc-derived, Eocene formations in Luzon could very well be traces of the now consumed East Asia Sea-proto-Philippine Sea Plate. Within the same period, we modified the Palawan Microcontinental Block (PCB), positioned at the trailing edge of the proto-South China Sea to include the whole Mindoro island and the Romblon Island Group in Central Philippines. Pieces of the consumed Izanagi Plate, the proto-South China Sea and continental-derived sediments from Asia mainland are reflected in the Mesozoic metamorphic rocks and the Eocene sedimentary formation in western Mindoro. Finally, we model Cebu, Bohol and Negros islands in Central Philippines as being at the leading oceanic edge of the Indo-Australian Plate during the early Cenozoic. With the northward movement of the Indo-Australian plate and the trench roll back of the southern margins of the Philippine Sea Plate, the accretion of the Cretaceous arc-related rocks of Cebu, Bohol and Negros onto the Philippine arc by the end of Eocene or early Oligocene becomes a possibility.

1. Introduction

Southeast Asia tectonics involved long-term convergence of various plates, including the proto-Philippine Sea Plate, proto South China Sea, proto-Pacific Plate and the Indo-Australian Plate. Presumably, these plates had occupied the region until the early Cenozoic when marginal basin openings resulted to the current tectonic framework of the region (Rangin et al., 1999; Metcalfe, 2011; Zahirovic et al., 2014; Hall and

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* Corresponding author.
E-mail address: kqueano@gmail.com (K.L. Queaño).

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Spakman, 2015; Wu et al., 2016). Consequent to Cenozoic basinal opening and attendant plate subduction are the accretion and/or subduction of oceanic and continental-derived fragments; oceanic plateaus or seamounts, formation of island arc systems and uplift of the overriding plate attributed to subduction-related deformations (McCabe et al., 1987; Yumul et al., 2003; Pubellier et al., 2004; Queaño et al., 2007a). Erosion of these accreted and/or uplifted terranes provides mechanisms by which their end product, the sedimentary units, may be scrutinized for provenance studies, tectonic setting and plate affiliation (Gabo et al., 2009; Suggate et al., 2014; Suzuki et al., 2017; Dimalanta et al., 2018; Yan et al., 2018). To demonstrate, oceanic basins of nearby active island arcs are isolated from inputs of continental margin turbidity currents. On the contrary, oceanic basins at the leading edge of continental plates may contain continental-derived sediments that may either be accreted onto or be completely subducted at a plate margin. With this in mind, markers (e.g., field characteristics; composition) from sedimentary rocks formed during and after plate convergence could provide significant inputs in modeling the making of an island arc.

The Philippine archipelago has been the locus of plate interaction between various plates. The present-day tectonics of the arc involves the convergence between the South China Sea of the Sunda Plate, and the West Philippine Basin of the Philippine Sea Plate (Fig. 1). While the setting is seemingly easy to comprehend, a different perspective can be said about the Philippine arc's early evolution. More recent plate reconstruction models based on regional geology, computer-based reconstructions, mantle tomography and slab unfolding suggest involvement of the proto-Philippine Sea, the proto-South China Sea, the East Asian Sea, and the Indo-Australian plates in the Philippine arc formation starting the Cretaceous to Eocene (e.g. Rangin et al., 1999; Hall, 2002; Tamayo et al., 2004; Queaño et al., 2007b; Wu and Suppe, 2017; Huang et al., 2019; Dimalanta et al., 2020; Rodrigo et al., 2020; Yumul et al., 2020). Except for the Indo-Australian plate, these plates were consumed by subduction under much of Southeast Asia. Nonetheless, it would be interesting to look into the possible imprints of and attendant tectonic processes related to the activities of these "consumed plates" from the data set that we have collected from the Cretaceous to Eocene clastic and epiclastic rocks for the past 17 years in north and central Philippines. In this paper, we present these data sets (sedimentologic attributes, rock associations, petrology, paleontology, geochronology and geochemistry) and complement them with previously generated geologic information. The syntheses are then used to examine their provenance or plate affinity, providing inputs for modeling the birth of Philippine arc in the context of East and Southeast Asia's regional tectonics during the late Mesozoic to early Cenozoic.

2. Tectonic framework

Southeast Asia has been an icon in arc-continent collisions and marginal basin formations. These events are manifested in the islands comprising the Philippine Mobile Belt (PMB), which had been part of the Philippine Sea Plate (PSP) almost throughout the Cenozoic based on existing models (Hall, 2002; Pubellier et al., 2004; Queaño et al., 2007a; Zahirovic et al., 2014; Wu et al., 2016). As it will be shown in Section 5.2, exceptions do exist as to their PSP affinity for some tectonic elements of the PMB. The present setting shows that the PMB is almost exclusively bound by subduction zones, namely, the Manila Trench-Negros Trench-Sulu Trench to the west, and the East Luzon Trough-Philippine Trench to the east. Between northern Luzon and Taiwan, however, the East Luzon Trough seemingly connects with the Luzon-Okinawa Fracture Zone, a non-transform discontinuity of the Philippine Sea Plate (Lallemand, 2016). The ~1200-km-long sinistral Philippine Fault transects the PMB, with offshore extensions to the northwest of Luzon and south of eastern Mindanao (Aurelio et al., 1991; Barrier et al., 1991; Armada et al., 2012).

The collision of the different plates in the early Cenozoic provided the main triggering mechanism for the opening of present-day marginal basins that surround the Philippine arc and other regions in SE Asia. As in the case of the South China Sea, the Sulu Sea and the West Philippine Basin, these Cenozoic marginal basins also feature plateaus, aseismic ridges, fracture zones and submerged volcanic arcs that are currently subducting underneath the Philippine arc. Similarly, consequent to the marginal basin opening are the fragmentation and eventual emplacement or consumption along subduction zones of Mesozoic oceanic plates in SE Asia (Yumul et al., 2003; Pubellier et al., 2004; Tamayo et al., 2004). The presence of several Mesozoic ophiolites of diverse geochemistry in the Philippines and surrounding regions attests to the existence of the "proto-plates" prior to the inception of Cenozoic SE Asia. Pubellier et al. (2004) and Tamayo et al. (2004) treated these ophiolites as either "relatively autochthonous ophiolites" resulting from the shortening of marginal basins or "highly displaced ophiolites" formed as a consequence of oblique subduction. Emerging references to these "proto-plates' in SE Asia include the Izanagi Plate, the proto-Philippine Sea Plate (PSP), proto-South China Sea Plate and proto-Molucca Sea Plate among others (Zamoras and Matsuoka, 2001; Dimalanta et al., 2020; Yumul et al., 2020). More controversies are highlighted for the proto-PSP in recent works, with Zahirovic et al. (2014) dividing the proto-PSP into northern and southern segments. On the other hand, Wu et al. (2016) prefers putting the proto-PSP as part of the so-called East Asia Sea that once occupied the region between the Pacific Ocean and Indian Ocean. An earlier work of Deng et al. (2015), however, confined the proto-PSP as developing at the northern margin of Indo-Australia. In this paper, we attempt to look into how provenance of the Late Mesozoic to early Cenozoic sedimentary units in the Philippine arc relate to existence of these proto-plates in SE Asia now consumed following the region's multi-stage tectonic evolution.

3. Methodology

The primary data were obtained from the series of field expeditions that we had conducted as part of research-related activities for the past 17 years. Additional information was also collected from our past expeditions done alongside geophysical surveys (paleomagnetic, gravity and magnetic surveys), mineral exploration, field class activities and geohazard assessment and mapping in Luzon and Central Visayas. Results by previous workers from these regions also served as critical inputs for evaluating and testing models for the Philippine arc and Southeast Asia.

Limestone samples for paleontologic analysis were submitted to the Mines and Geosciences Bureau (Central Office) - Department of Environment and Natural Resources (MGB-DENR) in Quezon City, Philippines. Geochemical results from the Mesozoic to Eocene rock formations were integrated to deduce their possible sources and tectonic setting. These results should address the limitations in using paleocurrent indicators deduced from sedimentary structures in rocks, which traditionally have been used for provenance studies. This sedimentological approach would also not be feasible for regional geodynamic studies involving a tectonically-complex regime such as the Philippines where tectonic elements have different plate origins. As also reflected in the paleomagnetic results from the arc gathered previously (e.g., Fuller et al., 1983; Queaño et al., 2007a), deformation affecting the Philippine arc since its inception makes complex block rotations about a vertical axis very likely, further limiting the use of paleocurrent indicators.

Geochemical results from pillow basalts associated with the Eocene sedimentary formations (Caraballo and Bangui) in northern Luzon herein reported were obtained from the unpublished geochemical work of Queaño (2006) (Table 1). Whole rock major element and trace elements (Sc, V, Cr, Ni, Cu and Zn) abundances from these rocks were determined using X-ray fluorescence spectrometry (XRF), while the other remaining trace elements used VG Elemental Plasma Quad 3 inductively coupled plasma-mass spectrometer (ICP-MS) at the

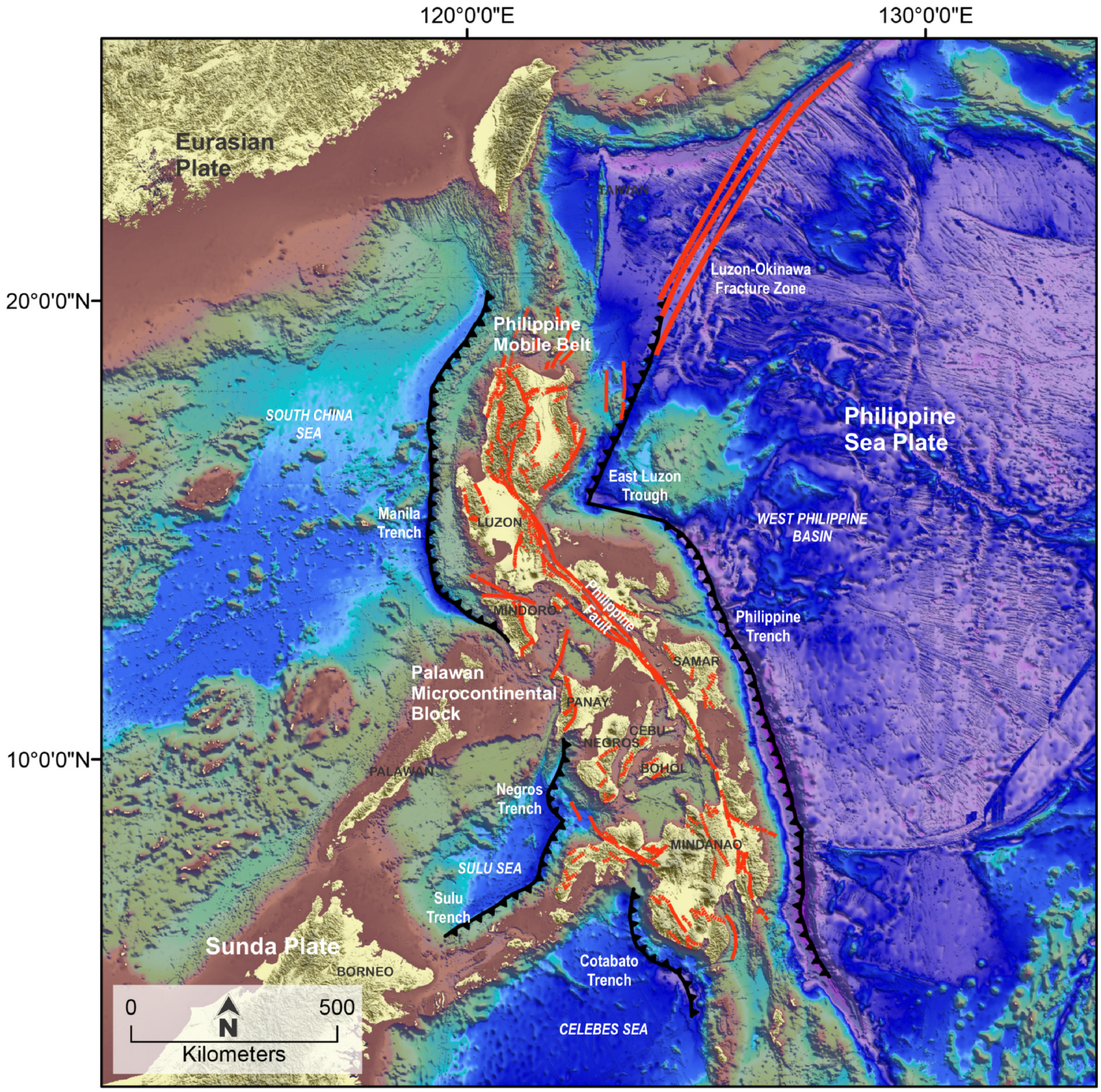

Fig. 1. Regional tectonic setting of the Philippines (data from openly sourced General Bathymetric Chart of the Oceans (GEBCO), 2019 Grid dataset).

Department of Earth Sciences of The University of Hong Kong. On the other hand, whole rock major oxide compositions of rocks from the Tumbaga Formation in southeastern Luzon and the Maybangain and Kinabuan formations in Southern Sierra Madre were analyzed using the Pananalytical Axios Max X-ray fluorescence spectrometer at the Bureau Veritas Mineral Laboratories in Canada. The Inductively Coupled Plasma-Mass Spectrometer (ICP-MS) ELAN 9000 of the Bureau Veritas Mineral Laboratories in Canada was used for the whole rock trace element concentrations for samples from the same formation. Based on replicate samples, the analytical precision of the data is less than 1% for the major oxides and up to 10% for the trace elements. The results from the aforementioned samples were integrated with those obtained from the published work of Concepcion et al. (2011) and Rodrigo et al. (2020).

4. Early Cenozoic sedimentary formations: New data and interpretations

4.1. Caraballo Formation, Northern Sierra Madre, Luzon

The Caraballo Formation is the most extensive rock unit in the Northern Sierra Madre (NSM) in Luzon. This formation was originally introduced as the Caraballo Group of Formations by JICA-MMAJ (1975), consisting of "sub-formations" I, II and III. Ringenbach (1992) lumped these sub-formations and subsequently referred to this rock unit as the Caraballo Formation. Owing to the lack of distinctive physical and mineralogic characteristics amongst the sub-formations (JICA-MMAJ, 1975, 1977), the latter name and definition are adopted for this study.

The Caraballo Formation consists of a deep-water basinal sequence of epiclastic volcanogenic deposits, volcaniclastic rocks, and lava flows. Along the coast of northeastern Luzon, a 50-meter-thick section of the formation is exposed. The unit consists of pillow basalts conformably overlain by hemipelagic, silicified red siltstones and green sandstones as well as epiclastic units in the form of conglomerates and sandstones

Table 1
Major oxide and trace element data of the volcanic rocks of the Caraballo and Bangui Formations.

Locality	Caraballo Formation				Bangui Formation						
Sample No.	NEL-18	WSM-1–29	WSM-41	WSM-44	CVA-5	CVA-7	CVA-14	IR-30	IR-34	IR-35	IR-37
SiO2	49.08	65.56	49.46	67.28	46.95	47.83	61.49	51.08	52.52	47.15	74.40
TiO2	0.88	0.68	0.77	0.74	0.80	0.90	0.66	0.98	0.78	0.84	0.28
Al2O3	18.08	15.62	16.16	14.03	16.02	16.33	14.75	14.90	14.94	15.71	13.18
Fe2O3*	10.68	5.29	9.28	6.14	9.80	9.54	7.25	9.54	8.38	10.24	2.62
MnO	0.20	0.11	0.17	0.10	0.16	0.16	0.13	0.14	0.16	0.20	0.05
MgO	3.90	2.19	8.52	1.33	8.10	8.23	4.42	7.09	7.90	10.54	0.61
CaO	9.14	0.98	7.35	1.26	8.92	7.96	2.70	10.39	9.46	9.15	2.00
Na2O	3.05	5.96	4.49	6.39	2.86	5.17	4.92	4.89	4.25	3.26	5.87
K2O	0.80	0.70	0.17	0.63	0.80	0.19	1.34	0.05	0.31	0.27	1.03
P2O5	0.08	0.14	0.10	0.23	0.10	0.14	0.07	0.13	0.09	0.09	0.04
LOI	3.75	3.28	4.11	2.06	4.46	4.62	3.42	2.64	2.77	4.02	1.23
Total	99.65	100.52	100.58	100.20	98.99	101.06	101.17	101.83	101.55	101.47	101.32
Fe2O3* = Total iron											
Trace elements (in ppm)											
Sc	38.01	24.91	37.70	19.27	27.25	32.13	33.47	31.74	38.78	52.32	7.20
V	349.52	51.39	230.81	42.77	242.77	247.81	182.41	262.63	224.07	240.00	33.36
Cr	17.73	67.58	317.67	13.75	250.85	286.92	73.31	389.56	349.69	475.12	12.37
Ni	25.02	3.05	113.44	3.19	68.08	8.57	29.12	194.92	183.48	264.09	3.10
Cu	91.59	7.52	69.50	7.01	78.76	91.45	72.39	35.34	48.42	68.40	−1.80
Zn	81.58	80.61	73.42	73.37	68.98	72.67	72.33	76.86	71.78	115.73	32.02
Zr	37.49	114.10	60.86	133.10	37.86	67.31	100.40	67.04	49.29	61.07	128.20
Rb	13.60	11.82	2.21	6.50	12.65	2.33	20.09	0.67	3.38	4.87	15.84
Sr	144.10	149.90	334.20	155.40	227.20	199.20	134.90	135.60	128.10	149.50	137.00
Y	21.80	42.73	22.93	53.75	17.35	22.50	28.61	25.32	20.29	23.69	27.11
Nb	0.32	0.88	0.76	1.78	0.98	2.43	1.38	0.94	0.68	0.81	1.22
Cs	0.12	0.16	0.03	0.01	0.20	0.01	0.05	0.02	0.02	0.03	0.05
Ba	28.48	65.47	79.18	98.59	62.51	23.87	141.30	2.63	23.69	33.43	203.50
La	1.45	3.74	3.05	6.97	2.19	3.75	6.33	3.12	2.27	2.59	6.73
Ce	4.80	11.85	9.09	21.28	6.10	10.59	15.64	9.17	6.75	8.15	15.79
Pr	0.85	2.23	1.47	3.21	1.04	1.63	2.33	1.53	1.14	1.35	2.13
Nd	5.04	13.27	7.68	17.11	5.64	8.60	11.27	8.15	6.16	7.51	9.50
Sm	1.87	4.62	2.52	5.73	1.76	2.60	3.12	2.60	2.12	2.59	2.54
Eu	0.71	1.42	0.86	1.57	0.75	0.97	0.88	0.96	0.85	0.89	0.64
Gd	2.55	5.94	3.08	6.79	2.38	3.23	3.73	3.31	2.66	3.20	3.31
Tb	0.49	1.06	0.54	1.22	0.42	0.55	0.62	0.58	0.45	0.55	0.56
Dy	3.58	7.47	3.86	8.88	2.85	3.86	4.43	4.10	3.32	3.91	3.94
Ho	0.73	1.51	0.77	1.78	0.58	0.78	0.90	0.82	0.67	0.80	0.83
Er	2.21	4.58	2.29	5.36	1.67	2.23	2.71	2.48	1.94	2.36	2.63
Tm	0.29	0.58	0.29	0.69	0.21	0.29	0.35	0.32	0.24	0.30	0.35
Yb	2.19	4.44	2.20	5.39	1.62	2.13	2.64	2.41	1.91	2.28	2.92
Lu	0.30	0.61	0.30	0.72	0.22	0.29	0.37	0.31	0.25	0.30	0.41
Hf	1.31	3.39	1.58	3.84	1.02	1.65	2.57	1.75	1.33	1.62	3.64
Ta	0.11	0.06	0.07	0.09	0.07	0.13	0.09	0.08	0.06	0.07	0.08
Pb	1.49	8.69	1.88	3.24	1.70	0.99	2.69	1.67	1.10	1.38	3.03
Th	0.08	0.17	0.14	0.73	0.14	0.20	0.57	0.13	0.10	0.11	1.41
U	0.04	0.13	0.08	0.40	0.08	0.09	0.17	0.07	0.04	0.04	0.79

(Fig. 2A-B). The pillow basalts are commonly vesicular and exhibit either an aphanitic or porphyritic texture (with plagioclase as phenocrysts). The epiclastic deposits are mostly thick to very thick conglomerate beds with few intervening thin to thick beds of tuffaceous sandstones and mudstones. In most places, the conglomerates contain subangular to rounded, pebble- to boulder-sized andesitic to basaltic clasts set in a tuffaceous sandy matrix. The conglomerates have either planar or erosive contacts with the underlying beds. Some units grade upwards to coarse- to medium-grained, parallel laminated parallel and/or cross-laminated sandstone. Such characteristics of the conglomerates and associated facies suggest that they were most likely deposited as debris flows or high-density turbidity flows.

Along the western flank of NSM, a section composed of alternating beds of volcanic breccia and basaltic flows and associated tuffaceous sediments is exposed. It is at least 500-meter-thick. In most outcrops, the lavas are pillowed and are overlain by tuffaceous siltstones to fine sandstones. The volcanic breccia consists of subangular to angular, pebble- to cobble-sized basaltic to andesitic fragments set in a tuffaceous matrix. The volcanic breccia is usually massive, with thickness of 5–30 m. A number of basaltic dikes, presumably of similar age to the pillow basalts and volcanic breccia, intrude the Caraballo Formation rocks.

Petrochemical discrimination plot of the extrusive igneous rock samples from the Caraballo Formation shows clustering in the andesite/basalt field (Fig. 3A; Pearce, 1996). The Nb/Yb vs Th/Yb plot (Fig. 3B; Pearce, 2008) reveals N-MORB affinity with possible input of subduction components. The Th-Hf/3-Ta, Th-Zr/117-Nb/16 and Th-Hf/3-Nb/16 diagrams (Wood, 1980), however, show preferential plotting of the samples in the arc field. Additional information on the tectonic affinities of the rocks is given by the REE concentrations of the rocks normalized to chondrite (values from Sun and McDonough, 1989). The patterns show marked depletion in Ta and Ti and enrichment in Rb and Ba. The geochemical results are consistent with field observations showing a close association between the volcanic rocks and arc-derived epiclastic rocks of the Caraballo Formation.

Ringenbach (1992) and Billedo (1994) assigned a Middle to Late Eocene age for the Caraballo Formation based on the K-Ar dating of basalt samples and paleontological data from sediments overlying the pillow basalts. Billedo (1994) estimated the formation to be 6–10 km thick.

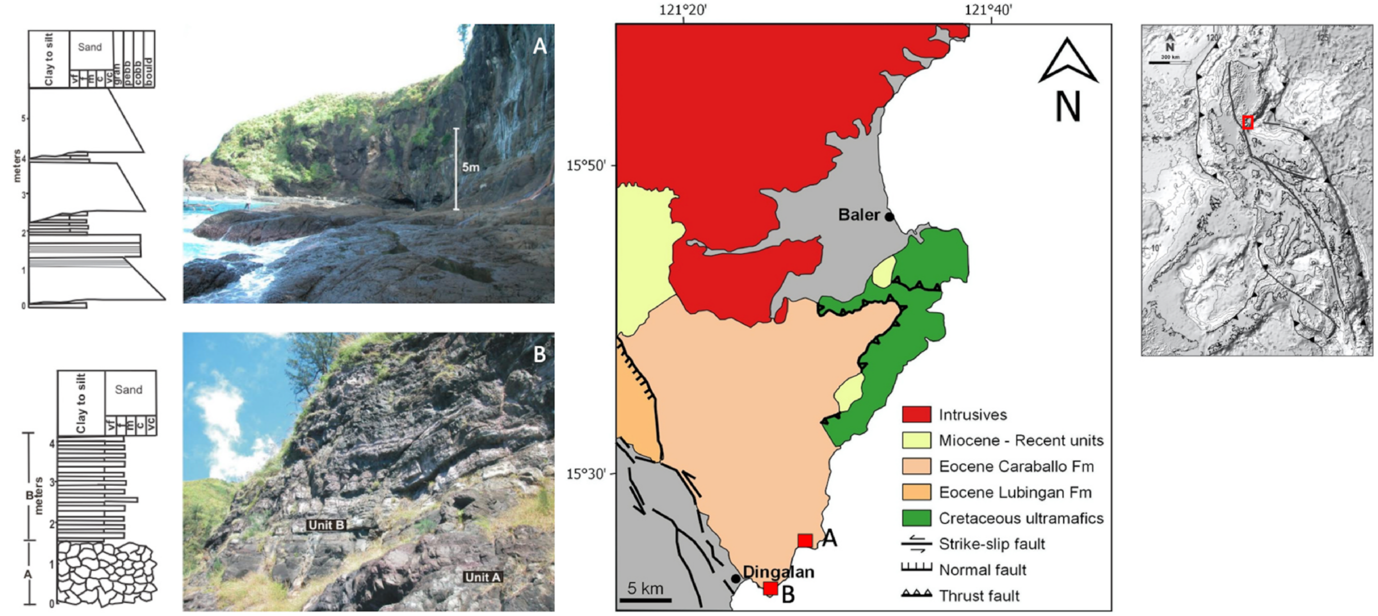

Fig. 2. Outcrops of the Caraballo Formation. (a) Epiclastic rocks exposed along the coast of Dingalan (GPS: 15° 25.17′ N, 121° 28.38′ E); (b) Pillow basalts (Unit A) overlain by fine sedimentary rocks (Unit B) of the Caraballo Formation (GPS: 15° 23.02′ N, 121° 26.12′ E).

It is worth noting that the Lubingan Formation exposed adjacent to the Philippine Fault at the southern part of NSM could in fact belong to the Caraballo Formation. This formation was defined by Rutland (1968) for the thick sequence of mainly greenschist facies sedimentary and volcanic rocks and minor marbles at the southern end of NSM and was included by previous workers (e.g., Billedo, 1994) as part of the pre-Cenozoic basement of eastern Luzon. However, paleontological investigation of a carbonate sample indicates it is Eocene based on the presence of *Nummulites* sp. (Hashimoto et al., 1978). With this, Encarnacion (2004) suggested that the protoliths of the metamorphic rocks were probably the Eocene volcaniclastics of the Caraballo Formation and the Eocene-Oligocene plutons in the area.

4.2. Maybangain Formation, Southern Sierra Madre, Luzon

The Maybangain Formation was named by Melendres and Versoza (1960) for the limestone and clastic-volcanic rocks outcropping along the Maybangain Creek, Tanay, Rizal in the western portion of the Southern Sierra Madre (SSM). Much of the description of the formation (e.g., Schöll and Duyanen, 1988; MGB, 2010) is based on the exposures in the southwestern part of SSM where turbiditic epiclastic rocks and limestones belonging to the formation were noted. In this work, the formation was observed in eastern SSM, particularly along Umiray River and the coast of Dingalan municipality (Fig. 4). Along the Umiray River, the formation consists of folded epiclastic rocks, particularly breccias with intervening units of calcareous thin- to medium-thick (5–25 cm) beds of sandstones and siltstones (Fig. 4A). The breccias consist of pebble- to cobble-sized clasts of basaltic to andesitic fragments set in a tuffaceous, sandy matrix (Fig. 4B). Huge blocks of cream- to buff-colored, recrystallized limestones occur intermittently within the coarse epiclastic rocks (Fig. 4C). These limestones are interpreted as olistoliths as also reported by Ringenbach (1992). Paleontologic analyses of two limestone samples indicate the presence of Upper Cretaceous benthonic foraminifera (*Globotruncana linneiana* (d'Orbigny), *Globotruncana ventricosa* (White), *Globotruncana bulloides* Vogler, *Globotruncana arca* Cushman, *Rugoglobigerina rugosa* (Plummer), *Globigerinelloides* sp., ?*Globotruncanella petaloidea* (Gandolfi), *Heterohelix* sp., *Globotruncan*ita sp. Similar Upper Cretaceous limestone olistoliths were earlier reported by Schöll and Duyanen (1988) within a 1200-m thick pile of turbiditic epiclastic rocks of the Maybangain Formation exposed on the western flank of the SSM (Fig. 4D).

Along the eastern coast of SSM, in Dingalan, area, the formation consists mainly of coarse epiclastic deposits, mostly breccias, with intervening beds of reddish to greenish, fine- to medium-grained sandstones and mudstones (Fig. 4). Outcrops along the Dingalan coast closely resemble the epiclastic units observed along the coast north of Dingalan in NSM where the Caraballo Formation was mapped. Radiolarian work by Ishida et al. (2011) on the outcrops along Dingalan suggested a middle Eocene age for the units. This age is also somewhat similar to the age assigned to the Caraballo Formation. Ishida et al. (2012) named the units as the Cabog Formation. This work, however, prefers to retain the name Maybangain Formation for the outcrops, as this name has long been established by previous workers (e.g., Reyes and Ordonez, 1970; Hashimoto et al., 1979; Haeck, 1987; Ringenbach, 1992). For the Eocene outcrops in the Southern Sierra Madre, the Mines and Geosciences Bureau (MGB) (2010) reported a thickness in excess of 2.5 km.

4.3. Bangui Formation, northern Luzon Central Cordillera

The term "Bangui" was introduced by Smith (1907, in MGB, 2002) in reference to the sandstone member of the "Baruyen Series" in northwestern Luzon. Pinet and Stephan (1990) described the Bangui Formation as comprising greywackes, conglomerates, tuffs, volcanic flows and limestones. They also included the olistostrome as part of this formation. In this study, however, the said olistostrome unit, which contains ophiolitic clasts (e.g., serpentinite, gabbro, basalt) and cherts among others, is excluded as part of the Bangui Formation. Previous observations made in the region by Queaño et al. (2017) indicate that the said deposits constitute part of a tectonic mélange.

In this work, the Bangui Formation was observed in several localities in Cagayan and Ilocos Norte. The base of the formation consists of interbeds of green sandstones and red siltstones that conformably overlie the pillow basalts (Fig. 5A1-A2). This is best observed along the coast of Claveria, Cagayan. The sandstone beds are a few centimeters to a meter-thick. Most of the sandstones grade normally to siltstones and are parallel and/or convolute laminated. On the other hand, the pillow basalts are commonly porphyritic and amygdaloidal. They extend for about 200 m along the coast.

At higher stratigraphic levels, the formation is dominated by

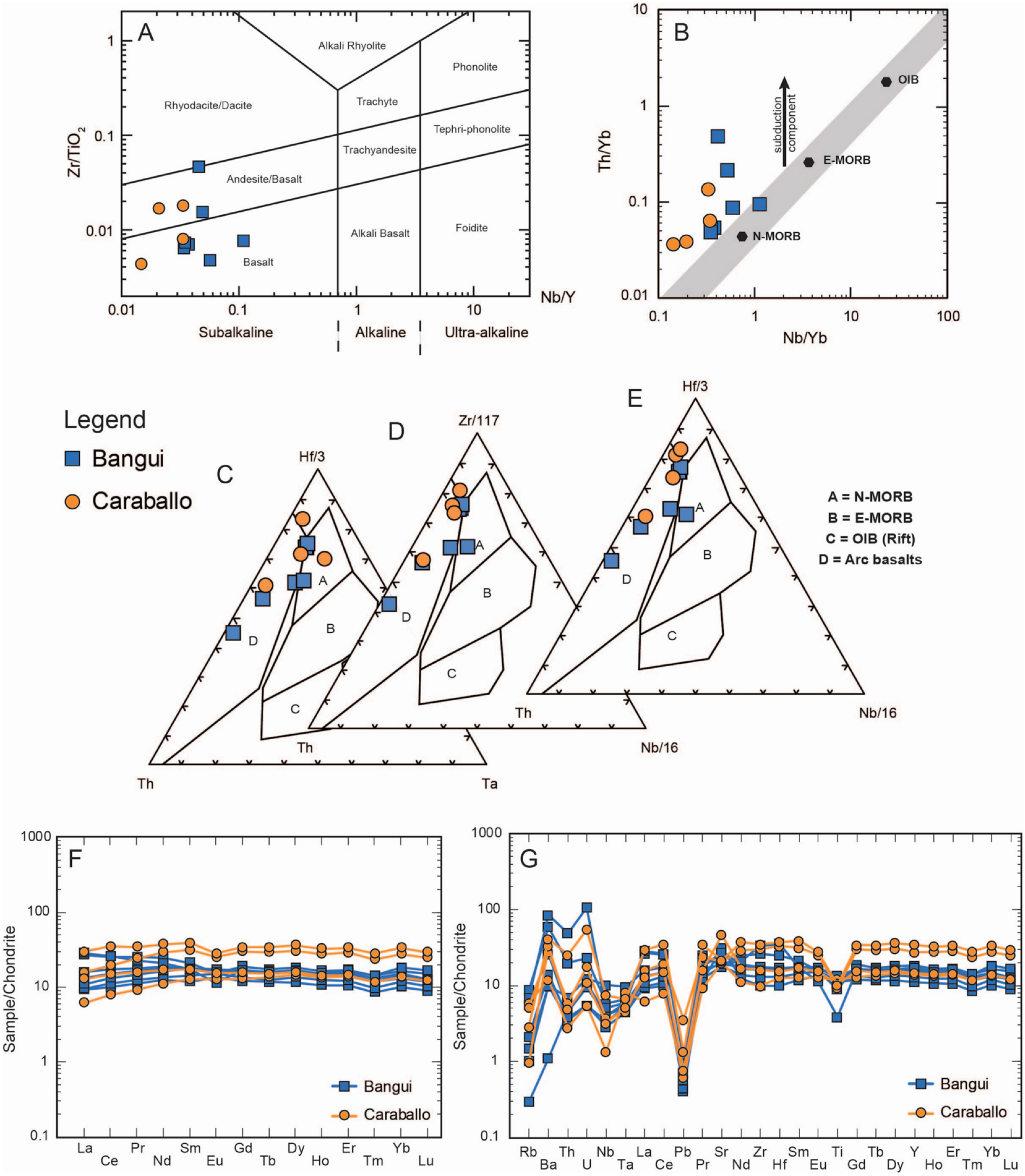

Fig. 3. Geochemical plots of the volcanic rocks of the Caraballo and Bangui formations. (a) The subalkaline volcanic rocks classify as basalts and andesites in the Nb/Y vs Zr/TiO_2 diagram (Pearce, 1996). (b) Nb/Yb vs Th/Yb reveal NMORB signatures with addition of subduction of components (Pearce, 2008). (c-e) Ternary diagrams using Th, Hf, Ta and Nb consistently show dominant arc affinity (Wood, 1980). (f-g) Rare earth elements (REE) normalized to chondrite (Sun and McDonough, 1989) show relatively flat patterns. Extended trace element diagram shows enrichment in Rb and Ba with depletion in Ti and Ta typical in arc related rocks.

polymictic conglomerates that are best exposed in Ilocos Norte (Fig. 5B1-B2). Most of the conglomerates are massive with a maximum thickness of 100 m. The conglomerates contain pebble- to cobble-sized andesitic to basaltic clasts and minor red siliceous mudstones embedded in a tuffaceous, sandy matrix. Occasionally, the conglomerates are associated with sandstone and siltstone interbeds. Along the national road between Cagayan and Ilocos Norte, the interbedded unit associated with the conglomerates is almost vertically oriented, reflective of the highly deformed nature of the Bangui Formation.

Petrochemical discrimination plot of the extrusive igneous rock samples from the Bangui Formation shows clustering in the andesite/basalt field similar to that of the Caraballo Formation (Fig. 3A; Pearce, 1996). In terms of tectonic affinity, the Bangui samples also register N-MORB with subduction components (Fig. 3B; Pearce, 2008). The Th-Hf/3-Ta, Th-Zr/117-Nb/16 and Th-Hf/3-Nb/16 diagrams (Fig. 3C-E; Wood, 1980) seem to show a more preferential plotting towards the arc field, with two of the samples plotting on or near to the arc or arc-N-MORB boundary. Additional information on the tectonic affinities of

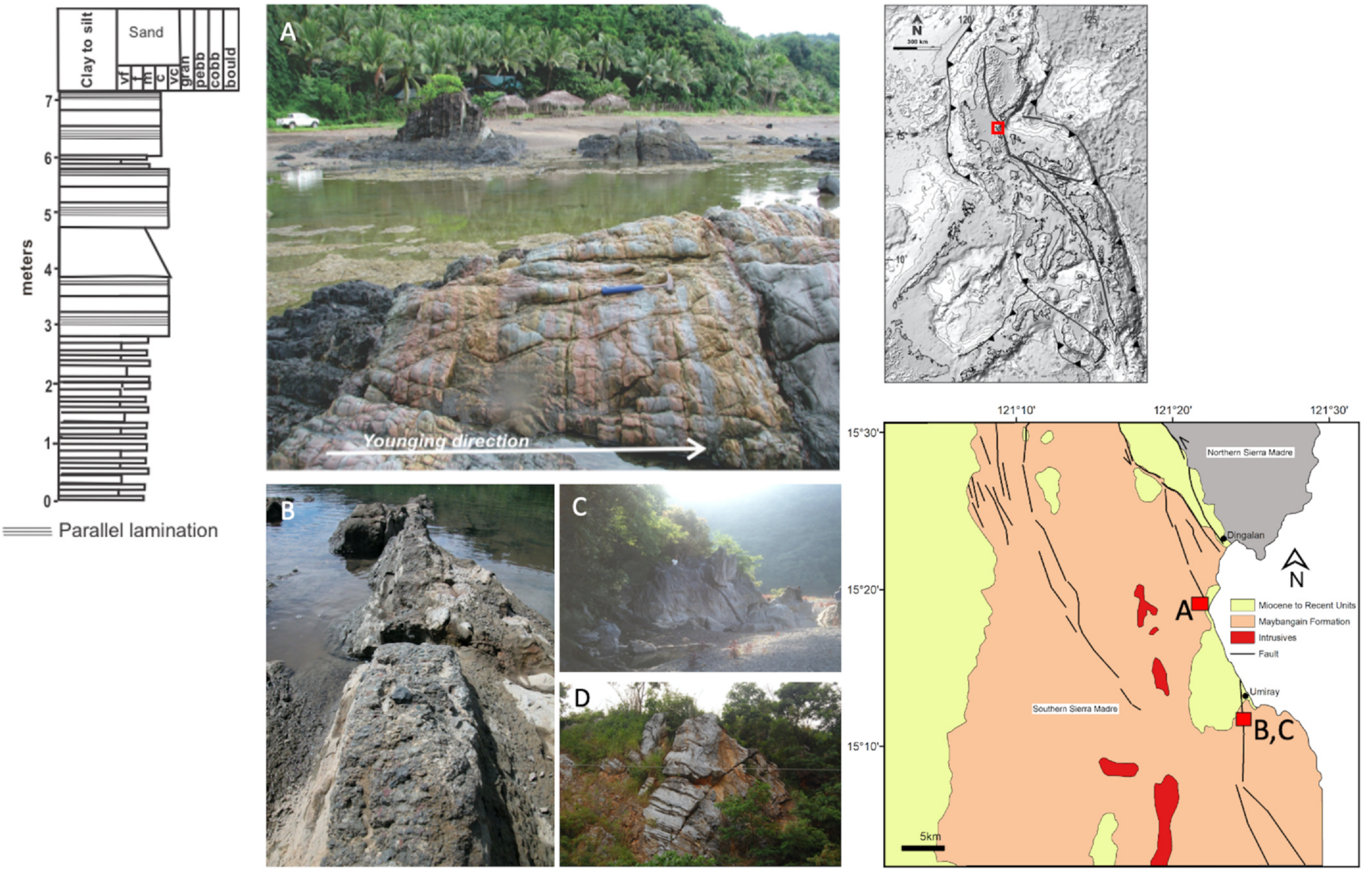

Fig. 4. Outcrops of the Maybangain Formation. (a) Interbedded red and green siliceous mudstone and siltstone along the coast of Dingalan, eastern Southern Sierra Madre, Luzon; (b) Breccia (with chert/siliceous mudstone, basalt and limestone clasts set in a tuffaceous sandy matrix) along Umiray River, Dingalan; (c) Limestone olistolith of the Maybangain Fm. observed along Umiray River, Dingalan; (d) Limestone olistolith noted along a road in Rizal province in the western flank of Southern Sierra Madre.

the rocks is given by the REE concentrations of the rocks normalized to chondrite (values from Sun and McDonough, 1989; Fig. 3F-G). The pattern shows a marked depletion in Ta and Ti and enrichment in Rb and Ba (except for one sample). The geochemical results are consistent with field observations showing a close association between the volcanic rocks and arc-derived epiclastic rocks of the Bangui Formation.

The BMG (1981) reported Upper Eocene marbles intercalated with clastic rocks and gave a thickness of at least 2000 m for the Bangui Formation. As will be explained in the latter section, the Bangui Formation is correlative with the Caraballo Formation in the Northern Sierra Madre Range.

4.4. *Tumbaga Formation, southeastern Luzon*

The Tumbaga Formation represents the clastic units best exposed in the community of Tumbaga in Jose Panganiban, Camarines Norte in SE Luzon. This formation was previously called the Universal Formation by Meek (1941) in reference to the rocks exposed at the now defunct Universal Exploration and Mining Company. MGB (2010) renamed the formation as the Tumbaga Formation.

The sedimentary sequence is composed mostly of interbedded grayish to greenish sandstones and siltstones and few conglomerates, that are usually moderately to strongly magnetic (Fig. 6A-B). Outcrops of the formation are highly deformed, with bed dips usually in excess of 70°. The sandstones and siltstones commonly display structures of the Bouma Sequence, although such internal sedimentary structures are not observable particularly in outcrops that had undergone silicification or intense weathering. Coarser varieties (lithic sandstones and conglomerates) contain several mafic and quartz detritals as well as granule- to pebble-sized lithic fragments of peridotite and granodiorite. These were likely derived from the older basement rock (Cretaceous Cadig Ophiolitic Complex), and the batholithic body (Early Eocene Paracale Granodiorite). Excavations done in the southeastern portion of Jose Panganiban revealed the presence of a bedded marble oriented N25W/77SW. Based on this orientation, this unit appears to overlie the clastic unit of the Tumbaga Formation. MGB (2010) treats this marble as comprising the upper member of the formation.

Plots using whole rock major element data point to a primarily mafic igneous provenance on the F1-F2 diagram of Roser and Korsch (1988) (Fig. 7A). On the Zr-15Al_2O_3-300TiO_2, the Tumbaga samples generally plot between the gabbro and granite compositions, although closer to the gabbro compositions (Fig. 7B). Using trace element data to further constrain the provenance of the Tumbaga clastic rocks, we use the Zr vs TiO_2 and the Hf vs La/Th diagrams. The Tumbaga samples cluster within the intermediate igneous rock field (Fig. 7C). On the Hf vs La/Th diagram, the samples occupy the mixed felsic/basic source to andesitic arc source fields (Fig. 7D). These geochemical plots are supportive of source contribution from the Cadig Ophiolitic Complex and the Paracale Granodiorite.

Whole rock geochemical data are also used to constrain the tectonic setting of the source rocks. In the Fe_2O_3 + MgO vs Al_2O_3/SiO_2 and TiO_2 diagrams, clastic rocks of the Tumbaga Formation plot close to the oceanic island arc field (OIA) (Fig. 8A-B). The same OIA affinity is observed in the trace element plots using Co-Th-Zr/10 and Th vs La (Fig. 8C-D).

The age of the formation is ill-constrained. Based on stratigraphic position, a Paleocene to Eocene age was assigned to the formation (Miranda and Caleon, 1979; BMG, 1981). MGB (2010) assigned a

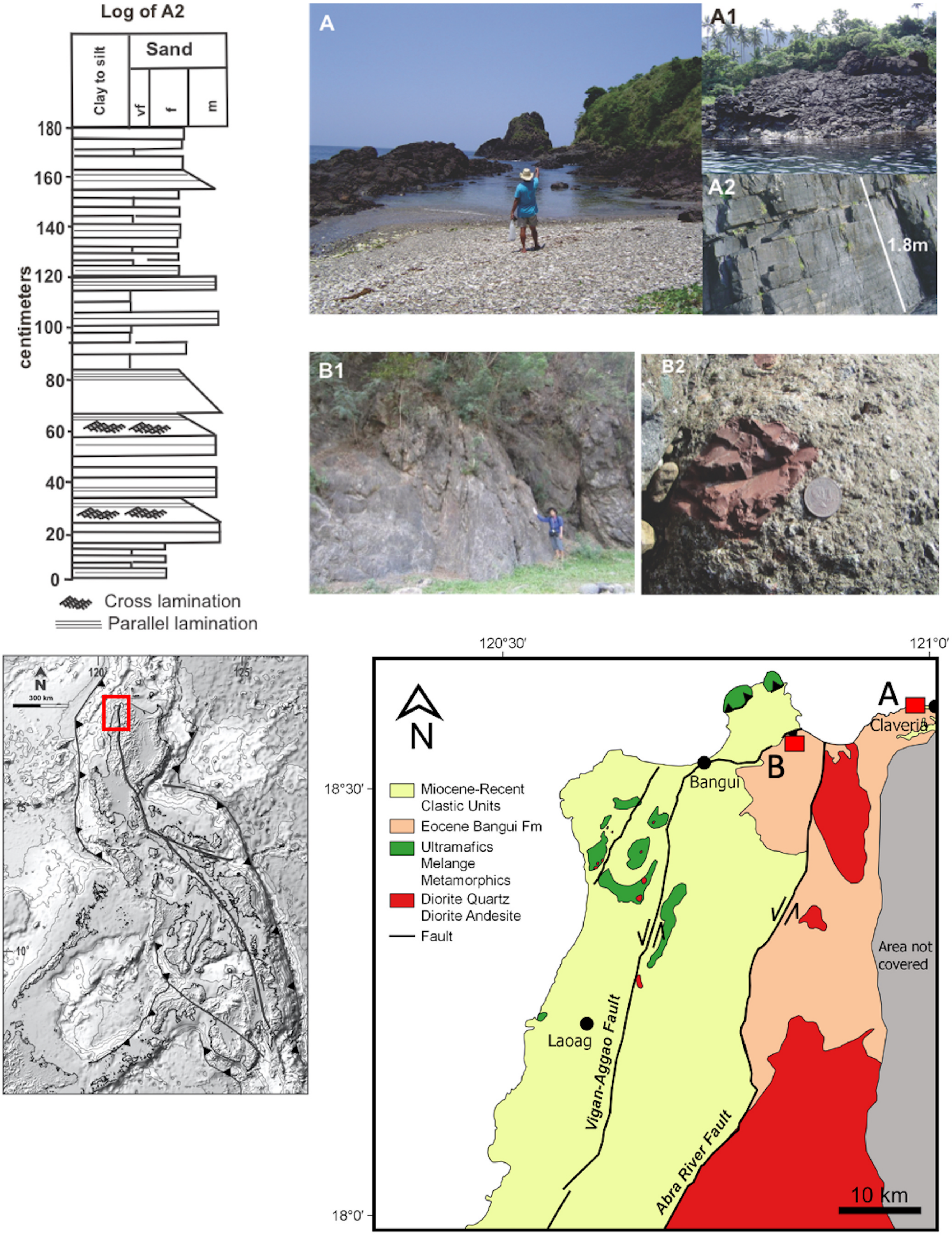

Fig. 5. Outcrops of Bangui Formation. (a) Coastal section of Claveria municipality in northern Luzon where pillow basalts (GPS: 18° 35.47′ N, 121° 0.33′ E) (a1) overlain by Interbedded sandstone and siltstone (a2) were observed overlying the pillow basalts viewed from A. (b1) Conglomerates of the Bangui Formation containing pebble- to cobble- andestic to basaltic fragments and few cherts set in a tuffaceous sandy matrix (GPS: 18° 31.83′ N, 120° 50.07′ E) (b2) Close-up view of the conglomerate.

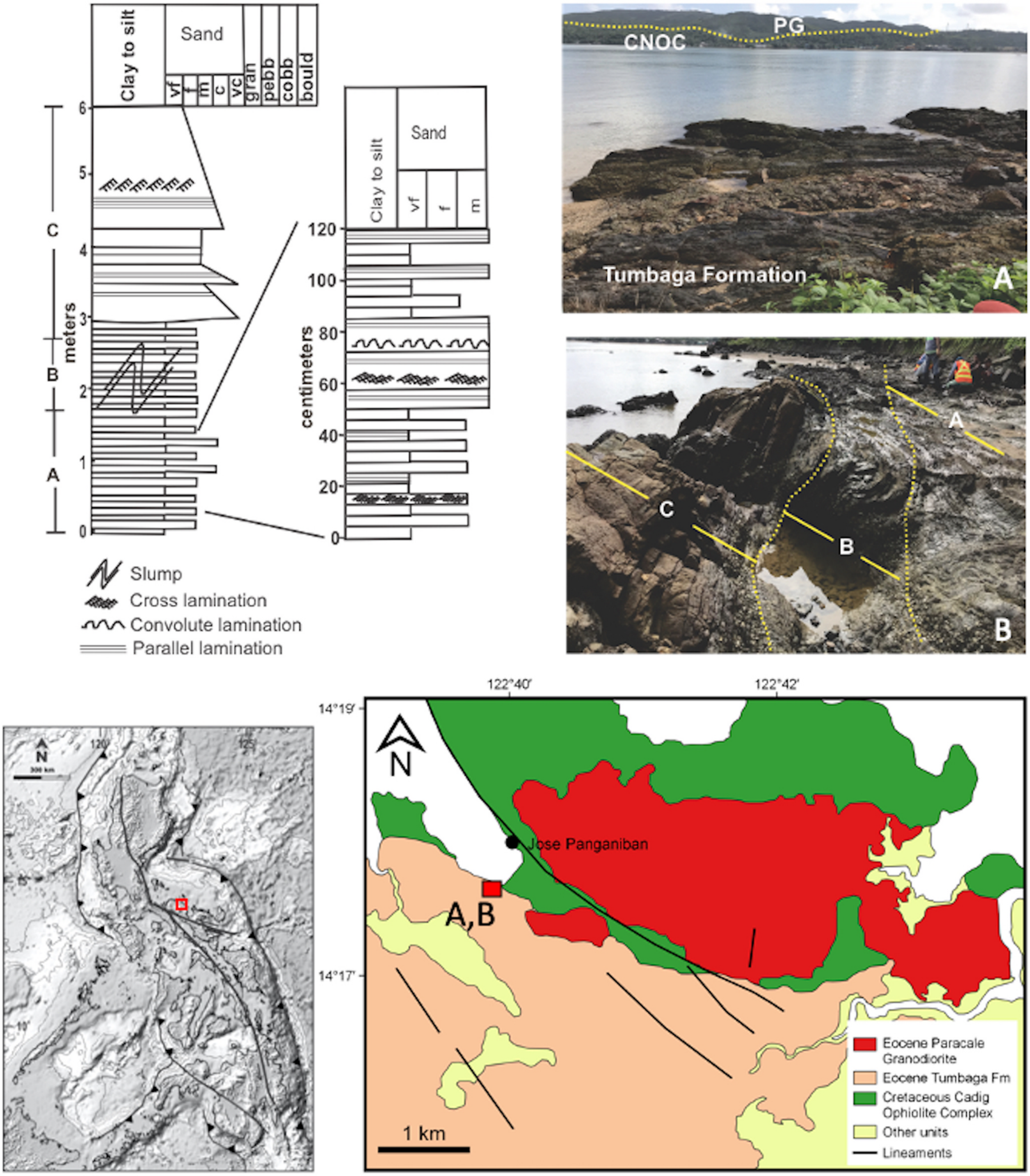

Fig. 6. Outcrops of the Tumbaga Formation along the coast of Jose Panganiban, Camarines Norte (GPS: 14° 17.50′ N, 122° 41.30′ E).

probable Eocene age based on correlation with other sequences in the region.

4.5. Central Visayas

4.5.1. Lasala Formation

Hashimoto (1981) called the rocks exposed along the Lasala River in northern Mindoro as the Lasala Formation. The formation is composed of rhythmically interbedded quartz arenite and shale with minor conglomerate, mudstone, limestone and basalt flows (Fig. 9A-B). Petrographic analyses of the medium-grained sandstones show that they are predominantly quartzose indicating derivation from continental sources (Concepcion et al., 2011). Whole rock geochemical data for the Lasala clastic rocks reveal derivation from a felsic provenance (Fig. 7A-D). On the tectonic discrimination diagrams using major and trace element compositions, the Lasala samples generally plot within the CIA

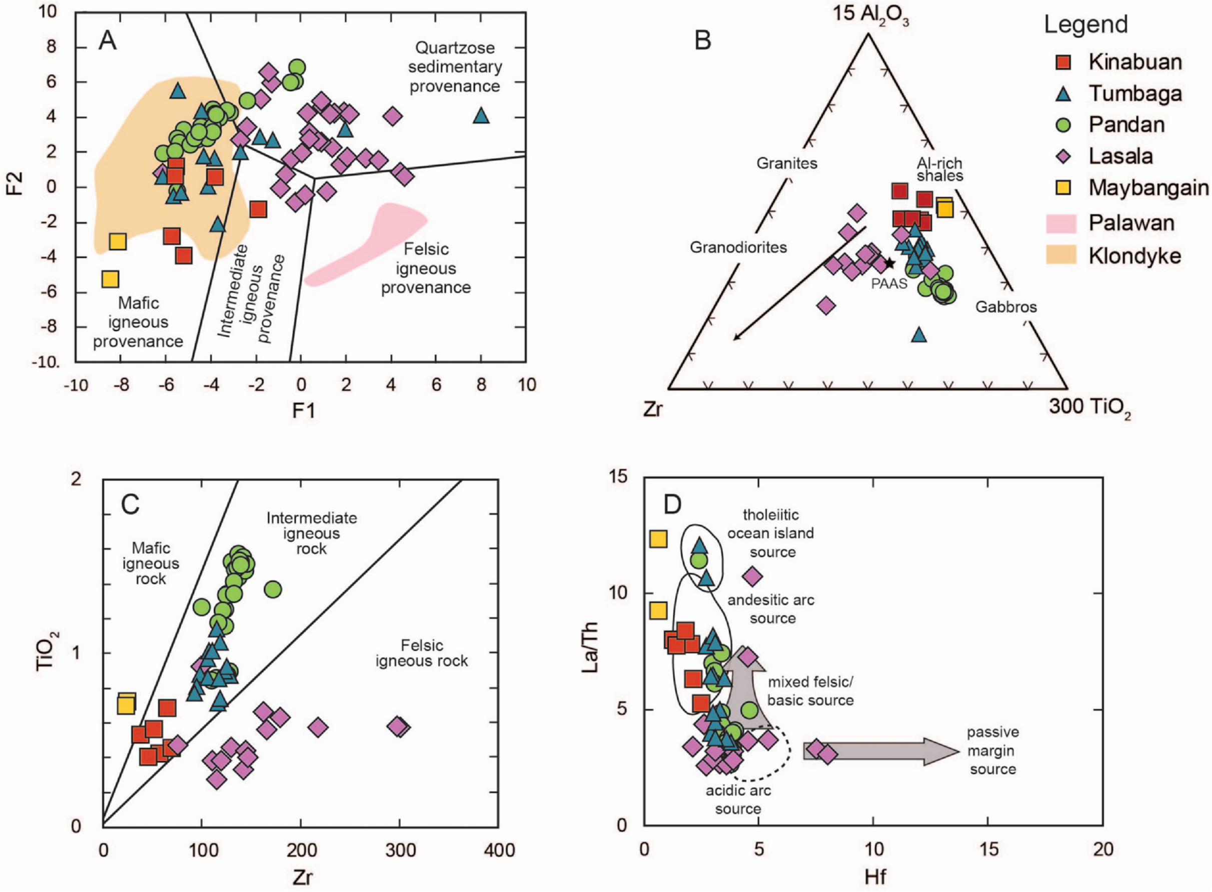

Fig. 7. Diagrams to discriminate the provenance of samples from the Maybangain, Tumbaga, Lasala and Pandan formations. (a) F1-F2 discriminant function diagram of Roser and Korsch (1988). (b) Zr-15*Al_2O_3-300*TiO_2 diagram of Garcia et al. (1994). (c) TiO_2 vs Zr plot of Hayashi et al. (1997). (d) La/Th versus Hf (ppm) diagram of Floyd and Leveridge (1987). Fields corresponding to the Palawan and Klondyke samples are shown for comparison. Data from Dimalanta et al. (2018).

field with some samples plotting in the ACM and PCM fields (Concepcion et al., 2011).

Based on the presence of the foraminifers: *Pellatispira mirabilis* (Umbgrove), *Operculina* sp. cf. *O. saipanensis* Cole, *Amphistegina radiata* (Fichtel and Moll), *Spherogypsina* sp., and species belonging to the Family Rotalidae, a Late Eocene age was assigned to the formation (Faure et al., 1989). Detrital zircon U-Pb dating of a coarse-grained arenite sample collected from the Lasala Formation yielded a wide range of zircon age peaks (Dimalanta et al., 2018). Two clusters were identified where one of the clusters is between 2.4 and 1.5 Ga and the other is between 983 and 46 Ma. Dating conducted by Knittel et al. (2017) on several samples yielded zircon age peaks at ca 1.90–1.85 Ga, 850–600 Ma and 300–110 Ma.

In this study, the formation was observed along the rivers in northwestern Mindoro island (Fig. 9). It is dominantly composed of fine-to medium-grained quartz arenite that unconformably overlies the Mesozoic rocks of the Halcon Metamorphics. The sandstones are usually well-sorted. In some outcrops, lithic fragments of basalt and chert were observed. The bed orientation of the Lasala Formation is highly variable.

Concepcion et al. (2011) reported upper Eocene-lowermost Oligocene nannofossils from a mudstone sample obtained from the Lasala Formation. The calcareous nannofossil assemblage includes *Coccolithus pelagicus* (Wallich) J Schiller, *Cyclicargolithus floridanus* (Roth and Hay) Bukry, *Dictyococcites bisectus* (Hay, Mohler and Wade) Bukry and Percival, *Reticulofenestra bisecta* (Hay, Mohler and Wade) Roth, *Reticulofenestra umbilicam* (Levin) Martini and Ritzkowski and *Sphenolithus* spp. This assemblage indicates a deep marine environment with shallow water influence.

4.5.2. Pandan Formation

The Pandan Formation was first coined by Corby (1951) for the highly deformed metamorphosed limestone and clastic units with minor coal stringers exposed along the Pandan River in Central Cebu. A Late Cretaceous age was assigned for the formation based on the presence of Globotruncana species in limestone and clastic rocks (Porth et al., 1989). BMG (1981) implied that the formational age could extend to Paleocene based on the age of the clastic units exposed in the western portion of the island, as reported by Balce (in Hashimoto et al., 1977). Porth et al. (1989), however, did not find any Paleocene rocks in the said section of the formation.

In this work, the Pandan Formation consists of clastic units, mainly conglomerates, sandstone and mudstones, which are highly thrusted/backthrusted (northwest and SE verging) and folded. At a regional scale, the Pandan Formation seemingly incorporates huge blocks of the so-called Lutopan Diorite dated as 120–108 Ma (Walther et al., 1981; Kerntke et al., 1992; Deng et al, 2015; this work) based on U-Pb zircon age. Such information features an old accretionary complex for the island. Detrital zircon U-Pb geochronologic data from the Pandan Formation show zircon peaks indicative of Early Cretaceous (112.6 ± 1.5 Ma).

The Pandan Formation is best observed in eastern-central Cebu where the stratigraphic unit is well-exposed. The approximately 150-m thick succession includes interbedded sandstone and siltstone and normally graded conglomerates (Fig. 10A-B). The interbedded sandstone-siltstone makes up the lower part of the succession. This consists of moderately weathered, interbedded gray fine-grained sandstone and gray to greenish siltstone. The sandstone beds (~0.02–0.5 m) are often thicker than the siltstone beds (0.01–0.2 m). Some sandstone beds

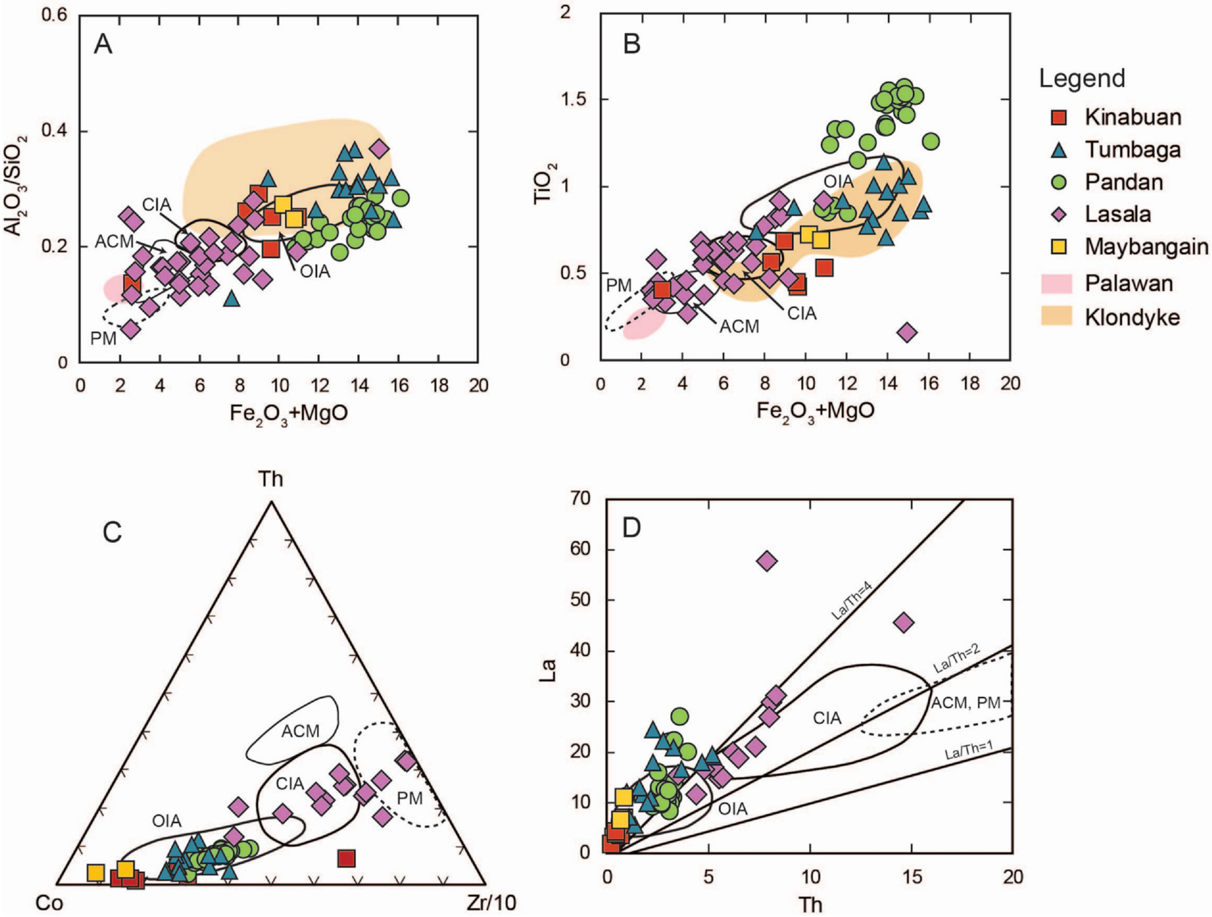

Fig. 8. Tectonic setting discrimination diagrams for the clastic rocks. (a) TiO_2 versus (Fe_2O_3 + MgO) and (b) Al_2O_3/SiO_2 versus (Fe_2O_3 + MgO) plots (both after Bhatia, 1983). (c) Co-Th-Zr/10 diagram of Bhatia and Crook (1986). (d) Th versus La diagram after Maravelis and Zelilidis (2010). Legend: OIA - oceanic island arc, CIA - continental island arc, ACM - active continental margin, PM - passive margin. Tectonic setting after Bhatia (1983). Fields and symbols as in Fig. 7.

contain parallel lamination and/or cross lamination, while mudstone beds usually display parallel lamination. Silicification and chloritization have masked internal sedimentary structures in most beds.

The normally graded, matrix-supported conglomerate facies is composed of rounded to subrounded, dominantly cobble- to boulder-sized clasts of mostly amygdaloidal andesite to basalt set in a grayish to greenish, coarse-grained sandy matrix. Petrographic analyses of the associated sandstone suggest the presence of lithic volcanics, plagioclase and clinopyroxene detritals. These observations reflect derivation from the Cansi Volcanics, providing evidence of the unconformable relationship between the two formations. Rodrigo et al. (2020) also reported the presence of quartz, said to have been derived from the Lutopan Diorite, as well as clasts of quartz-muscovite schist and muscovite schist derived from metamorphic rocks formed at moderate to deeper metamorphic crustal environments.

The conglomerate normally grades from medium- to coarse-grained sandstone that is faintly parallel-laminated. The base of the conglomerate bed is usually sharp and erosional, often cutting the sandstone facies. Rip-up clasts of sandstone derived from the underlying layer can be noted at the base of some conglomerate beds. Sandstone beds interlayered with conglomerates are also observed. The greenish to dark gray sandstone is medium- to coarse-grained. The irregular tops and, in some sections, the laterally discontinuous nature of the sandstone beds is a result of the incision made by the conglomerates. The sandstone beds are generally massive, although chloritization of the rocks may have masked the internal sedimentary structures. Lithic andesite and basalt as well as some mafic minerals are notable.

In the northwestern portion of the study area, the Pandan Formation mainly consists of at least 200 m-thick interbedded sandstone and mudstone. Bed thickness ranges from 0.2 to 0.3 m. The mudstone contains fine sand lamination, although some beds lack internal structure. The sandstone beds display Ta, Tb (lower parallel lamination) and Tc (ripple or convolute lamination or Td (upper parallel lamination) and Te (mud) of the Bouma Sequence.

The intimate association of the interbedded sandstones and mudstones with the conglomerates implies a genetic link between them. The conglomerates may be interpreted as channel deposits and the interbedded sandstones and mudstones as overbank deposits. The common occurrence of ripples and convolute laminations in some sandstone beds suggest high rates of deposition from suspension by turbidity currents.

Major element compositions are utilized to determine the composition of the source rocks of the Pandan Formation. On the F1-F2 diagram of Roser and Korsch (1988), the majority of the Pandan samples plot in the mafic igneous provenance field (Fig. 7A). The plot of Zr-$15Al_2O_3$-$300TiO_2$ shows the Pandan samples plotting closer to the gabbro composition (Fig. 7B). In the Zr vs TiO_2 diagram, however, the Pandan samples cluster within the intermediate igneous rock field (Fig. 7C). The low Hf but wide range of La/Th ratios sees the Pandan clastic rocks plotting near the mixed felsic/basic source with some samples plotting within the andesitic arc source field (Fig. 7D). These geochemical plots suggest contributions from both mafic and more silicic sources, as also earlier suggested by Rodrigo et al. (2020). In the tectonic setting diagrams, samples from the Pandan Formation clearly plot near and within the OIA field (Fig. 8A-D).

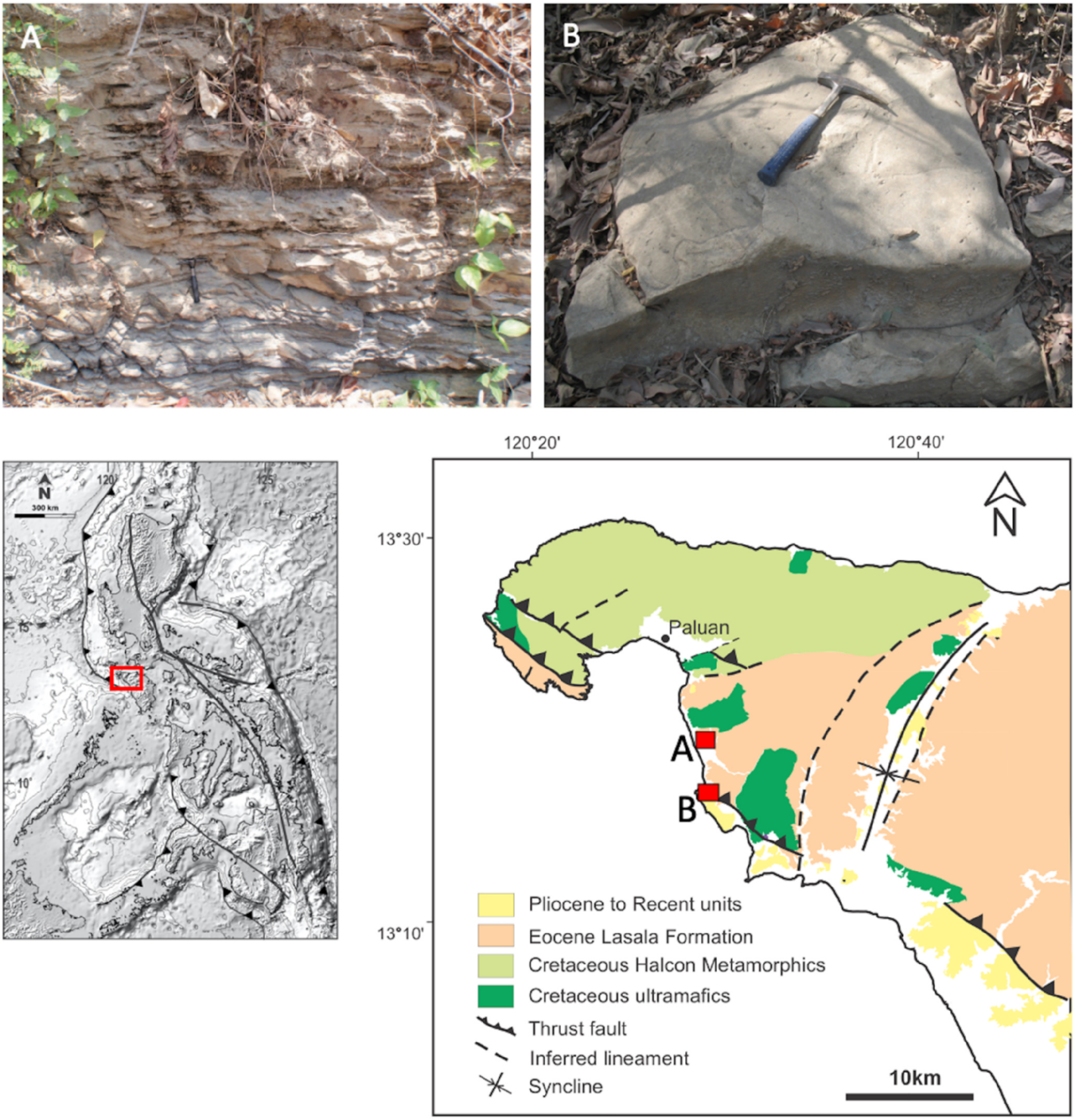

Fig. 9. Outcrops of the Lasala Formation in western Mindoro. (a) Rhythmically interbedded sandstone and shale sequence of the Lasala Formation in Paluan (GPS: 13° 18.18′ N, 120° 29.91′ E); (b) Minor limestone beds in Paluan (GPS: 13° 18.19′ N, 120° 30′ E).

5. Discussion

5.1. Provenance and depositional environment of Upper Cretaceous to Eocene units

The Upper Cretaceous-Lower Eocene stratigraphic formations in the Philippines provide a record of the arc's complex tectonic evolution and paleo-geographical history. Having formed in the early stages of arc development, these formations evolved in response to arc-related processes such as subduction and magmatism, as well as terrane accretion following back-arc rifting and formation of marginal basins now surrounding the archipelago (e.g. Mitchell et al., 1986; Faure et al., 1989; Encarnacion et al. 1993; Dimalanta and Yumul, 2006; Queaño et al., 2008). Mapping of these units suggests that these are mainly products of submarine mass transport processes that commonly involve turbidity currents, slumping and debris flows (Fig. 11). The stacking and repetition of the different facies (e.g., channelized and unchannelized facies) clearly reflect multiple depositional events that are consequential to the arc's interaction with plates now consumed under the Philippine arc and the rest of SE Asia. Lateral juxtaposition of similar facies (e.g., channel-fill sequences) deposits, however, should not be discounted as contributory to the formation of stacked sequences (e.g. Mutti and Normark, 1987; Clark and Pickering, 1996).

In northern Luzon, continued subduction of these plates provided

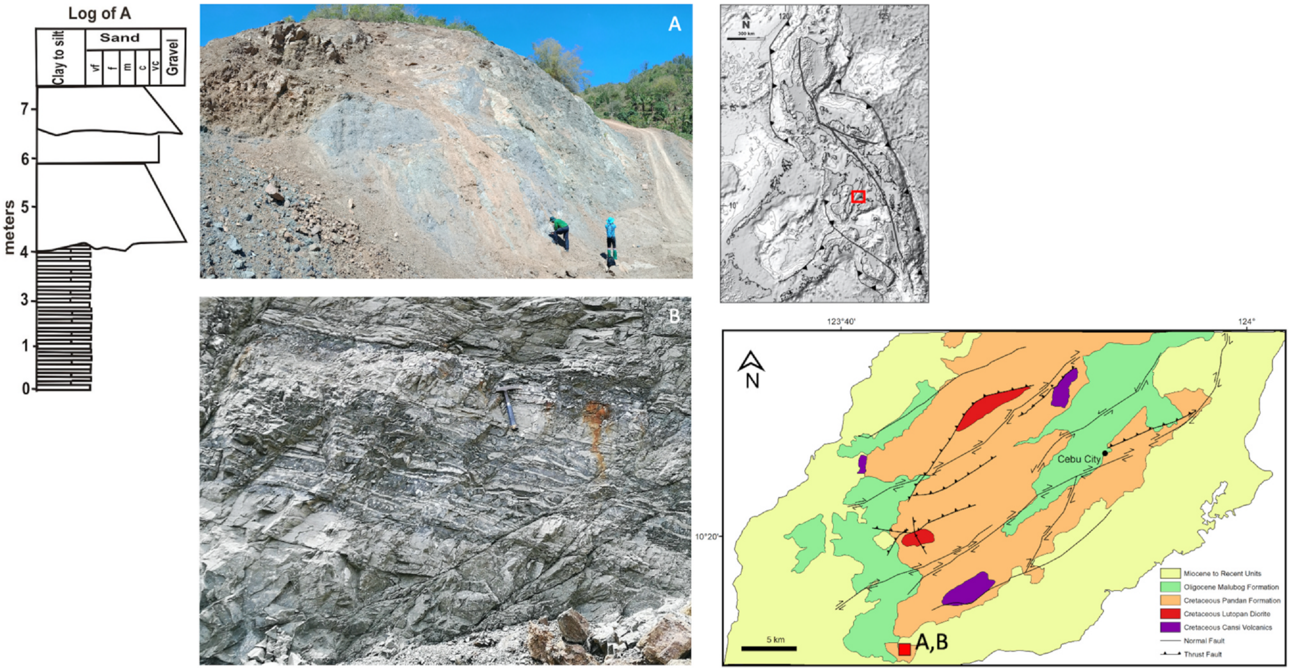

Fig. 10. Outcrops of the Pandan Formation in a quarry area in Barangay Pangdan, Naga City, Cebu (GPS: 10° 18.28′ N, 120° 43.41′ E). (a) Dark gray to black sandstone and siltstone interbeds overlain by normally graded conglomerate and sandstone beds; (b) Dark gray to black interbeds of shale and fine sandstone.

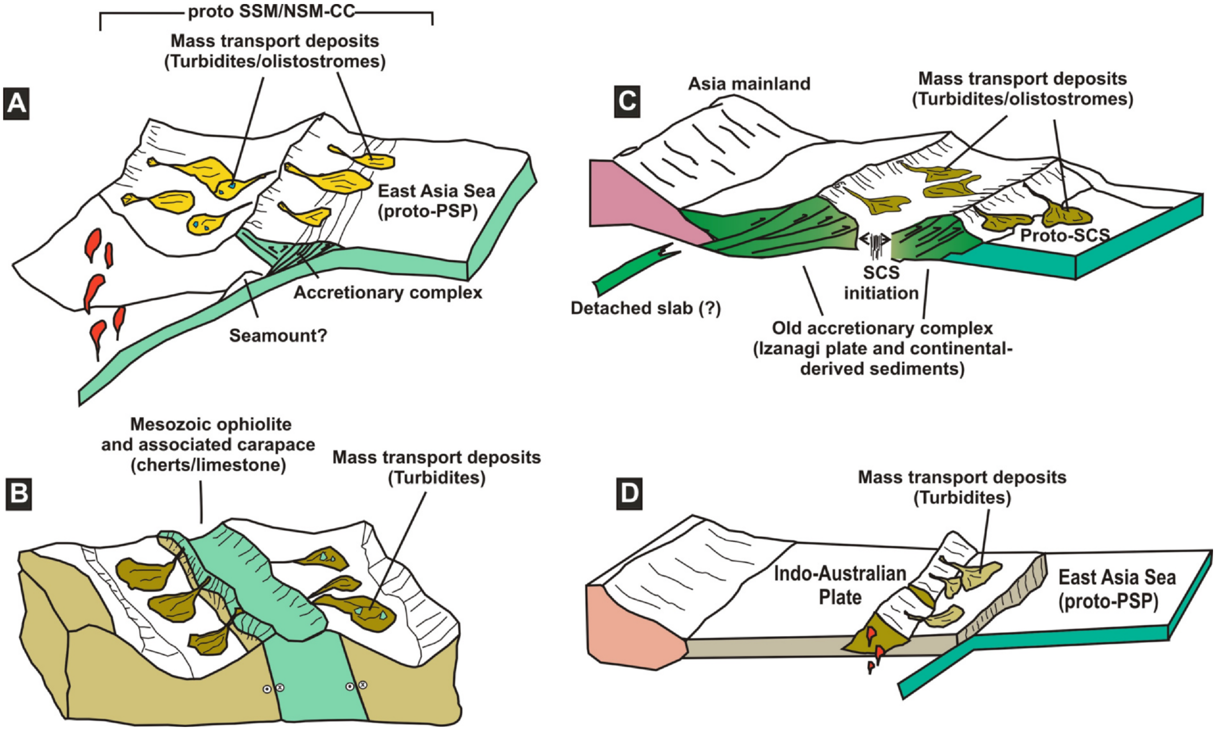

Fig. 11. Conceptual models for the formation of the late Mesozoic to early Cenozoic stratigraphic units in northern and Central Philippines in the context of SE Asia's tectonic evolution. (A) Caraballo Formation, Bangui Formation and Maybangain Formation in northern Luzon; (B) Tumbanga Formation in southeastern Luzon; (C) Lasala Formation in Mindoro Island and; (D) Pandan Formation in Cebu Island.

the mechanism in having an active magmatic arc (herein referred to as the proto-Northern Luzon arc), providing high relief and large amounts of erodible, intra-arc materials for sedimentation (e.g., as in the case of Caraballo Formation and Bangui Formation), mainly in the forearc region. Similarly, tectonic over-steepening at accretionary wedge fronts and retro-wedge fronts of doubly-verging accretionary wedges may have provided important mechanisms to allow extra-basinal clasts, including ophiolite-derived fragments (e.g. basalt) and olistoliths (e.g., Upper Cretaceous limestone olistoliths in the Maybangain Formation; see succeeding discussion) derived from the accreted materials, to be included within the deposits. In northeastern Luzon, the accretionary complexes consist largely of a late Early to Late Cretaceous ophiolite, referred by previous authors as the Casiguran Ophiolite. This ophiolite, which lies adjacent to the Caraballo Formation, has thick to very thick cherts and pelagic limestone capping this unit. While it is beyond the scope of this study to look into the chemistry of the "ophiolitic" fragments in the Caraballo Formation, these fragments are likely sourced from the ophiolite.

It is also worth noting that the Casiguran Ophiolite forms part of the series of supra-subduction zone (SSZ) ophiolites (e.g., Camarines Norte Ophiolite Complex; Samar Ophiolite; Pujada Ophiolite) accreted on the eastern side of the Philippine arc (e.g. Andal et al., 2005; Queaño et al., 2013; Balmater et al., 2015; Guotana et al., 2017; Olfindo et al., 2019; Dimalanta et al., 2020). These ophiolites (some with preserved sedimentary carapace) are usually mapped as basement (oldest rocks) in unconformable contact with the Upper Cretaceous to Eocene stratigraphic units. As observed in the Southern Sierra Madre, the Maybangain Formation also includes Cretaceous limestone olistoliths bearing age similarities with those associated with the accreted ophiolites in eastern Luzon (e.g., Billedo, 1994; Billedo et al., 1996). Deformation of the frontal wedge should provide an important mechanism for these limestones to be exposed and remobilized later as olistoliths in the Maybangain Formation. Subduction of an oceanic bathymetric high beneath the accreted Mesozoic terrane resulting in its deformation may be possible. However, there is no evidence to support this at the moment.

Interestingly, David et al. (1996, 1997) also reported Upper Cretaceous limestone olistoliths within the uppermost Cretaceous to Eocene formations (Codon Formation and Yop Formation) in Catanduanes island, offshore of southeastern Luzon. These exotic blocks range in size from 5 cm to 200 m. The olistostrome matrix consists mainly of andesitic volcaniclastics, with some matrix exhibiting shearing at the base of the megablocks of limestone. Paleontological analyses of the limestone blocks indicate Early Cretaceous and Late Cretaceous ages for the limestones. Some blocks of pillow basalts that were likely derived from the Camarines Norte Ophiolite Complex were also observed in the formation. While gravity sliding of these olistolith bodies could have also resulted from similar mechanism as that of the Maybangain Formation, David et al. (1997) presented polyphase sinistral faulting attributed to a proto-Philippine Fault System as the main mechanism to initiate uplift and sliding of these older ophiolitic and limestone bodies. The upheaval of the Camarines Norte Ophiolite Complex and the arc rock (the Paracale Granodiorite) intrusive to the ophiolite following the strike-slip faulting in the region may also explain their exposure and subsequent erosion, providing extra-basinal sources for the Eocene Tumbaga Formation. A combination of deformational processes related to oblique subduction, accretion and strike-slip faulting would not be surprising, though, if one is to base on the Philippine arc's evolution and the current setting of the archipelago. Numerous structural studies (Karig, 1983; Haeck and Karig, 1985; Jolivet et al., 1989; Rangin et al., 1989; Billedo, 1994) were done in the Philippine archipelago suggesting the presence of strike-slip fault systems that predate (as far back as Paleocene) movement of the Philippine Fault.

The generation of these arc-related submarine deposits, isolated from inputs of continental margins, are notable in the Bangui Formation. The same can be said for the Caraballo Formation and all other Upper Cretaceous to Eocene units (e.g. Maybangain, Tumbaga) in eastern Luzon. This would have an important implication on their basinal sources and plate affinity (see Section 5.2). As in the case of the Caraballo Formation in the NSM and the Bangui Formation in the northern portion of the Luzon Central Cordillera, these deposits are associated with pillow basalts that represent the early stages of island arc development (Fig. 11). The geochemistry of the pillow basalts from the two formations reflecting similar arc affinity for these rocks provides additional evidence (Fig. 3).

As earlier noted, the Maybangain Formation in the coastal area of eastern Sierra Madre bears compositional and age similarities with the Caraballo Formation (except for the absence of limestone olistoliths). The major and trace element plots of the Tumbaga Formation also reflect provenance from mafic to intermediate igneous rocks in an oceanic island arc setting (Figs. 7 and 8). While no geochemical plots are currently available for the Eocene units, arc- and ophiolite-derived turbiditic clastic rocks are also reported in other regions of eastern Philippines (eastern Visayan region and Mindanao) (GOP, 2010).

Queaño et al. (2007a) reported that early Cenozoic magmatic activity in Luzon is almost synchronous with the observed onset of arc development in the Visayan region and eastern Mindanao based on compilation of previously generated data (e.g., Rangin and Pubellier, 1990; JICA-MMAJ-MGB, 1990). This suggests that these regions were likely situated within the same geological province during their early stage of evolution. A different scenario would not apply though for Central Philippines where Miocene arc-continent collision involving the Palawan Microcontinental Block of Eurasian affinity and the Philippine Mobile Belt of Philippine Sea Plate affinity had long been recognized. The Eocene to earliest Oligocene Lasala Formation in Mindoro island, that incorporates continent-derived sediments, in addition to the metamorphic suite of various protoliths, represents the oldest sedimentary sequence formed prior to this collision (Concepcion et al., 2011; Dimalanta et al., 2018).

Dimalanta et al. (2018) reported whole-rock geochemical data from the Eocene Lasala Formation which affirm the continental affinity of the rock, with the detrital zircon U-Pb ages (983–46 Ma; with clustering at 186 Ma) suggestive of Cathaysian origin that indicate the Yanshanian magmatic events. Such continental derivation of sediments is also registered elsewhere (particularly in Palawan and western Panay southwest and west) in the Philippine arc. With this information, the deep marine deposits of the Lasala Formation have provenance and basin/plate affinity different from the other Upper Cretaceous to early Cenozoic. In the course of the evolution of the Philippine arc and its interaction with the already "consumed plate" hosting the Lasala Formation, this stratigraphic unit occurs as part of the accretionary complex in western Mindoro.

A more intriguing formation of similar occurrence as the Lasala Formation is the Pandan Formation in central Cebu island. While its facies point to a deep marine, turbidity-laden epiclastic deposits, its compositional make-up (and interpreted source rock) is not reflective of the ages being reported for the Pandan Formation (Early to Late Cretaceous) and its components (e.g., Lutopan Diorite of late Early Cretaceous; pelagic limestone of Late Cretaceous age) based on U-Pb zircon and paleontological dating. This may somehow reflect the complex evolution of the Pandan Formation from its inception to accretion onto the Philippine arc. Whole-rock geochemical analyses by Rodrigo et al. (2020) suggest derivation from an oceanic island arc setting, with influence from an active margin/collision boundary based on tectonic discrimination diagrams. Being within a perceived old accretionary complex similar to the Lasala Formation, the Pandan Formation would have to be derived from a basin whose plate affinity likely differs from the other Late Mesozoic to Early Cenozoic sedimentary formations earlier described (see succeeding section). A forearc basin formation is suggested for the Pandan Formation based on the presence of Cretaceous serpentinized peridotite dykes (collectively referred to as the Bantoon Peridotite by Santos-Yñigo, 1951) intrusive into the formation.

5.2. *Tectonic implications: Mesozoic to Early Cenozoic evolution of the Philippine arc in the context of SE Asia tectonic reconstruction*

The early Cenozoic is important for SE Asia as it marks the marginal basin (e.g., Celebes Sea, West Philippine Basin, and South China Sea) formation now surrounding the Philippines, and the consumption of the old Mesozoic basins underneath the archipelago. The presence of Mesozoic (and even older) to early Cenozoic rocks in the Philippines is a reflection of the geodynamic regime during this period, with the Philippine arc being formed at the center amidst the interaction of various plates in East Asia. A number of workers (e.g., Hall, 2002; Queaño et al., 2007a,b; Zahirovic et al., 2014; Wu et al., 2016) has presented plate reconstruction from the late Mesozoic to Cenozoic in SE Asia, showing marked variations in the configuration (e.g., PSP), positioning (e.g. PSP and the bounding trench; proto-SCS) and the naming of the consumed plates (e.g. proto-PSP vs East Asian Sea north). For instance, Queaño et al. (2007a) modeled northern Luzon and the eastern regions of the Philippine arc as developing at the southern margin of the Philippine Plate sometime during the Eocene. Although having subtle differences on the orientation of Luzon, this model supports that of Deschamps and Lallemand (2002) but is in stark contrast to that presented by Hall (2002) which puts Luzon in the eastern margin of Asia. The paleomagnetic data presented by Queaño et al. (2007a), however, provide a very strong argument that Luzon and possibly the rest of eastern Philippines were coupled with the Philippine Sea Plate which has moved ~20° northward from a sub-equatorial position since the Eocene (Haston and Fuller, 1991; Hall et al., 1995a, b; Queaño et al., 2007a; Yamazaki et al., 2010). Ishida et al. (2011, 2012) also reported a low paleolatitudinal position, particularly for northern Luzon, based on the reported radiolarian assemblages that they have obtained from the clastic units of the Eocene Cabog Formation (herein correlated with the more established, Maybangain Formation). More recent plate reconstruction models (e.g., Zahirovic et al., 2014; Wu et al., 2016) also largely followed the model of Queaño et al. (2007a) for most of the Philippine arc. Wu et al. (2016), in particular, noted that the Luzon paleolatitudes were in agreement with the Benham Rise ODP Site 262 time series within the adjacent southern west Philippine basin.

For the southeastern regions (eastern Visayas and eastern Mindanao) of the Philippine arc, Zahirovic et al., (2014) suggested a Late Mesozoic to early Cenozoic (~60 Ma) arc inception for these regions prior to their accretion with Luzon. They modeled these regions as having evolved from the northeastern Gondwana margin related to the northward transfer of eastern Borneo, Mangkalihat, West Sulawesi and East Java at ~140 Ma. Surprisingly, Wu et al. (2016) virtually excluded Visayas and Mindanao in their tectonic model of SE Asia during the Cenozoic.

We review more recent reconstructions and see how the data on the late Mesozoic to early Cenozoic rock formations of the Philippines herein presented would fit into these reconstructions.

5.2.1. Luzon Island

In reviewing tectonic models for Luzon and adjoining regions, two crucial observations come into play, being as follows: (1) The components of the Eocene rock formations (Caraballo, Bangui, Maybangain, Tumbaga), which reflect the early formation of the Philippine arc in the northern and eastern Luzon, are essentially island arc rocks incorporating older ophiolitic and oceanic sediments. This suggests formation in an oceanic plate with no marked inputs of continental derivation; (2) Adjoining the aforementioned rock are thrusted Mesozoic ophiolite units in eastern Luzon. Particularly for northeastern Luzon, Lewis and Hayes (1983) delineated from offshore seismic reflection profiles stratigraphic sequences and east-verging thrust faults just east of these ophiolite bodies. They further interpreted these features as defining complexes that are morphologically similar to a trench-subduction system. All these observations offer a strong support for an earlier subduction event predating the present-day activity of the East Luzon Trough. This event, in turn, provided the mechanism for the Eocene arc formation and accretion of Mesozoic ophiolite and associated sediments east of the Philippine arc. Based on the Eocene to Oligocene ages obtained from stratigraphic formations and radiometric dating (MMAJ-JICA, 1977; Wolfe, 1981; Billedo et al., 1996) of plutonic batholiths, subduction may have at least stopped sometime during the Oligocene to early Early Miocene. Previous workers (e.g., Yumul, 1991; Yumul et al., 1992, 2003; Lewis and Hayes, 1983) marked this period as the time arc polarity reversal occurred in the Luzon-Taiwan region and subduction commenced along the Manila Trench. It is worth noting, however, that previous workers (e.g., Stephan et al., 1986; McCabe et al., 1987; Deschamps and Lallemand, 2002; Queaño et al., 2007a,b) implied a much earlier time of the Manila Trench initiation. Regardless, the cessation of the early Cenozoic subduction east of the Philippine arc also paved the way for Luzon and adjoining regions to eventually be coupled and rotate clockwise with the PSP in the remaining periods of the Cenozoic to bring them to their current latitudinal positions.

Dimalanta et al. (2020) synthesized all data pertaining to the Mesozoic ophiolites lining the eastern coast of the Philippine arc. These ophiolites of mostly Early to Late Cretaceous ages have mantle to crustal geochemistry that have mid-oceanic and supra-subduction signatures (Dimalanta et al., 2020). With the presence of pelagic limestone and/or cherts that usually accompany these ophiolites (and as components of the early Cenozoic formations herein described), an open marine- or highly evolved back-arc basin generation is preferred that is located at great distances from the continent. Dimalanta et al. (2020) believed that these Mesozoic ophiolites are remnants of the now consumed proto-Philippine Sea Plate which used to extend a few degrees north of the equator to around 15° south based on limited paleomagnetic dataset. Earlier on, Deng et al. (2015) suggested that the proto-PSP (and the proto-Philippine arc) may have developed though back-arc rifting at the leading edge of the Australian plate margin further south of the equator. Paleolatitude-wise, this would have provided support to the proto-PSP origin proposed by Dimalanta et al. (2020). Being near the continental margin of the Australian plate, however, sediment contributions from the continent should at least be observed in the compositional make-up (including geochemistry) of the proto-PSP remnants and associated Mesozoic sedimentary carapace. Unfortunately, this is not the case, if we are to refer to the synthesis of Dimalanta et al. (2020) on the proto-PSP. Although not explicitly stated, Zahirovic et al. (2014) presented the proto-PSP as developing at the southern margin of the Izanagi Plate. Alternatively, Wu et al. (2016) mentioned that the proto-PSP is correlative to the north East Asia slab which they introduced, following the identification of slabs that lie ~600–1000-km depths below the present-day Philippine Sea. The downside of this correlation, however, is that the southerly extension of the north East Asia slab only extends a few degrees north of the equator (Wu et al., 2016) which would be incompatible with a more southerly extension for the proto-PSP (e.g., Zahirovic et al., 2014; Deng et al., 2015; Dimalanta et al., 2020). Regardless of how we should call this Mesozoic plate, the development of the West Philippine Basin within this Mesozoic plate, coupled with oblique subduction along the Philippine arc, should account for the tectonic features (accreted Mesozoic ophiolites along the Philippine arc; Eocene arc rocks) that we see in this region (Fig. 12). Previous workers (Karig, 1983; Pubellier et al., 2004) suggested that oblique subduction of the bounding plates has been affecting the Philippine arc throughout much of its Cenozoic history. This event induced strain partitioning and development of wrench faulting which also provided a mechanism for the docking of ophiolite in eastern Philippines. While suggesting a similar mechanism for emplacement for the ophiolite in southeastern Luzon, Geary and Kay (1989) also interpreted that the Cretaceous ophiolites in southeastern Luzon originated at the southwestern margin of the West Philippine Basin or were a fragment of the proto-West Philippine Basin. David et al. (1997) also presented polyphase sinistral faulting attributed to a proto-Philippine Fault System as the main mechanism to initiate amalgamation and uplift of Mesozoic ophiolite and pelagic limestone in southeastern Luzon.

As stated in Section 5.1, previous workers (Rangin and Pubellier, 1990; JICA-MMAJ-MGB, 1990; Queaño et al., 2017) implied an almost synchronous magmatic activity and onset of arc development in Luzon and the eastern half regions of Visayas and Mindanao. This suggests similar geological province and Cenozoic arc evolution for these regions. Intra-arc rifting in northern Luzon, however, also ensued, sometime during the Oligocene to early Miocene periods (e.g., Wolfe, 1981; Maleterre, 1989; Florendo, 1994; Yumul et al., 2000; Yumul

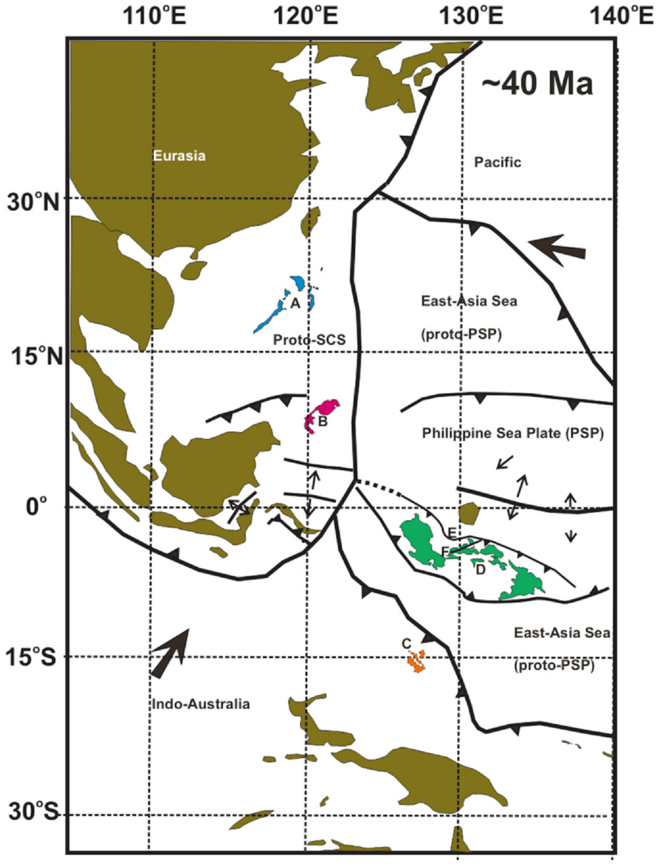

Fig. 12. Revised simplified tectonic model of SE Asia highlighting the position of the tectonic elements comprising the Philippine arc at ~40 Ma (Sources; Deschamps and Lallemand, 2002; Queano et al., 2007; Zahirovic et al., 2014; Wu et al., 2016). A-Palawan Microcontinental Block (Palawan, Mindoro, Western Antique, Romblon Island Group); B-Western Mindanao; C: Central Philippines (Cebu, Negros and Bohol); D; Luzon, Eastern Visayas and Eastern Mindanao; E: Proto-East Luzon-Philippine Trench; F: Proto-Philippine Fault (?).

et al., 2003), separating the Caraballo Formation of the NSM from the Bangui Formation of the Central Cordillera.

5.2.2. *Palawan Microcontinental Block*

In the case of the Palawan Microcontinental Block (PCB), this block has long been recognized as having originated from the SE margin of mainland Asia. Tracing the extent of this terrane in the Philippines has been an arduous task with the easternmost collision boundary with other elements of the Philippine Mobile Belt being placed at different locations (Karig, 1983; Sarewitz and Karig, 1986; Faure et al., 1989; Tamayo et al., 2001; Zamoras et al., 2008; Dimalanta et al., 2009; Yumul et al., 2009; Gabo et al., 2015). Regardless, its terrane characteristics are clear. The PCB rocks, including those of the Lasala Formation, occur as accreted continental-oceanic- (chert, pelagic limestone, pillow basalt) and metamorphic derived sediments of pre-Late Cretaceous age. Dimalanta et al. (2018) reported U-Pb dating of zircons from the Lasala Formation showing a bimodal age distribution of 239–48 Ma. They correlated these to two major episodes of magmatism, the Paleoproterozoic and Yanshanian magmatism, in mainland Asia. Old accretionary complexes of PCB origin are also well-exposed in northern Palawan consisting of Upper Paleozoic to Mesozoic sedimentary sequences of limestone-chert and continental-derived clastics rocks (Hashimoto and Sato, 1968; Holloway, 1982; Zamoras and Matsuoka, 2004; Marquez 2003). Metamorphic equivalents of these rocks are found in Mindoro, being referred to as the Halcon Metamorphics (Hashimoto and Sato, 1968; Holloway, 1982).

While the PCB's terrane characteristics are not questioned, previous workers seemingly have conflicts as to how to put the PCB in their reconstruction of SE Asia. Faure and Natalin (1992) suggested that a Western Philippines Microcontinent had collided with the South China Block during the Mesozoic. This idea implies that the accretionary complexes that define the PCB could be part of this microcontinental block. On the other hand, Hall's (2002) reconstruction shows the PCB emerging sometime around 85 Ma, within the so-called Luconia-Dangerous Grounds continental fragment (accreted to Asia mainland ~90 Ma) of unknown origin. While such models provide an interesting insight into the PCB's origin, these would not fit into the context of what we know about the PCB. The association of chert-pelagic limestone and mainland Asia-continental derived turbiditic clastic rocks (including the Lasala Formation) that are sequentially thrusted as accretionary complexes would go against the PCB developing within the continental Luconia-Dangerous Ground. Zamoras and Matsuoka (2001, 2004) suggested an offscrape accretion period along the southeastern margin of mainland Asia for complexes in northern Palawan of Middle Jurassic to Early Cretaceous. Modeled for the Late Jurassic, Zahirovic et al. (2014) model that reflects a northwest subducting oceanic Izanagi Plate along an active margin of eastern Asia better reflects the compositional make-up and origin of the PCB units. The Mesozoic ophiolitic fragments (e.g. pillow basalts of the Lower Cretaceous Mangyan Ophiolite) included in the Halcon Metamorphic-accretionary complex, and possibly the basaltic fragments in the Lasala Formation in Mindoro could very well also be derived from the now consumed Izanagi Plate.

5.2.3. *Central Philippines*

The reconstruction of Central Philippines in the context of SE Asia becomes more challenging with the presence of accreted Early to Late Cretaceous arc rocks, mainly the Pandan Formation, and its contributory sources, the Lutopan Diorite and Cansi Volcanics, in Central Cebu island. A forearc basin formation is suggested for the Pandan Formation as described in Section 5.1. Old accretionary complex, represented mainly by the fore-arc-generated Early Cretaceous Southeast Bohol Ophiolitic Complex (SEBOC), is also seen in the southern portions of Bohol island southeast of Cebu island (Barretto et al, 2000; Yumul et al., 2001; Faustino et al., 2003). These features in Central Philippines clearly involve a paleo-subduction for their generation (Yumul et al., 2001; Deng et al., 2015).

Previous workers (Barretto et al., 2000; Yumul et al., 2001; Faustino et al., 2003) suggested that the SEBOC accreted at the margin of an unknown arc sometime in the Late Cretaceous. Deng et al. (2015) provided an alternative model suggesting that the SEBOC developed in a forearc basin of the Cretaceous Cebu arc founded on the proto-Philippine Sea Plate that developed at the leading edge of the Australian margin. On the other hand, the latest work of Yumul et al. (2020) suggests a proto-South China origin for the Pandan Formation and other Cretaceous rocks in Cebu as fragments of the proto-South China Sea.

The spatial distribution of the Cretaceous arc-related rocks in Cebu and Bohol and the subequatorial position of the Philippine arc in the Oligocene (which marks the accretion of the Cretaceous units in Cebu based on the overlying Oligocene PMB-affiliated Malubog Formation), it is easier to visualize these Cretaceous arc-related units in Central Philippines as originating from the south. This somehow supports the earlier suggestion of Deng et al. (2015), but placing reservations on a proto-PSP on which the said rocks in Central Philippines are founded. Reference to the proto-Philippine Sea Plate remains confusing based on conflicting geological information (e.g, Zahirovic et al., 2014, Deng et al., 2015; Wu et al., 2016). Intra-oceanic arc that may have formed either at the leading oceanic edge of the Australian Plate or at the proto-Molucca Sea Plate (or simply Molucca Plate) situated at the frontal margin of the said plate during the 115–125 Ma period based on Zahirovic et al. (2014) model seemingly offers the better alternative for the origin of Cretaceous rocks in Central Philippines.

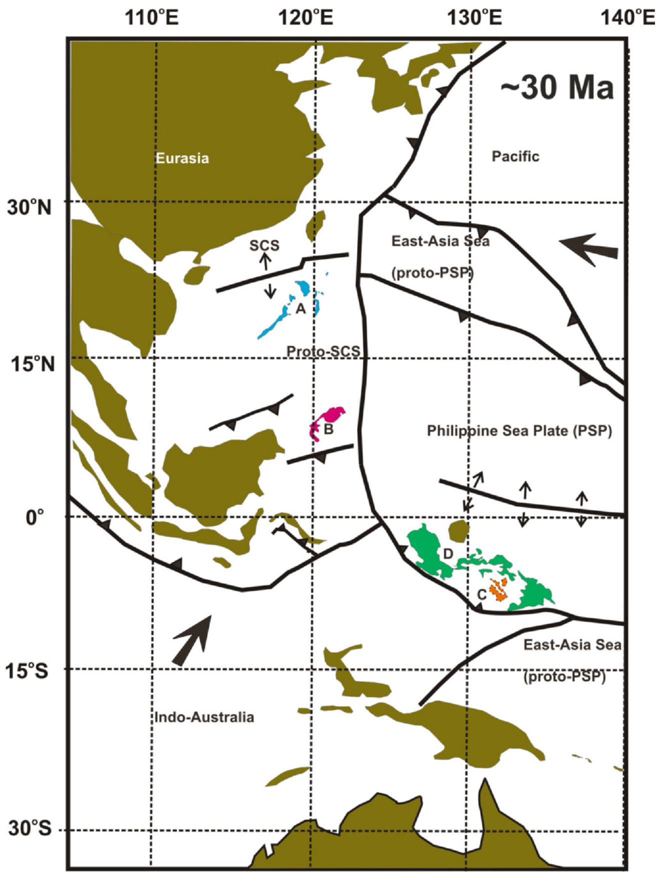

Fig. 13. Revised simplified tectonic model of SE Asia highlighting the position of the tectonic elements comprising the Philippine arc at ~30 Ma (Sources; Deschamps and Lallemand, 2002; Queano et al., 2007; Zahirovic et al., 2014; Wu et al., 2016).

5.2.4. *Simplified plate tectonic model for the Philippine arc and Southeast Asia*

Figs. 12 and 13 provide a revised simplified tectonic model for Luzon during the early Cenozoic. Wu et al's (2016) paleogeographic maps were initially used as templates to show a simple model for the paleographic position of the Philippine archipelago at 40 Ma and 30 Ma. Modifications were made on the templates, taking into consideration the geological data gathered in this study as earlier discussed as well as those of other workers (e.g., Deschamps and Lallemand, 2002; Hall, 2002; Queaño et al., 2007a; Zahorivic et al., 2014). Wu et al (2016) at 40 Ma is in congruence with the paleogeographic position, at least for Luzon as perceived in this manuscript based on the geologic information that we have gathered from the Philippine archipelago. Wu et al (2016) and Zahirovic (2014) actually based their paleogeogaphic positioning of Luzon and adjacent regions of the Philippine archipelago, taking note of the results of Queano et al. (2007) which placed important constraints in the positioning of the Philippine arc at 40 Ma and 30 Ma.

Note, however, that there is still a significant number of conflicting information about the positioning of the tectonic elements in SE Asia, even in the more recent models (e.g., Zahirovic et al., 2014; Wu et al., 2016). Except for the Philippine arc, it is beyond the scope of this paper to resolve these conflicts. However, the timing of the clockwise rotation of the PSP is one of the key differences that also affected the positioning of the different elements, including the Philippine arc. While Wu et al. (2016) took a novel approach in using the plume origin to model the PSP, previous paleomagnetic as well as other geological and geophysical results (e.g., Hall et al., 1995a,b; Deschamps and Lallemand, 2002; Pubellier et al., 2003, 2004; Queaño et al., 2007a) provide critical inputs in the tectonic modeling. This is particularly important for modeling Luzon and neighboring regions whose evolution would not simply fit in Wu and others' (2016) plume origin model approach. As a note, the extensive regional structural work by Pubellier et al. (2003) in SE Asia provided an alternative model for the earlier reconstruction of the region (e.g., Hall, 2002). 'Applying structural and kinematic constraints, Pubellier et al. (2003) presented a GIS-based reconstruction for the region starting at 20 Ma which showed a more easterly position for the boundary between the PSP (including Luzon) and Eurasia and a different positioning for Sulawesi, Borneo and Celebes Sea when compared to the model of Hall (2002). Queaño and others' (2007a) revised modeling of Hall (2002) based on paleomagnetic and other geologic data they gathered from northern Luzon generally agree with the reconstruction of Pubellier et al. (2003).

In the proposed revisions to latest models, we retain the Eocene Philippine arc as developing in East Asia Sea of Wu et al. (2016) or the proto-PSP depicted by Zahirovic et al. (2014) at ~40 Ma. The proposed revision shown in the model does not give reference to the north East Asia as the proto-PSP from which the Mesozoic ophiolites (now accreted into the eastern Luzon sometime in the late Eocene, the latest being the Oligocene) were believed to have been derived. Considering that Luzon and the eastern regions of the Philippine arc are situated at subequatorial paleolatitudes, it would actually be difficult to reconcile these Mesozoic ophiolite fragments to have simply come from the north East Asia Sea.

The ~40 Ma time period was chosen to plot the locations of the Mesozoic and Early Cenozoic tectonic elements of the Philippines, using the data herein presented. This period essentially marks the start of most arc generation in the Philippines. A subduction zone (proto-East Luzon Trough) separating the Benham Plateau and the Philippine arc was placed to explain the spatial distribution of Eocene arc rock and Mesozoic ophiolite materials comprising the accretionary complex east of Luzon. The subduction would not only provide the mechanism for the Eocene formation but would also explain the formation of old strike-slip fault responsible for the uplift of Mesozoic rocks to provide additional sources to the Eocene basin deposit (e.g. Maybangain Formation) in southeastern Luzon.

In the reconstruction, the Romblon Island Group and the whole Mindoro island were added as part of the Palawan Microcontinental Block (PCB) derived from the southeastern Asia mainland. This was a modification to the previous model (e.g. Hall, 2002; Queaño et al., 2007a) on PCB and in consideration of more recent findings (e.g. Dimalanta et al., 2009; Concepcion et al., 2011; Canto et al., 2012) on the PCB terranes in Central Philippines. Lastly, we model the Cretaceous arc rocks in Cebu and Bohol as having been formed as oceanic island arc developed at the leading edge of Indo-Australia as discussed previously. Although tentatively, we also include the Cretaceous basement rock of Negros island just west of Cebu island as having similar affinity with the Cretaceous arc rocks of Cebu and Bohol. The Lower (?) to Upper Cretaceous Basak Formation comprises the basement of Negros (GOP, 2010). While very limited information is available for the Basak Formation, an arc affinity is suggested for the unit based on the presence of volcanic flows associated with epiclastic rocks, bearing compositional similarities with those of the Pandan Formation of Cebu island. With the northward movement of the Indo-Australian plate and the trench roll back of the southern margins of the Philippine Sea Plate, the accretion of the Cretaceous arc-related rocks of Cebu, Bohol and Negros onto the Philippine arc by the end of Eocene or early Oligocene now becomes a possibility.

6. Conclusions and future work

We have presented revisions to the more recent models on the tectonic evolution of Southeast Asia by considering geologic data from the Upper Mesozoic to Lower Cenozoic sedimentary formations in northern and Central Philippines. These formations are products of submarine transport processes that bear imprints left behind by the now consumed plates in the region. These plates include the East Asia Sea-proto-Philippine Sea Plate, Izanagi Plate and the oceanic leading edge of the Indo-Australian Plate.

While we support a subequatorial paleolatitude for Luzon that developed at the southern margin of the East Asia Sea-proto-Philippine Sea Plate, we also invoke a proto-East Luzon Trough separating the Benham Plateau and the Luzon arc. In fact, this had been proposed by earlier workers in northern Luzon. The presence of Eocene arc rocks and a well-developed accretionary prism east of Luzon indisputably mark subduction event in this region until the early Oligocene. Oblique subduction, which has long been in operation since the inception of the Philippine arc, resulted in the accretion of Mesozoic ophiolites and their sedimentary carapace along eastern portions of the arc. We used the present-day setting of the Philippines to also suggest the formation of the proto-Philippine Fault that was consequential to the oblique subduction during the early Cenozoic. Movement of this structure should also account for the accretion and uplift of the Mesozoic oceanic plate fragments, as demonstrated in southeastern Luzon. Mesozoic ophiolitic complexes that line the eastern Philippine arc as well as the ophiolitic and pelagic limestone and chert fragments included in the arc-derived, Eocene sedimentary formations in Luzon could very well be traces of the now consumed East Asia Sea or proto-Philippine Sea Plate.

We modified the Palawan Microcontinental Block (PCB) that originated at the trailing edge of the proto-South China Sea to also include the whole Mindoro island and the Romblon Island Group in Central Philippines. With this model, the Mesozoic metamorphic rocks and Early Cenozoic sedimentary rocks in western Mindoro have components derived from the consumed Izanagi Plate, the proto-South China Sea Plate and the continental-derived sediments from Asia mainland. In contrast, during the ~40 Ma period, we model Cebu, Bohol and Negros islands in Central Philippines as originating from the leading oceanic edge of the Indo-Australian Plate before their accretion into the Philippine Mobile Belt (PMB). Their transfer to the PMB was facilitated with the northward movement of the Indo-Australian plate and the trench roll back of the southern margins of the Philippine Sea Plate.

Our future work should enable us to further determine the Philippine arc evolution and to contribute in refining tectonic models for Southeast Asia. The Mindanao island, most especially its western and central portions, in southern Philippines largely remains to be the missing link in the tectonic reconstruction of the region due to the scarcity of data. Obtaining more geologic information from these areas would enable the revisions in the existing tectonic models of the Philippines and Southeast Asia as a whole to be tested.

CRediT authorship contribution statement

Karlo L. Queaño: Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing, Visualization. **Graciano P. Yumul:** Writing - original draft, Writing - review & editing, Investigation. **Edanjarlo J. Marquez:** Writing - original draft, Writing - review & editing, Investigation. **Jillian A. Gabo-Ratio:** Investigation, Writing - review & editing, Visualization. **Betchaida D. Payot:** Writing - review & editing, Investigation, Formal analysis. **Carla B. Dimalanta:** Writing - original draft, Writing - review & editing, Investigation.

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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