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Geology of Northwestern Mindoro and its offshore Islands: Implications for Terrane Accretion in West Central Philippines

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Abstract

In over four decades, terrane studies of Mindoro Island have evolved from one terrane- to three terrane-models. Recent mapping of northwestern Mindoro and the islands of Lubang and Ambil roughly agrees with a 1990 suggestion that the island is composed of two terranes: the Central Range and the San Jose Platform. However, in contrast to this older model, our study, which takes into consideration the petrochemical and paleontological characteristics of the units, subdivides Northwest Mindoro into the Amnay Ophiolite and the Halcon Metamorphic terranes. Southwest-verging thrust faults parallel to the currently active Manila Trench demarcate the younger Amnay Ophiolite from the latter. Components of the older Mangyan Ophiolitic Complex, formerly thought to represent a terrane distinct from the metamorphic body, are now suggested to occur as isolated bodies enclosed within the schists of the Halcon Metamorphics. The timing of incorporation of these megaclast materials and the regional metamorphism that occurred is constrained by the deposition of the sedimentary sequences of the Late Eocene Lasala Formation. Current research also suggests that these younger sedimentary units are of continent-derived character. Therefore, accretion of the Cretaceous Mangyan Ophiolitic Complex marks the collision between the Cretaceous oceanic lithosphere and mainland Asia that is considered to be the protolith of the Halcon Metamorphics. A subsequent collision occurred which led to the amalgamation of the Amnay Ophiolite suite to the metamorphosed terrane.

Keywords : *accretionary complex, arc-continent collision, geology, Mindoro, Palawan Continental Block, tectonostratigraphic terrane*

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1. Introduction

Mindoro and the smaller islands of Lubang and Ambil lie along a broad zone in the west central Philippines where the imprints of the suturing of the Palawan Continental Block (PCB) and the Philippine Mobile Belt (PMB) are well exposed (Fig. 1) (Hamilton, 1979; Taylor and Hayes, 1980; Holloway, 1982; McCabe et al., 1982; Yumul et al., 2005). The former displays continent-derived materials including occasional pieces of oceanic lithosphere, whereas the latter consists of oceanic and island arc fragments. This suturing has resulted in the amalgamation of numerous terranes, the boundaries and origins of which remain controversial.

Previous studies envisage Mindoro to be composed of from one to five terranes (e.g., Gervasio, 1966; Karig, 1983; Karig et al., 1986; Rangin et al., 1985; Marchadier and Rangin, 1990) (Figs. 2a to 2d). These tectonostratigraphic terranes are fault-bounded geologic entities of regional extent characterized by a distinctive geologic history (Jones et al., 1983). Currently, southwest-verging thrust faults that lie parallel to the active Manila Trench separate the NW-SE trending tectonic slices.

Some workers consider Mindoro to be a small block, slightly pulled apart from the main part of Palawan during the Oligocene and rewelded by Middle Miocene (Hashimoto, 1981; Holloway, 1982; Rangin et al., 1985; Marchadier, 1988). Other workers believe the island to be made up of a southwest block possessing characteristics akin to the continent-derived Palawan Continental Block (PCB) and a northeast block having island arc affinity (PMB). The origin of the islands of Lubang and Ambil is highly disputed (e.g. Karig, 1983; McCabe et al., 1982, 1985; Mitchell et al., 1986; Sarewitz and Karig, 1986). This work examines this controversial issue using as basis new field, petrologic and geochemical data.

Determining the evolution of northwestern Mindoro and the offshore islands to its northwest provides information useful in understanding the impacts of continent-arc suturing, which is an important process in continent accretion and growth.

2. Tectonic Setting

Mindoro, Lubang and Ambil islands lie south of Luzon, in the west central portion of the Philippine Archipelago (Fig. 1). On the west of the islands, oceanic crust of the South China Sea currently subducts along the Manila Trench, the terminus of which is exposed in southern Mindoro. The Verde Island Passage separates the islands from Luzon, with the floor of the Passage dissected by the west-northwest trending submarine sinistral strike-slip Sibuyan Sea Fault. The Sibuyan Sea bounds Mindoro on the east, whereas the NW Sulu Sea basin lies south of the island.

Tectonic configuration in the area specifically around the islands has been largely controlled by the collision and subsequent suturing of the PCB and the PMB (e.g., Hamilton, 1979; Taylor and Hayes, 1980; Holloway, 1982; McCabe et al., 1982). Rifting of the PCB from mainland Asia began as crustal attenuation during the Paleocene to Eocene, evolving into sea floor spreading during Eocene to Miocene to form the South China Sea (Holloway, 1982; Taylor and Hayes, 1983; Hall 2002; Hsu et al., 2004). The SSE migration of the PCB and the northwest movement of the PMB led to the oblique collision of the two blocks (Faure et al., 1989; Zamoras et al., 2008). Indentation of the oceanic leading edge of PCB with the PMB and its subsequent subduction possibly started during the early Miocene with this collision event terminating during the Pliocene as exposed in Mindoro Island (Bellon and Yumul, 2001; Yumul et al., 2003, 2005). These events resulted in several indentation features (e.g. seismic gaps, volcanic arc gaps, steep slabs). Ophiolite emplacement, cusping and microblock rotation are observed and are believed to be related to this collision, as well (McCabe et al., 1985, Marchadier and Rangin, 1990; Jumawan et al., 1998; Yumul et al., 2008). Ramos et al. (2005) demonstrated the occurrence of seismic gaps along the boundary of the PCB and the PMB “relative to areas to the east (Philippine Fault Zone and Philippine Trench), north (Manila Trench) and south (Negros and Cotabato Trenches)”. In addition, the slow convergence between the PCB and the PMB or cessation of subduction caused by the impingement of the indenter induces only shallow and low magnitude earthquakes of strike-slip nature.

3. Analytical Techniques

Field surveys ranging were conducted in northwestern Mindoro, Lubang and Ambil. Petrographic, geochemical and paleontological analyses were done on representative rocks collected during the fieldworks. These consist of metamorphic rocks, ophiolitic rocks and clastic and carbonate sedimentary rocks.

A minimum of 400 grains per sample were point-counted to get a good approximate of the proportions of quartz, feldspar, and lithic fragments in the medium-grained sandstones. A detailed description of the petrographic analysis of these rocks can be found in Concepcion et al. (2012). Paleontological ages of the sedimentary rocks were constrained using calcareous nannofossil assemblages at the Paleontology Laboratory of the National Institute of Geological Sciences (NIGS), University of the Philippines, Diliman, Quezon City. The Mines and Geosciences Bureau (MGB), Department of Environment and Natural Resources also conducted foraminiferal analysis revealing similar range of ages obtained from the calcareous nannofossils (Table 1).

4. Results

Field data and laboratory results suggest that northwestern Mindoro, Lubang and Ambil are underlain by the following rock formations, from base to top: the Halcon Metamorphics, a thick clastic sedimentary rock sequence, an ophiolite complex and intercalated clastic and carbonate rock pile. The distribution and stratigraphic relationship of these rock formations are illustrated in Figs. 3a and 3b. Detailed descriptions of each formation are provided below.

4.1 Halcon Metamorphics

The basement rocks of northwestern Mindoro, Lubang and Ambil consist of various types of metamorphic rocks and subordinate amounts of ophiolitic fragments collectively designated as the Halcon Metamorphics (Caagusan, 1966; Faure et al., 1989; Concepcion et al., 2012). Most of the metamorphic rocks represent varieties of schists, namely, quartz-muscovite schist, quartz-biotite schist, plagioclase-quartz-mica schist, chlorite schist, talc schist and graphite schist (Figs. 4a to 4d). In addition, the formation includes subordinate meta-igneous rocks, marble, quartzite, phyllite, slate and amphibolites.

Field exposures and petrographic analysis suggest that the majority of the protoliths of the Halcon Metamorphics represent sequences of intercalated clastic rocks and small bodies of carbonate rocks that show the imprints of low to medium grade metamorphism. This observation is evident in a number of outcrops where the sedimentary structures are still preserved. Relict sedimentary bedding, from less than half a meter to several meters thick, is evident from the compositional difference, color change and grain size variation of granular minerals in the different beds (Fig. 4a). Metamorphic transformation manifests through the occurrence of metamorphic assemblages dominated by mica, quartz and plagioclase and alignment of platy minerals (Figs. 4b and 4d), with the resulting foliation often subparallel to the relict bedding. To note, metamorphism could have developed prior to the latest deformation event because the orientations of the axes of foliation display complex folding (Fig. 3a).

Other than the clastic rocks, igneous rocks also comprise the protoliths of the metamorphic rocks. This observation is noted in northwestern Mindoro where metamorphic rocks with relict bedding are intruded by silicic rocks exhibiting the same degree of metamorphism. These silicic rocks were previously described as having granitic compositions, comprising the Camarong Gneiss (e.g., Caagusan, 1966; Knittel et al., 2010). Caagusan (1966) reports the unit to show a gneissic texture and a mineral assemblage consisting mostly of mica, quartz, oligoclase and albite, with occasional actinolite. In tectonic discrimination diagrams that use trace elements, the rocks plot in the volcanic arc granite field (Knittel et al., 2010).

Interestingly, schists enclosing megaclasts of ophiolitic fragments, with the largest up to several km wide, were also observed in northwestern Mindoro (Fig. 4e). These clasts consist of peridotites, gabbros and basalts, the latter often showing pillow structures. Similar to the clastic sequence, the ophiolitic rocks display the effects of low to medium grade metamorphism. The peridotites are extensively altered to serpentine or talc, with their chromian spinels transformed to magnetite. In gabbros and basalts, amphibole or chlorite replaces pyroxene and plagioclase is albitized (Fig. 4f). The groundmass of the volcanic rocks is composed of clay and chlorite or the prehnite-pumpellyite assemblage.

It is worth noting that previous studies referred to the said ophiolitic bodies as the Mangyan Ophiolitic Complex (Hashimoto, 1981). However, given that they occur as megaclasts within the metamorphic rocks, these ophiolitic bodies are treated in this study as part of the Halcon Metamorphics (Figs. 5a and 5b). The ophiolitic bodies, mainly peridotite, could also be traced in Ambil Island. Rangin et al. (1985) mapped these units as part of the Ambil-Puerto Galera Ophiolitic Complex. Harzburgite, the dominant lithology, is cut by numerous veins of clinopyroxene-bearing dunite, mostly dipping to the SE. The dunite is, in turn, traversed by variably oriented pyroxenite veins. The youngest intrusion, based on crosscutting relationship, consists of medium-grained gabbro. This meta-ophiolite is associated with the Burburungan Amphibolite, which is thought to be part of the Halcon Metamorphic Complex (Peña, 2008).

The derivation of metamorphic rocks from different protoliths is also reflected in the ages of the rocks reported by previous workers for the Halcon Metamorphics. For instance, Knittel and Daniels (1987) proposed a Carboniferous to Early Permian (359-271 Ma) Sr model isotopic age for the protoliths of the marble. They also reported a 240-180 Ma Sr isotopic age for the Camarong Gneiss which is herein treated as part of the Halcon Metamorphics. A slightly older mean age of a 251 ± 2.6 Ma (n=20) for a meta-granodiorite sample believed to represent the Camarong Gneiss, however, is reported by Knittel et al. (2010) using U-Pb dating of zircon grains. Detrital zircons from sediment samples from Camarong River yield similar mean ages of 258±3 Ma (n=32) and 259±4 Ma (n=26). Knittel et al. (2010) reported a younger Cretaceous age of 86±2 Ma (n=1) and 86±3 Ma (n=4) based on zircons extracted from the sediment samples collected from Camarong River. This is consistent with the early Cretaceous age of the Mangyan Ophiolic Complex which occurs as megaclasts within the Halcon Metamorphics. This ophiolitic unit was dated by Hashimoto (1981) as Early Cretaceous based on the foraminiferal assemblage in sediments capping the pillow basalt unit.

4.2 Lasala Formation

The Lasala Formation unconformably overlies the Halcon Metamorphics. It is a thick sedimentary sequence consisting of interbedded medium-grained quartz arenite and dark gray shale with subordinate coralline limestones, conglomerates and basalt flows that are widely exposed at the west and southwestern coasts of Paluan and central portions of northwestern Mindoro.

In Lubang Island, one third of the area is composed of predominantly recrystallized reefal limestone and calcareous conglomeratic deposits of the Lasala Formation (Fig. 5c). Fragments of scleractinian corals that are 10 cm to 30 cm in diameter, foraminifera species that yielded an Eocene age and angular pebble- to cobble-size mica schist fragments that are embedded in a calcareous matrix are found in the limestone (Fig. 5d). Hills of conglomerates occurring proximally to the limestone units and along the Hulagaan coast (southeastern Lubang Island) consist of fine-grained sandy matrix with subrounded, cobble- to boulder-size quartz and quartz-mica schists evidently derived from the nearby units of the Halcon Metamorphics. Quartz sandstones, mudstones, minor conglomerates with intercalated basalt flows, agglomeratic deposits and limestone characterize a bedded sequence of this formation near Paluan. It is exposed along the coast which extends up to 10 kilometers long and bed thickness varies from less than a meter to about 2 meters. Finer grained units are typically composed of alternating beds of gray sandstone and dark gray shale. Coarse crystalline limestone also outcrops to the south near Paluan.

Good exposures of the clastic sequence were observed along the Pagbahan River (west of Mamburao) where interbeds of highly indurated medium-grained quartz arenite and dark gray shale extend up to 200 meters (Concepcion et al., 2012). Sandstones with subordinate conglomerate beds were also noted at the Mamburao-Abra de Ilog boundary. In this area, the rocks are conglomeratic to lithic sandstone, light to dark gray in color, moderately to highly fractured and moderately weathered with beds striking NE and dipping SE. Notably cobble- to boulder-size chert clasts in conglomerates interbedded with near vertical sandstone beds are exposed in the shoreline near Mount Igsoso.

Paleontological dating of nannofossil assemblages yielded a Late Eocene to Early Oligocene age for the Lasala Formation (Faure et al., 1989; Concepcion et al., 2012; this work) (Table 1). These assemblages further suggest a deep marine environment receiving sediment influx from the shallow portions of the sea (Fig. 5d). Concepcion et al. (2012) proposed that the principal source of these sediments was a nearby continent (Figs. 6a, 6b). Further processing of the geochemical data of Concepcion et al. (2012) was done. The Al_2O_3/TiO_2 in sedimentary rocks was used to deduce the source rock type. Available geochemical data show that most Archean sandstones are characterized by Al_2O_3/TiO_2 ratios >10. Samples with ratios between 20-50 correspond to intermediate to felsic igneous source rocks (e.g. Sugitani et al., 2006; Yan et al., 2012). In the case of the Lasala samples, the Al_2O_3/TiO_2 values range from 15 to 44 consistent with their derivation from felsic igneous rocks (Fig. 6a). The Zr-Hf plot of the Lasala samples shows a positive correlation between Zr and Hf (Fig. 6b). Rudnick and Gao (2003) proposed a Zr concentration of 132 ppm and Zr/Hf ratio of 35.5 for the average continental crust. The Zr concentration in the Lasala samples ranges from ~60 to 500 ppm and Zr/Hf varies between 33 and 44. These are all consistent with a continental crustal composition.

4.3 Amnay Ophiolite Complex

The Amnay Ophiolite Complex (AOC) outcrops as a narrow NW-SE trending elongated body, the NW terminus of which is located near Mount Igsoso (Rangin et al., 1985; Jumawan et al., 1998; Yumul et al., 2009). Although extensively cut as tectonic slices, the ophiolite presents a complete upper mantle to oceanic crust sequence. The former includes residual peridotites, which are dominated by harzburgite with subordinate dunite and lherzolite and a layered ultramafic sequence composed of harzburgite, pyroxenites and websterite. The latter consists of layered gabbro, isotropic gabbro, a sheeted basaltic dike complex and pillow basalt (Figs. 5e and 5f). Pelagic mudstone caps the pillow basalt unit. The AOC is separated from the Halcon Metamorphics and Lasala Formation by NW-SE oriented, southwest verging thrust faults that parallel the current trend of the Manila Trench.

Geochemical studies of the AOC basalts demonstrate the existence of enriched-mid oceanic ridge basalts formed as a function of mantle source mixing following a veined mantle model proposed for the South China Sea mantle. Work done by Yumul et al. (2009) revealed that the volcanic rocks of the Amnay Ophiolite Complex are characterized by transitional MORB-IAT geochemical signatures indicating their formation in a back-arc basin setting. The chemistry of the spinels and pyroxenes of the lherzolites and harzburgites suggest that they are products of low degrees of partial melting (Yumul et al., 2009).

Rangin et al. (1985) speculate that the AOC probably represents a fragment of the West Philippine Sea crust based on its oceanic character and Middle Oligocene age. The latter was determined by the paleontological dating of its sedimentary carapace (Rangin et al., 1985).

4.4 Balanga Formation

The Balanga Formation unconformably overlies the Lasala Formation and the AOC. It outcrops as patches of small hills within a NNE-SSW trending narrow depression from Abra de Ilog to Mamburao. The formation displays sub-horizontal sequences consisting of tuffaceous and fossiliferous sandstone and siltstone, with minor conglomerate and limestone (Fig. 5g). Sandstone-siltstone sequences are mostly composed of devitrified volcanic ash, which, in some cases, are zeolitic. The limestone is generally massive with abundant coralline fragments. Petrographic analysis reveals the presence of facies variation in the limestone including boundstone, grainstone and packstone. Moderate recrystallization of the carbonates occurs in some outcrops.

Previously identified to be of Late Pliocene to Pleistocene age (Zepeda et al, 1992), paleontological dating in the present study yields an Early Pliocene to Early Pleistocene for the Balanga Formation (Table 1). This is based on the nannofossil assemblage which includes *Pseudoemiliana lacunosa* and *Helicosphaera carteri* (Fig. 5h).

5. Discussion

Northwestern Mindoro and the islands of Lubang and Ambil lie within the zone of collision and subsequent suturing of a continent derived (PCB) block and oceanic-island arc (PMB) fragments. Because of the complex tectonic interactions related to these events, the provenance of the different rock formations is often overprinted. Newly collected data suggest that the basement rocks of the surveyed areas (Halcon Metamorphics) were originally marine sedimentary sequences showing features similar to the ocean plate stratigraphy as defined by Wakita and Metcalfe (2005). The sequence is made up of (from oldest to youngest) “pillow basalt, limestone, chert, siliceous shale, shale and sandstone”. The evolution of an oceanic plate can be tracked from its formation at a mid-oceanic ridge until its destruction at an oceanic trench (Wakita and Metcalfe, 2005). A minimum age of Carboniferous to Early Permian for the protoliths of the metamorphosed sedimentary sequence is provided by Knittel and Daniels (1987). This is close to the ages reported for basement complexes in northern Palawan, southern Romblon (Carabao Island melànge) and NW Panay, which are all thought to be continent-derived materials (Zamoras et al., 2008; Gabo et al., 2009). The presence of megaclasts of ophiolitic materials enclosed in marine sediments is typical of accretionary complexes along subduction zones (e.g. Cawood et al., 2009; Jahn, 2010; Isozaki et al., 2010).

Knittel et al. (2010) report a 270-250 Ma range for the granitic rocks that intruded the protoliths of the schists. They speculate that the magmatic activity that produced these granitic rocks was associated with the episode recorded by arc granites along the southeastern margin of southern Asia, and thus supporting the continent affinity model for the Halcon Metamorphics.

Aside from the Halcon Metamorphics, the Lasala Formation is also continent-derived (Concepcion et al., 2012). It is not therefore surprising that the Lasala Formation could have been sourced from the Halcon Metamorphics, which the former unconformably overlies.

The AOC has been demonstrated to be a fragment of the South China Sea (e.g., Rangin et al., 1985; Perez et al., this issue). Its current location nearest to the Manila Trench and its tectonic relationship with respect to the older rock formations are typical features of unsubducted materials along subduction zone complexes.

The distribution of the Balanga Formation suggests the presence of a seaway between the Paluan peninsula and mainland Mindoro during the Plio-Pleistocene. This shallow basin was likely formed during the deformation of the underlying rocks at the time of the Middle to Late Miocene collision. The NE-SW trending syncline is the morphological expression of the NW-SE regional stress induced by the collision. Fossil assemblages provide support for a shallow marine environment of deposition prior to exhumation.

The variation in the protoliths of the metamorphic rocks can be traced to its perceived evolution. As earlier pointed out, given the age of the Halcon Metamorphics, the said unit comprises the Palawan Continental Block (PCB). Previous workers (e.g. Karig, 1983; Rangin et al., 1985; Faure et al., 1989) recognized that the PCB was derived from the southeastern margin of mainland Asia. Zamoras and Matsuoka (2004) interpreted this region as an active margin involving the subduction of the Izanagi Plate (also referred to as the proto-Pacific Plate) beneath the southeastern margin of mainland Asia sometime during the Middle to Late Jurassic (Fig. 7a). They modeled the Izanagi Plate to comprise of seamounts capped by pelagic limestone alongside chert deposits. The continued subduction of the Izanagi Plate allowed some of the said rocks, including continent-derived sediments brought into the basin, to be scraped off to form an accretionary complex at the southeastern mainland Asia margin. Such tectonic features involved the initial subduction of sediments, followed by backthrusting of these materials, including sections of the oceanic plate from which pieces of the so-called Mangyan Ophiolitic Complex were derived (Fig. 7b). These conditions explain the different lithologies preserved as blocks within the now metamorphic rocks of the Halcon Metamorphics. Continued accretion-related tectonism likewise resulted to the metamorphism of the unit, thus forming the Halcon Metamorphics.

During the Late Eocene to Oligocene, subduction had ceased along the southeastern margin of mainland Asia. By that time, rifting within the southeastern China margin commenced. This event marks the start of the formation of the South China Sea (Fig. 7c). As to what triggered the rifting is still unclear, although extrusion tectonics (Tapponier et al., 1982) and trench rollback (Rangin et al., 1990) have been considered as possible causes. The rifting and subsequent spreading event allowed the PCB, which also carried with it rocks of the Halcon Metamorphics, to be translated southeastward. As spreading progressed, shedding of sediments from the newly rifted mass, as well as from the southern margin of mainland Asia, into the newly formed South China Sea Basin occurred. These sediments now comprise the Lasala Formation. This interpretation is consistent with field observations as well as the petrographic and geochemical results suggesting derivation of the Lasala Formation from continental crustal materials and the Halcon Metamorphics. This spreading also resulted in the formation of the younger South China Sea oceanic lithosphere, fragments of which were later emplaced and preserved onland as the Amnay Ophiolite Complex.

As the South China Sea continued to widen, the PCB was pushed farther southeastward to eventually collide with the PMB. This Middle to Late Miocene collision is marked by the accretion of the Halcon Metamorphics, the Lasala Formation and the Amnay Ophiolite with the Philippine Mobile Belt (Fig. 7d). West-verging thrust faults that bound these lithologic units are consistent with the history of a series of accretion events. The Balanga Formation, consisting of relatively undeformed units, marks the end of this collision event in Mindoro Island.

The reconstructed history of the formations leads to the identification of two distinct terranes: (1) Halcon Metamorphic terrane and (2) Amnay Ophiolite terrane (Fig. 2d). The metamorphic terrane is chiefly composed of the Halcon Metamorphics and the Lasala Formation. Both are sedimentary in origin but only the Halcon Metamorphics is characterized by varying degrees and several episodes of metamorphism. These formations are separated by NW-trending, SW-verging thrust faults from the AOC. The Balanga Formation, occurring in both terranes, marks the final welding of the two terranes. This model is in agreement with the terrane boundaries delineated by Marchadier and Rangin (1990).

6. Conclusions

Pervasively metamorphosed ophiolitic fragments occurring as blocks within the Halcon Metamorphics suggest that pieces of an oceanic floor were ripped off and incorporated into the accretionary complex of mainland Asia which later underwent regional metamorphism. Younger silicic intrusives within this unit exhibit a low degree of metamorphism which implies a second metamorphic event during the Late Miocene. Schist fragments found within the Lasala sedimentary package suggest that metamorphism must have occurred before the Late Eocene. This also suggests continental affinity for the metamorphic body. Based on the petrochemical and field evidences, the model shows that the Halcon Metamorphics and the Lasala Formation must have been from the same nearby continental source prior to rifting during the Late Eocene. This provides further evidence for a continental affinity of their protoliths. Occurrence of marble, ophiolitic fragments within the metamorphic body, conformable chlorite schists and quartz-biotite schists depicts a sedimentary nature for the Halcon Metamorphics.

This work supports the terrane boundaries proposed by Marchadier and Rangin (1990) which subdivides Mindoro Island into the Central Range and the San Jose Platform. However, this study, which takes into consideration the petrochemical and paleontological characteristics of the geologic units, identifies two distinct terranes: (1) Amnay Ophiolite terrane and (2) Halcon Metamorphics terrane. The Halcon Metamorphics terrane includes both metamorphosed (Halcon Metamorphics) and unmetamorphosed sedimentary packages (Lasala Formation). This is separated by NW trending SW verging thrust-fault from the crust-mantle sequence represented by the AOC.

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References:

Bellon, H., Yumul Jr., G.P., 2001. Miocene to Quaternary adakites and related rocks in Western Philippine arc sequences. Comptes Rendus de l'Académie des Sciences – Series II – Earth and Planetary Science 333(6), 343-350.

Caagusan, N.L., 1966. Petrography of the metamorphic rocks of northern Mindoro. Bull. Inst. Filipino Geologists 1, 22-46.

Cawood, P. A., Kröner, A., Collins, W. J., Kusky, T. M., Mooney, W. D., Windley, B. F., 2009. Accretionary orogens through Earth history, in: Cawood, P. A., and Kröner, A. (eds.) Earth Accretionary Systems in Space and Time. Geological Society, London, Special Publications 318, 1–36.

Concepcion, R.A.B., Dimalanta, C.B., Yumul Jr., G.P., Faustino-Eslava, D.V., Queaño, K.L., Tamayo Jr., R.A., Imai, A., 2012. Petrography, geochemistry and tectonics of a rifted fragment of Mainland Asia: evidence from the Lasala Formation, Mindoro Island, Philippines. International Journal of Earth Sciences 101, 273-290.

Faure, M., Marchadier, Y., Rangin, C., 1989. Pre-Eocene synmetamorphic structure in the Mindoro-Romblon-Palawan Area, West Philippines, and implications for the history of southeast Asia. Tectonics 8(5), 963-979.

Gabo, J.A.S., Dimalanta, C.D., Asio, M.G.S., Queaño, K.L., Yumul Jr., G.P., Imai, A., 2009. Geology and geochemistry of the clastic sequences from Northwestern Panay (Philippines): Implications for provenance and geotectonic setting. Tectonophysics 479(1-2), 111-119.

Gervasio, F.C., 1966. A study of the tectonics of the Philippine archipelago. Philippine Geologist 20, 51-75.

Hall, R., 2002. Cenozoic geological and plate tectonic evolution of SE Asia and SW Pacific: computer-based reconstructions, model and animations. Journal of Asian Earth Sciences 20(4), 353-431.

Hamilton, W., 1979. Tectonics of the Indonesian r egion. U S Geological Survey, Professional Paper 1078, 345.

Hashimoto, W., 1981. Geologic development of the Philippines, in: Kobayashi, T., Toriyama, R., Hashimoto, W. (eds.) Geology and Paleontology of SE Asia 22, 83-170.

Holloway, N.H., 1982. North Palawan block, Philippines: its relation to Asian mainland and role in evolution of the South China Sea. American Association of Petroleum Geologists Bulletin 16, 1355-1383.

Hsu, S., Yeh, Y., Doo, W., Tsai, C., 2004. New bathymetry and magnetic lineations identifications in the northernmost South China Sea and their tectonic implications. Marine Geophysical Researches 25, 29-44.

Isozaki, Y., Aoki, K., Nakama, T., Yanai, S., 2010. New insight into a subduction-related orogen: A reappraisal of the geotectonic framework and evolution of the Japanese Islands. Gondwana Research 18(1), 82–105.

Jahn, B.-M., 2010. Accretionary orogen and evolution of the Japanese Islands - Implications from a Sr-Nd Isotopic Study of the Phanerozoic Granitoids from SW Japan. American Journal of Science 310, 1210-1249.

Jones, D.L., Howell, D.G., Coney, P.J., Monger, J.W.H., 1983. Recognition, character and analysis of tectonostratigraphic terranes in western North America, in: Hashimoto, M., Uyeda, S., (eds.) Accretion Tectonics in the Circum-Pacific Regions, Advances in Earth and Planetary Sciences. D. Reidal Publishing Company, New York, 21-35.

Jumawan, F.T., Yumul, G.P. Jr., Tamayo, R.A. Jr., 1998. Using geochemistry as a tool in determining the tectonic setting and mineralization potential of an exposed upper mantle-crust sequence: Example from the Amnay ophiolitic complex in occidental Mindoro, Philippines. Journal of the Geological Society of the Philippines 53, 24-48.

Karig, D.E., 1983. Accreted terranes in the northern part of the Philippine archipelago. Tectonics 2(2), 211-236.

Karig, D.E., Sarewitz, D.R., Haeck, G.D., 1986. Role of strike-slip faulting in the evolution of the allochthonous terranes in the Philippines. Geology 14, 852-855.

Knittel, U., Daniels, U., 1987. Sr-isotopic composition of marbles from the Puerto Galera area (Mindoro, Philippines): Additional evidence for a Paleozoic age of a metamorphic complex in the Philippine island arc. Geology 15(2) 136-138.

Knittel, U., Hung, C.H., Yang, T.F., 2010. Permian arc magmatism in Mindoro, the Philippines: An early Indosinian event in the Palawan Continental Terrane. Tectonophysics 439(1-2), 113-117.

Marchadier, Y., 1988. The southern end of the Manila trench in the continental domain: Stratigraphic and tectonic studies of Mindoro and Tablas, Islands (Philippines). Thesis, Universite Pierre et Marie Curie, Paris, 370pp.

Marchadier, Y., Rangin, C., 1990. Polyphase tectonics at the southern tip of the Manila trench, Mindoro-Tablas Islands, Philippines. Tectonophysics 183(1-4), 273-287.

McCabe, R., Almasco, J., Diegor, W., 1982. Geologic and paleomagnetic evidence for a possible Miocene collision in western Panay, centr al Philippines. Geology 10(6), 325-329.

McCabe, R., Almasco, J., Yumul Jr., G.P., 1985. Terranes in the Central Philippines, in: Howell D. (ed.), Tectonostratigr aphic Terranes of the Circum-Pacific Region, Earth Series 1. Circum-Pacific Council on Energy and Mineral Resources Series 1, 421–435.

Mitchell, A.H.G., Hernandez, F., De la Cruz, A.P., 1986. Cenozoic evolution of the Philippine archipelago. Journal of Southeast Asian Earth Sciences 1, 1-20.

Peña, R. (ed.) 2008. Lexicon of Philippine Stratigraphy. Geological Society of the Philippines, Mandaluyong City, 364pp.

Perez, A.D.C., Faustino-Eslava, D.V., Yumul Jr., G.P., Dimalanta, C.D., Tamayo Jr., R.A., Yang, T.F., Zhou, M.F., in press. Enriched and depleted characters of the Amnay Ophiolite upper crustal section and the regionally heterogeneous nature of the South China Sea mantle. Journal of Asian Earth Sciences Special Issue (this issue).

Ramos, N.T., Dimalanta, C.B., Besana, G.M., Tamayo Jr., R.A., Yumul Jr., G.P., Maglambayan, V.B., 2005. Seismotectonic reactions to the aArc-continent convergence in Central Philippines. Resource Geology 55 (3), 197-204.

Rangin, C., Stephan, J.F., Muller, C., 1985. Middle Oligocene oceanic crust of South China Sea jammed into Mindoro collision zone (Philippines). Geology 13, 425-428.

Rangin, C., Jolivet, L., Pubellier, M., 1990. A simple model for the tectonic evolution of southeast Asia and Indonesia region for the past 43 m.y. Bulletin de la Societe geologique de France 8, 889-905.

Rudnick, R.L., Gao, S., 2003. Composition of the Continental Crust. Treatise on Geochemistry, Elsevier Ltd.

Sarewitz, D.R. Karig, D.E, 1986. Processes of allochthonous terrane evolution, Mindoro Island, Philippines. Tectonics 5(4), 525-552.

Sugitani, K., Yamashita, F., Nagaoka, T., Yamamoto, K., Mimura, K., Suzuki, K., 2006. Geochemistry and sedimentary petrology of Archaean clastic sedimentary rocks at Mt. Goldsworthy, Pilbara Craton, Western Australia: Evidence for the early evolution of continental crust and hydrothermal alteration. Precambrian Research 147, 124-147.

Tam, T.A.III, 2005. Geochemical comparison of the sandstones – shales of the Zigzag, Klondyke and Amlang Formations with possible older igneous rock sources (Pugo Metavolcanics, Northern Sierra Madre) of the Baguio District, Luzon, Philippines. M.S. Thesis, University of the Philippines, 105p.

Tam, T.A.III, Yumul, G.P.Jr., Ramos, E.G.L., Dimalanta, C.B., Zhou, M.-F., Suzuki, S., 2005. Rare earth element geochemistry of the Zigzag - Klondyke sedimentary rock formations: Clues to the evolution of the Baguio Mineral District (Luzon), Philippines. Resource Geology Special Issue 55, 217-224.

Tapponier, P., Peltzer, G., LeDain, A., Armijo, R., Cobbold, P., 1982. Propagating extrusion tectonics in Asia: new insights from simple experiments with plasticine. Geology 10, 611-616.

Taylor, B., Hayes, D.E., 1980. The tectonic evolution of the South China Basin, in: Hayes, D.E. (ed.) The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands. American Geophysical Union Monograph 23, 89-104.

Taylor, S.R., McLennan, S., 1985. The Continental Crust: Its Composition and Evolution. Blackwell Scientific, Oxford.

Wakita, K., Metcalfe, I., 2005. Ocean plate stratigraphy in east and southeast Asia. Journal of Asian Earth Sciences 24, 679–702.

Yan, Y., Xia, B., Lin, G., Cui, X., Hu, X., Yan, P., Zhang, F., 2007. Geochemistry of the sedimentary rocks from the Nanxiong Basin, South China and implications for provenance, paleoenvironment and paleoclimate at the K/T boundary. Sedimentary Geology 197, 127-140.

Yan, Z., Wang, Z., Yan, Q., Wang, T., Guo, X., 2012. Geochemical constraints on the provenance and depositional setting of the Devonian Liuling Group, East Qinling Mountains, Central China: Implications for the tectonic evolution of the Qinling Orogenic Belt. Journal of Sedimentary Research 82, 9-20.

Yumul Jr., G.P., Dimalanta, C.B., Tamayo Jr., R.A., Maury, R.C., 2003. Collision, subduction and accretion events in the Philippines: A synthesis. The Island Arc 12, 77-91.

Yumul Jr., G.P., Dimalanta, C.B., Tamayo Jr., R.A, 2005. Indenter-tectonics in the Philippines: Example from the Palawan Microcontinental Block-Philippine Mobile Belt collision. Resource Geology 55(3), 187-196.

Yumul Jr., G.P., Dimalanta, C.B., Maglambayan, V.B., 2008. Tectonic setting of a composite terrane: A review of the Philippine island arc system. Geosciences Journal 12(1), 7-17.

Yumul Jr., G.P., Jumawan, F.T., Dimalanta, C.B., 2009. Geology, geochemistry and mineralization potential of the South China Sea oceanic lithosphere as revealed by the Amnay Ophiolitic Complex, Mindoro, Philippines. Resource Geology Special Issue 59(3), 263-281.

Zamoras, L.R., Montes, M.G.A., Queaño, K.L., Marquez, E.J., Dimalanta, C.B., Gabo, J.A.S., Yumul Jr., G.P., 2008. Buruanga Peninsula and Antique Range: Two contrasting terranes in Northwest Panay, Philippines featuring an arc-continent collision zone. Island Arc 17, 443-457.

Zamoras, L.R., Matsuoka A., 2004. Accretion and post-accretion tectonics of the Calamian Islands, North Palawan Block (Philippines). Island Arc 13, 506-19.

Zepeda-Agadier, M.A., Tumanda, F.P., Revilla, A., 1992. The Paleogene-Neogene sequence of southwest Mindoro island, Philippines – stratigraphy and events. Bureau of Mines, Unpublished Technical Report.

FIGURE CAPTIONS

Fig. 1. Neotectonic setting of the Philippines showing the delineated collision boundary (modified from Zamoras et al., 2008). Map generated using the Shuttle Radar Topography Mission data (source: eros.usgs.gov).

Fig. 2a.-b. Evolution of the previously proposed tectonostratigraphic terranes present in NW Mindoro and the offshore islands of Lubang and Ambil. c. The work of Concepcion et al. (2012) suggests that the whole of Mindoro island is part of the Palawan Continental Block. d. This study proposes a two-terrane model – an ophiolite terrane (Amnay Ophiolite) and a metamorphic terrane which contains blocks of an older oceanic lithospheric fragment (Halcon Metamorphics).

Fig. 3a. Geologic map of NW Mindoro and the offshore islands of Lubang and Ambil showing the distribution of the formations comprising these regions (modified from Concepcion et al., 2012). A dominant NW-SE foliation trend is observed in NW Mindoro. b. Composite stratigraphic column illustrating the stratigraphic relationships of the various formations present in the study area.

Fig. 4a. Alternating beds of quartz muscovite schist and chlorite schist as seen in Lubang Island. b. The xenoblastic flattened quartz grains, albite and muscovite which make up the quartz muscovite schist point to a quartz-rich clastic rock protolith. c. Outcrop along the Paluan coast showing mica schist underlain by chlorite schist. d. Actinolite schist. e. The amphibolites near Abra de Ilog exhibit an alignment of prismatic amphiboles. f. Amphibolite sample showing the parallel alignment of amphibole and plagioclase. Letters in the geologic map (left) correspond to the location of the outcrops.

Fig. 5a. Serpentinized harzburgite block enclosed in schist as exposed in southern Paluan. b. Photomicrograph of serpentinized peridotite near Paluan. c. Reefal limestone member of the Lasala Formation exposed in Lubang Island. d. The limestone sample contains Nummulites, Amphistegina, algae, echinoid spines, corals and fragments of mollusk shells commonly found in shallow marine environments. e. Bulbous pillows exhibited by the basalts of the Amnay Ophiolite Complex as seen in Sta. Cruz. f. Photomicrograph of an aphanitic basalt showing spherulitic plagioclases. g. Tuffaceous sandstone-siltstone interbeds of the Balanga Formation were noted in the Mamburao area. h. Nannofossils such as *Pseudoemiliana lacunosa* constrain the age of the Balanga Formation to Pliocene-Pleistocene. Letters in the geologic map (left) correspond to the location of the outcrops.

Fig. 6. The major and trace element compositions of the Lasala Formation samples (white squares) reported by Concepcion et al. (2012) were used to plot: a. the Al_2O_3/TiO_2 - Al_2O_3 diagram (Taylor and McLennan, 1985) and b. Zr-Hf diagram (Sugitani et al., 2006). The Lasala samples are generally characterized by Al_2O_3/TiO_2 of ~20 indicating that these were sourced from felsic igneous rocks. High Zr/Hf is typically observed in felsic rocks. Fields of the Nanxiong sedimentary rocks (continent-derived) (Yan et al., 2007) and the Baguio samples (oceanic island arc-derived) (Tam, 2005; Tam et al., 2005) are shown for comparison.

Fig. 7. Schematic diagram for the tectonic evolution of northwest Mindoro. a. Collision and subduction of the Izanagi Plate beneath the southeastern margin of mainland Asia during Middle to Late Jurassic. b. Materials from the Izanagi Plate were incorporated in the accretionary complex, followed by the backthrusting, forming part of the protolith of the Halcon Metamorphics. Continued accretion resulted to metamorphism of the Halcon Metamorphics. c. Cessation of subduction and rifting of the southeastern margin of mainland Asia commenced during Late Eocene to Oligocene. Spreading that followed the rifting resulted to the translation of the Palawan Continental Block (with Halcon Metamorphics) southeastward. d. Continued spreading resulted to the formation of the South China Sea oceanic lithosphere and subsequent emplacement of the Amnay Ophiolite Complex. See text for discussion. Legend: Green with pink blocks = Halcon Metamorphics with clasts of the Mangyan Ophiolitic Complex; orange = Lasala Formation; purple = Amnay Ophiolite Complex; blue = South China Sea.

Table 1. Calcareous nannofossil assemblages in the Lasala and Balanga formations. Samples were analyzed at the National Institute of Geological Sciences (NIGS) and the Mines and Geosciences Bureau (MGB).

Figure 1

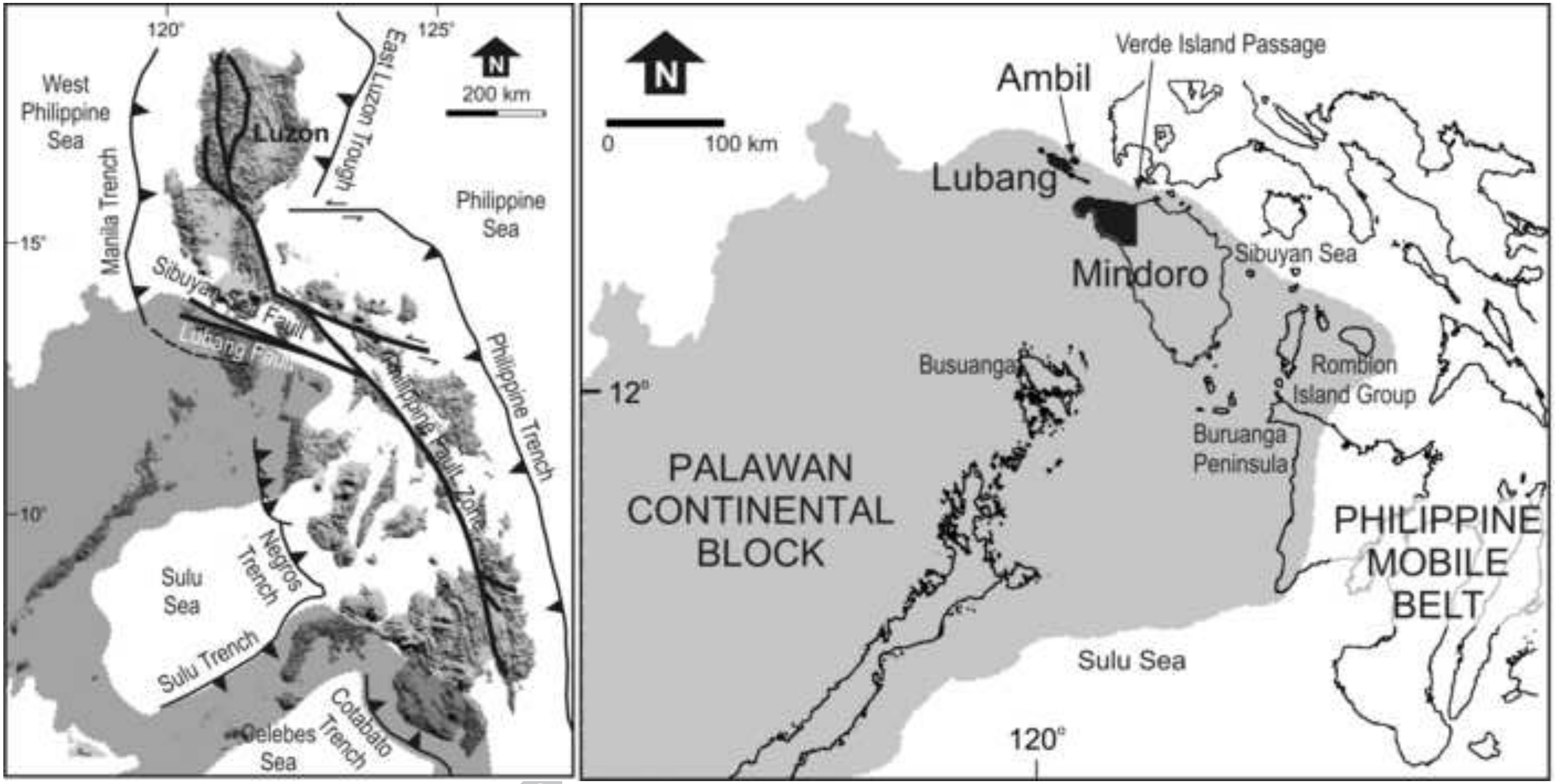

120°
125°
N
200 km
West Philippine Sea
Manila Trench
Luzon
East Luzon Trough
Philippine Sea
15°
Sibuyan Sea Fault
Lubang Fault
Philippine Fault Zone
Philippine Trench
10°
Sulu Sea
Negros Trench
Sulu Trench
Celebes Sea
Cotabato Trench
N
0
100 km
Verde Island Passage
Ambil
Lubang
Mindoro
Sibuyan Sea
12°
Busuanga
Rombion Island Group
Buruanga Peninsula
PALAWAN CONTINENTAL BLOCK
PHILIPPINE MOBILE BELT
Sulu Sea
120°

Figure 2

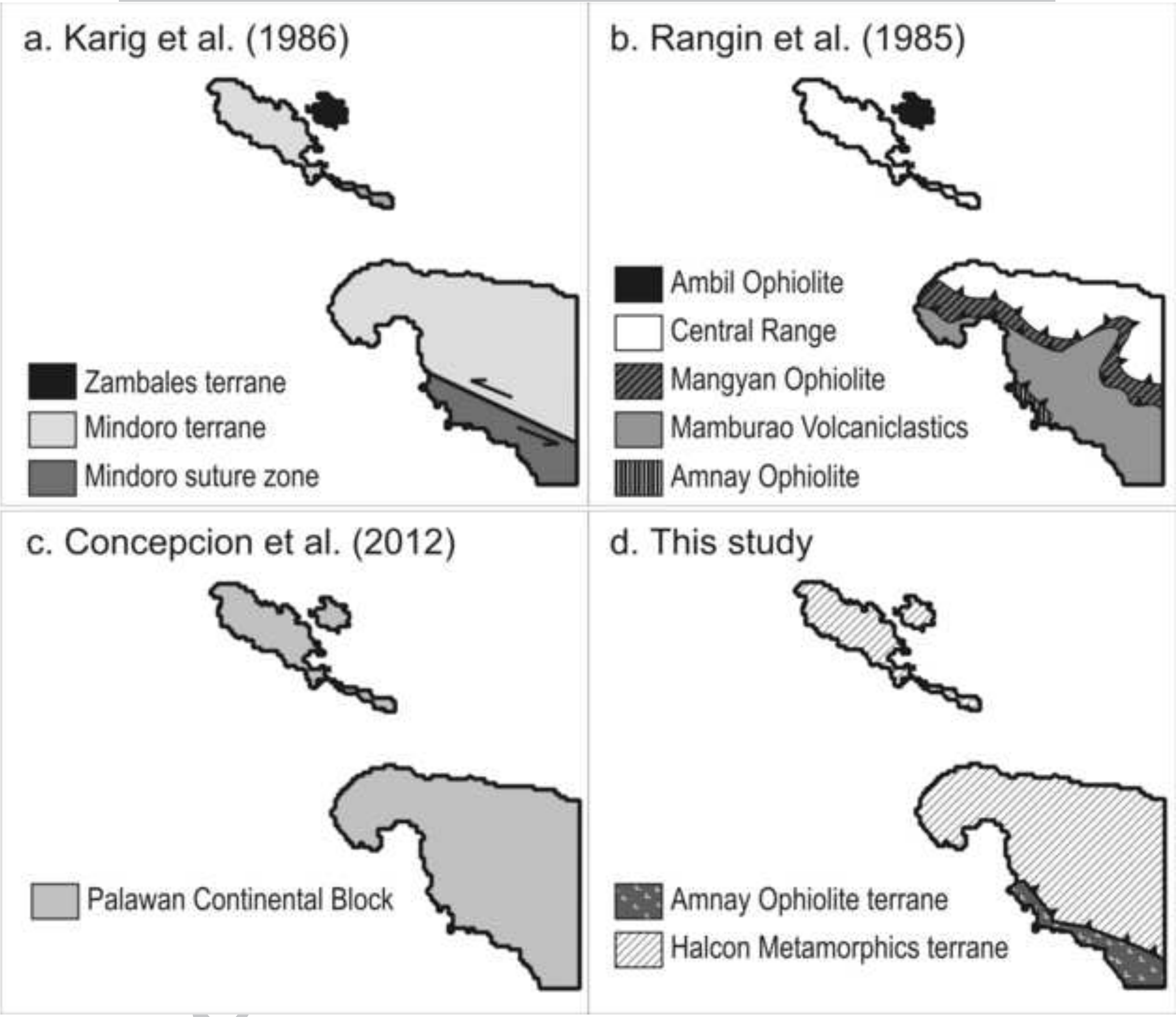

a. Karig et al. (1986)
Zambales terrane
Mindoro terrane
Mindoro suture zone
b. Rangin et al. (1985)
Ambil Ophiolite
Central Range
Mangyan Ophiolite
Mamburao Volcaniclastics
Amnay Ophiolite
c. Concepcion et al. (2012)
Palawan Continental Block
d. This study
Amnay Ophiolite terrane
Halcon Metamorphics terrane

Figure 3

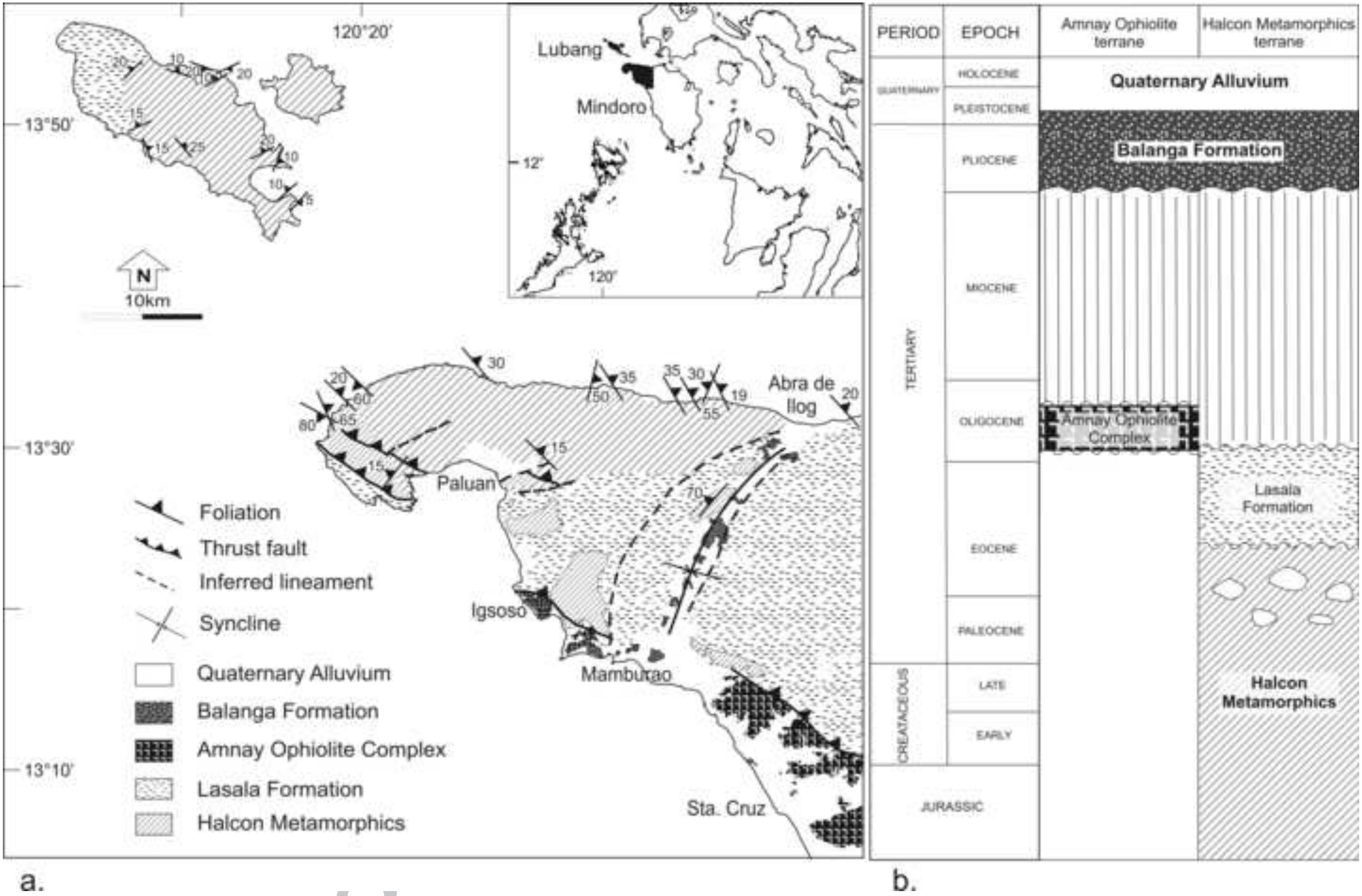

120°20'
13°50'
13°30'
13°10'
N
10km
Lubang
Mindoro
12°
120°
Paluan
Abra de Ilog
Igsoso
Mamburao
Sta. Cruz
Foliation
Thrust fault
Inferred lineament
Syncline
Quaternary Alluvium
Balanga Formation
Amnay Ophiolite Complex
Lasala Formation
Halcon Metamorphics
a.
PERIOD
EPOCH
Amnay Ophiolite terrane
Halcon Metamorphics terrane
QUATERNARY
HOLOCENE
PLEISTOCENE
TERTIARY
PLIOCENE
MIOCENE
OLIGOCENE
EOCENE
PALEOCENE
CREATACEOUS
LATE
EARLY
JURASSIC
Quaternary Alluvium
Balanga Formation
Amnay Ophiolite Complex
Lasala Formation
Halcon Metamorphics
b.

Figure 4

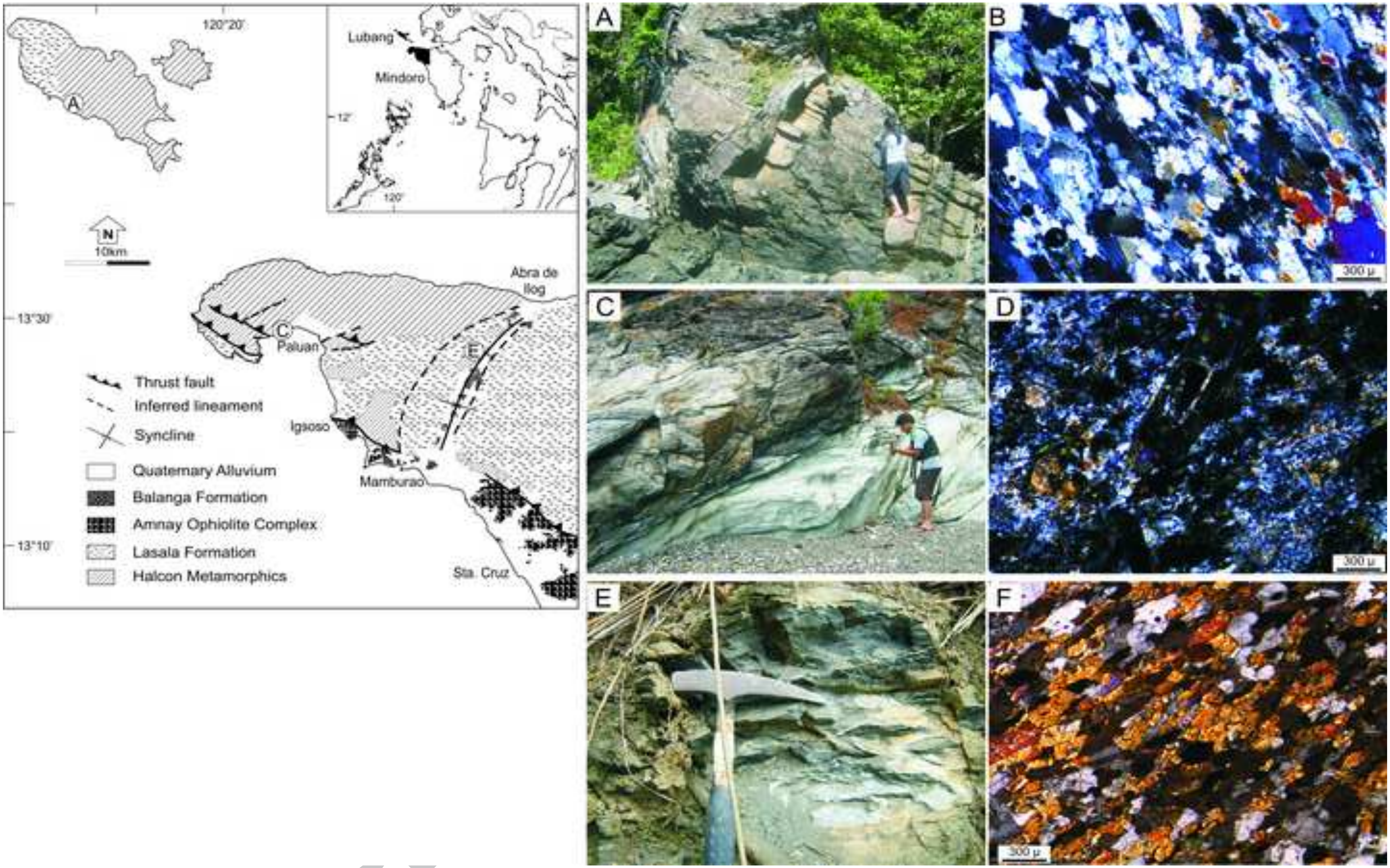

120°20'
Lubang
Mindoro
12°
120°
A
N
10km
Abra de Ilog
13°30'
C
Paluan
E
Igsoso
Mamburao
13°10'
Sta. Cruz
Thrust fault
Inferred lineament
Syncline
Quaternary Alluvium
Balanga Formation
Amnay Ophiolite Complex
Lasala Formation
Halcon Metamorphics
A
B
300 μ
C
D
300 μ
E
F
300 μ

Figure 5

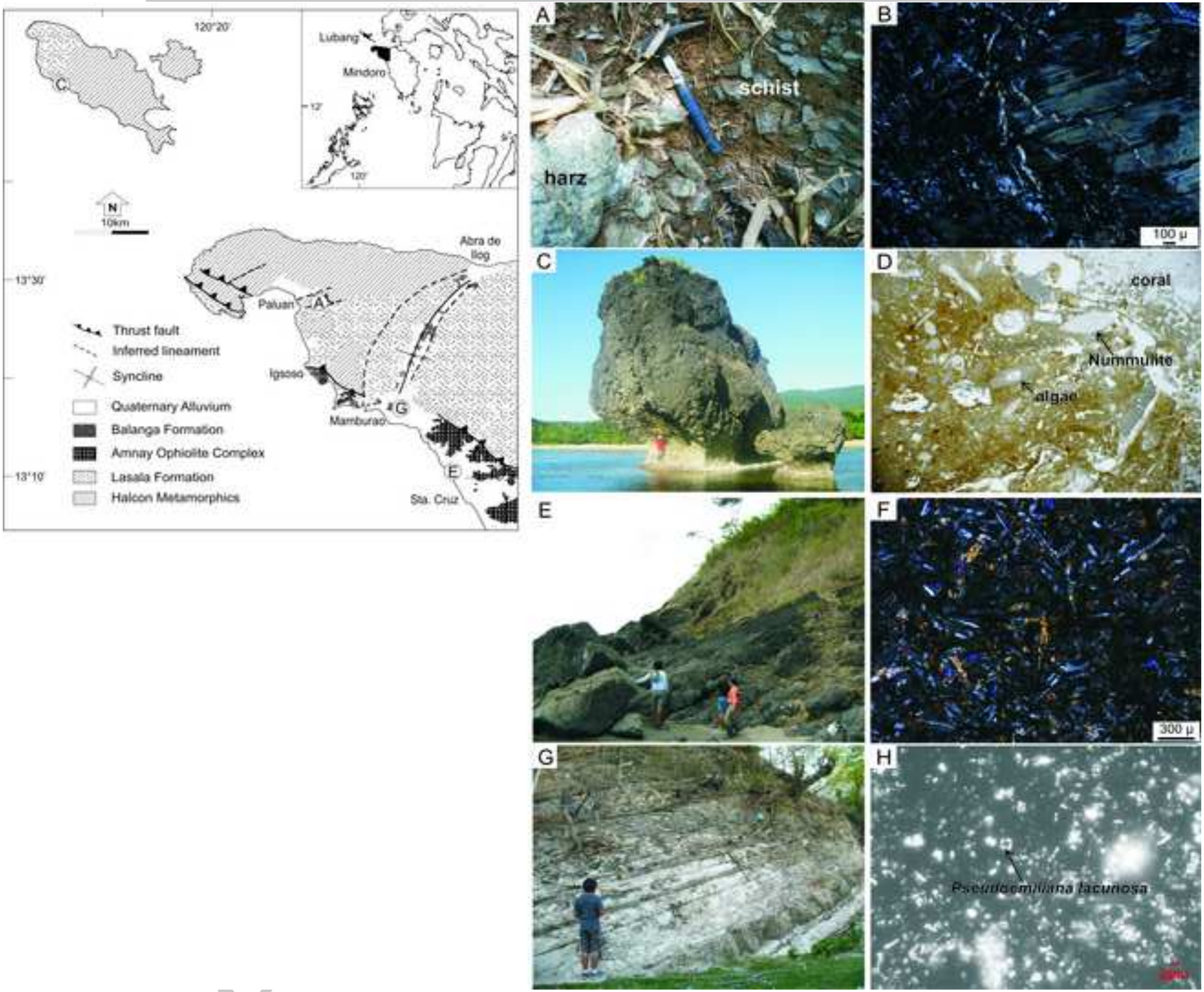

120°20'
Lubang
Mindoro
12'
120'
C
N
10km
Abra de Ilog
13°30'
Paluan
A
Igsoso
Mamburao
G
E
13°10'
Sta. Cruz
Thrust fault
Inferred lineament
Syncline
Quaternary Alluvium
Balanga Formation
Amnay Ophiolite Complex
Lasala Formation
Halcon Metamorphics
A
harz
schist
B
100 µ
C
D
coral
Nummulite
algae
E
F
300 µ
G
H
Pseudoemiliana lacunosa

Figure 6

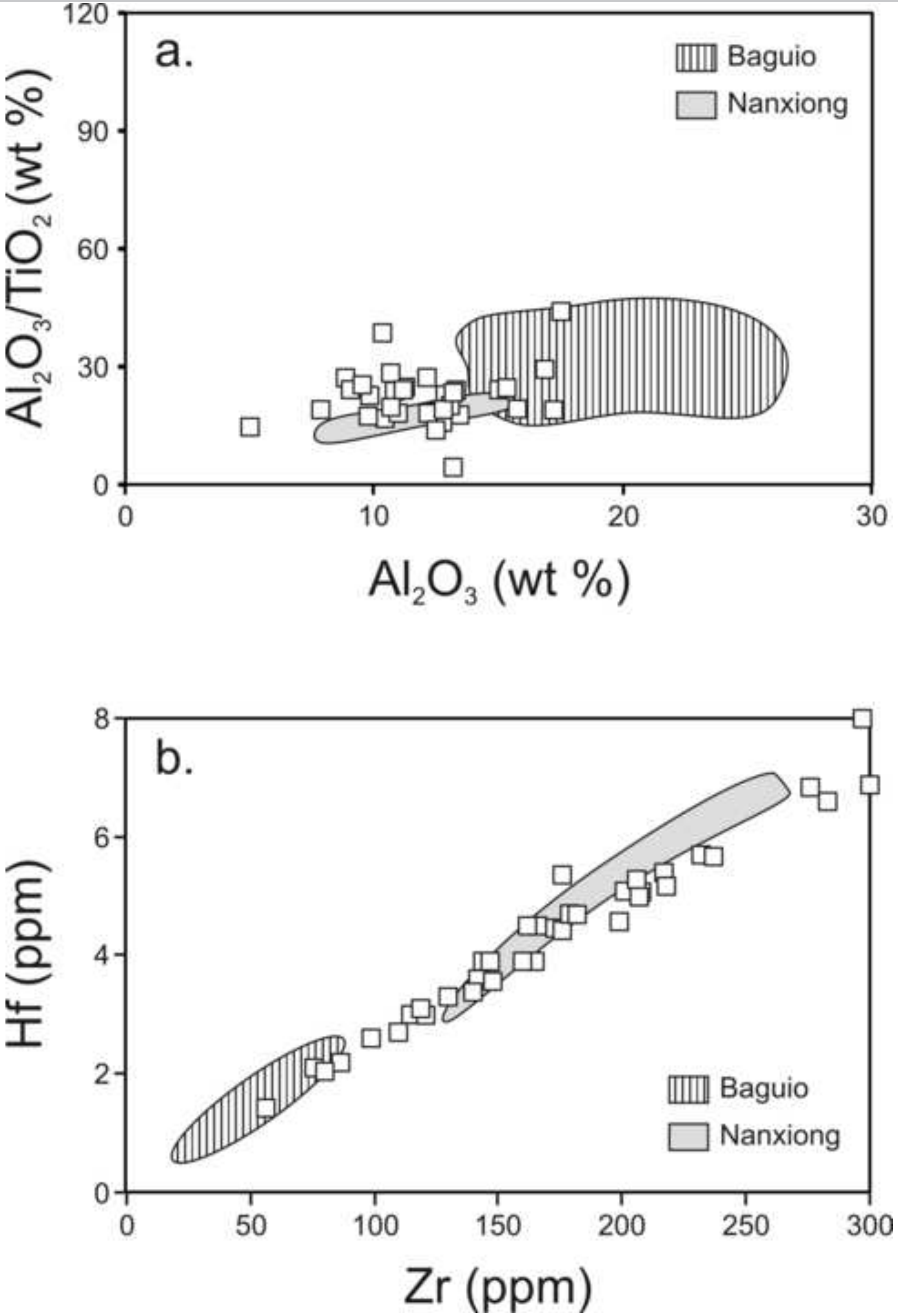
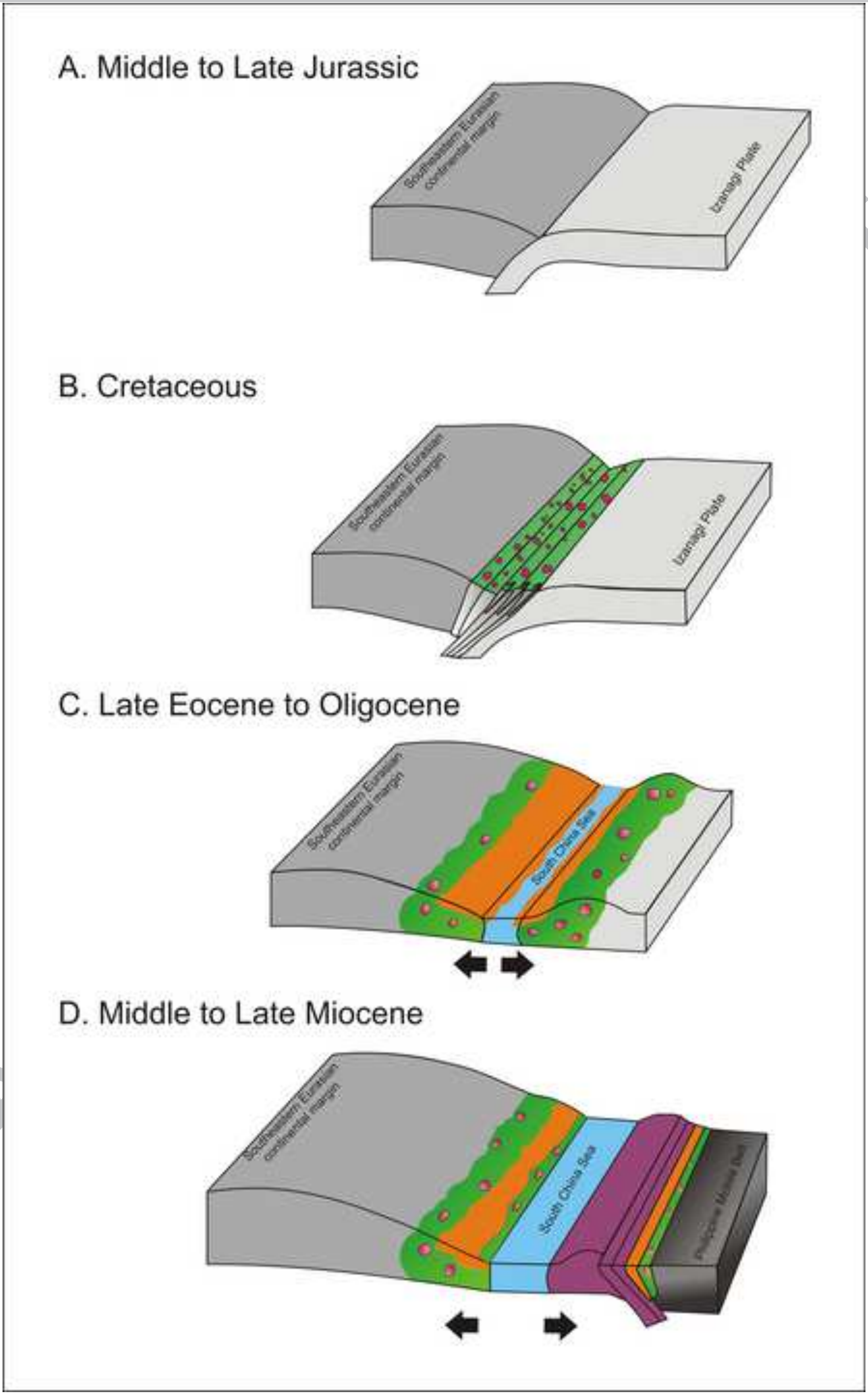

a.
Baguio
Nanxiong
Al_2O_3/TiO_2 (wt %)
0
30
60
90
120
0
10
20
30
Al_2O_3 (wt %)
b.
Hf (ppm)
0
2
4
6
8
0
50
100
150
200
250
300
Zr (ppm)
Baguio
Nanxiong

Figure 7



A. Middle to Late Jurassic

B. Cretaceous

C. Late Eocene to Oligocene

D. Middle to Late Miocene

Table 1

Table 1.

Sample No.	Formation	Assemblage	Age	Paleo-environment	Analyst	References
See reference for details	Lasala	*Pellastispira mirabilis* *Operculina* cf. *saipanensis* *Amphistegina radiate* *Rotalidae sp.* *Spherogypsina sp.*	Late Eocene	shallow marine	A.G.S. Fernando (NIGS)	Faure et al. (1989)
MIN-0513-PAG-02		*Sphenolithus spp.* *Dictyococcites bisectus/ Reticulofenestra bisecta* *Cyclicargolithus floridanus* *Helicosphaera compacta* *Cyclicargolithus* cf. *abisectus*	Late Eocene to Oligocene			Concepcion et al. (2012)
MIN-040408-7A-LF		*Cyclicargolithus floridanus* *Coccolithus pelagicus* *Sphenolithus spp.* *Dictyococcites bisectus/ Reticulofenestra bisecta* *Reticulofenestra umbilica* *Ericsonia formosa* Eocene *Clausicoccus fenestratus* Paleogene	late Middle Eocene to earliest Oligocene			
MIN-0512-MAAL-05		*Cyclicargolithus floridanus* *Dictyococcites bisectus/ Reticulofenestra bisecta* *Sphenolithus* spp.	Late Eocene to Oligocene			

Sample No.	Formation	Assemblage	Age	Paleo-environment	Analyst	References
MIN-0407-DVF-7	Lasala	*Sphenolithus spp.* *Cyclicargolithus floridanus* *Coccolithus pelagicus* *Dictyococcites bisectus/ Reticulofenestra bisecta* *Clausicoccus fenestratus* Paleogene *Ericsonia formosa* Eocene *Reticulofenestra umbilica* *Zygrhablithus bijugatus* Paleogene	late Middle Eocene to earliest Oligocene		A.G.S. Fernando (NIGS)	Concepcion et al. (2012)
MIN-0407-DVF-7		*Globigerina spp.* *Catapsydrax dissimilis* *Globorotalia (T.) increbescens* *Globigerina ampliapertura*	Late Eocene to Early Oligocene	deep marine	MGB	
MIN-LTA 040408-7A		*Globigerina spp.* *Catapsydrax dissimilis* *Globigerina tripartite* *Globigerina angiporoides* *Globigerina* cf. *tapuriensis*	Early Oligocene			
Lubang 08-7A		*Textularia sp.* (bispiral) *Biplanispira?* sp. *Nummulites*? *Amphistegina* Algae, corals, miliolid	Late Eocene	shallow marine	M.M. De Leon (NIGS)	
MIN-LTA 040408-18C	Balanga	*Calcidiscus leptoporus* *Calcidiscus macintyre* *Helicosphaera carteri* *Helicosphaera selli* *Pontosphaera japonica* *Pontosphaera multipora* *Pontosphaera* spp. *Pseudoemiliana lacunosa* *Reticulofenestra* spp. *Scyphosphaera* sp.	Pliocene to Pleistocene	shallow marine	M.M. De Leon (NIGS)	This study