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Onland signatures of the Palawan microcontinental block and Philippine mobile belt collision and crustal growth process: A review

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ABSTRACT

The collision of the Palawan microcontinental block with the Philippine mobile belt had significantly influenced the geological evolution of the Philippines. Multiple collisions involving several fragments, through space and time, resulted into the collage of terranes of varying origin exposed in this part of central Philippines. Cusping of the overriding plate, volcanic arc gap, ophiolite emplacement, incipient back-arc rifting, island rotation and tilting, raised coastal terraces, metamorphism, intrusion of igneous rocks and steepened subducted slab as seen in focal mechanism solutions are some of the manifestations of this collision. A late Early Miocene to early Middle Miocene age (20–16 Ma) is proposed for the major collision between the Palawan indenter and the Philippine mobile belt. The collision boundary is located from the northern part of Mindoro through the central mountain range swinging east of Sibuyan Island in the Romblon Island Group and finally threading along the Buruanga Peninsula and eastern side of the Antique Ophiolite Complex before exiting and connecting with the Negros Trench. The collision, through accretion and crustal thickening, has contributed to the crustal growth of the Philippine archipelago.

Contents

1. Introduction

Crustal growth processes worldwide, as exemplified in the Philippines, can be attributed to arc magmatism, ophiolite emplacement or terrane accretion and suturing generally brought about by collision and strike-slip faulting (e.g. Rudnick, 1995; Condie,

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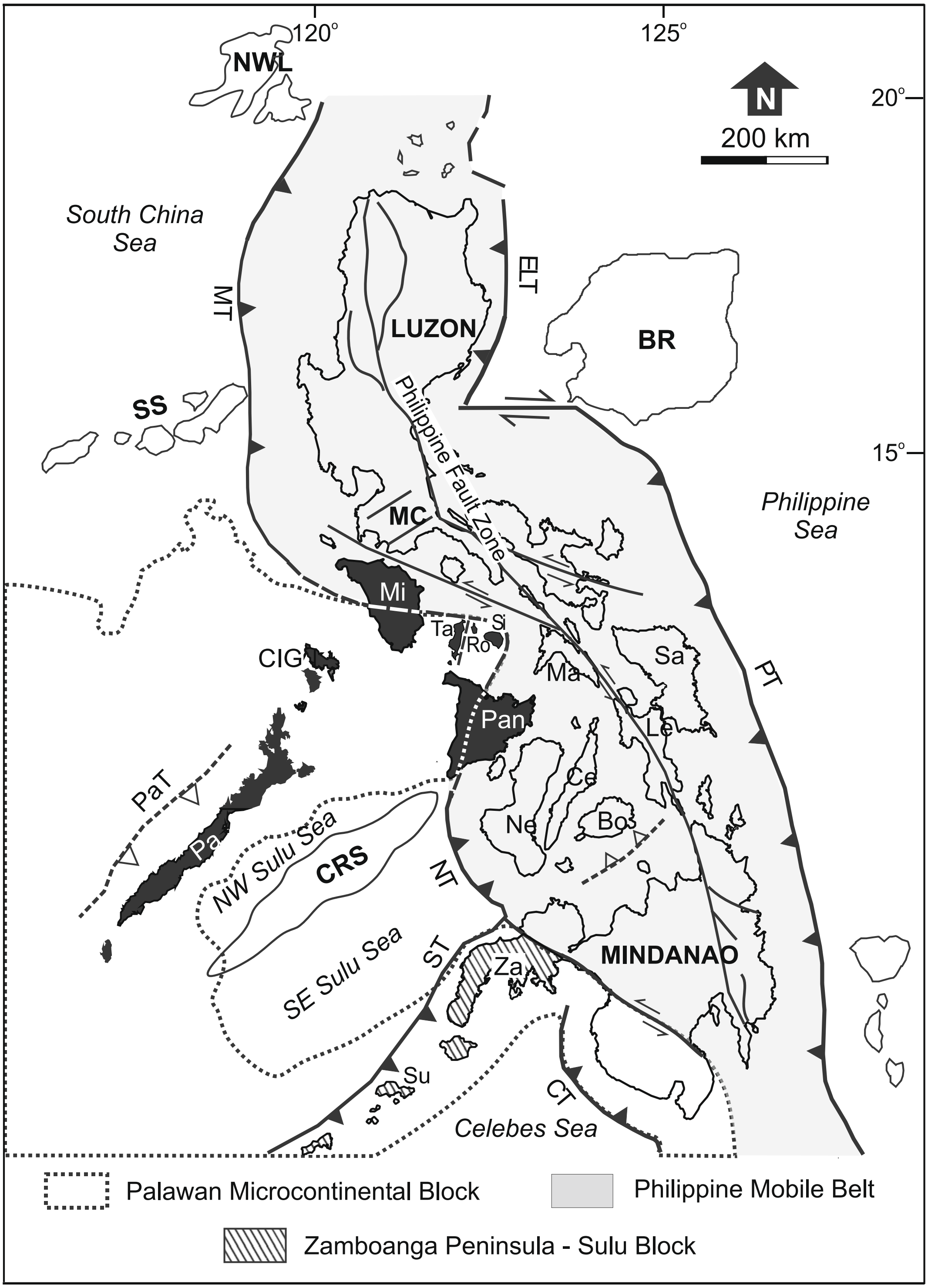

Fig. 1. The Philippine Island arc system is bounded on the western and eastern sides by oppositely-dipping subduction systems. Sandwiched between the subduction systems is a seismically-active zone, the Philippine mobile belt (light gray-shaded region). Features of the collision between the Philippine mobile belt and the Palawan microcontinental block are preserved in Palawan, Mindoro, Romblon Island Group and Panay (islands in black). The Romblon Island Group is made up of three islands: Tablas, Romblon and Sibuyan. The dashed line immediately east of Tablas Island is the Tablas fault. See text for discussion. Legend: NWL = Northwest Luzon oceanic bathymetric high, BR = Benham Rise, SS = Scarborough Seamount; CSR = Cagayan de Sulu Ridge, MT = Manila Trench, ELT = East Luzon Trough, PT = Philippine Trench, PaT = Palawan Trough, NT = Negros Trench, ST = Sulu Trench, CT = Cotabato Trench, Mi = Mindoro, Ta = Tablas, Ro = Romblon, Si = Sibuyan, CIG = Calamian Island Group, Pa = Palawan, Pan = Panay, Ne = Negros, Ma = Masbate, Sa = Samar, Le = Leyte, Ce = Cebu, Bo = Bohol, Za = Zamboanga and Su = Sulu, MC = Macolod Corridor.

1997; Dimalanta and Yumul, 2003; Dimalanta and Yumul, 2004; English and Johnson, 2005; Campbell and Kerr, 2007). The term "crustal growth" is used here to refer to the net increase in volume or mass of juvenile crust through lateral or vertical additions (e.g. Dimalanta et al., 2002; Dimalanta and Yumul, 2006). Arc magmatism has been ascribed to the subduction zones bounding the Philippine Island arc system. On the eastern side, the Philippine Sea plate is consumed along the west-dipping East Luzon Trough –

Philippine Trench. Magmatic arcs on the western side were produced by subduction along east-dipping trenches. These include the Manila Trench along which the east subbasin of the South China Sea plate subducts. The southeast subbasin of the Sulu Sea plate plunges along the east-dipping Negros Trench and the southeast dipping Sulu Trench. The Celebes basin plate goes down along the northeast-dipping Cotabato Trench (e.g. Balce et al., 1976; Rangin et al., 1999). Any stress brought about by the interaction of the subducting and overriding plates that are not absorbed by the subduction zones is taken up by a major left-lateral strike-slip fault zone, the Philippine fault zone, that cuts the whole Philippine archipelago (e.g. Yumul et al., 2008 and references therein) (Fig. 1). Consistent with what is observed in island–continental arc systems surrounding the Western Pacific region (e.g. Kirillova, 2003; Xenophontos and Osozawa, 2004; Arai et al., 2007), the Philippines is also made up of terranes of oceanic, continental and ophiolite derivations (e.g. Andal et al., 2005; Faustino et al., 2006; Queaño et al., 2008).

The Philippines is surrounded by oceanic basins containing several oceanic bathymetric highs that have started or are about to interact with the archipelago (Fig. 1). Along the eastern side, the Benham Rise, an oceanic plateau (e.g. Barrier et al., 1991; Hickey-Vargas, 1998; Savov et al., 2006), is about to reach the East Luzon Trough which will ultimately result into geologic and structural deformations in this part of northern Luzon. Offshore eastern Mindanao, there is a chain of small oceanic bathymetric highs revealed by available bathymetric maps that is about to reach the Philippine Trench (Sandwell and Smith, 1997). West of the archipelago, the Northwest Luzon oceanic bathymetric high is responsible for the observed cusping of the Manila Trench between southern Taiwan and northwest Luzon (Bautista et al., 2001). The Zamboanga Peninsula–Sulu block has collided with Central Mindanao (e.g. Yumul et al., 2004). A major oceanic bathymetric high-related collision that had affected the geologic evolution of the Philippines is the collision of the Palawan microcontinental block with the Philippine mobile belt. As a consequence, the Philippine archipelago is considered to be made up of two major geological blocks: a seismically-active block (Philippine mobile belt) and an aseismic block (Palawan microcontinental block) (e.g. Santos-Yñigo, 1949; Gervasio, 1966) (Fig. 1). The collision between the Palawan microcontinental block indenter and the Philippine mobile belt is an excellent example of the collision of a continental margin with an oceanic island arc. This arc-continent collision, as will be shown later, has contributed significantly to the concentration of existing crusts and ultimately crustal growth in the Philippines. In addition, the event can explain some of the features that have been recognized and mapped recently in the Philippines. Such recognition provides crucial information for further understanding the geological features observed not only in the Philippines, but in other areas of arc-continent collision (e.g. Aitchison et al., 1995; Huang et al., 1995; Byrne and Liu, 2002; Brown et al., 2006; Vos et al., 2007).

2. Geologic outline

The geologic outline of four areas (Palawan–Calamian Island Group, Mindoro, Romblon Island Group and western Panay), as presented, will highlight the recognized collision-related features in these localities.

2.1. Palawan–Calamian Island Group

The main Palawan Island is NE–SW trending and is made up of two blocks: northern Palawan block made up of continent-derived sedimentary and metamorphic rocks and the southern Palawan block made up of oceanic-derived rock formations, as exemplified by the Palawan Ophiolite Complex (e.g. United Nations Development Programme, 1985; Mitchell et al., 1986) (Fig. 2a). The oldest reported sequence in the Philippines, consisting of Upper Paleozoic to Mesozoic chert, clastic rocks and carbonates, is found in the northernmost tip of Palawan Island and in the Calamian Island Group (Fig. 2a). The continent-derived sediments in northern Palawan are made up of quartz-rich sandstones, pebbly mudstones, turbidites and mudstones (Sales et al., 1997; Suzuki et al., 2001; Zamoras and Matsuoka, 2001) (Fig. 2b). Paleontological dating revealed a Late Cretaceous to Eocene age for this sedimentary succession (Suzuki et al., 2000). Point counting of medium- to coarse-grained sandstone samples shows that the sedimentary rocks consist mostly of 46–50 modal % quartz, 6.5–11 modal % feldspar (plagioclase > K-feldspar) and abundant acidic volcanic rock fragments (Suzuki et al., 2000) (Fig. 2c). When plotted on the QFL diagram showing the provenance fields (Dickinson et al., 1983), the samples plot mostly in the recycled orogen field (Suzuki et al., 2000, 2001) (Fig. 3). The Palawan sandstones exhibit SiO_2 values ranging from 73% to 81% and $Fe_2O_3 + MgO$ values varying from 1.51 to 2.96. Results of whole rock geochemical analyses are consistent with the results of petrographic analyses which show that the rocks were possibly sourced from the southern margin of the Asian continental block (Suzuki et al., 2000).

Metamorphic rocks that make up the northern Palawan block are composed of schists, phyllites, quartzites and slates (United Nations Development Programme, 1985). The protoliths of these metamorphic rocks are sandstones, mudstones and, in some cases, conglomerates. Based on mineral assemblage and illite crystallinity values of 0.24–0.40 expressed in $\Delta 2\Theta$ data, these rocks have undergone moderately high-pressure, low-temperature, medium-grade metamorphism (Suzuki et al., 1998, 2000). Isotopic datings of amphibolite and kyanite–chlorite–muscovite schist comprising the metamorphic sole of the Palawan Ophiolite Complex converge at an isochron age of 34 Ma (^{39}Ar–^{40}Ar dating of hornblende from amphibolite and muscovite from schist) (Encarnación et al., 1995). This metamorphic event is ascribed to subduction during the southward migration of the rifted continental fragment from south China (e.g. Holloway, 1982; Clift et al., 2008; Hall et al., 2008).

The Palawan Ophiolite Complex, as exposed in the south, has been assigned a Late Cretaceous to Eocene age of formation based on the radiolarians extracted from the chert (Raschka et al., 1985). The volcanic rocks include boninites; the mantle complex is dominated by harzburgites characterized by spinel having Cr# (Cr/Cr + Al) of 0.50–0.75 (e.g. Claveria and Fischer, 1991). The Palawan Ophiolite Complex, a supra-subduction zone ophiolite, has undergone a relatively high degree of partial melting. Published works on Palawan had concluded that the Capoas Granite is another manifestation of the continental setting of Palawan (Bureau of Mines and Geosciences, 1981) (Fig. 2a). The assumption here is that the Capoas Granite is old and at least Cretaceous in age similar to its surrounding rocks. Work done by Encarnación and Mukasa (1997) had shown, through U-Pb dating of monazite, that the Capoas Granite formed at 13.4 Ma. They attributed its formation to a post-rifting, non-collisional setting with the magmatism possibly related to the heating of the Palawan lithosphere. The intrusion occurred after the reported rifting (37–16 Ma) of the South China Sea (Taylor and Hayes, 1980; Taylor and Hayes, 1983; Briais et al., 1993; Barckhausen and Roeser, 2004; Hsu et al., 2004). Paleomagnetic studies and comparison of lithological data suggest that the Palawan Block originated from the southern border of mainland Asia and has undergone clockwise rotation during the opening of the South China Sea (Almasco et al., 2000; Suzuki et al., 2000).

Northeast of Palawan Island is a group of small islands that belong to the Calamian Island Group (CIG). Fieldwork in one of the islands, Busuanga, showed that it consists of accreted limestones

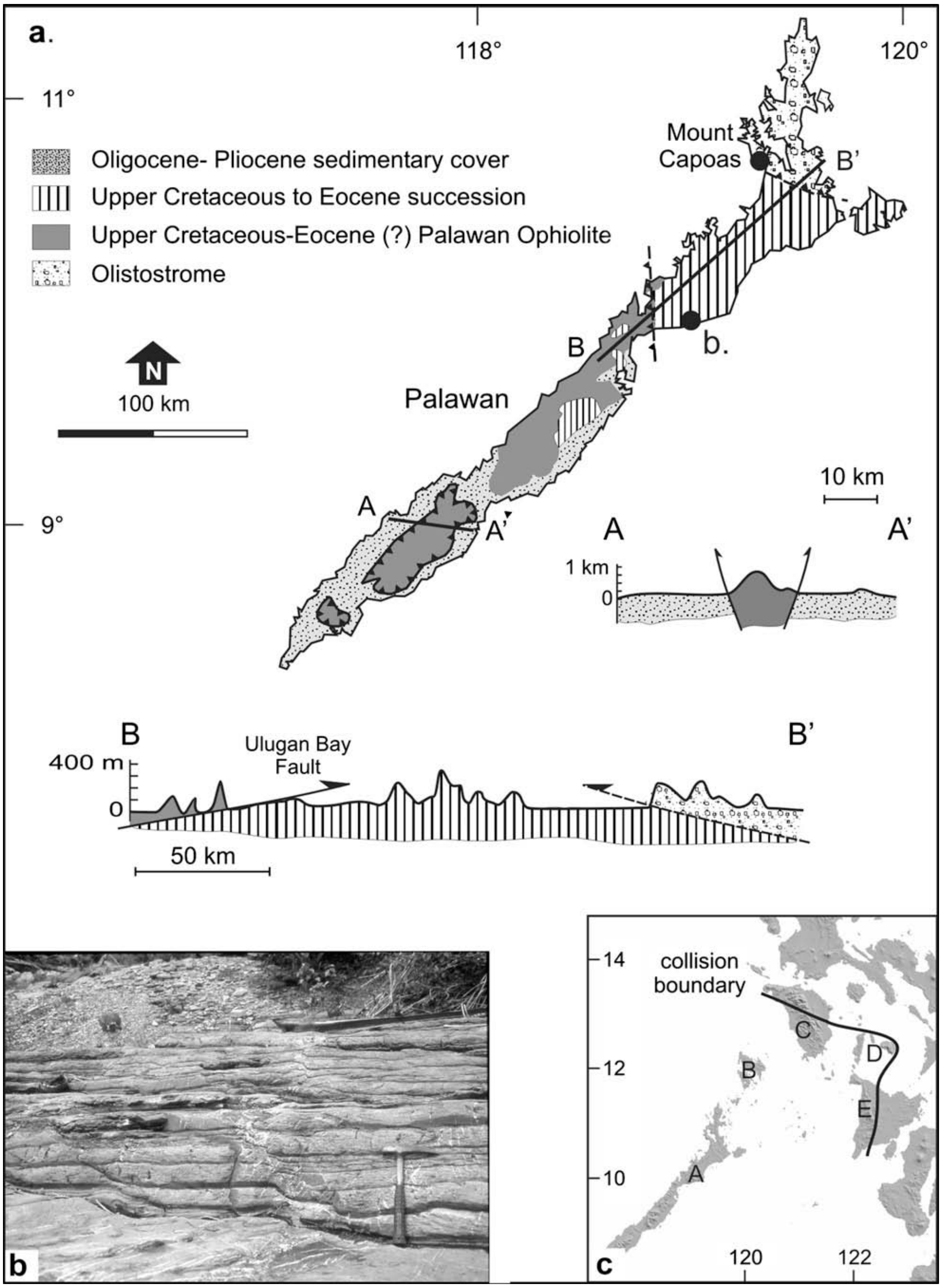

Fig. 2. (a) Geologic map and geologic cross sections of Palawan Island which can be divided into two blocks: the northern block is made up of continent-derived sedimentary and metamorphic rocks and the southern block is underlain by a complete Ophiolite sequence. The boundary between the two blocks is defined by the Ulugan Bay fault (dashed line). Map and cross section modified from Suzuki et al. (2000). Stratigraphy and formational names are from Aurelio and Peña (2002). (b) Photo of Palawan turbidites, which form part of the Upper Cretaceous to Eocene succession, as seen in Honda Bay. Photo courtesy of S. Suzuki (location of the outcrop is shown in a, marked by black circle and labelled b). (c) The collision boundary in Central Philippines (solid black line) goes from western Mindoro to east of the Romblon Island Group then east of the Antique Range in Panay Island. A = Palawan, B = Calamian Island Group, C = Mindoro (Fig. 4), D = Romblon Island Group (Fig. 5) and E = Panay (Fig. 7).

and cherts intercalated with trench-fill clastic sedimentary rocks. These exposures correspond to an accretionary prism and define an oceanic plate stratigraphy (e.g. Wakita and Metcalfe, 2005). Early studies showed that the sedimentary rocks in the Calamian Island Group range from Middle Permian to Jurassic in age (e.g. Tumanda 1991, 1994; Yeh and Cheng, 1996). Zamoras and Matsuoka (2004) had recently worked on the chert, clastic and limestone sequences in Busuanga and established an age range of Middle Jurassic to Early Cretaceous. Work by Marquez et al. (2006) showed that pelagic deposition in Busuanga and surrounding islands took place over a long period (~100 MY). For that matter, a younger equivalent of this accretionary prism is the Upper Cretaceous–Eocene Rajang Group and the overlying Eocene to Lower Miocene Crocker Formation in Northern Borneo (Hutchison, 1989; Hutchison et al., 2000; Balaguru and Nichols, 2004; Clift et al., 2008). The Crocker Formation is made up of turbidites and mudstones and is believed to have been deposited during the early stages of the India–Asia collision (Hall et al., 2008).

The evolution of the Palawan microcontinental block is associated with the Andean subduction along the Asian continental margin that occurred during the Cretaceous which resulted into volcanism (Jahn et al., 1976; Yumul, 1994). This was followed by

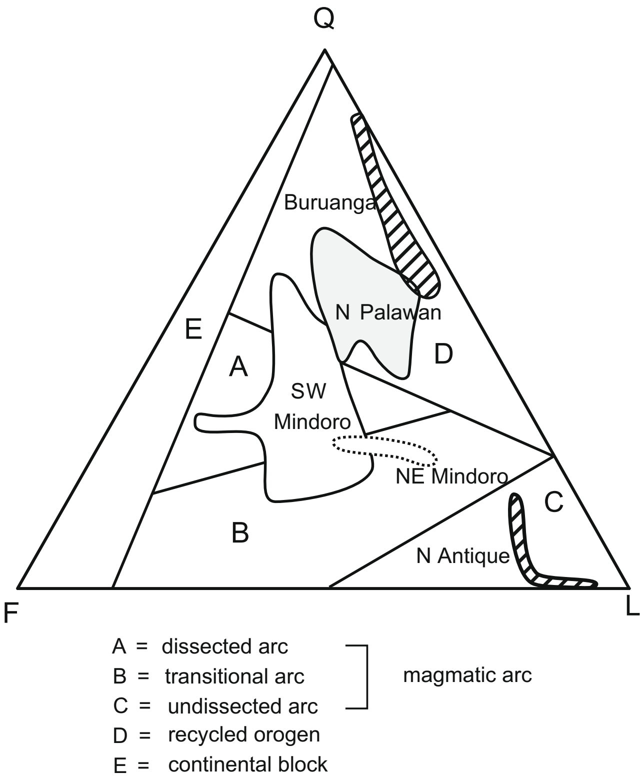

Fig. 3. Sandstone samples from northeast and southwest Mindoro, North Palawan, Buruanga and northern Antique are plotted on the QFL diagram (Dickinson et al., 1983). Palawan data from Suzuki et al. (2001); northeast and southwest Mindoro data from Sarewitz and Karig (1986a) and Panay (Buruanga and North Antique) samples from Dimalanta et al. (2007) (unpublished data).

rifting and drifting of Palawan southward. As a consequence, the South China Sea opened up during the Late Eocene to Early Miocene (37–16 Ma) period (Hsu et al., 2004) involving a more expanded duration compared to what had previously been suggested (32–16 Ma) (e.g. Taylor and Hayes, 1983; Briais et al., 1993). The southward migrating Palawan microcontinental block ultimately collided with the northwestward moving Philippine mobile belt (Yumul et al., 2003a, 2007). The emplacement of the Cretaceous Palawan Ophiolite Complex during the Oligocene and the Mesozoic accretion of the Middle Jurassic to Early Cretaceous accretionary complex deposits along the southern margin of mainland Asia bear witness to ancient subduction events that Palawan had experienced even before it collided with the Philippine mobile belt.

2.2. Mindoro Island

Some investigators have mapped Mindoro Island as part of the Palawan microcontinental block (e.g. Bird et al., 1993). Others, however, believed that it is only the southwest microcontinental portion which can be associated with Palawan (Karig, 1983; Sarewitz and Karig, 1986a). Mindoro is made up of two blocks: the northeast block which has island arc, Philippine mobile belt-affinity and the southwest block which has Palawan microcontinental block characteristics. Sedimentary rocks from northeast Mindoro plot in the transitional arc field in the QFL diagram whereas those from the southwest Mindoro area plot from the transitional arc through dissected arc to recycled orogen fields (Fig. 3) (Sarewitz and Karig, 1986a). The location of the boundary between the two blocks varies but can generally be placed in a NW–SE direction following the central mountain range of Mindoro (Fig. 4a). Three Ophiolite belts have been recognized in the island: Eocene Lubang–Puerto Galera, Cretaceous Mangyan and the mid-Oligocene Amnay Ophiolitic Complexes (Fig. 4b and c) (e.g. Hashimoto and Sato, 1968; Rangin et al., 1985; Karig et al., 1986; Jumawan et al., 1998). Mélanges, specifically broken formations, related to strike-slip faulting, were mapped associated with the Lubang-Puerto Galera and Mangyan ophiolitic complexes. The emplacement of the Lubang – Puerto Galera Ophiolitic Complex is believed to be strike-slip fault related (Karig et al., 1986). The presence of an amphibolite sole beneath the ultramafic rock complex of the Mangyan Ophiolitic Complex suggests that it was emplaced right after its generation and could have involved spreading ridge thrusting similar to what has been reported elsewhere (Mitchell, 1985; Boudier et al., 1988; Hacker et al., 1996). The Amnay Ophiolitic Complex is modelled to have been emplaced through scissor-type collision (Rangin et al., 1985; Stephan et al., 1986). The volcanic rocks of the Amnay Ophiolitic Complex exhibit calc-alkaline, sub-alkaline to minor tholeiitic characteristics. Whole rock geochemistry show negative Ti–Nb–Zr anomalies (Fig. 6). The gabbros show a plagioclase – clinopyroxene crystallization order consistent with a mid-ocean ridge setting. The spinel chemistry has a Cr# [Cr/(Cr + Al)] ⩽ 0.60 (Jumawan et al., 1998). These petrographic and geochemical characteristics are consistent with generation in a back-arc basin with minor subduction component similar to those formed in other western Pacific marginal basins (e.g. Hawkins, 2003; Yumul, 2003; Hickey-Vargas, 2005; Pearce and Stern, 2006; Hergt and Woodhead, 2007).

Karig (1983) reported the collision of the Palawan microcontinental block and the Philippine mobile belt to be in southwest Mindoro involving the formation of a subduction-related foreland thrust belt. The collision had terminated by Pliocene time as evidenced by the deposition of the Upper Miocene to Lower Pliocene (11–3 Ma) (Gradstein et al., 2004) Punso Conglomerate on top of the two colliding blocks (Fig. 4) (e.g. Karig, 1983; Sarewitz and Karig, 1986a). Sarewitz and Karig (1986b) later on called upon large-scale transpressional strike-slip faulting as responsible for juxtaposition of the northeast and southwest Mindoro blocks.

Mindoro exposes metamorphic rocks formed through regional events, ophiolite emplacement-related events and ocean floor heating. Marble samples from the Puerto Galera area were assigned a late Paleozoic age based on their Sr isotopic compositions (Knittel and Daniels, 1987) (Table 1). Sarewitz and Karig (1986b) suggest an age older than Late Cretaceous for the metamorphic rocks distributed in central and northern Mindoro based on the age of the overlying units. A 59 Ma age is reported for the amphibolite and garnet amphibolite based on K–Ar dating on hornblende separates (Faure et al., 1989). The age of the metamorphic complex in Mindoro Island ranges from Late Paleozoic to Eocene (Sarewitz and Karig, 1986b; Knittel and Daniels, 1987; Faure et al., 1989). The old age suggests that the metamorphic complex in Mindoro Island represents a terrane accreted during one of the collision events that affected the island (Knittel and Daniels, 1987).

The locations of the collision boundary for Mindoro vary from offshore east Mindoro, through central Mindoro to southwest Mindoro (e.g. Marchadier and Rangin, 1990; Sarewitz and Lewis, 1991). The age of collision ranges from Early to Middle Miocene (e.g. McCabe et al., 1985; Karig et al., 1986; Milsom et al., 2006). The presence of several ophiolites indicates that the island had undergone multiple collisions (Yumul et al., 2003a, 2005a). The occurrence of multiple collisions can explain the seemingly contradictory findings of several workers placing the collision and suture zones in different parts of Mindoro.

2.3. Romblon Island Group

The geology of the three bigger islands of the Romblon Island Group, Tablas, Romblon and Sibuyan, are presented here. Tablas

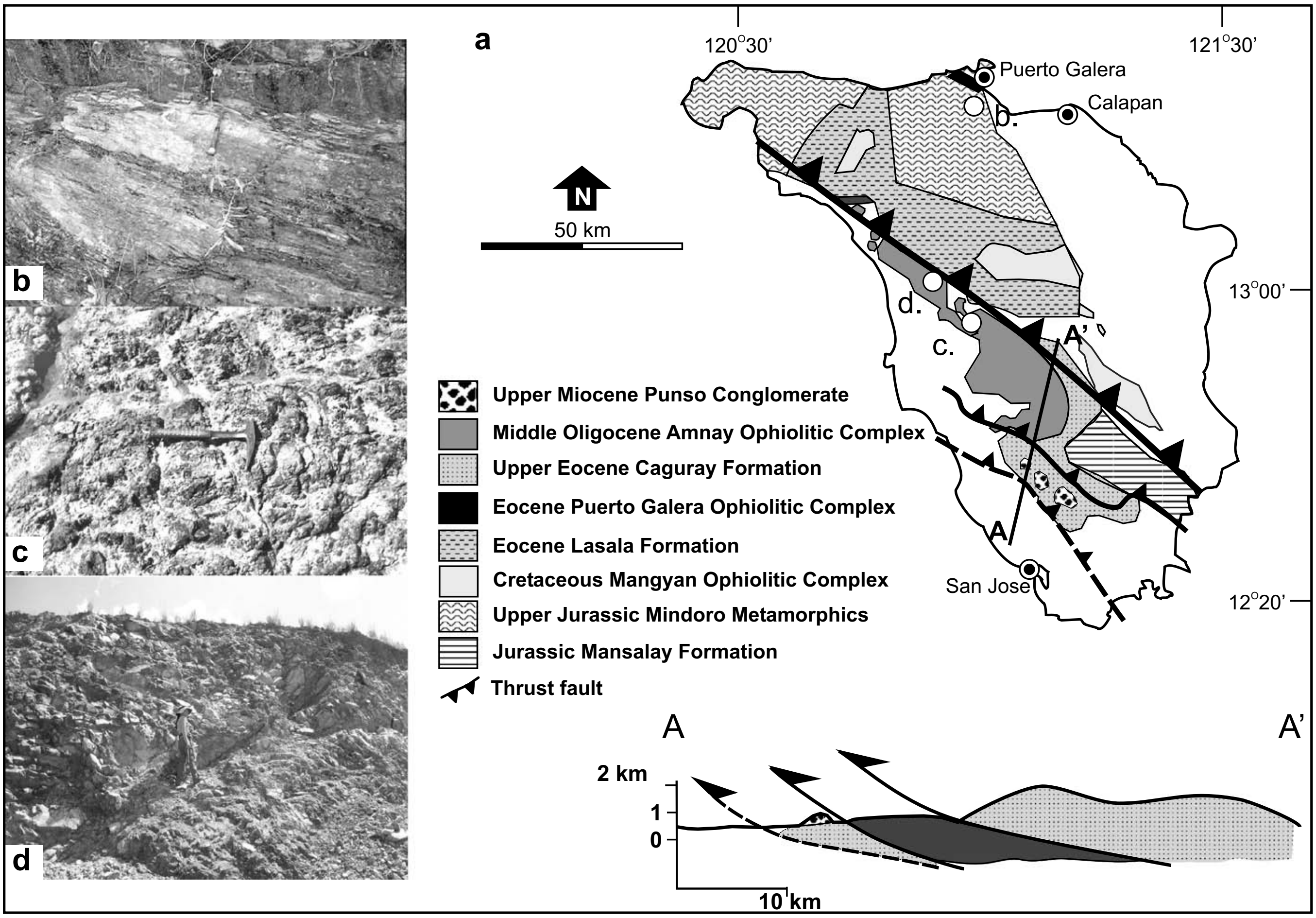

Fig. 4. (a) Mindoro Island is divided into the northeast block (of island arc affinity) and southwest block (of continental affinity) by the Southwest Mindoro Thrust Zone (Sarewitz and Karig, 1986a). Photos show the (b) phyllite exposed in Puerto Galera, northern Mindoro, (c) diabase–gabbro dikes and (d) harzburgite section of the Amnay Ophiolite Complex (locations of the outcrops are shown as open circles on the map). Geologic map and cross section modified from Jumawan et al. (1998) and Sarewitz and Karig (1986a).

consists of gabbro and peridotite units of an ophiolite suite (Sibuyan Ophiolite Complex), intrusive and volcanic rocks, schists and Early Miocene to Pleistocene sedimentary sequences. Romblon is made up almost wholly of schists and marbles with limited exposures of Pleistocene sedimentary units along the southern coastline of the island. Sibuyan is made up of a metamorphic complex and the Sibuyan Ophiolite Complex (Faure et al., 1989) (Fig. 5a). The metamorphic complex includes quartz mica schist, chlorite schist, talc–chlorite schist and isolated outcrops of phyllite (Fig. 5b). Protoliths of the quartz-mica schist range from quartz-rich sandstone through granite to rhyolite which is indicative of continent derivation (Fig. 5c). The relatively flat multi-element patterns (normalized to the primitive mantle values of Sun and McDonough, 1989) with slight negative Nb–Zr–Ti anomalies displayed by the volcanic rock-derived metamorphic rocks suggest a dominant mid-ocean ridge affinity with slight subduction influence (Fig. 6a) (Dimalanta et al., 2006). Petrographic analyses suggest that the metamorphic rocks have undergone medium-grade metamorphism (Faure et al., 1989; S. Suzuki, pers. comm.). The Sibuyan ophiolite Complex, on the other hand, is made up of harzburgites and dunites, pyroxenites, layered and isotropic gabbros, diabase dike swarms and basaltic-andesitic pillow lavas and flow deposits. East-verging, west-dipping thrust faults define the boundary of the ophiolite with its surrounding rocks. The linear gravity and magnetic anomalies correspond to the normal and thrust faults mapped in Sibuyan, as well as in Tablas and Romblon. Modeling of gravity and magnetic anomalies show that units of the ophiolite are emplaced as tectonic slices bound by normal and thrust faults (Dimalanta et al., 2006). Mantle tomography images beneath Central Philippines reveal the presence of hot regions down to depths of 200 km (Besana et al., 1997; Ramos et al., 2005). The hot regions are attributed to the slow convergence between the Palawan microcontinental block and the Philippine mobile belt which provides the high temperatures that keep the subducting slab in a molten or plastic state. This can account for the absence of a subducting slab in the tomography images as well as the absence of deep seismic activity in this region (Ramos et al., 2005).

The volcanic rocks of the Sibuyan Ophiolite Complex are tholeiitic and exhibit back-arc affinity with associated subduction signature (i.e. negative Ti, Zr and Nb anomalies) (Dimalanta et al., 2006) (Fig. 6b). The Sibuyan Ophiolite Complex was emplaced through backthrusting during late Early Miocene. Late Early Miocene (20–18 Ma) volcanic rocks intrude this ophiolitic complex (Table 1) (Bellon and Rangin, 1991). The emplacement is believed to be a consequence of the collision between the Palawan microcontinental block and the Philippine mobile belt. The metamorphic rocks in the Romblon Island Group are also believed to be related to the collision event. Isotopic ages obtained recently for a quartz mica schist and mica schist from Tablas and Romblon, respectively, both yielded whole rock K–Ar ages of 12 Ma (analyst: H. Bellon; Table 1) (Yumul et al., 2005b). Other workers believed that the collision extended all the way to Middle Miocene (e.g. McCabe et al., 1982;

Table 1
Ages of metamorphic rocks, overlap sediments, volcanic rocks and emplacement of Ophiolite Complexes in Palawan, Mindoro, Romblon Island Group and Panay.

Lithologic unit	Location	Age (Ma)	Methodology	Interpretation	References
Metamorphic rocks					
Kyanite–chlorite–muscovite schist	Central Palawan	Late Eocene (34.3 ± 0.2)	^{39}Ar-^{40}Ar isotopic dating	Age of regional metamorphism	Encarnación et al. (1995)
Phyllite, schist, gneiss	Northern Mindoro	Pre-late Cretaceous	Age of overlying units	Age of regional metamorphism	Sarewitz and Karig (1986a)
Marble	Northern Mindoro	Late Paleozoic	^{87}Sr/^{86}Sr isotopic dating	Age of regional metamorphism	Knittel and Daniels (1987)
Amphibolite and garnet amphibolite	Mindoro	Middle Paleocene (59)	^{40}K–^{40}Ar of hornblende	Age of formation	Faure et al. (1989)
Overlap sediments					
Punso conglomerate	Southwest Mindoro	Late Miocene to early Pliocene	Planktonic foraminifera and nanofossil assemblage	Sediments on top of the collided North Palawan block and Philippine mobile belt as exposed in Mindoro; age signifies suturing of the two blocks	Karig (1983), Marchadier and Rangin (1990)
Binoog formation	Tablas Island	Early to middle Miocene	Planktonic foraminiferal assemblage	Sediments on top of the collided North Palawan Block and Philippine mobile belt as exposed in tables; age signifies suturing of the two blocks	Maac and Ylade (1988)
Fragante formation	Northern Antique range	Middle Miocene	Foraminiferal assemblage in the limestone unit (Analyst: M. De Leon)	Sediments on top of the Buruanga Peninsula and Antique Range; age signifies suturing of the two blocks	Zamoras et al. (in press)
Age of emplacement					
Palawan Ophiolite Complex	Palawan	Late Eocene (34 ± 0.6)	^{39}Ar–^{40}Ar isotopic dating	Age of Ophiolite obduction	Encarnación et al. (1995)
Lubang-Puerto Galera Ophiolitic Complex	Mindoro	Oligocene	Regional correlation	Regional correlation with the Zambales Ophiolite complex in western Luzon suggests this age of emplacement	Karig (1983), Yumul (2007)
Mangyan Ophiolitic complex	Mindoro	Late oligocene	Regional correlation	Regional correlation shows the Ophiolite to have been emplaced by this time	Hashimoto and Sato (1968), Yumul et al. (1997)
Amnay Ophiolitic complex	Mindoro	Early middle Miocene	Paleontological dating of sediments	Age of youngest sediments involved in thrusting and folding related to obduction of Ophiolite	Rangin et al. (1985)
Sibuyan Ophiolite Complex	Tablas	Pre-late early Miocene	Intrusion of the Ophiolite by the tablas volcanics (19.9–18.0)	Syn-collision magmatism; signifies that the ophiolite had already been formed/emplaced by early Miocene	Bellon and Rangin (1991)
Antique Ophiolite Complex	Antique	Middle to late Miocene	Paleontological dating of sedimentary deposits	Ophiolite clasts included in the sedimentary deposits signify the Ophiolite has been emplaced, exposed and eroded	Rangin et al. (1991)
Volcanism					
Granite	Northern Palawan	Middle Miocene (13.4)	^{207}Pb/^{235}U dating (monazite from granite)	South China Sea post-rift magmatism	Encarnación and Mukasa (1997)
Andesite, rhyolite	Tablas Island	Late early Miocene (19.9–18)	Whole rock ^{40}K–^{40}Ar isotopic dating	Syn-collision magmatism	Bellon and Rangin (1991)
Quartz diorite	Buruanga Peninsula, Northwest Panay	Late early Miocene (19.5)	Whole rock ^{40}K-^{40}Ar isotopic dating	Syn-collision magmatism	Bellon and Rangin (1991)

Queaño et al., 2007). Furthermore, petrographic and geochemical evidence show that the metamorphic complex is derived from continental materials. Unconformably overlying the older units in the Romblon Island Group is the Binoog Formation. This was dated Early to Middle Miocene based on the foraminiferal assemblage in the carbonate and clastic units (e.g. Maac and Ylade, 1988) (Table 1). These are all consistent with the model that the collision boundary between the Palawan microcontinental block and the Philippine mobile belt is offshore east of Sibuyan. The reported age of magmatic activities (whole rock K–Ar isotopic dating: 20–18 Ma) (Bellon and Rangin, 1991), metamorphic events (whole rock K–Ar isotopic dating: analyst: H. Bellon; 12 Ma) (Yumul et al., 2005b; Dimalanta et al., 2006), field geological data (Faure et al., 1989) and available geophysical data (Ramos et al., 2005) support a late early to Early Middle Miocene (20–16 Ma) (Gradstein et al., 2004) age of collision with the collision boundary in the vicinity of eastern offshore Sibuyan.

2.4. Panay Island

Two areas, the Buruanga Peninsula and Antique where the Antique ophiolite is exposed, were studied in Panay Island in relation to the collision (Fig. 7a). Buruanga Peninsula was previously mapped to be made up of a metamorphic complex consisting of greenschist, chert, quartzite, marble and metavolcanics (Francisco, 1956; Bureau of Mines and Geosciences, 1981). Our work on the area, however, reveals a chert–limestone–clastic sequence with the metamorphic rocks limited to the boundary with the sedimentary rocks (Fig. 7b and c). In addition, a quartz diorite body dated 19.5 Ma exposed in Buruanga Peninsula suggests a magmatic activity during the Early Miocene (e.g. Bellon and Rangin, 1991). The chert–limestone–clastic sequence, which defines an ocean plate stratigraphy, is similar and correlative to the rock formation in Busuanga of the Calamian Island Group, Palawan. Jurassic radiolarian assemblage (JR5-JR6, Callovian to Oxfordian) has been rec-

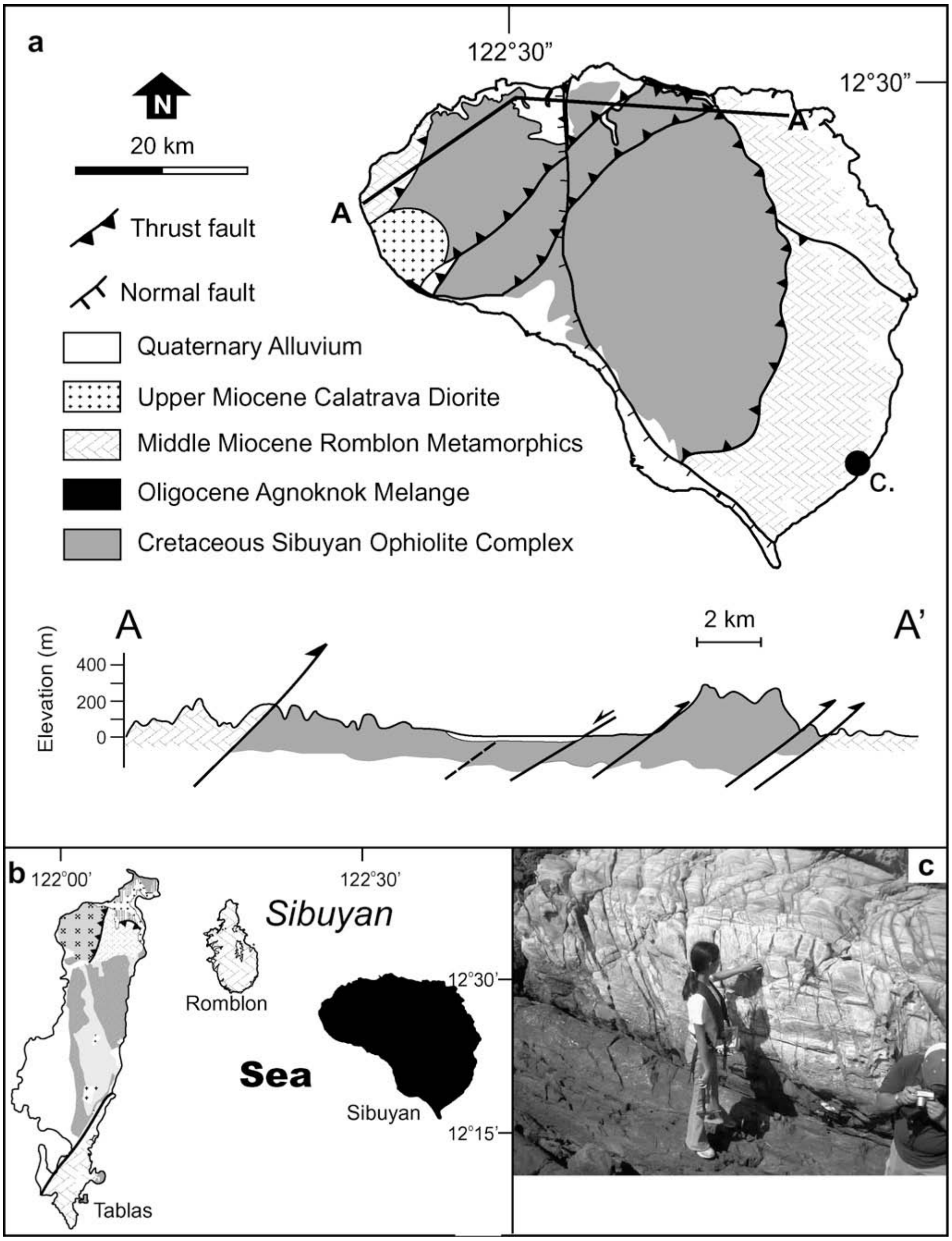

Fig. 5. (a) The boundary of the collision zone is placed further east of Sibuyan Island where units of the Sibuyan Ophiolite Complex are exposed as tectonic slices and thrust against the metamorphic rocks (geologic map and cross section modified from Dimalanta et al., 2006). (b) Geologic map for the Tablas and Romblon Islands which form part of the Romblon Island Group. (c) Photo of a schist outcrop in Sibuyan Island (location of outcrop is shown as a black circle on the Sibuyan geologic map).

ognized for the first time in Buruanga Peninsula (Yumul et al., 2007; Zamoras et al., in press). Aside from a similarity in age, the clastic rocks within the peninsula exhibit characteristics similar to the sedimentary rocks from northern Palawan. The sedimentary rocks in Buruanga Peninsula include quartz-rich sandstones which are characterized by 72–85% SiO_2 and $Fe_2O_3 + MgO$ values ranging from 1.99 to 5.2. On the QFL diagram, both Buruanga Peninsula and Palawan samples occupy the recycled orogen field (Fig. 3).

Units of a complete ophiolite sequence, the Antique Ophiolite Complex, are exposed in the southern Antique Range. These include a serpentinized harzburgite mantle section, layered mafic rocks with thin dunite beds, sheeted dikes, pillow basalts and basaltic sheet flows, red cherts, mudstones and green siltstones (e.g. Tamayo et al., 2001). An Early Cretaceous age (Barremian–Aptian) has been assigned to the ophiolite based on radiolarians found in the chert (Rangin et al., 1991). The ophiolite units are emplaced along northwest-verging thrust faults. The geochemistry of the volcanic rocks shows a transitional geochemical signature between mid-ocean ridge basalt and island arc tholeiite as shown by the negative Nb–Zr–Ti anomalies similar to what is observed among island arc volcanic rocks (e.g. Tatsumi, 2005; Castillo et al., 2007) (Fig. 6b). Tamayo et al. (2001) modeled the emplacement as accretion in a forearc setting that occurred during the Miocene related to the collision between the Palawan microcontinental block and the Philippine mobile belt. The collision of the two blocks is sealed by the deposition of the Middle Miocene Fragante Formation (Table 1). Structural data and initial geophysical evidence suggests that the boundary between the Buruanga

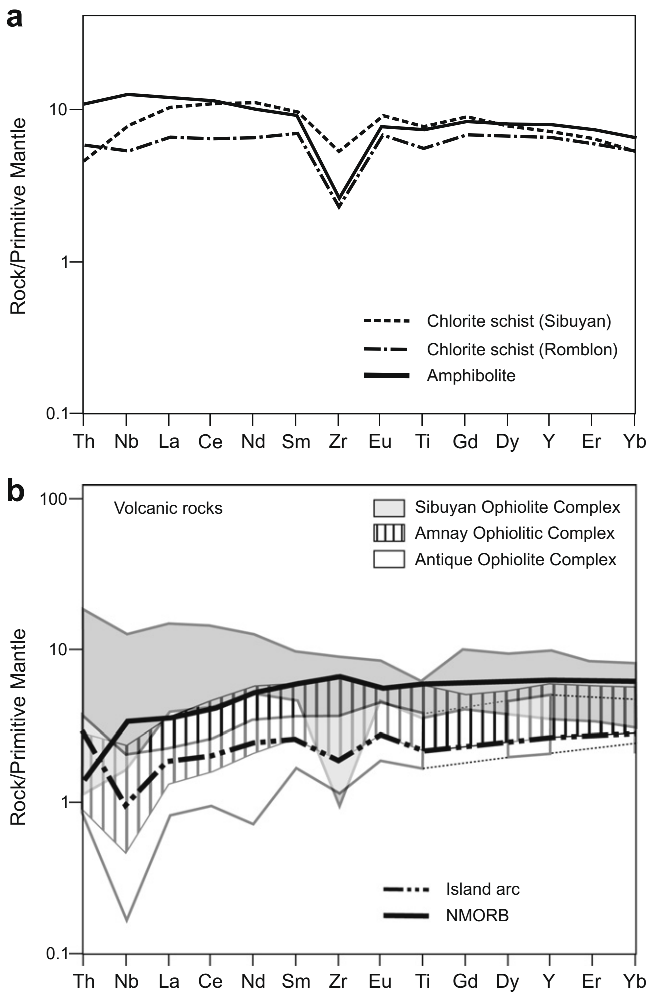

Fig. 6. (a) Multi-element patterns normalized to the Primitive Mantle values of Sun and McDonough (1989) for the chlorite schists and amphibolites from the Romblon Island Group. (b) Multi-element patterns normalized to the Primitive Mantle values of Sun and McDonough (1989) for the volcanic rocks (basalts and diabases) of the Amnay (Mindoro), Antique (Panay) and Sibuyan (Romblon Island Group) Ophiolite Complexes. Amnay data from Jumawan et al. (1998) and Antique data from Tamayo et al. (2001). Patterns for typical island arc and NMORB (Wilson, 1989) rocks are shown for comparison.

Peninsula and the Antique Ophiolite Complex is a thrust fault (Fig. 7a) (Zamoras et al., in press). The sedimentary rocks from Northern Antique when plotted on the QFL diagram show an undissected arc affinity (Fig. 3).

3. Discussion

3.1. Collision and crustal growth signatures

The evidence for the collision of the Palawan microcontinental block and Philippine mobile belt are varied and have been well documented. Cusping of the Philippine mobile belt due to the indentation of the Palawan indenter has been reported (McCabe et al., 1982; McCabe, 1984). Paleomagnetic studies and the morphology and trends of the islands of central Philippines reveal that these islands have rotated (McCabe et al., 1987; Yumul et al., 2000). Mindoro rotated counter-clockwise whereas Panay, Negros, Leyte and Bohol rotated clockwise. As pointed out, the NE-SW trend of these islands is at an angle with the NW–SE trend of Masbate, Leyte and Samar which is believed to be the original orientation of all the islands in central Philippines (Yumul et al., 2000). Other evidence of collision include the steepening of the subducting slab, the presence of a volcanic arc gap due to the cessation of subduction resulting from collision (e.g. Yumul et al., 2003b), and the emplacement of ophiolites, either along the forearc region through thrusting (e.g. Antique Ophiolite Complex, Antique Province), along the back arc region through back thrusting (Sibuyan Ophiolite Complex, Romblon Province) or within the suture zone itself through scissor-type closure (Amnay Ophiolitic Complex, Mindoro Province) (Rangin et al., 1985; Bautista et al., 2001; Tamayo et al., 2001). Sarewitz and Lewis (1991) have also recognized initial rifting within the Sibuyan Sea which they believed will ultimately be oceanized. This rifting within the Sibuyan Sea can be related to the ongoing collision in the area. The rifting of the Macolod Corridor has been attributed by Pubellier et al. (2000) to the ongoing impingement of Palawan with the Philippine mobile belt (Fig. 1). Emergent and submergent features have also been noted in central Philippines which could be attributed to the collision event. Raised terraces mark the coastline along San Jose, southwest Mindoro indicating emergence whereas Calapan, northeast Mindoro experiences coastal subsidence (Fig. 4). This tilting of Mindoro is attributed to the collision. Raised terraces have also been encountered in Tablas, Romblon which can also be related to the ongoing collision.

Lastly, crustal growth and crustal thickening are generally expected from arc-continent collision events (e.g. Rudnick, 1995; Condie, 1997; Dimalanta and Yumul, 2006). Available crustal thickness maps for the Philippines show thickened crust occurs east of Sibuyan Island, from the Bicol region to Masbate and southwestward to Panay Island (Dimalanta and Yumul, 2003, 2004; Wu et al., 2004) (Fig. 8). This is consistent with the model which shows that Sibuyan Island is situated at the leading edge of the indenter block, the Palawan microcontinental block, which is colliding with the Philippine mobile belt. Crustal thickening will be more obvious along the island arc side (Philippine mobile belt) than on the continental side as shown by available laboratory experiments (e.g. Keep, 2000).

3.2. Collision events: questions and answers

A look at the distribution of accretionary prism complexes, emplaced ophiolites and mélange distributions suggest that there were at least five collision and accretion events that occurred in this part of central Philippines. These include: (1) The Permian to Cretaceous accretionary prism composed of chert–limestone–clastic sequence exposed in Busuanga, Calamian Island Group) and Buruanga (Panay Island) which formed when Palawan was still part of mainland Asia; (2) The southward translation of Palawan resulted into its collision with an oceanic fragment derived from the south that was eventually emplaced as the Palawan Ophiolite Complex; (3) Regional correlation studies suggest that the Lubang–Puerto Galera Ophiolite in central Mindoro had been emplaced during the Oligocene; (4) The Cretaceous Mangyan Ophiolitic Complex was emplaced during the Cretaceous-early Tertiary period; and (5) The Palawan microcontinental block and Philippine mobile belt collided during late Early Miocene to early Middle Miocene resulting into the emplacement of the Amnay Ophiolitic Complex, Sibuyan Ophiolite Complex and Antique Ophiolite Complex, among others. The age of metamorphism (middle Miocene), the age of the overlap sediments covering the colliding blocks involved (middle Miocene), the age of the volcanic and intrusive rocks (late Early Miocene) from samples collected from Mindoro, Romblon Island Group and western Panay all support the notion that the collision occurred during the late Early Miocene to early Middle Miocene. The boundary of the collision, based on

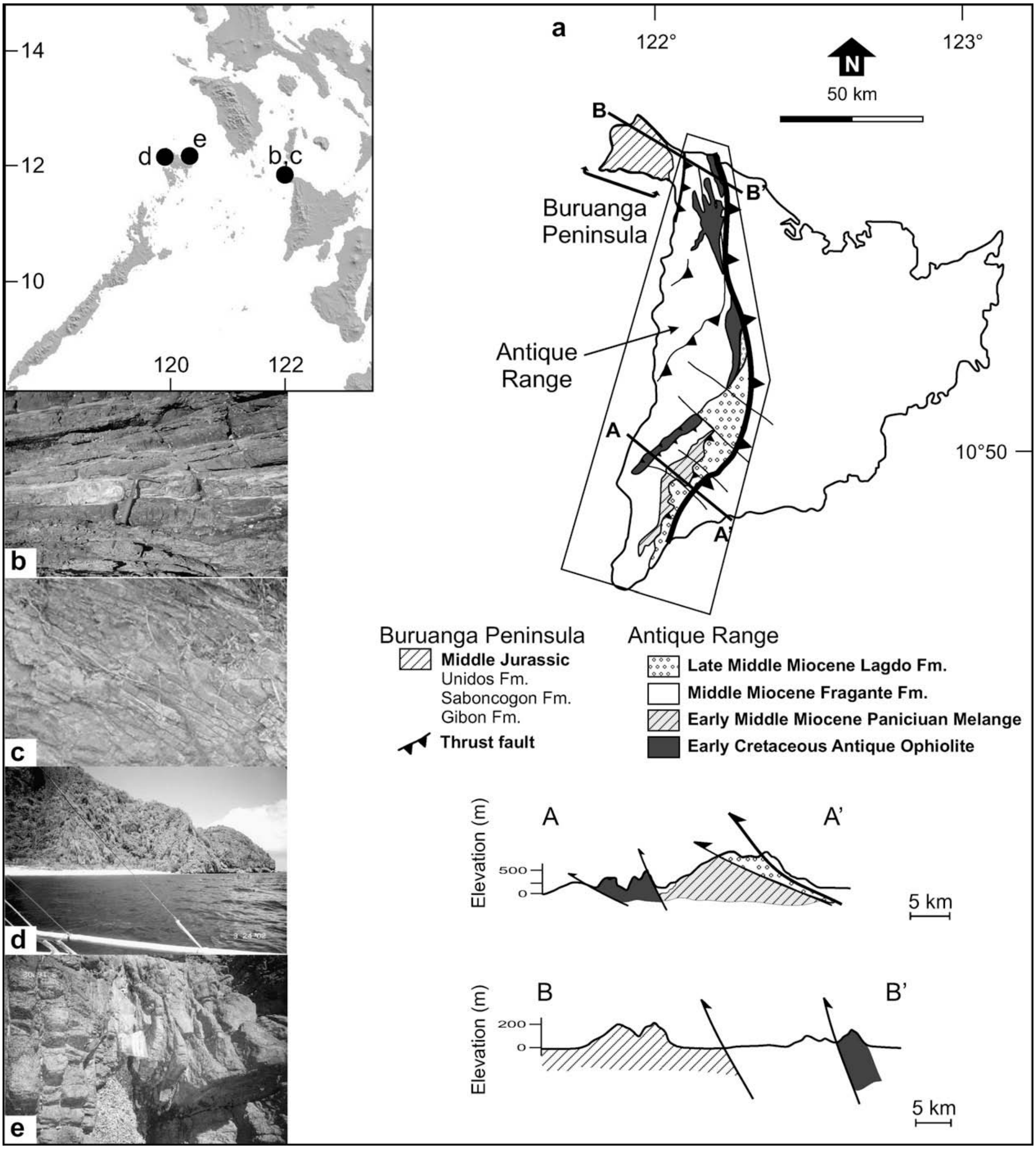

Fig. 7. (a) Two areas investigated in Panay Island related to the collision event are Buruanga Peninsula and Antique. Buruanga Peninsula is dominantly made up of siliceous mudstone, chert and limestone sequence whereas the Antique Range exposes the Antique Ophiolite Complex (geologic map and cross section modified from Tamayo et al., 2001; Zamoras et al., 2008). (b) Siliceous mudstone and (c) chert units that comprise the oceanic plate stratigraphy of Buruanga Peninsula bears a striking similarity to the OPS of the same age in Busuanga Island in the Calamian Island group, Palawan (d) limestone and (e) chert (see Fig. 2c for location of Calamian Island Group). Photos courtesy of E.J. Marquez and L.R. Zamoras. Locations of the outcrops are shown as filled circles in the inset map.

rock exposures and subsurface information, would be from western to central Mindoro to offshore eastern Sibuyan Island and would swing to the south towards Buruanga Peninsula and eastern side of the Antique Ophiolite Complex (Fig. 2d).

Nonetheless, several workers find it difficult to reconcile an Early Miocene collision between the Palawan microcontinental block and the Philippine mobile belt (e.g. Hall, 2002; Queaño et al., 2007). Utilizing the magnetic lineations in the South China Sea and the reported spreading rate, other workers insist that by early Miocene, Palawan would still be far up north and will not be in its present position. Regional modelling and palinspathic reconstruction had resulted into a model that calls upon a middle to Late Miocene and even Pliocene collision between the Palawan indenter and the Philippine mobile belt (e.g. Hall, 2002; Pubellier et al., 2003; Queaño et al., 2007). However, all of these reconstructions are model dependent. Recent models (e.g. Clift et al., 2008) show the Dangerous Grounds and Palawan were in a position quite far south by 20 Ma supporting the preferred late early Miocene collision model of Palawan with the Philippine mobile belt. Clearly, there are still a lot of gaps that need to be filled up if we are to fully understand the evolution which this part of central Philippines has undergone. However, one can look at the possibility that the

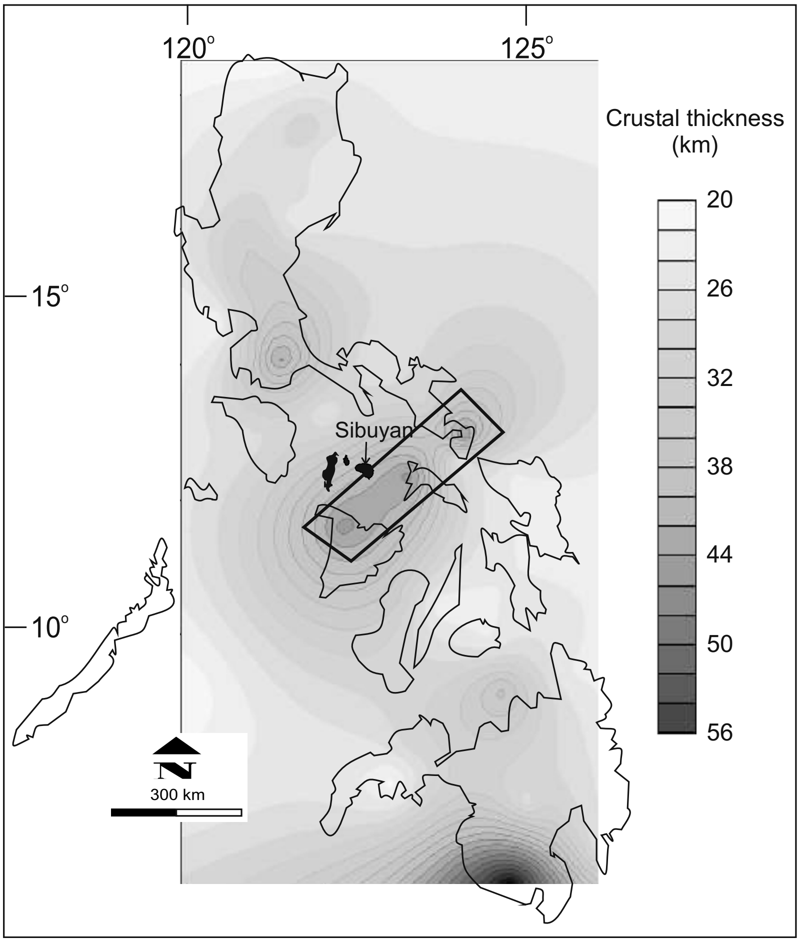

Fig. 8. Crustal thickness map for the Philippines shows a region of thickened crust (enclosed in box) in Central Philippines immediately east of Sibuyan Island.

reported early to middle Miocene and Pliocene collisions are both correct. This can happen if multiple collisions involving several fragments at different time frames occurred similar to what has been mapped in other parts of the world (e.g. Pubellier et al., 2004; Zhou et al., 2007; Malinovsky et al., 2008).

4. Conclusions

Several oceanic bathymetric highs have collided or are about to collide with the Philippine mobile belt. A major collision event that shaped the geologic and tectonic evolution of the Philippines was the collision between the Palawan microcontinental block, the indenter, and the Philippine mobile belt, acting as the upper plate. This major collision zone resulted into net crustal growth for the archipelago. Different collision-related signatures have been noted which reveal how dynamic the collision process could be. A late early Miocene to early middle Miocene age of collision is forwarded. The possibility of several fragments involved in multiple collisions through space and time is not discounted as this can explain some of the contradictions observed in the areas studied.

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