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NEW CONSIDERATION ON THE CRETACEOUS SUBDUCTION ZONE OF CILETUH-LUK ULO-BAYAT-MERATUS: IMPLICATIONS FOR SOUTHEAST SUNDALAND PETROLEUM GEOLOGY

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ABSTRACT

The history of plate convergence in southern and southeastern Sundaland recorded subduction of oceanic plate during Jurassic to Late Cretaceous started from Meratus, Bantimala, Luk Ulo, to Ciletuh. The geochronology of subduction is based on subduction-related high pressure to ultra/very high pressure glaucophane schists and eclogites. Subduction chased in Bantimala and Meratus trenches in mid-Cretaceous due to docking of West Sulawesi and Paternoster-Kangean microcontinents, respectively. During the Late Cretaceous, subduction migrated to Paternoster trench resulting in volcanic and magmatic rocks as well as forearc sediments in Meratus and Bantimala. In Paleogene time, Meratus and Bantimala separated by the opening of the Makassar Straits, sitting on Paternoster and West Sulawesi microcontinents.

Subduction in Ciletuh and Luk Ulo continued into the Late Cretaceous, but possibly with different characters of subduction compared to that of Early Cretaceous due to the absence of Late Cretaceous subduction-related metamorphic rocks. Jiwo Hills, Bayat which has been considered as the continuation of Luk Ulo, is considered not to compose the subduction zone due to the absence of subduction-related rock assemblage. The mid-Cretaceous glaucophane schist of Bayat may relate with docking of SE Java microcontinent in this area. Eocene shallow marine Wungkal-Gamping carbonate shows that Bayat is different with Luk Ulo and Ciletuh which in Eocene were characterized by slope trench olistostromal deposits of Karangsambung and Ciletuh Formations, respectively.

Configuration of plate convergence during the Cretaceous implies petroleum possibilities of southeastern Sundaland related to the presence of some Australian-origin microcontinents. Newly acquired deep seismic data in south offshore East Java, eastern East Java Sea, and South Makassar Straits show the presence of Mesozoic-Paleozoic bedded horizons typical NW Shelf of Australia which are proven to be productive or other proven prolific Australoid microcontinents like Bintuni, Seram, or Buton. Pre-Tertiary petroleum system may develop in southeastern Sundaland.

INTRODUCTION

Sundaland –presently mostly in Western Indonesia, with its western, southern, southeastern and eastern boundaries are present Sumatra, Java, eastern Java Sea-Bone Bay, and western Tomini-Gorontalo Bay, respectively (Satyana, 2010a) have positioned as active margins of plates convergence since the Mesozoic (Figure 1). The boundaries at Sumatra and Java are still accommodating the convergence of plates forming present subduction zone of Sumatra and Java Trenches. Whereas, the southeastern and eastern boundaries of Sundaland are presently no subduction zones due to collision of some terranes in the Late Cretaceous until the Neogene had ceased the subduction of oceanic plates in this area.

Cretaceous (Late Cretaceous) subduction zone of southern and southeastern margins of Sundaland have been recognized since 1970s (Katili, 1972; Asikin, 1974; Hamilton 1979). This Cretaceous subduction zone is defined based on the presences of Cretaceous mélange in Java (Ciletuh, Luk Ulo, Bayat) and Southeast Kalimantan (Meratus-Pulau Laut). Mélange is a mixture of deformed rock fragments and blocks embedded in a matrix formed in subduction trench. Most geologists and publications still believe and use this subduction zone.

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However, the author of this paper doubt that Bayat and Meratus-Pulau Laut compose the subduction zone, continuing Ciletuh and Luk Ulo subduction sites. Field studies in Bayat (Prasetyadi et al., 2002, 2005; Satyana and Prasetyadi, 2013; Satyana, 2013b) show that Bayat has no mélange typical of subduction trench and comparable to Luk Ulo as defined previously (Hamilton, 1979). This indicate that Bayat may not a subduction continuation of Luk Ulo. Meratus-Pulau Laut has ophiolites and few mélanges, but field studies and geophysical data (Satyana and Armandita, 2008) show that the ophiolites exposed in the way different with those of Ciletuh and Luk Ulo (Satyana, 2003; Satyana, 2012). Most of rock fragments and blocks of the Meratus-Pulau Laut mélange are older than those of Ciletuh and Luk Ulo (Wakita et al., 1997; Wakita, 2000). This indicate that Meratus may not a subduction continuation of Luk Ulo.

Basement geology of southeastern Sundaland to the south and east of the Cretaceous subduction zone which was considered as whole oceanic crust (Katili, 1972; Hamilton 1979), now is considered differently based on works of regional tectonics (Budiyani et al., 2003), zircon geochronology at the Southern Mountains of East Java (Smyth et al., 2003; 2005; 2007), deep seismic survey in offshore East Java Sea and South Makassar Strait (Emmet et al., 2009; Granath et al., 2009), and recent seismic survey in offshore eastern Java forearc (Deighton et al., 2011; Nugraha and Hall, 2012). All of these works indicate that microcontinent/s may exist under East Java, East Java Sea and South Makassar Strait.

Another Cretaceous mélange complex are exposed in Bantimala area, South Sulawesi. Based on works of Sukamto (1975a, 1982, 1986), Wakita et al. (1994, 1996), Wakita (2000); Parkinson et al. (1998), and Maulana (2010, 2013) it is known that this complex is different with that of Luk Ulo. The presence of microcontinent in Bantimala subduction complex is indicated, not typical of subduction in Ciletuh and Luk Ulo area although subduction in Luk Ulo and Bantimala may contemporaneous.

Taken into account all these published and unpublished works, it shows that Cretaceous (Late Cretaceous) subduction zone at the southeastern Sundaland is not as simple as previously considered (Katili, 1972; Asikin, 1974; Hamilton, 1979). This paper will propose new paleotectonic reconstruction in the Cretaceous based on recent progress, data, and considerations. The area under discussion is also the area of focusing petroleum exploration. Hence, this study has some implications for petroleum exploration in this area both for existing Tertiary basins (like Barito, East Java, South Makassar, South Sulawesi) and unidentified pre-Tertiary basins underlying the Tertiary basins in East Java forearc, East Java Sea, and South Makassar Basins.

METHODS

This study is to integrate many published and unpublished works in southern, southeastern and eastern Sundaland on various aspects. Main previous works are listed in the references. The works include aspects on: regional geology and tectonics, petrotectonics of ophiolites, metamorphic geology, radiolarian biostratigraphy, zircon geochronology, gravity modeling, seismic interpretation, and petroleum geology.

Field studies were conducted by the author of this paper in several field sessions to Ciletuh, Luk Ulo, Bayat, Meratus Mountains, and Bantimala.

Results of previous works and field studies are synthesized to result in new paleotectonic reconstruction of Southeastern Sundaland in Cretaceous time and its implications for petroleum exploration of both pre-Tertiary and Tertiary objectives.

RESULTS

Geologic Setting of Sundaland

The term Sundaland strictly defines the landmass of southeast Asia. In Indonesia, it includes Sumatra, Java, Kalimantan-Borneo and offshore areas among them as cores, as well as Eastern Java Sea, Makassar Straits, and Western Sulawesi as drifted parts of Sundaland. Based on the presences of rifted structures in the Tertiary sections appearing on new acquired seismic data of the Bone and Tomini Bays, it is believed that the eastern boundary of the Sundaland is western parts of the Bone and Tomini Bays (Satyana, 2010a).

Sundaland is assembled by many terranes –mostly microcontinents rifted from the Gondwanaland in the southern hemisphere since the Late Paleozoic, drifted to the north-northwest and collided with other terranes closing the successive Tethyan oceans (Metcalfe, 2013). The final assembly of the Sundaland took place in the Late Cretaceous, after that some dispersions of the southeastern and eastern margins of Sundaland took place (Satyana, 2003; 2012).

Cretaceous subduction zone under our discussion is one of the mechanism of how the southern and southeastern parts of Sundaland was accreted by accretionary prisms following subduction as well as collision of terranes which ended the subduction (Figures 1-3, Table 1).

Presently, the subduction is taking place to the west and south of the Sundaland at Sumatra and Java trenches, respectively where Indian oceanic plate subducts below Eurasia plate occupied by Sumatra and Java at its margins. Subduction below eastern margin of the Sundaland ceased since the Late Cretaceous and Neogene as response to collision of terranes to the east of Sulawesi.

The following descriptions will discuss the key areas at the southern and southeastern margins of Sundaland significant to define the Cretaceous (Late Cretaceous) subduction zones proposed by Katili (1972) and Hamilton (1979) and key areas to the east of this subduction zones important to reconstruct the paleotectonic setting during the Cretaceous proposed within this paper. The descriptions will include: Ciletuh, Luk Ulo, Bayat, Meratus, Bantimala, suspect microcontinent of SE Java, suspect microcontinent of South Makassar, and suspect microcontinent of South Sulawesi.

The summary of stratigraphic correlation and rock assemblages comparison, with some pictures of the areas can be seen on Figures 2 and 3, as well as Table 1.
Having described each key areas, the paper will examine previous interpretation of the Late Cretaceous subduction zone of southern and southeastern Sundaland comprising Ciletuh-Luk Ulo-Bayat-Meratus, and propose new consideration of this based on the characteristics of each key areas and newly identified microcontinents at the southeastern margins of Sundaland, and eventually present new paleotectonic reconstruction and its petroleum implications.

Ciletuh, West Java

Asikin (1974) was one who firstly recognized that pre-Tertiary basement rock complex in the Ciletuh area – SW Sukabumi, West Java are mélange and comparable to the same complex exposed in Luk Ulo area, Central Java. The first detailed publication of Ciletuh mélange as part of the subduction zone was from Suhaeli et al. (1977). Figure 4 is the simplified geological map of Ciletuh area.

The area was firstly mapped by Duyfjes (1940) and Sukamto (1975b). Martodjojo et al. (1978) discussed the stratigraphic relationship between Ciletuh Formation, an Eocene deposits to the underlying mélange. Unpublished works on Ciletuh are from Rochman et al. (1983), discussing pre-Tertiary rocks of Ciletuh and Satyana (1988), discussing petrotectonic setting of Ciletuh based on ophiolite study on Gunung Badak, one of three mélange areas in Ciletuh. The following explanation is mainly based on Suhaeli et al. (1977).

The pre-Tertiary rocks are well exposed in the Ciletuh area and can be divided into three areas of exposures: (1) Gunung Badak and its surrounding area in the north, (2) Tegal Pamidangan, Gunung Beas, Citisuk River, Tegal Cicalung and Tegal Butak areas in the central part of Ciletuh, and (3) Cibuaya in the south. The pre-Tertiary rocks in these areas can be divided into three groups, namely ophiolite, sedimentary and metamorphic rocks. The ophiolite consist of peridotite, gabbro and pillowed basaltic lava. The sedimentary rocks comprise graywacke, limestone, red shales and chert. The metamorphic rocks consist of serpentinite, phyllite and blue/glaucophane schist.

In Gunung Badak area the pre-Tertiary rocks consist of peridotite, gabbro, pillowed basalt, phyllite, serpentinite, graywacke, limestone and shale. Approximately 3.5 kilometers to the South, in the central area, pre-Tertiary outcrops are composed of peridotite, gabbro, pillowed basalt associated with red shales, phyllite, schist and graywacke. In Gunung Badak and the Citisuk River, basalt is mixed with peridotites and gabbros. In some localities (Citisuk River) red shales are associated with the basalts suggesting they were submarine extrusions. Parkinson et al. (1998) also reported the presence of volcanic breccia and hyaloclastite.

Highly tectonic influences such as brecciation, mylonitization, shearing and serpentinization are generally found in peridotite. In some places asbestos fills the joints found in this rock. Gabbros are generally medium to coarse grained and dark grey colored. Gabbro is also observed at the Citisuk River as dykes intruding peridotite. Parkinson et al. (1998) reported that gabbro dykes are amphibolitized.

Greenish serpentinite can be recognized at Tegal Pamidangan, Gunung Beas, the Citisuk and Cikepuh Rivers and Tegal Sabuk in the central part of Ciletuh area. These rocks are usually found near the fault contact. Relict peridotites near the serpentinite are still visible at the Tegal Sabuk area. Thus it is considered that this serpentinite was derived from peridotite due to the high stress. Blue/ glaucophane schists can be widely encountered in the middle part of the area (Pasir Luhur). They are seen to be well foliated and greenish-grey in color. Under the microscope it can be seen that almost all of the minerals are dominated by mica, plagioclase and also glaucophane. In some places near the Koneng Hideung area are outcrops of hard, fine to medium, white quartzites. The same outcrops are also noticed at the Citisuk River. It is characterized by the presence of quartz veins. Dark grey, well foliated phyllites are noticed on Gunung Badak. Parkinson et al. (1998) reported that quartzite contain glaucophane, also the existence of epidote amphibolite and crossite-epidote metamafic rock. Eclogite has not been reported from Ciletuh complex.

Graywackes are noticed at the area around the Gunung Beas and Gunung Koneng Hideung. They crop out as boudins in a sheared shale matrix. Limestones that underwent slight metamorphism are exposed on Gunung Badak and chert is locally encountered north of Tegal Pamidangan.

In Cibuaya/ Citirem area, the exposures are dominated by pillow lavas. These outcrops are observed in the Cibuaya area and near the sea shore of the lower course of the Cibuaya River. Unlike the basaltic outcrops found in the northern area, these basaltic lavas are not influenced by high deformation.

In the area of Gunung Badak and around the Citisuk River, ophiolite rocks are mixed with metamorphic rocks and sedimentary rocks of different environments. Each of the rock units are bounded by fault contacts. The stratigraphy of the areas is very difficult to ascertain. These difficulties are mainly the result of the disruption of lateral continuity. No continual distribution of these rocks were visible. These strongly suggest that the complex of the rocks in Ciletuh area is a mélange complex. Dark grey sheared shales crop out in association with the ophiolite group, metamorphic and other rocks may the matrix of mélange complex. They are barren of fossils.

Lack of fossils in the sedimentary rocks of this group is a main problem in solving the stratigraphic position of the mélange complex, but reworked Late Cretaceous planktonic foraminifera of Pseudotextularia sp. and Globotruncana sp. are found in the shale of the Ciletuh Formation which unconformably overlies the unit of the rock complex. These fossils might be derived from the shales of this rock complex and suggest that mélange complex are of pre-middle Eocene in age.

Luk Ulo, Central Java

Luk Ulo, in Karangsambung village, north Kebumen, Central Java is a very well known site in the geology of Indonesia due its basement outcrops. Luk Ulo area was firstly investigated in detail by Harloff (1929), but Asikin (1974) who firstly called the basement outcrops in this area as mélange in terms of plate tectonic theory . The mélange complex of Luk Ulo is a remnant of tectonic mixture of Late Cretaceous subduction.

Later detailed investigations on Luk Ulo mélange were conducted by several workers on several aspects include: petrology of the ophiolites (Suparka, 1988), radiolarian chert biostratigraphy (Wakita et al., 1994), deformation of the mélange complex, and petrology of metamorphics (Parkinson et al., 1998 and Kadarusman et al., 2010). Another detailed work related to Luk Ulo mélange complex is from Prasetyadi (2007) who reinterpreted the mélange complex based on newly identified overlying Eocene olistostromal deposits in the northern part of the complex called the Bulukuning Formation and Larangan Complex (Figure 5).

The Luk Ulo Mélange Complex consists of tectonic blocks of various rocks (dismembered ophiolites, volcanic rock, pelagic sediments, continental margin sediments, and metamorphic rocks) embedded in pebbly shale and highly sheared shale matrix.

Dismembered ophiolite constitute a large tectonic slice in the complex. The ophiolite consists of pillow basalt, dolerite, gabbro, sepentinized peridotite, lherzolite and serpentinite, and are affected by greenschist-to zeolite-facies metamorphism. Some datings on ophiolite were conducted. K-Ar dating on basalt and dolerite resulted in ages of 81±4 Ma and 85±4 Ma Suparka, 1988). But pillowed basaltic lavas in Kali Muncar is of Early Cretaceous (120-130 Ma) and 100-110 Ma in Wagir Sambeng, Cacaban River (Wakita et al., 1994).

The volcanic rock is represented by rhyolite which is distributed along the Medana and Cacaban Rivers and at Totogan. It has been considered as quartz porphyry, 65 Ma (latest Cretaceous/ earliest Paleocene) in age based on fission track dating (Ketner et al., 1976). The rock developed as light grey or pale brown lava and tuff. The rhyolitic tuff is not welded, and contains pumices. The rhyolitic lava consists of phenocrysts of K-feldspar. Both lava and tuff are tectonically crushed. Suparka (1988) reported the presence of dacite that may be the part of volcanic rock and dated as 67.7±3 Ma. Ketner et al. (1976) asked the presence of rhyolitic lava and tuff in the mélange complex which is not easily accepted because the sites of formation of mélange and acid volcanic rocks they thought should be hundreds of kilometres apart. Hamilton (1979) suggested that the quartz porphyry, anomalous here in a mélange terrain, may owe its presence to melting caused by subduction beneath the wedge of very young hot Indian Ocean lithosphere.

The pelagic sedimentary rock is mainly chert and associated siliceous shale containing radiolaria. The chert is mostly reddish brown and sometimes interbedded with light grey or red limestone. The alternation of chert and limestone is underlain by basaltic pillow lava. The chert and siliceous shale, 1994, 1997). The radiolarian chert was originally pelagic sediments deposited as radiolarian ooze on the ocean floor (Wakita, 2000).

Sandstones of various types, pebbly shale and basaltic conglomerate may represent the continental margin sediments. Sandstone usually alternated with shale. The ratio of sandstone and shale is diverse in places. The sandstone beds show graded bedding. The most dominant rock type of sandstone is volcaniclastic arenite, which consist of mostly fragments of plagioclase and intermediate to basic volcanic rocks, but sandstone of tectonic blocks in fault zone and sandstone of broken formation along the Cacaban River includes fragments of schists and felsic volcanic rocks. Sandstone of shallow marine environment occur along the Cacaban River. It contains a number of foraminifera fragments and a minor of glauconite. The sandstone includes angular to subrounded fragments of quartz, feldspar, micas, felsic to basic volcanic rocks, and schist. Pebbly shale includes subrounded to rounded clast within a shale matrix which is not foliated. The clast are composed mainly on intermediate to basic volcanic rocks and shale, rarely of unwelded dacitic tuff and quartz-mica schist. Basaltic conglomerate, greenish grey in color, consists of basaltic pebbles and cobbles within a small amount of shale matrix which includes subangular to subrounded fragments of basalt, shale and limestone.

Various metamorphic rock types are present in Luk Ulo: phyllite, schists, eclogite, gneiss, quartzite, marble and some other metamorphics rocks in minor. Miyazaki et al. (1998), Parkinson et al. (1998) and Kadarusman et al. (2010) investigated the metamorphic facies based on P-T evolutions. The best outcrops of the Lok Ulo metamorphic complex, which are associated with dismembered ophiolite, are along the Muncar and Gua Rivers. They consist of HP rocks of eclogites, glaucophane rock and blueschist, and medium pressure rocks such as garnet amphibolite and greenschist. The petrological studies concerned of HP rock types (eclogite and blueschist) showing mineral assemblages with jadeite and lawsonite (Miyazaki et al., 1998; Parkinson et al., 1998) and tourmaline (Kadarusman et al., 2010).

Kadarusman et al. (2010) argued that the metamorphic rocks of Luk Ulo have experienced quite contrasting P-T evolutions. Based on this Kadarusman et al. (2010) concluded that there are two kinds metamorphic rocks with different kinds of protoliths and differ in P-T evolution as well. (1) The first group (called `oceanic plate protolith') consists of fine-grained metabasites with metapelitic intercalations ranging from greenschist to amphibolite facies. These metamorphic rocks have experienced peak P-T conditions of 360-400°C close to 20 kbar. High-pressure rocks such as eclogite, partially containing lawsonite and tourmaline, jadeite-glaucophane schist and blueschist crop out in a thin zone between the low-grade schists and a serpentinite zone along Kali Muncar. They are associated with a succession of metabasalt, serpentinite, chert and red limestone as common constituents of an ophiolite. (2) The second group (called `continental crustal protolith') consists of low to high grade medium pressure metapelites, calc-silicate rocks, and metagranites (gneisses, quartzites, marbles, felsic granulites), and minor bimodal low grade metavolcanic. They were metamorphosed at T = 580 -620 °C and P = 5-6. These rocks are presumably associated with a monotonous sequence of metapelites from the chlorite zone up to the garnet zone exposed in the northern and eastern part of the Karangsambung area (e.g. Kali Loning). The metamorphic rocks were dated to know their ages of formation. The K-Ar dating of muscovite from quartz-mica schists yielded ages of 117 Ma (Ketner et al., 1976), 101.7± 5 Ma (Suparka, 1988), 115± 6 Ma and 110± 6 Ma (Miyazaki et al., 1998). Based on whole rock Rb-Sr dating on phyllite samples, the age is 85 Ma (Ketner et al., 1976). The K-Ar dating based on phengite and eclogite are 124 ± 2 Ma and 119 ± 2 Ma, respectively (Parkinson et al., 1998).

As for the mélange complex, Wakita et al. (1994) showed that the duration of subduction and accretion forming the mélange complex can be estimated based on the age of the terrigenous and hemipelagic (siliceous) shales along with the associated pillow lava. The age of pillow lavas is of 100-130 Myr, while the oldest terrigenous rock is the shale of middle Cretaceous age (100-110 Ma). The youngest rock is the siliceous shale of latest Cretaceous age in the Medana River. As the terrigenous rocks in the accreted sequences are usually as young as or slightly younger than hemipelagic siliceous shale, the youngest terrigenous rocks may be of latest Cretaceous or earliest Paleocene age. These age data suggest that the accretion of pillow lava and pelagic to hemipelagic sediments in the Luk Ulo Mélange Complex occurred during middle Cretaceous to latest Cretaceous or earliest Paleocene time. All components of the Luk Ulo Mélange Complex range in age from Early Cretaceous to earliest Paleocene, meaning that the tectonic mixing during subduction took place during Late Cretaceous - Paleocene time. Unconformably, marked by a tectonic contact, the mélange complex of Luk Ulo is overlain by olistostromal deposits of Karangsambung Formation which contain Eocene Nummulitic fossils.

Jiwo Hill-Bayat, Central Java

Asikin (1974), Ketner (1976), Hamilton (1979) mentioned the pre-Tertiary basement rocks in Jiwo Hill, in Bayat village, to the southeast of Klaten, Central Java. The area was believed to be comparable with Luk Ulo. The first detail geological investigation in the Jiwo Hill was conducted by Bothé (1929, 1934) and Sumosusastro (1956). Another classic literature for the area is from Sumarso and Ismoyowati (1975) who investigated its stratigraphy. Recent geological investigations and studies for the Jiwo Hill were conducted by Prasetyadi et al. (2002), Prasetyadi and Maha (2004), Prasetyadi et al. (2005), Prasetyadi (2007) and Setiawan et al. (2013). Figure 6 shows simplified and updated geological map of Jiwo Hills, Bayat area.

(Bothé, 1929, 1934) reported that metamorphic basement of the Jiwo Hills forms an extensive outcrops. It consists of crystalline limestone, gneisses, phyllites, mica schists and radiolarites. The latter have been intruded by ultrabasic rocks. The age of this basement complex is doubtful. Bothé (1929) found several specimens of *Orbitolina* in a limestone pebble of a Neogene conglomerate nearby and concluded that at least a part of these beds is of Cretaceous age. Referred to unpublished manuscript by Bothé, ca. 1940, Ketner et al. (1976) and Hamilton (1979) listed that basement rocks of the Jiwo Hill consist of: phyllite, slate, varied greenschist, limestone, radiolarian limestone, radiolarian chert, serpentinite, quartzite, gneiss, and amphibolite; all contorted and highly sheared. These rocks are poorly exposed and incompletely characterized. Neither blueschist nor eclogite have been reported (Parkinson et al., 1998).

However, detailed more recent geological studies of Bayat area (Setiawan, 2000; Prasetyadi et al. 2002, Prasetyadi and Maha, 2004; Prasetyadi et al., 2005, Prasetyadi, 2007; Setiawan et al., 2013 did not find rock assemblages as shown above). Pre-Tertiary rock complex of the Jiwo Hill, Bayat area is mainly composed of metamorphic rocks comprising phyllite, schist and marble. Setiawan et al. (2013) reported the presence of glaucophane schist and serpentinite in West Jiwo Hill. Recent absolute dating was conducted on this pre-Tertiary basement, on two mica schist samples and resulted in 98.05±2.10 Ma and 98.54±1.45 Ma (mid-Cretaceous/ Cenomanian - Prasetyadi, 2007).

Phyllite predominates the rock complex and is exposed both in West and East Jiwo Hills. Quartz and calcite veins fill the phyllitic foliations. Microscopically, quartz mineral predominates the rock (60-70%), followed by chlorite and sericite (20-25%), opaque mineral and epidote (5 %). This composition indicates the protolith may be derived from pelitic rocks.

Schists and marbles are exposed in some places such as Gunung Jokotuo, Semangu, Cakaran and Jabalkat. Schists petrographically consists of quartz (40-50%), calcite (15-20 %), orthoclase (10-15%), muscovite (10-15%), and minor opaque minerals and epidote. Based on this mineralogical composition the schist is within greenschist facies. A psammitic (sandstone) rock may form the protolith of the schist. The marble is exposed in Gunung Jokotuo embedded in phyllite, microscopically consists of 85 % calcite, 10 % quartz, and small amount of opaque mineral.

Recent paper by Setiawan et al. (2013) show that rarely epidote-glaucophane schist crop out near the exposure of serpentinite in western part of this complex (Figure 6). Several carbonate sedimentary rocks are converted to garnet-wollastonite skarn under the contact metamorphism probably caused by diabase intrusion. Epidote-glaucophane schist mainly consists of glaucophane, epidote, quartz, phengite, titanite, and hematite. The serpentinites might facilitate exhumation of the blueschist in the Jiwo Hills.

Lunt (2013) reported in Jiwo Hills the presence of minor gabbro and dolerite. This may be misinterpreted Eocene-Oligocene rocks as pre-Tertiary. A number of basaltic dykes and a gabbroic intrusion (Gunung Pendul intrusion) intruded the phyllite and Wungkal-Gamping Formation. K-Ar dating of gabbro and basalt in Bayat area indicates ages of 39.8 – 31.3 Ma (Eocene to early Oligocene) (Sutanto et al. 1994).

Overlying unconformably the pre-Tertiary rock is the Eocene Wungkal-Gamping Formation comprising conglomerate, Nummulitic limestone, quartz sandstone and claystone. Based on nannoplankton analysis, age of the claystone indicates Late Middle Eocene (Setiawan, 2000).

Meratus Complex, South Kalimantan

A northeast-southwest trending pre-Tertiary assemblage of chaotically intercalated rocks crop out over large areas of the Meratus and Bobaris Mountains of southeast Kalimantan and neighboring Laut Island. Asikin (1974) was the first who identified that the rocks composing the Meratus Mountains is a mélange complex. Detailed geological and tectonic studies on the Meratus Complex was conducted by Priyomarsono (1985), Sikumbang (1986) and Heryanto (2010). Several later studies on various aspects of the geology of this region were from Wakita et al. (1998), Parkinson et al. (1998), Wakita et al. (1999), Wakita et al. (2000) investigating the petrology and biostratigraphy of the mélange complex and its relation to other mélange complex in Java and Sulawesi. Pubellier et al. (1999) investigated the structural features of the Meratus Mountains inferring its accretion history. Hartono et al. (2000) discussed the magmatic evolution of South Kalimantan. Heryanto and Hartono (2003) reviewed the stratigraphy of the Meratus Mountains and proposed new subdivision. Satyana and Armandita (2008) used gravity data and modeling to constraint the origin of the Meratus Uplift. Simplified geological map of the Meratus Mountains using new pre-Tertiary stratigraphic subdivision can be seen on Figure 7.

Dominant lithologies include serpentinized peridotite and pyroxenite with gabbro and plagiogranite intrusions (Bobaris and Meratus ophiolites) (Parkinson et al., 1998), shale-matrix mélange with clasts of limestone, chert, and basalt (Laut Island only), pelagic sediments with a Middle Jurassic-late Early Cretaceous radiolarian biostratigraphy (Wakita et al., 1998), clastic and carbonate sediments, and the variety of metamorphics (Pelaihari Phyllite and Hauran Schists). These rock complex were overlain by volcaniclastics and turbidites of middle Cretaceous Alino Group and Late Cretaceous Manunggul Group.

Based on detailed surface mapping in the Meratus Mountains, Sikumbang (1986) developed the geological model for the Pre-Tertiary evolution of the area. His work provides the framework for a possible interpretation of the complex tectonic evolution of this area since the Early Cretaceous. Based on fossil evidence and radiometric dating, he postulated a mid-Cretaceous period of N-S subduction and volcanic arc formation of Alino Group along the eastern margins of Sundaland. This was followed by a Late Cretaceous arc-continent collision with oblique subduction/ obduction resulting in Manunggul Group volcanoclastic and turbidites. Shallow shelf to slope sediments of Early Cretaceous Paniungan Formation and Orbitolina-bearing Batununggal Formation, Meratus Ophiolite, pelagic sediments and metamorphic rocks were all involved in the processes of subduction and collision of the Meratus Complex.

Heryanto and Hartono (2003) and Heryanto (2010) based on the new mappings with more detailed scales and new absolute datings reviewed the stratigraphy of the Meratus Mountains of Sikumbang (1986) and proposed new subdivision. The significant changes of the stratigraphic subdivision are the names of Alino and Manunggul Groups no longer used. The previous mid-Cretaceous Alino Group consisting of Pudak and Keramaian formations currently becomes Late Cretaceous Pitap Group comprising Pudak, Keramaian and Manunggul formations and partly into Late Cretaceous Haruyan Group. The previous Late Cretaceous Manunggul Group is also included into the Pitap Group and partly Haruyan Group.

The faulted southeast margin of the Bobaris ophiolite is locally overlain by Late Cretaceous turbidites and volcaniclastics of Manunggul Group (now Pitap and Haruyan Groups) and sedimentary conglomerates containing serpentinite, pyroxenite, gabbro and greenstone (Parkinson et al., 1998). These turbidites and conglomerates, which include the “Pamali Breccia” are diamondiferous.

Ultramafic rocks comprise 90 % of the Meratus ophiolite. They mainly consist of dark green serpentinized peridotite, lherzolite, harzburgite and dunite with minor pyroxenite, and are intimately associated with gabbro and amphibolite. The rocks are sheared and faulted. The best age estimate of the ultramafic rocks in the Meratus Complex is probably around 200 Ma (latest Triassic- earliest Jurassic; Pt-Os dating by Coggon et al., 2010). They must be older than the associated Middle Jurassic to late Early Cretaceous radiolarian cherts (Wakita, 2000), which formed the pelagic cover of the ocean floor. The ultramafic rocks are variably affected by low-grade metamorphism. Mafic rocks layered and massive gabbros are cropped out as olivine- to quartz gabbro and associated with dolerite. Dikes of plagiogranite, quartz diorite and trondjehmite are associated with microgabbro. K-Ar dating on hornblende in gabbro and plagiogranite yields ages of 120-150 Ma and 118-131 Ma for microdolerite.

Metamorphic rocks include glaucophane schist, garnet mica schist, quartz mica schist, piemontite schist, amphibolite and phyllite. They occur as wedge-shaped tectonic blocks in fault contact with ultramafic rocks and Cretaceous formations (Wakita et al., 1999; Wakita, 2000). Sikumbang (1986) subdivided the metamorphic rocks of the Meratus region into the widely distributed greenschist-to-epidote amphibolite-grade Hauran Schists and the lower-grade, Pelaihari Phyllites, comprising phyllite and slate, which are poorly exposed and restricted to the Pelaihari area. The Hauran Schist includes glaucophane schist, chloritoid-quartz schist, kyanite-quartz-phengite-chloritoid schist, quartz-muscovite schist, micaceous metaquartzite, barroisite-epidote schist, metagabbro garnet mica schist, quartz-mica schist, piemontite schist and amphibolite. The protoliths of the Hauran Schist were predominantly pelitic and basic rocks, although the chloritoid and kyanite-bearing schists are probably derived from bauxites and evaporites (Wakita, 2000). Along the northwest margin of the Hauran Schist terrane in Martapura region, near the fault contact with the Bobaris ophiolite, glaucophane, kyanite and/or chloritoid-bearing quartz schist crop out. They may constitute a discrete tectonic block separate from the Hauran Schist suite, the paucity of exposure makes field relations unclear. The sialic nature of these rocks suggests that, unlike the other Hauran schists, they are of continental parentage, probably derived from continental sedimentary cover rocks such as laterite (Parkinson et al., 1998; Wakita, 2000). The most common metamorphic assemblages based on P-T analysis suggest that these rocks may have been recrystallized at pressures of ~18 kbar or higher, revealing HPLT metamorphism in a deep subduction environment, possibly between 30-50 km. K-Ar age data of micas from the Hauran Schist vary from 108-119 Ma (Sikumbang, 1986; Sikumbang and Heryanto, 1994), and 165-180 Ma (Zulkarnain et al., 1996; Wakita et al., 1998). These two age variations indicate two facies of HPLT metamorphism as response to subduction episodes of Early-Middle Jurassic (165-180 Ma) and Early Cretaceous (108-119 Ma).

Mélanges do not occur in the Meratus Mountains but are distributed on Laut Island (Wakita et al., 1997, 1998, 1999; Parkinson et al., 1998; Wakita, 2000). The most distinct outcrop of mélange occurs along the southwestern coast of Laut Island. The mélange includes clasts and blocks of chert, siliceous shale, basalt, limestone, marl and manganese carbonate nodules embedded within a sheared shale matrix. Sandstone or other coarse-grained terrigenous sediments are lacking in the mélange. The shale matrix is usually sheared to some degree. Chert and limestone are thinly bedded. Basalt is mainly lava, and pillow structures are sometimes preserved. Limestone clasts are locally dominant in the mélange. Fragments of manganese carbonate nodules are rare. The clasts are subrounded to subangular, lenticular to blocky in shape. Clasts in the mélange are usually less than 1 m in long axis, but sometimes reach several meters long. The chert sometimes includes well-preserved radiolarians ranging in age from Middle Jurassic to Early Cretaceous (late Albian to early Cenomanian) age (Wakita et al., 1997). Siliceous shale clasts are light gray, gray or reddish brown in color, and composed of terrigenous fragments, radiolarian skeletons and other detrital materials. Some of them include radiolarians of Early Cretaceous age. The age of mélange formation is estimated as slightly younger than the youngest age of the components of the mélanges.

The Meratus Complex also include the mid-Cretaceous shelf sediments of Paniungan and Batununggal Formation, mid-Cretaceous to early Late Cretaceous volcaniclastic deposits of Alino and Manunggul Groups and Late Cretaceous flysch-turbiditic sediments deposited in forearc basin (Late Cretaceous Pitap Formation of the Manunggul Group) (Sikumbang, 1986; Wakita, 2000). Presently, all of these rocks are grouped under the Late Cretaceous Pitap and Haruyan Groups (Heryanto and Hartono, 2003; Heryanto, 2010). The Pitap Group consist of interbedded shale, siltstone, sandstone, conglomerate, and very compacted polimict breccia, locally containing *Orbitolina*-bearing limestone clasts. The Haruyan Group consists of lava (Pitanak Formation), volcanic breccia and volcanic sandstone (Paau Formation). The previous Alino Group was older than the Manunggul Group. Currently, the Pitap and Haruyan Groups are contemporaneous (Late Cretaceous) and interfingering. They unconformably overly the mid-Jurassic to Early Cretaceous Meratus ophiolites, metamorphics, pelagic sediments, and mélange. K/Ar ages of lava in Pitanak Formation yield 83±2 to 66±11.6 Ma (Sikumbang, 1986). The Late Cretaceous volcanics of the Meratus Mountains were resulted from subduction process. The magmatic source is probably a sub-oceanic mantle above the subducted slab, resulted in andesitic magma.

Granitoid rocks are well widely exposed at the western flank of the Meratus Range near Kandangan and Barabai. The main rock types are holocrystalline hypidiomorphic granite, tonalite, trondhjemite, and diorite. The geochemical characteristics and K-Ar results suggest that most of the granites were produced in an island arc environment in the Lower Cretaceous. This granitoid rocks may have been caused by a subduction of the Early Jurassic or Triassic oceanic crust beneath the oceanic crust of the Sundaland margin. The HPLT metamorphic rocks of 180-165 Ma were also caused by this subduction.

Bantimala- Barru, South Sulawesi

The presence of ultramafic and metamorphic rocks in the SW part of the South Arm of Sulawesi (later known as Bantimala and Barru areas) has been known since the work of von Steiger (1915) in Pangkajene area. The occurrence of radiolarian chert in the Bantimala area has been known since the early 20th century. Hamilton (1979) mentioned the rock complex in this area were formed in an environment of subduction. Further investigation on these rock complex called as the mélange complex in Bantimala and Barru areas, South Sulawesi were conducted by Sukamto (1982) through the systematic geological mapping of Pangkajene and Watampone Sheet, scale 1:250,000. Simplified geological map of Bantimala and Barru areas is shown on Figure 8.

Barru area, 30 kms to the north of Bantimala, the complex consist of metamorphic, ultramafic and sedimentary rocks, but with no typical mélange like that occurs in the Bantimala area. The complex is not well characterized and crops out over a much more restricted area than the Bantimala Complex. The rock complex include serpentinized peridotite, clastic sedimentary rocks and variably garnetiferous quartz-mica schists (Parkinson et al., 1998). A phengite K-Ar age of 106 Ma was reported for a quartz-mica schist (Wakita et al., 1994). Syafri et al. (1995) reported lawsonite eclogite with two retrograde blueschist overprints. They estimated the peak P-T conditions of the eclogite stage to be ~21 kbar and 520 °C, and the successive blueschist retrograde stages to be ~13 kbar and 500 °C , and 8 kbar and 360 °C. The recent paper by Munasri (2013) reported the first discovery of Early Cretaceous (Valanginian to Barremian) radiolarians from the Barru area, extracted from manganese carbonate nodule embedded in dark reddish shale. Middle Cretaceous radiolarian cherts were reported from Bantimala area. Based on radiolarian data, Munasri (2013) suggested that the Barru and Bantimala Complexes were not derived from single accretionary complex as previously regarded. The hemipelagic dark reddish shale with manganese carbonate nodule of the Barru Complex are considered to have been deposited in Early Cretaceous time and accreted at the subduction trench during late Early Cretaceous (Aptian) time.

Basement rocks of mélange complex crop out more extensively in Bantimala area, 40 kms northeast of Makassar. Detailed petrotectonic study of the Bantimala mélange complex was firstly conducted by Sukamto (1986). In this study, Sukamto (1986) showed that the mélange complex consists of rock associations of Triassic to Early Cretaceous allochthonous rock association which tectonically mixed up and imbricated, consisting of: Kayubiti ultramafics, Bontorio metamorphics, Paremba sandstone, Dengeng-Dengeng basalt, schist breccia, and chert. Later studies on Bantimala area were conducted on several aspects, including: radiolarian chert biostratigraphy (Wakita et al., 1994), metamorphic basement (Miyazaki et al., 1996; Parkinson et al., 1998; Maulana et al., 2010, 2013) and mélange complex (Wakita et al., 1996).

The Bantimala Complex is a tectonic assemblage of slabs and blocks consisting of sandstone, shale, conglomerate, chert, siliceous shale, basalt, ultramafic rocks, schist, schist breccia and felsic intrusive rocks (Wakita, 1999).

Jurassic shallow marine sedimentary rocks (Paremba Sandstone) are incorporated as tectonic slabs in the Bantimala Complex. The lower part of the Paremba Sandstone along the Bontolio River is composed of thin bedded sandstone and shale, intercalated with thin limestone layers. Some shallow marine sedimentary structures such as ripple and convolute laminations are recognized. The upper part of the formation is rich in conglomerate which includes pebbles mainly of basalt and schist, Ammonites, gastropods and brachiopods of the Lower and Middle Jurassic are reported from the Paremba Sandstone (Sukamto and Westermann, 1992).

The ultramafic rocks of Bantimala are mostly serpentinized peridotite, with local chromite lenses. They are unconformably overlain by sandstone of the Balangbaru Formation (Hasan, 1991). Late Cretaceous Balangbaru submarine fan deposits are composed of flysch-type sedimentary rocks, such as interbedded sandstone, shale and conglomerate. The Oldest cover rocks for the Bantimala Complex are propylitized volcanic rocks consisting of breccia, lava and tuff mainly of andesitic and partly of basaltic and trachytic composition. K-Ar dating on lava yielded an age of 58.5 Ma (Hamilton, 1979).

Low grade greenschists and glaucophane-bearing schists occur as imbricate slices in the Bantimala Complex (Wakita, 2000). Peak P-T conditions have been estimated at around 350-450 °C and 5-8 kbar (Miyazaki et al., 1996, Parkinson, et al., 1998), and K-Ar ages are generally in the range 111-114 Ma. Very high pressure metamorphic rocks also occur, but are much less abundant. They occur as small tectonic blocks and slabs associated with serpentinite and comprise eclogite and garnet-glaucophane rock ($P = 18\text{-}24$ kbar, $T = 580\text{-}620$ °C), coesite-bearing jadeite quartzites ($P > 27$ kbar, $T = 720\text{-}760$ °C) and garnet amphibolite (Miyazaki et al., 1996, Parkinson, et al., 1998). K-Ar ages of phengite for the VHP rocks are generally older than for the low-grade schist country rocks: 132±7 Ma, 113±6 Ma and 124±6 Ma (garnet-glaucophane rock; Wakita et al., 1996) and 137±3 Ma (eclogite; Parkinson et al., 1998).

Recent paper by Maulana et al. (2013) discussing the protolith origins of eclogite and blueschist rocks from the Bantimala Complex. SiO2 contents of the eclogites are 43.3–49.6 wt%, with Na2O + K2O contents 3.7–4.7 wt%. The blueschists show a wider range of compositions, with SiO2 = 40.7–63.8 wt% and Na2O + K2O = 2.7–4.5 wt%. Trace element data suggest that the eclogite protoliths include both enriched and normal mid-oceanic ridge basalt and also gabbroic cumulates. The blueschists show more variation in protoliths, which include normal mid-oceanic ridge basalt, Oceanic Island Basalt and Island Arc Basalt. All the protoliths were subducted, metamorphosed to blueschist/eclogite-facies and subsequently exhumed.

Polymict mélange in the Bantimala Complex generally occurs in narrow zones between tectonic slices, and includes clasts and blocks of chert, sandstone, and siliceous shale with subordinate basalt, limestone and schist embedded within a variably sheared shale matrix (Wakita, 2000).

Chert layers, 1 to 20 cm thick, are interbedded with thinner shale layers less than 1 cm thick. The bedded chert is mostly red or reddish brown, and sometimes pale green or gray in color. The chert is mainly composed of skeletons of radiolarians. The radiolarian chert is unconformably underlain by brecciated schist in the Bantimala Complex (the famous "unusual unconformity" of Sukamto, 1978). The basement of brecciated schists is overlain by a 2 m thick sandstone bed. The sandstone bed is covered by alternating beds of sandstone and radiolarian chert. The sandstone is composed of quartz, micas, plagioclase and rock fragments of metamorphic rocks, shale, and chert. From the base of unconformity and stratigraphically upwards, the sandstone beds become thinner and less common and are gradually replaced by bedded chert. The bedded chert is intercalated with siliceous shale beds and rarely with very thin beds and laminae of sandstone. The stratigraphic succession of the outcrop shows the change of sedimentary environment from proximal to distal facies. Well-preserved middle Cretaceous (late Albian to early Cenomanian) radiolarians have been extracted from chert unconformably underlain by brecciated schist in the Bantimala Complex (Wakita et al., 1994).

Microcontinents of Southeast Sundaland

Present-day Asia comprises a heterogeneous collage of continental blocks, derived from the Indian–west Australian margin of eastern Gondwana, and subduction related volcanic arcs assembled by the closure of multiple Tethyan and back-arc ocean basins now represented by suture zones containing ophiolites, accretionary complexes and remnants of ocean island arcs. The Phanerozoic evolution of the region is the result of more than 400 million years of continental dispersion from Gondwana and plate tectonic convergence, collision and accretion. This involved successive dispersion of continental blocks, the northwards translation of these, and their amalgamation and accretion to form present-day Asia (Metcalfe, 2013). Indonesia, as part of Asia, was also built by a number of terranes rifting and drifting from Gondwana during Early Devonian to Paleogene (Satyana, 2010).

In SE Sundaland area there are a number of microcontinents considered to compose the area, colliding or docked the main part of the Sundaland during pre-Tertiary (Cretaceous). They are named, proposed and interpreted in some various ways, such as: Paternoster (Situmorang, 1989; Hutchison, 1989; Metcalfe, 1994, 1996, 2013), Paternoster-Kangean, including West and South Sulawesi (Manur and Barraclough, 1994; Parkinson et al., 1998; Wakita, 2000; Satyana, 2003, 2004, 2010), Bawean (Smyth et al., 2007; Metcalfe, 2013), East Java (Bransden and Matthews, 1992; Sribudiyani et al., 2003; Smyth et al., 2005; 2007; Seubert and Sulistyaningsih, 2008; Deighton et al., 2010; Metcalfe, 2013), East Java-Makassar Straits (Parkinson et al., 1998; Emmet et al., 2009; Granath et al., 2009, 2010, 2011), Argoland (Hall et al., 2009). These microcontinents separated from NW Australia in the Late Triassic–Late Jurassic by opening of the Ceno-Tethys and accreted to SE Sundaland by subduction of the Meso-Tethys in the Cretaceous (Metcalfe, 2013).

The following remarks discuss some of these microcontinents important for revisiting the Cretaceous subduction zone considered by many workers involved Luk Ulo, Bayat, Meratus, and Bantimala-Barru areas.

Southeast Java Microcontinent

What is proposed here as Souheast Java Microcontinent is East Java Continental Fragment of Smyth et al. (2007) and East Java Microcontinent of Metcalfe (2013). The name of SE Java Microcontinent is proposed to clarify the dimension of the microcontinent which is limited to the area of southeastern margin of Java (southern onshore East Java and south offshore of East Java), not to confuse with bigger East Java Microcontinent proposed by other workers which extends northeastwards to the South Makassar Straits and SW Sulawesi.

The presence of this microcontinent was firstly proposed by Smyth et al. (2005) based on provenance studies of Early Cenozoic volcanic rocks in Southern Mountains of East Java. Dating of zircons provide insight into the basement character and suggest that continental crust of Gondwana (possibly Western Australian) origin lies beneath part of the Southern Mountains Zone. Further studies on this (Smyth et al., 2007) confirmed the consideration (Figure 9).

The igneous rocks of the Early Cenozoic arc, found along the southeast coast, contain only Archean to Cambrian zircons. In contrast, clastic rocks of north and west of East Java contain Cretaceous zircons, which are not found in the arc rocks to the south. The presence of Cretaceous zircons supports previous interpretations that much of East Java is underlain by arc and ophiolitic rocks, accreted to the Southeast Asian margin during Cretaceous subduction. However, such accreted material cannot account for the older zircons. The age populations of Archean to Cambrian zircons in the arc rocks are similar to Gondwana crust. Smyth et al. (2007) interpreted the East Java Early Cenozoic arc to be underlain by a continental fragment of Gondwana origin and not Cretaceous material as previously suggested. Melts rising through the crust, feeding the Early Cenozoic arc, picked up the ancient zircons through assimilation or partial melting. They suggested a Western Australian origin for the fragment, which rifted from Australia during the Mesozoic and collided with Southeast Asia, resulting in the termination of Cretaceous subduction. Continental crust was therefore present at depth beneath the arc in south Java when Cenozoic subduction began in the Eocene.

Hall et al. (2009) interpreted that the microcontinent designated here as SE Java Microcontinent is not underlain by Archaean basement as suggested by Smyth et al. (2007), but by sediments (up to Triassic age) derived from Archaean, Proterozoic and Palaeozoic basement in western Australia. This better accounts for the range of ages in the zircon data and with the existence of long-lived structuresand pathways feeding sediment to the offshore Canning Basin. The microcontinent proposed by Smyth et al. (2005, 2007) is indicated at its offshore extension based on new 2D-seismic acquired on offshore area to the south of East Java (Deighton et al., 2011). Long-offset 2D marine seismic reflection data images the deep section and basement under mid-late Tertiary forearc fill. The seismic data show the relatively thin Miocene and younger sediments of the offshore Java Basin are underlain by a further 3+ seconds TWT of block-faulted parallel-bedded sedimentary section, with similarities in seismic character to Mesozoic sections from the northern Exmouth Plateau, outer Browse and outer Roebuck Basins of the Australian NW Shelf. Deighton et al. (2011) suggested that the Argo abyssal plain, NW Australia, presumably an origin for SE Java continental fragment. SE Java Microcontinent will be significant to revisit the status of Jiwo Hills, Bayat area in terms of Cretaceous subduction zone.

Paternoster-Kangean Microcontinent

The Paternoster-Kangean Microcontinent defined here includes the Paternoster Block which was outlined by Hutchison (1989) and the East Java Sea-Kangean Block called as East Java microplate by Brandsden and Matthews (1992) and Manur and Barraclough (1994). Argoland now is proposed by Hall et al. (2009) to include this microcontinent and other microcontinent in SE Sundaland. Paternoster is a stable continental block that appears to have once been continuous with west Sulawesi when it was attached to Kalimantan before the Paleogene opening of the Makassar Straits (Hutchison, 1989).

The presence of the Paternoster-Kangean microcontinent is well constrained by the bathymetry, geophysical data, and exploration wells penetrated this basement high. The Paternoster Block is called the Paternoster Platform because it is a very flat and homogeneous shelf with water depths between 30 m and 60 m, and is covered by a large open epeiric sea crossed by active currents. It is surrounded by reefs forming tidal flats and a few islands along the northern, eastern, and southeastern borders. Around the platform, the continental slope is relatively steep, especially on the north-eastern edge where it corresponds to a set of faults (Adang/Paternoster Fault Zone) (Burollet et al., 1986). Wells drilled in the Paternoster area found granitic to granodiorite basement (Rubah-1, Pangkat-1) (Satyana et al., 2004).

To the south, the Paternoster Block continues to the similar basement high called Kangean Block/East Java Microplate/Bawean Pre-Tertiary Basement (Bransden and Matthews, 1992; Manur and Barraclough, 1994), it is a microcontinent with no clear border with the Paternoster Block. The underlying Pre-Tertiary basement of the Bawean area includes basinal sedimentary rocks, igneous intrusives and altered volcanics. The oldest known rocks are meta-sedimentary and range in age from Jurassic through to Late Cretaceous.

Pre-Tertiary basement rocks penetrated by wells in the East Java Basin comprise diverse lithologies. These range from low-grade metamorphics (phyllite, quartzite and meta-tuff) in the northwest, through acidic igneous rocks (rhyodacites and vitric tuff) in the central, to intermediate igneous rocks (monzonite and diorite) in the southeastern part. At the eastern end of the basin in the Kangean/Lombok area, four wells penetrating pre-Tertiary basement found metavolcanics, quartzite, chert, and serpentinized amphibolite.

Metamorphic radiometric dates range from latest Jurassic to Late Cretaceous, with an apparent modal peak in the mid Cretaceous (Bransden and Matthews, 1992).

To the south, the Paternoster-Kangean microcontinent is terminated by another major strike-slip fault, the Rembang-Madura-Kangean-Sakala Fault Zone (Satyana et al., 2004). Basement High, to the north of Madura Island called the North Madura Platform is part of Kangean Microcontinent. Wells located offshore to the north of the Madura Island found basement lithology related with acidic to intermediate igneous rocks such as rhyodacites (JS 19 W-1), vitric tuff (JS 19 A-1), monzonite (JS 44A-1) and diorite (JS 8-1). Based on the basement lithology penetrated by wells around the South Makassar Strait (the Paternoster area), regional gravity area and tectonic map, the micro-continent is considered to extend as far as east of the Kangean islands, to extend northeastward to the westernmost Sulawesi, and westward to the offshore south of Kalimantan (JS-1 Ridge).

The presence of Paternoster-Kangean Microcontinent is also recently amplified by newly acquired deep seismic data called JavaSPAN data sets (Dinkelman et al., 2008; Emmet et al., 2009; Granath et al., 2009, 2010). In early 2008, a regional long-offset, deep crustal, over 9800 km 2-D reconnaissance seismic data were acquired using a maximum offset of 9000 m and a 18 second record length. The data are being processed to PSDM level thus imaging the lower crust and Mohorovicic discontinuity. Dinkelman et al. (2008), Emmet et al. (2009), and Granath et al. (2009, 2010) have shown that the East Java Sea is underlain by structures similar to various locations on the Australian NW and Arafura shelves, and called the block the East Java terrane . The terrane is bounded on the east by the central Sulawesi suture (Bergman et al.1996), which Granath et al. (2009) projected south of the southwest arm of Sulawesi to the eastern edge of the Flores Sea. The Meratus suture bounds the terrane to the west. The Paternoster-Kangean Microcontinent is included within the terrane.

The Paternoster-Kangean Microcontinent will be significant to revisit the relation of Meratus to Luk Ulo Cretaceous subduction zone.

West Sulawesi Microcontinent

The presence of pre-Mesozoic continental basement in western Sulawesi was firstly indicated among others by Hutchison (1989). Further studies by Sukamto and Westermann (1992), Wakita et al. (1996), Parkinson et al. (1998) and Wakita (2000) confirmed the presence of a microcontinent in West Sulawesi.

Jurassic continental clastics called the Paremba Sandstone are sedimentary formation on a continental fragment detached from Gondwanaland (Wakita, 2000). As the Paremba Sandstone is older than the high P/T metamorphic rocks, the formation is older than the accretion and collision stage. The sandstone is incorporated within the tectonic assemblage in the Bantimala Complex as tectonic slices detached from a colliding microcontinent in late Cretaceous time (Wakita, 2000). The microcontinent in Bantimala Complex is required to explain the mechanism of exhumation of very high-pressure metamorphic rocks.

Bergman et al. (1996) investigated the Tertiary tectonic and magmatic evolution of western Sulawesi, and also considered the parental crustal mass involved in magmatic evolution. Western Sulawesi is characterized by Late Miocene to Pliocene extrusive and intrusive rocks form a cogenetic volcanoplutonic complex of calk-alkalic to mildly alkalic, potassic, and shoshonitic felsic and mafic magmatic rocks of bimodal composition which were erupted and intruded during a short period of Middle Miocene to Pliocene (3-18 Ma) lithospheric melting. Based on new Rb-Sr, Nd-Sm, and U-Pb isotope, and major and trace element geochemical data, parental source rocks of the Miocene melts were Late Proterozoic to Early Paleozoic crustal and mantle lithospheric assemblages which became heated and melted owing to a continent-continent collision in which west-vergent continental lithosphere derived from the Australian-New Guinea plate was subducted beneath easternmost Sundaland. Geochemical evidence (Elburg et al., 2003) and zircon dating (van Leeuwen et al., 2007) indicate continental crust may lie beneath much of west Sulawesi and it has an Australian origin (van Leeuwen et al., 2007).

The outline of the West Sulawesi Microcontinent is not known since the dispersion/slivering during the Paleogene complicated the outline. West Sulawesi Microcontinent may constitute the eastern margin of the Paternoster-Kangean Microcontinent. Smyth et al. (2007) and Hall et al. (2009) considered that East Java and West Sulawesi may form a single fragment, called the East Java–West Sulawesi, recognising that it may be a number of smaller fragments, interpreted to have rifted from the West Australian margin, and added to Sundaland in the mid Cretaceous.

The East Java–West Sulawesi block is interpreted as the Argo block (Hall et al., 2009).

DISCUSSION

The foregoing descriptions tell about the characteristics of each area important to build the paleotectonic setting of SE Sundaland. Based on the ages of lithologies on each area, the Jurassic and Cretaceous are the most important periods for the paleotectonic setting of SE Sundaland. Although Ciletuh, Luk Ulo, Bayat, Meratus, and Bantimala Complex as well as SE Java, Paternoster-Kangean, and West Sulawesi Microcontinents have broadly similar positions in the continental margin of SE Sundaland, they show different rock assemblages, lithologic characteristics, and ages. Different rock assemblages and ages will result in different geologic histories. The following discussions will argue some issues related to tectonic position of Bayat (Jiwo Hills) and Meratus Mountains before we discuss tectonic synthesis of the whole areas in SE Sundaland, and its petroleum implications.

Bayat/Jiwo Hills May Not a Subduction Complex and a Continuation of Luk Ulo

The rock assemblages and ages based on new mappings, age dating, studies partly published by Prasetyadi et al. (2002), Prasetyadi and Maha (2004), Prasetyadi et al. (2005), Prasetyadi (2007), and Setiawan (2013) showed that Bayat has no rock assemblages like those exposed in Luk Ulo area (Table 1). Pre-Tertiary rock assemblages reported by previous author (Bothé, 1929, 1934) (radiolarian limestone, radiolarian chert, amphibolite) have not been found. Minor basalt, gabbro and dolerite which was interpreted something like part of ophiolite (Ketner, 1976; Hamilton, 1979; Lunt, 2013) is not Cretaceous ophiolite, it is part of Eocene-Miocene extrusive and intrusive rocks intruded the phyllite and Eocene Wungkal-Gamping Formation. K-Ar dating of gabbro and basalt in Bayat area results in ages of 39.8 – 31.3 Ma (Eocene to early Oligocene) (Sutanto et al. 1994). Most of the metamorphic rocks exposed are phyllite rich in quartz.

Recent mapping, age datings, and studies show that Bayat may not a continuation of Luk Ulo which show rock assemblages related to Cretaceous subduction. No clear tectonic blocks of ophiolite and high pressured metamorphic rocks, no pelagic sediments of radiolarian chert and its associated siliceous shales and limestones found, no mélange as well. Dominant metamorphic rocks exposed are pyllites with subordinate slate, schist, and marble. All of these metamorphic rocks are rich in quartz and showing protoliths of continental pelitic rocks. The crystallization for metamorphism occurred in 98 Ma (mid-Cretaceous).

Recent paper by Setiawan et al. (2013) reported the discovery of high pressured glaucophane schists in West Jiwo Hill. However, this is not necessarily a high pressured metamorphism of subduction zone due to most of the rock assemblages related to subduction zone are absent in Bayat. Representative samples were plotted on the ACF diagram show that the protolith of metamorphic rocks from Jiwo Hills were derived from sedimentary rocks without any basic igneous rock signatures. This is different from those in the Bantimala, Luk Ulo, and Meratus Complexes, which have protolith of MORB, OIB, and arc signatures more than sedimentary rocks. Sedimentary rocks are much more developed in the continental crust. Therefore, it might have possibility that Jiwo Hills was a small continental crust.

Bayat may not comparable with Luk Ulo which show rock assemblages typical of subduction zone (dismembered ophiolite, HP to VHP metamorphic rocks, mélange, pelagic sediments). Mélange deposit, ophiolite, and oceanic plate stratigraphy (e.g. chert, pillow lava), which found in the Luk Ulo Complex were not observed in the Jiwo Hills (Setiawan, 2013). If Bayat was a continuation of Luk Ulo subduction trench in Early Cretaceous, the Bayat area should be in more oceanic position however, all rock assemblages in Bayat both pre-Tertiary and its overlying Eocene sediments were more continental, approaching terrestrial than those of Luk Ulo. The age of metamorphism and facies in Bayat (98 Ma, greenschist facies) compared to those of Luk Ulo (124-102 Ma, blueschist and eclogite) show a different history in metamorphism. Overlying Eocene sediments of slope deposits, olistostromal, of Karangsambung Formation in Luk Ulo area which show a depositional environment of slope of subduction trench, cannot be comparable with Eocene Nummulites-bearing Wungkal-Gamping Formation in Bayat area which show deposition in stable marine over a high area.

The author of this paper propose that Bayat was not a part of Early Cretaceous subduction zone in SE Sundaland continuing Luk Ulo. This confirmed Asikin (1974) who considered that basement rocks of the Jiwo Hill do not have the characteristics of mélange as those in Ciletuh and Luk Ulo areas. The continuation of Luk Ulo subduction trench located somewhere more to the north of Bayat area. Bayat was a part of SE Java microcontinent, located at its western margin. The microcontinent detached from NW Australia sometime in the Jurassic and docked Java to the east of Luk Ulo in mid-Cretaceous and resulted in high pressured metamorphism found in West Jiwo Hill (glaucophane schist, Setiawan et al., 2013).

Ophiolite Emplacement in the Meratus Mountains Could Be Different with Those of Ciletuh and Luk Ulo

The Meratus Mountains have long been believed as the Late Cretaceous subduction zone extending from the coeval subduction zone across Java exposed in Ciletuh and Luk Ulo areas. The present study shows that this is not as simple believed.

The Meratus mountain is made up of assemblage of ophiolite, submarine volcanics and deep-sea sediments. Presently, the mountains is a basement uplift separating the Barito from the Asem-Asem and Pasir Basins. The origin of the Meratus uplift has been debated. Many authors considered that the uplift related to compression due to collision of micro-continents to the east of Sulawesi and/or rifting of the Makassar Straits (such as van de Weerd and Armin, 1992). Recent seismic data in the Makassar Strait however, disprove this idea.

The Meratus Mountains is now understood as a collisional orogen/suture marking the collision of Schwaner and Paternoster micro-continents, ending the earlier subduction (Jurassic-Early Cretaceous). The suture was an oceanic crust in between the Schwaner and Paternoster microcontinents. The collision, taking place in the mid-Cretaceous had sandwiched the oceanic crust, detached part of the crust from the plate, re-emplaced the oceanic crust, and deformed them.

Satyana and Armandita (2008) proposed a new mechanism of the Meratus uplift based on tectonic interpretation of gravity and magnetic data (Figure 10). The Bouguer gravity anomaly map of the Meratus Mountains and its adjacent area is based on recent data acquired by Subagio et al. (2000). Some W-E and NW-SE gravity traverses crossing perpendicular relative the Meratus Mountains were surveyed. From the Barito Basin to the east of the Meratus Mountains, it can be seen that generally both positive and negative Bouguer anomaly trend SW-NE parallel with the mountain's trend called as the Meratus trend. The Barito Basin anomaly exhibits an asymmetrical form with a westward gentle gradient and a steep gradient in the east, suggesting a major fault contact along the western front of the Meratus Mountains. The lower range of anomalies with minimum value of -30 mGal in the northwest can be interpreted as the expression of thick sediments covering the basement. The Meratus Mountains is characterized by a positive gravity anomaly with a maximum value of +80 mGal.

Results of gravity modeling from all previous authors (Situmorang, 1987; Subagio et al. , 2000) indicate that in the eastern and central part of the profiles, an ultrabasic/ ophiolite (density 2.90 g/cm3, about 4 km thick) overlain granitic mass (density 2.68 g/cm3 thickness 26 km). The ophiolite layer underlay the pre-Tertiary rock units with a density of 2.40 g/cm3 and around 1 km thick and the Tertiary sediments with a density 2.20 g/cm3 and thickness of about 2 km. Gravity modeling implies continental collision. Note that the Meratus ultrabasic rocks are thin and overlying granitic continent (Subagio et al., 2000).

The gravity and magnetic data and modeling show that the Meratus Mountains is rootless. It is thin allochthonous oceanic slab, submarine volcanics and deep-sea sediments overlying thick subducted Paternoster micro-continent. Due to its buoyancy relative to the upper mantle, the Paternoster continent broke off its oceanic front and started to exhume in Late Cretaceous time. The exhumation of the Paternoster continent has uplifted the Meratus suture and effectively formed a subaerial mountain separating the adjacent basins in the Mio-Pliocene. This mechanism of continental exhumation provides a model for the origins of other collisional uplifts in Indonesia such as: eastern Sulawesi, Central Ranges of Papua and Timor (Satyana et al., 2008; Satyana and Armandita, 2008).

The importance of this result is that: (1) the ultrabasic rocks in the Meratus Mountains can be interpreted as thin allochtonous masses instead of deep seated intrusive body or rootless, (2) there is a continental crust beneath the Meratus ophiolite. Therefore, the Meratus Mountains is a thin allochthonous oceanic slab overlying a thick subducted Paternoster continent.

The presence of buoyant continental crust beneath dense thin oceanic slab and within dense upper mantle will cause the continental crust to resume its position to the surface. This process is called exhumation. Due to the buoyancy relative to the upper mantle, the subducted Paternoster continent broke off its oceanic front and started to exhume in Late Cretaceous time. The exhumation of the Paternoster continent has uplifted the Meratus ophiolite since then and effectively forming a subaerial mountains separating the adjacent basins in the Mio-Pliocene. This is the way of how the Meratus Mountains has been uplifted.

The origin of the Meratus Mountains accordingly related to subduction, accretion, and collision at the southeastern margin of the Sundaland from Late Jurassic to Late Cretaceous. During the Late Jurassic-Early Cretaceous there was Andean-type north-directed subduction of Meso-Tethys oceanic lithosphere beneath the Sundaland margin. At late Early Cretaceous, a Proterozoic-Paleozoic Gondwanan continental fragments called Paternoster collided with the southeastern part of the subduction zone. Part of the slab was detached became rootless and re-emplaced/ obducted onto the Paternoster microcontinent. Frontal part of the microcontinent underthrusted beneath the obducted ophiolite and accretionary prisms of Late Jurassic-Early Cretaceous subduction due to drag of the slab into the mantle. In the early Late Cretaceous, the frontal part of Paternoster broke off its junction to the slab, facilitating its exhumation since then and the Meratus Uplift initiated to take place. The collision of the continental fragments with the Sunda subduction system in the mid-Cretaceous would have necessitated outboard, oceanward migration of the subduction zone to facilitate continuing plate convergence.

The plate convergence in SE Kalimantan at the Meratus Mountains appears not similar to what occurred in Ciletuh and Luk Ulo. The plate convergence in the Meratus Mountains was earlier than those in Ciletuh and Luk Ulo, as shown by the age of its metamorphism related to subduction (180-165 Ma, Middle-Late Jurassic) and Middle Jurassic-late Early Cretaceous radiolaria, and involved obvious microcontinental collision and obduction of ophiolites which did not occur or obscure in Ciletuh and Luk Ulo areas. Present exposed ophiolites in Ciletuh and Luk Ulo may remnants of offscrapping process during continuous subduction of oceanic plate within trench (Andean-type orogene), whereas those in the Meratus Mountains were emplaced by obduction of part of oceanic slab due to collision of microcontinents (Alpine-type orogen).

Ben-Avraham and Nur (1982) proposed a model that all ophiolites are emplaced by collision in both Andean- and Alpine-type orogenes. In both geological settings, obduction of oceanic lithosphere onto the continental lithosphere is caused by the convergence of light, buoyant bodies such as oceanic plateaus, continental slivers, island arcs, or old hot spot traces. This is obvious for Meratus ophiolites but are unclear for those of Ciletuh and Luk Ulo, therefore warrant a different mechanisms for their emplacements, leading to different tectonic evolution discussed below.

Plate Convergence in South-Southeastern Sundaland during Jurassic - Cretaceous

Tectonic evolution of plates or microplates convergence in south-southeastern Sundaland (Central Indonesia) during Jurassic-Cretaceous based on petrotectonic assemblages of Meratus, Luk Ulo, and Bantimala have been discussed by Wakita et al. (1997), Parkinson et al. (1998), Wakita (1999), and Wakita (2000). The present study review these previous discussions, adding petrotectonic assemblages of Ciletuh and Bayat, and possible existences of some microcontinents in eastern Java, East Java Sea, and South Makassar Straits. New absolute dating of some rocks in the Meratus Mountains (Heryanto, 2010), Bayat (Prasetyadi, 2007), and published and unpublished data until recently in areas under discussion will affect the consideration on tectonic evolution of Central Indonesia.

Tectonic evolution of Central Indonesia during Jurassic and Cretaceous is based on key areas where petrotectonic assemblages of Jurassic-Cretaceous are exposed or exist, including: Ciletuh, Luk Ulo, Jiwo Hills/Bayat, Meratus Mountains, Bantimala and some microcontinents in this area (SE Java, Paternoster-Kangean, West Sulawesi microcontinents). Detailed discussion on each key area has been provided. Figure 11 shows paleotectonic setting of the region during the Early Cretaceous.

The first-clear history of plates convergence in this area was began by subduction of oceanic plate (Meso-Tethys Sea) in front of Paternoster-Kangean microcontinent beneath another oceanic plate in front of Schwaner/ SW Kalimantan microntinent in Early-Middle Jurassic. Based on Neogene-rotated Kalimantan principle, this subduction dipped to the north-northwestward (rotated anticlockwisely in Neogene to present westward). The maximum age of the slab is 200 Ma (boundary between Triassic and Jurassic) based on age dating of the serpentinized peridotite exposed in the Meratus Mountains (Coggon et al., 2010). The oceanic crust was also covered by radiolarian cherts of Middle Jurassic to late Early Cretaceous in age (Wakita, 2000). The subduction took place in 180-165 Ma (latest Early Jurassic-Middle Jurassic) (Zulkarnain et al., 1996; Wakita et al., 1998) based on HP metamorphics of Hauran Schists. The protoliths of the Hauran Schist were predominantly pelitic and basic rocks, showing that subducted oceanic plate is the source for metamorphism. Until late Early Cretaceous, radiolarian chert covered the subduction zone.

The latest Early Jurassic-Middle Jurassic subduction in " the Meratus Trench" continued through the Early Cretaceous until mid-Cretaceous. Somewhere around the Meratus Trench also developed the Bantimala Trench at which VHP metamorphic rocks of eclogite was formed deeply in the "Bantimala Trench" at 137 Ma from an environment of 18-27 kbar and 580-760 °C (Parkinson et al., 1998) derived from oceanic slab protoliths (Maulana et al., 2013). The Cretaceous complexes of the Meratus and Bantimala areas formed a single complex prior to the opening of the Makassar Straits.

Until by mid-Cretaceous time (around 100 Ma) subduction of the Meso-Tethys Sea took place everywhere in Central Indonesia, resulting in HP and VHP metamorphic rocks found in Ciletuh, Luk Ulo, Meratus Mountains and Bantimala areas. The subduction results in glaucophane schist of 117 Ma in Ciletuh, eclogite and blueschist of Luk Ulo showing mineral assemblages with jadeite and lawsonite (Miyazaki et al., 1998; Parkinson et al., 1998) and tourmaline (Kadarusman et al., 2010) with oceanic slab protoliths, 124-102 Ma in ages. Subduction continually took place in the Meratus Trench, resulting in Belawaiyan granite (101-131 Ma - Heryanto, 2010) and ~18 kbar or higher Hauran Schists and amphibolite formed in deep subduction environment, possibly between 30-50 km with ages of 108-119 Ma (Sikumbang, 1986; Sikumbang and Heryanto, 1994). Subduction continued in Bantimala Trench until 113 Ma based on K-Ar ages of phengite for the VHP rocks (Wakita et al., 1996).

In the meantime, some microcontinents called here as West Sulawesi and the Paternoster-Kangean microcontinents (the outlines of which are not known) after separating from NW Australia or northern Gondwanaland in Late Triassic-Jurassic (Metcalfe, 2013) drifted to the north approaching the Meratus and Bantimala trenches. The Jurassic shallow marine sedimentary rocks (Paremba Sandstone) exposed presently in Bantimala were deposited within this microcontinent. The upper part of the formation is rich in conglomerate which includes pebbles mainly of basalt and schist, *Ammonites*, gastropods and brachiopods of the Lower and Middle Jurassic (Sukamto and Westermann, 1992).

By Albian (112 Ma), the West Sulawesi microcontinent arrived at the Bantimala Trench (Wakita et al., 1996). After the arrival at the trench, the microcontinent was subducted, collided, and accreted within the accretionary wedge. After the collision and accretion of the microcontinental block, subduction ceased at the Bantimala Trench. Underthrusting of the light and buoyant continental fragment caused the rapid uplift and exhumation of HP metamorphic rocks. After metamorphic rocks of the Bantimala Complex appeared at the surface, they were eroded and provided 'schist breccia' and sandstone to a sedimentary basin in which radiolarian remains were deposited at a relatively high rate during the short interval between late Albian to early Cenomanian.

Paternoster-Kangean microcontinent, considered here separatedly from West Sulawesi, seems arrived later in the Meratus Trench. Considered as one microcontinent with West Sulawesi, several authors suggested that the arrival of Paternoster-Kangean microcontinent at the Meratus Trench was at Albian-Cenomanian (Situmorang, 1989), 120-115 Ma/ Aptian (Parkinson et al., 1998), middle Cretaceous between 110-115 Ma (Wakita, 2000), upper Early Cretaceous between 120-100 Ma (Satyana, 2003; Satyana and Armandita, 2008), 90 Ma - early Late Cretaceous (Hall et al., 2009). Just before the collision, the last subduction mélange formed in the Meratus Trench which now are outcropped in the Laut Island (Wakita, 2000), or Lokbulat melange, Heryanto, 2010).

Overlying unconformably ophiolites and metamorphics of Meratus are Late Cretaceous slope and fan deposits of Pitap Group, interfingering with volcaniclastic deposits of Haruyan Group (Heryanto, 2010). The more exact time of collision, emplacement of Meratus ophiolites and exhumation of deep-seated HP metamorphics can be estimated from the last stage of radiolarian chert and first inception of deposition of Pitap and Haruyan Group. The age range of Meratus radiolarian chert ended in late Early Cretaceous (Wakita, 2000) at around 110 Ma. The oldest dating of the Late Cretaceous volcaniclastic rocks is 83 Ma (Sikumbang, 1986) for andesitic lava of Pitanak Formation, Haruyan Group. The end of radiolaria indicated the area was too shallow presumably because of collision. The lowermost part of Late Cretaceous Pitap Group consists of various Early Cretaceous rock debris, indicating previously uplift and erosion of the Early Cretaceous Meratus ophiolites and metamorphics. Based on this, the collision of Paternoster-Kangean to the Meratus Trench took place in between 110-90 Ma. During around 20 million years in this interval, there was collision of Paternoster with SW Kalimantan/Schwaner, suturing of Meratus Trench, emplacement of ophiolites by obduction, early exhumation of metamorphic rocks, uplift and erosion of obducted ophiolites and some metamorphic rocks to compose basal fragments below the Pitap Group.

Renewed subduction occurred behind the Paternoster microcontinent which may initially a passive margin. The change of passive margin to active margin is considered due to "chocking" of Paternoster microcontinent to the Meratus Trench. This chock/collision had stopped the drifting of the microcontinent and spreading of oceanic plate behind it. To compensate tectonically this chocking, the uppermost part of oceanic plate in front of Paternoster was detached and obducted, the oceanic plate behind Paternoster due to continuing spreading by ridge push, changed from passive margin to become subduction zone. The subduction zone resulted in partial melting flowed up through Paternoster and triggered volcanism composed the Late Cretaceous volcaniclastic of Pitap and Haruyan Group. Granitic to dioritic intrusion in Pitap Group, dated 73-68 Ma (Heryanto, 2010), andesitic lava of Pitanak Formation dated 83-66 Ma (Sikumbang, 1986), tuff and tuff breccia all show these volcanic-magmatic suites of Late Cretaceous. Post-collision radiolarian chert of Bantimala, South Sulawesi (Wakita et al., 1996) recorded the intercalation of rhyolitic tuff layers along the Pateteyang River. This rhyolitic tuff of Bantimala may be partly contemporaneous with the Haruyan volcanics (Wakita, 2000).

The Late Cretaceous forearc sedimentation with depositional environments from slope to submarine fans developed above the Meratus and Bantimala Trenches. Above the Meratus Trench or at the forearc basin of the contemporaneous migrated trench behind the Paternoster, called here the Paternoster Trench, developed forearc deposits called Pitap Group (Heryanto, 2010, partly called as Alino Group of Sikumbang, 1986). The Pitap

Group consists of interbedded claystone, siltstone, sandstone, polymict breccia and conglomerate. Orbitolina-bearing limestone (Lower Cretaceous) present in the Pitap Group as olistoliths. Heryanto and Hartono (2003) included Pudak, Manunggul and Keramaian Formations into the Pitap Group. These three formations are interfingering to each other. Lower part of Pudak Formation consists of coarse fragments, very poor sorted from cm to several teens meters in diameters of fragments of volcanic rocks, limestones, sandstones, metamorphic rocks, igneous rocks, and ultrabasic rocks embedded within volcanic materials and partly conglomeratic. Gravity flow structure observed here. The deposits were interpreted as olistostromal deposits (Sikumbang, 1986). Upper part of Pudak Formation is finer-grained, mainly composed of volcaniclastic sediments, still showing the gravity flow structure. Sediments of Pudak Formation are interpreted to be deposited in slope to submarine fan. The slope was made by imbricated Early Cretaceous ophiolites, metamorphics and accretionary complex. Keramaian Formation is distal facies of Pudak Formation, interpreted to be deposited in deepwater of lower fan sediments. The Keramaian Formation consists of very fine-medium volcanic sandstones, interbedded with siltstone, claystone, fine clastic limestone, all showing turbiditic flysch deposits. Fossils, including *Radiolaria* are observed within this formation, showing age range from Late Cretaceous to Paleocene. Manunggul Formation is composed of breccia, conglomerate to mudstones deposited in upper fan to lower fan.

In Bantimala area, forearc sedimentation occurred in the trench slope during the Late Cretaceous. The tectonic setting of the Balangbaru Formation is interpreted as a small fore-arc basin, on the trench slope. The basement complex was uplifted, by thrusting from significant depth, prior to the deposition of the Balangbaru Formation. The Balangbaru Formation represents this sedimentation. Hasan (1991) analyzed the sedimentation and stratigraphic succession of this formation. The formation shows deep water flysch succession. Balangbaru Formation unconformably overlies a basement accretionary complex which is highly tectonized. The flysch itself is not internally deformed, but slightly tilted to the east. This suggests that by Upper Cretaceous times, when the flysch succession was deposited, Early Cretaceous subduction had ceased. Facies association and vertical sequence analyses indicate that the flysch succession was deposited by sediment gravity flows, including high- and low- density turbidity currents, and debris flow processes in a submarine fan environment, ranging from lower bathyal to abyssal environments. Hasan (1991) subdivided the Balangbaru Formation into three members based on the basis of lithostratigraphy and sequence. From bottom to top, these comprise : (i) the Allup Member, characterized by a chaotic fabric of debris flow deposits representing an inner fan facies association; (ii) the Panggalungan Member, characterized by 'distal turbidite' features representing an outer fan to basin plain facies association; (iii) the Bua Member, characterized by 'proximal turbidite' features representing a mid fan facies association. The composition of the sediment in the Balangbaru Formation shows progressive changes with time from the lower to upper part of the succession. Petrographic, heavy mineral and geochemical studies suggest that the sediments in the lower part were mainly derived from erosion of the basement accretionary complex, but the upper part was more influenced by a magmatic arc provenance.

Hasan (1991) considered that a ridge or structural high consisting of an uplifted basement accretionary complex separated the western province of the fore-arc basin (volcanic rich sediments of Upper Cretaceous age Pitap Group) from the flysch succession of the Balangbaru Formation (which lacks volcaniclastic material).

Subduction in the Meratus and Bantimala Trenches ended in mid-Cretaceous time due to collisions of the microcontinents. Subduction in Late Cretaceous time took place in the Paternoster Trenches resulting in Late Cretaceous volcaniclastics in the Meratus Mountains and may relate to some rhyolitic tuff which intercalated the radiolarian chert of lower Late Cretaceous in Bantimala area.

Subduction in Ciletuh and Luk Ulo in upper Early Cretaceous continued into the Late Cretaceous. Not much is known about the Cretaceous convergence in Ciletuh area due to scarcity of geological investigations. Tectonic relationship between Ciletuh and Luk Ulo is not known although some rocks of Ciletuh show similarities with those of Ciletuh. Ophiolites (peridotite, gabbro and pillow basalt), graywacke, limestone, red shales, serpentinite, phyllite, and glaucophane schist of

Ciletuh are similar to those of Luk Ulo. No radiolarian biostratigraphy has been conducted and published for Ciletuh, the presence of radiolarian chert is also not clear although its presence was reported by Suhaeli et al. (1977). No detailed metamorphic rocks study has been conducted and published for the Ciletuh, although an age of 117 Ma for the glaucophane schist was ever mentioned (the primary reference is unknown, mentioned in Prasetyadi, 2007). However, based on existing rocks and available publications, this study assumed that Ciletuh subduction was similar with Luk Ulo subduction, forming one belt of Cretaceous subduction.

The Luk Ulo Complex is characterized by rock assemblages indicating a continuous subduction from Early to Late Cretaceous (Wakita et al., 1994).

Radiolarian biostratigraphy indicates that the original succession before the tectonic disruption consists of pillow lava, limestone interbedded with chert, bedded chert, siliceous shale, shale and sandstone interbedded with shale in ascending order. This succession is identical to the mode of “oceanic plate stratigraphy” (Wakita et al., 1997) exemplifying the history from the birth of oceanic plate at the oceanic ridge to plate subduction at a trench after a long history of travel as moving oceanic floor. The chert in Luk Ulo Complex was a pelagic sediment deposited on the surface of the moving oceanic plate. The Luk Ulo Complex is a typical product of oceanic plate subduction from upper Early Cretaceous to Late Cretaceous.

However, the presence of subduction-related HP and VHP metamorphic rocks of glaucophane schists and eclogites in Luk Ulo only occurred in upper Early Cretaceous time (124-102 Ma), not continued into the Late Cretaceous, indicating something happened during the Late Cretaceous.

Uncontinued subduction-related metamorphism in Luk Ulo to Late Cretaceous possibly related to a microcontinent called as SE Java microcontinent which docked Java to the east of Luk Ulo in mid-Cretaceous time and resulted in HP metamorphism found in West Jiwo Hill, Bayat (glaucophane schist, Setiawan et al., 2013). The docking of the SE Java microcontinent ended the Cretaceous subduction zone from Ciletuh through Luk Ulo and eastern and northeastern extension. The timing of docking can be estimated from HP mica schist samples in Jiwo Hill, dating 98.05±2.10 Ma and 98.54±1.45 Ma (mid-Cretaceous/ Cenomanian - Prasetyadi, 2007).

During the latest Cretaceous, tectonically brecciated rhyolitic lava, with K-feldspar phenocrysts, and rhyolitic tuff, containing pumice are tectonically intercalated with sedimentary rocks of the Luk Ulo Complex, although exact relationships are unclear (Wakita, 2000). The age of the rhyolite (which was formerly reported as quartz porphyry) has been reported to be 65 Ma by the fission track method (Ketner et al., 1976). The Bantimala Complex is unconformably overlain by Paleocene propylitized volcanic rocks (Sukamto, 1986; Wakita et al., 1996).

During the earliest Tertiary, there was significant uplift everywhere in Western Indonesia. Part of the imbricated mélanges in Ciletuh and Luk Ulo Trenches exposed and became the provenances for olistostromal deposits at the lower part of middle Eocene Ciletuh and Karangsambung Formations deposited at the slope of trenches. Basement of Jiwo Hills, Bayat was also uplifted to shallow sea and became the substrate where shallow marine Wungkal-Gamping limestones were deposited and containing *Nummulites*. Meratus was still submerged in this time so it did not source the sediments for Eocene Tanjung Formations, but close to the Meratus there was development of pre-Tertiary basement topography in forms of rifted horst and grabens as suggested by gravity data (Kusuma and Darin, 1989). The source of these clastics was the exposed Schwaner Shield to the west and the intervening horst highs. The deposition and thickness of these sediments was governed by the topographic relief of the Paleocene horsts and grabens. The basal conglomerates of Tanjung contain an abundance of well rounded quartz pebbles to cobbles, with associated silicified rhyolite and volcanic debris (Kusuma and Darin).

The source of these sediments may uplifted Late Cretaceous Haruyan Group volcanics. The source for upper Paleocene Malawa Formation in Bantimala area was uplifted Late Cretaceous Balangbaru topographic highs (Hasan, 1991).

Paleocene to Eocene volcanic activity can be traced from South Sulawesi to the southwestern coast of Sumatra via Java Island (Soeria-Atmadja et al., 1998). Calk-alkali volcanic rocks are scattered throughout South Sulawesi (Yuwono et al., 1988) and Central Java (Suparka and Soeria-Atmadja, 1991). These data suggest that subduction-related magmatism occurred all along the southeastern margin of Sundaland at this time (Soeria-Atmadja et al., 1998).

However, definitive volcanic arc of Java did not come into being before Oligo-Miocene forming Old Andesite volcanic arc (presently the Southern Mountains of Java), and Middle to Late Miocene Camba-Enrekang volcanics in Western Sulawesi, showing the first definitive subduction zone in Tertiary was Oligo-Miocene subduction zone in offshore south Java, and Middle to Late Miocene subduction zone to the east of Western Sulawesi.
Following the collision of India to Eurasia in 50 Ma, Southeast Asia became the area of post-collision tectonic escape. Almost the whole SE Asia escaped extruded southwestward away from the collision. Major strike-slip faults and opening of marginal basins occurred as responses to escape tectonics. The opening of Makassar Straits was a response of tectonic escape. The Makassar Straits opening took place in the area of formerly Paternoster and West Salawati microcontinents. The opening occurred until Early Miocene, separating Meratus and Bantimala areas into their present positions.

Petroleum Implications

New configuration of plate convergence during Cretaceous in south and southeast Sundaland, especially by the presence of some microcontinents, has some implications for petroleum possibility.

Areas under discussion has produced petroleum for more than 120 years (East Java Basin) and more than 60 years (Barito Basin, west to the Meratus Mountains). Several discoveries are located at Paternoster Platform (including Ruby field, under development), and presence of numerous oil seeps in Banyumas area, to the southwest of Luk Ulo, and in South and West Sulawesi. All petroleum are sourced from and reservoired within Tertiary sediments. Many exploration wells drilled are also dry, especially in South Makassar and offshore areas around South Sulawesi.

All wells targeted Tertiary objectives. Newly acquired seismic data in East Java Sea, South Makassar Strait, and offshore south of East Java show the presence of pre-Tertiary bedded horizons that, not like in other areas of Western Indonesia which usually shows chaotic reflectors of typical basement, resemble prolific horizons of NW Shelf of Australia. Tectonic studies now consider that the pre-Tertiary horizons of East Java Sea, South Makassar, SE Java offshore areas are sedimentary sections overlying microcontinents that detached from NW Australia and emplaced in southeastern and eastern margin of Sundaland. When Tertiary objectives in these areas are failure due to some reasons, the targets of pre-Tertiary petroleum systems in South Makassar, East Java Sea, and SE Java Sea are interesting.

An origin of the SE Java microcontinent from NW Australia would imply the presence of Mesozoic and/or Palaeozoic sources might be present like those proven in NW Australia (Permian and Jurassic sections) (Figure 12). Deighton et al. (2011) indicated the presence of half-graben of probable Paleogene age in horizons now the inner forearc basin and appear to relate to gravity lows. If deeply buried enough they may provide matured equivalents of the Ngimbang lacustrine source rock found in the northern part of East Java. Seismic data also shows wide distribution of build ups may be reefal carbonates like that drilled by Alveolina-1 (Java Shell, 1972), offshore south of Yogyakarta, which intersected Middle Miocene reef carbonates with porosities of 25-40% and the Sandy facies may be expected in Paleogene half-graben and strong reflectors throughout the Mesozoic section suggests interbedded sand/shale/silt sequences. As for petroleum generation, assuming a modest geothermal gradient of 30°C/km, calculated temperatures are sufficient (>120°C) to expel hydrocarbons from the proposed Mesozoic section in the outer forearc basin. A thick forearc sag section was deposited in the last 15 Ma then peak temperatures should have been attained in the Late Tertiary, probably at present. Migration out of the basin should be facilitated by the relatively unfaulted sections updip.

As for the South Makassar Straits which overlies the Paternoster-Kangean and West Sulawesi microcontinents, newly deep seismic data (Figure 13) (Granath et al., 2009; Emmet et al., 2009) indicate that the pre-Tertiary in the East Java Sea terranes may be much more extensive and of Australian affinities opens the petroleum possibility. The easternmost Java Sea regions, underlain by the Kangean microcontinent may carry a stratigraphic section similar to the other NW Australian petroleum system or Australoid microcontinent like Buton which proven to be hydrocarbon area

(Satyana et al., 2013). All commercial hydrocarbon plays and production and also dry holes have been limited to the younger sequences above the base Middle Eocene unconformity, yet a substantial section lies below that unconformity. The younger and less-deeply buried strata in cores of synclines may be unmetamorphosed and may source pre-Tertiary hydrocarbon systems (Emmet et al., 2009).

CONCLUSIONS

1. Southern and southeastern Sundaland recorded the history of plate convergence as Jurassic to Late Cretaceous subduction zones in Meratus, Bantimala, Luk Ulo and Ciletuh. Jiwo Hills, Bayat which so far has been considered as continuation of Luk Ulo is not included into the subduction zone due to the absence of rock assemblage typical of subduction zone.
2. Subduction zone in Bantimala and Meratus Trenches chased in mid-Cretaceous due to docking of West Sulawesi and Paternoster-Kangean microcontinents, respectively. Subduction continued into the Late Cretaceous in Ciletuh and Luk Ulo but possibly with different characteristics than those of Early Cretaceous based on the presence of high pressured-very high pressured metamorphic rocks.
3. The presence of NW Australian-derived West Sulawesi, Paternoster-Kangean, and SE Java microcontinents give the petroleum possibilities of pre-Tertiary deposits overlying these microcontinents like their prolific counterparts in NW Shelf Australia, Bintuni, Seram, or Buton. Newly acquired seismic data show these possibilities.

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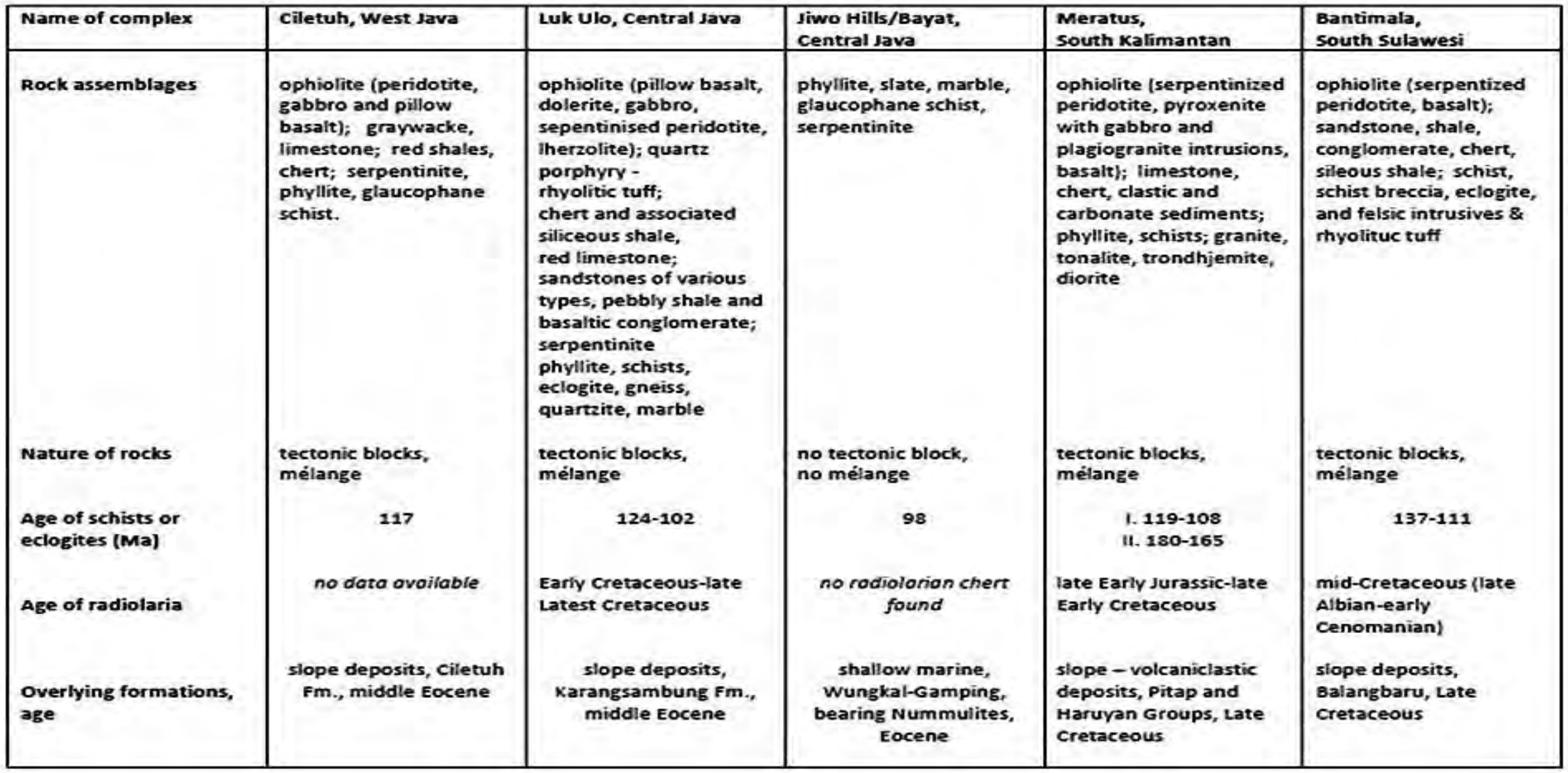
TABLE 1

CORRELATION OF JURASSIC TO CRETACEOUS ACCRETIONARY-COLLISION COMPLEX OF SOUTHERN AND SOUTHEASTERN SUNDALAND AND THEIR OVERLYING FORMATIONS.



Name of complex	Ciletuh, West Java	Luk Ulo, Central Java	Jiwo Hills/Bayat, Central Java	Meratus, South Kalimantan	Bantimala, South Sulawesi
Rock assemblages	ophiolite (peridotite, gabbro and pillow basalt); graywacke, limestone; red shales, chert; serpentinite, phyllite, glaucophane schist.	ophiolite (pillow basalt, dolerite, gabbro, sepentinised peridotite, lherzolite); quartz porphyry - rhyolitic tuff; chert and associated siliceous shale, red limestone; sandstones of various types, pebbly shale and basaltic conglomerate; serpentinite phyllite, schists, eclogite, gneiss, quartzite, marble	phyllite, slate, marble, glaucophane schist, serpentinite	ophiolite (serpentinized peridotite, pyroxenite with gabbro and plagiogranite intrusions, basalt); limestone, chert, clastic and carbonate sediments; phyllite, schists; granite, tonalite, trondhjemite, diorite	ophiolite (serpentized peridotite, basalt); sandstone, shale, conglomerate, chert, sileous shale; schist, schist breccia, eclogite, and felsic intrusives & rhyolituc tuff
Nature of rocks	tectonic blocks, mélange	tectonic blocks, mélange	no tectonic block, no mélange	tectonic blocks, mélange	tectonic blocks, mélange
Age of schists or eclogites (Ma)	117	124-102	98	I. 119-108 II. 180-165	137-111
Age of radiolaria	*no data available*	Early Cretaceous-late Latest Cretaceous	*no radiolarian chert found*	late Early Jurassic-late Early Cretaceous	mid-Cretaceous (late Albian-early Cenomanian)
Overlying formations, age	slope deposits, Ciletuh Fm., middle Eocene	slope deposits, Karangsambung Fm., middle Eocene	shallow marine, Wungkal-Gamping, bearing Nummulites, Eocene	slope – volcaniclastic deposits, Pitap and Haruyan Groups, Late Cretaceous	slope deposits, Balangbaru, Late Cretaceous

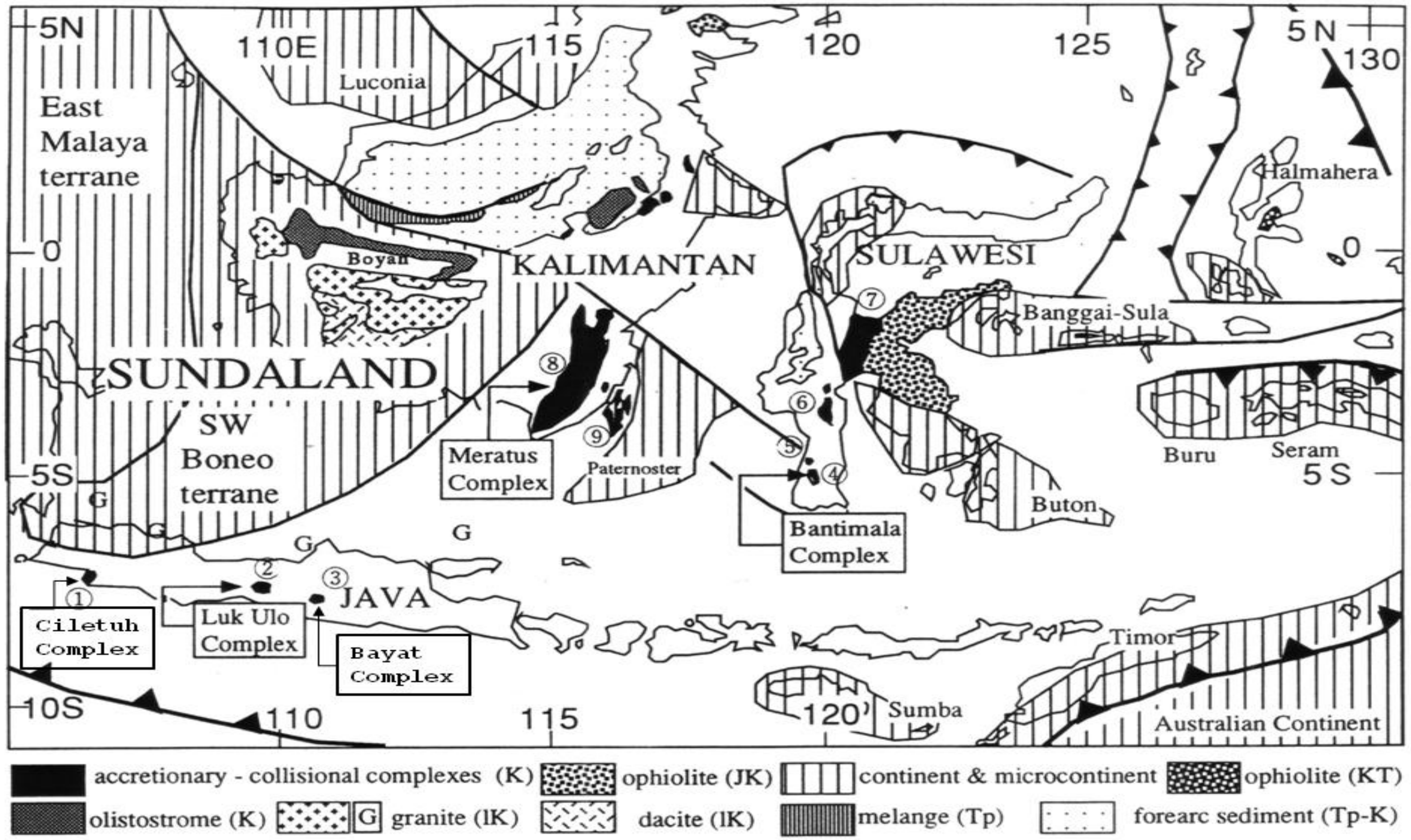


Figure 1 – Major components of Cretaceous accretionary-collision complexes of southern, southeastern, and eastern Sundaland (modified after Wakita, 2000). 1-Ciletuh, 2-Luk Ulo, 3-Jiwo/Bayat, 4-Bantimala, 5-Barru, 6-Latimojong, 7-Pompangeo, 8-Meratus, 9-Pulau Laut. Abbreviation of ages are: JK-Jurassic to Cretaceous, K-Cretaceous, lK-Early Cretaceous, mK-middle Cretaceous, uK-Late Cretaceous, Tp-Paleogene, KT-Cretaceous to Tertiary.

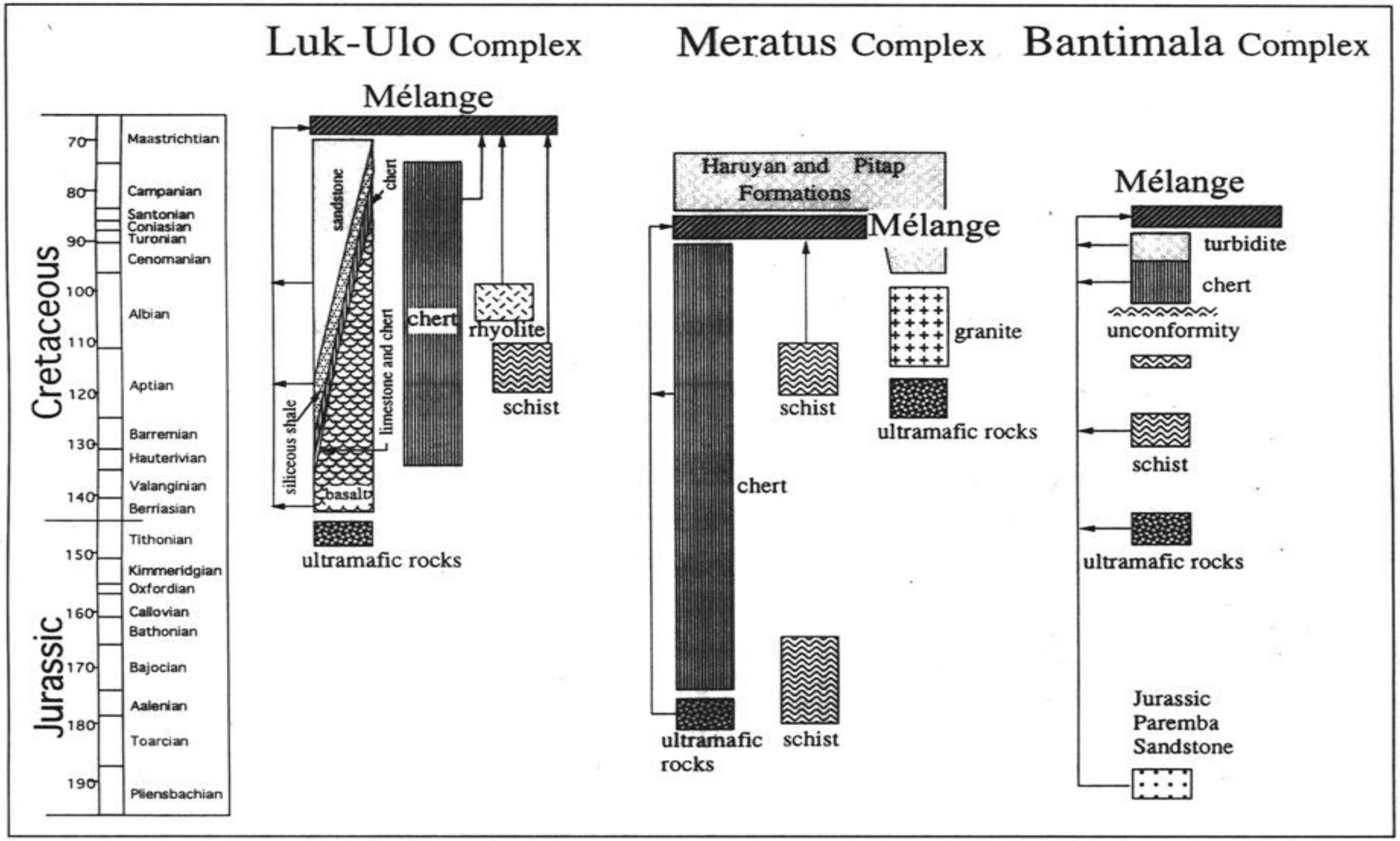


Figure 2 – Stratigraphic correlation of Luk ulo, Meratus, and Bantimala Complexes (after Wakita, 1999).

Figure 3 – Some pictures of Cretaceous accretionary-collision complexes of southern and southeastern Sundaland. A-pillow lava of Ciletuh. B-pillow lava of Luk Ulo, C-peridotite of Meratus Mountains, D-bedded radiolarian chert of Bantimala.

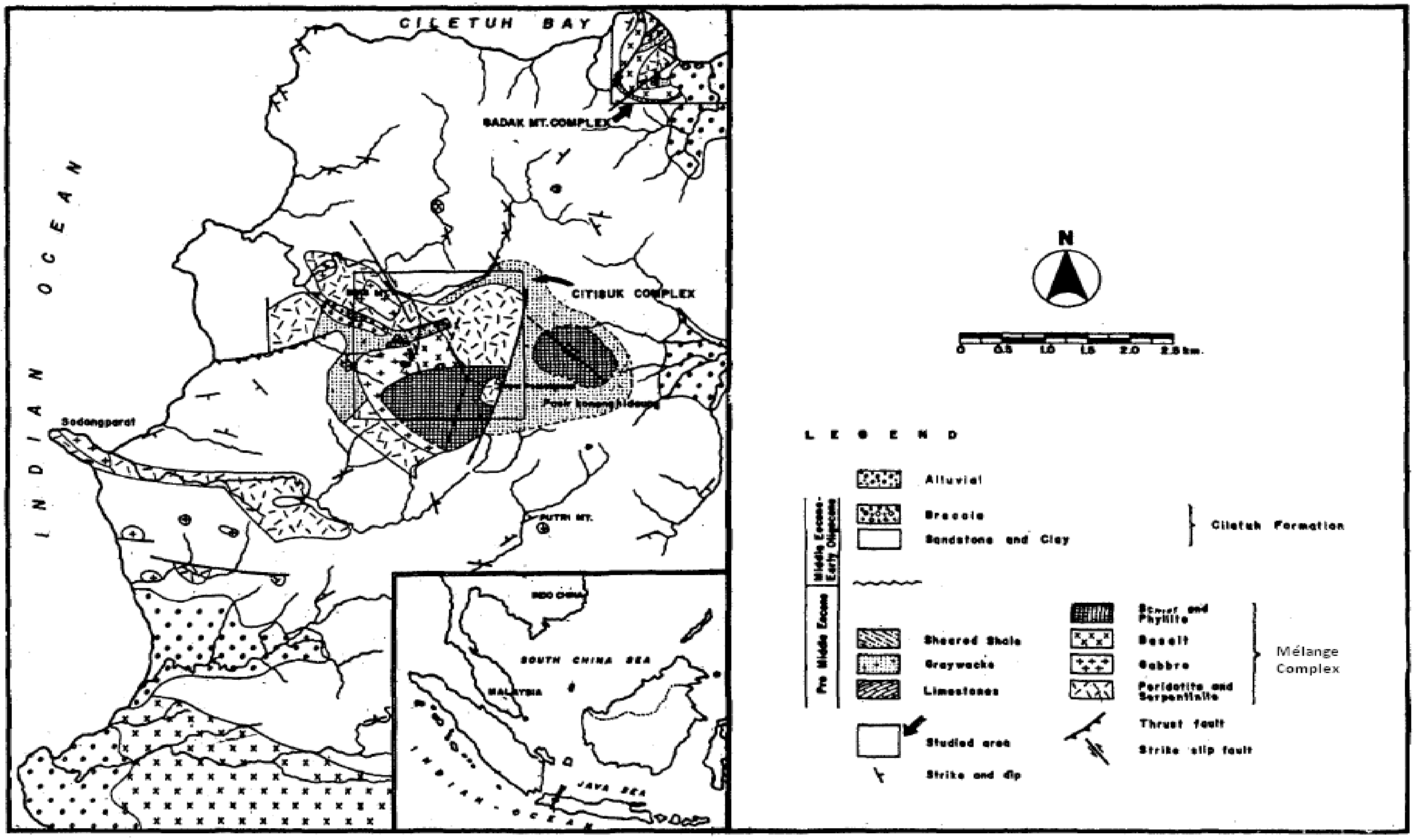


Figure 4 – Geological map of Ciletuh area, West Java (after Suhaeli et al., 1977). The exposures of Cretaceous accretionary complex are in Gunung Badak (north), Citisuk River (central), and Cibuaya River (south).

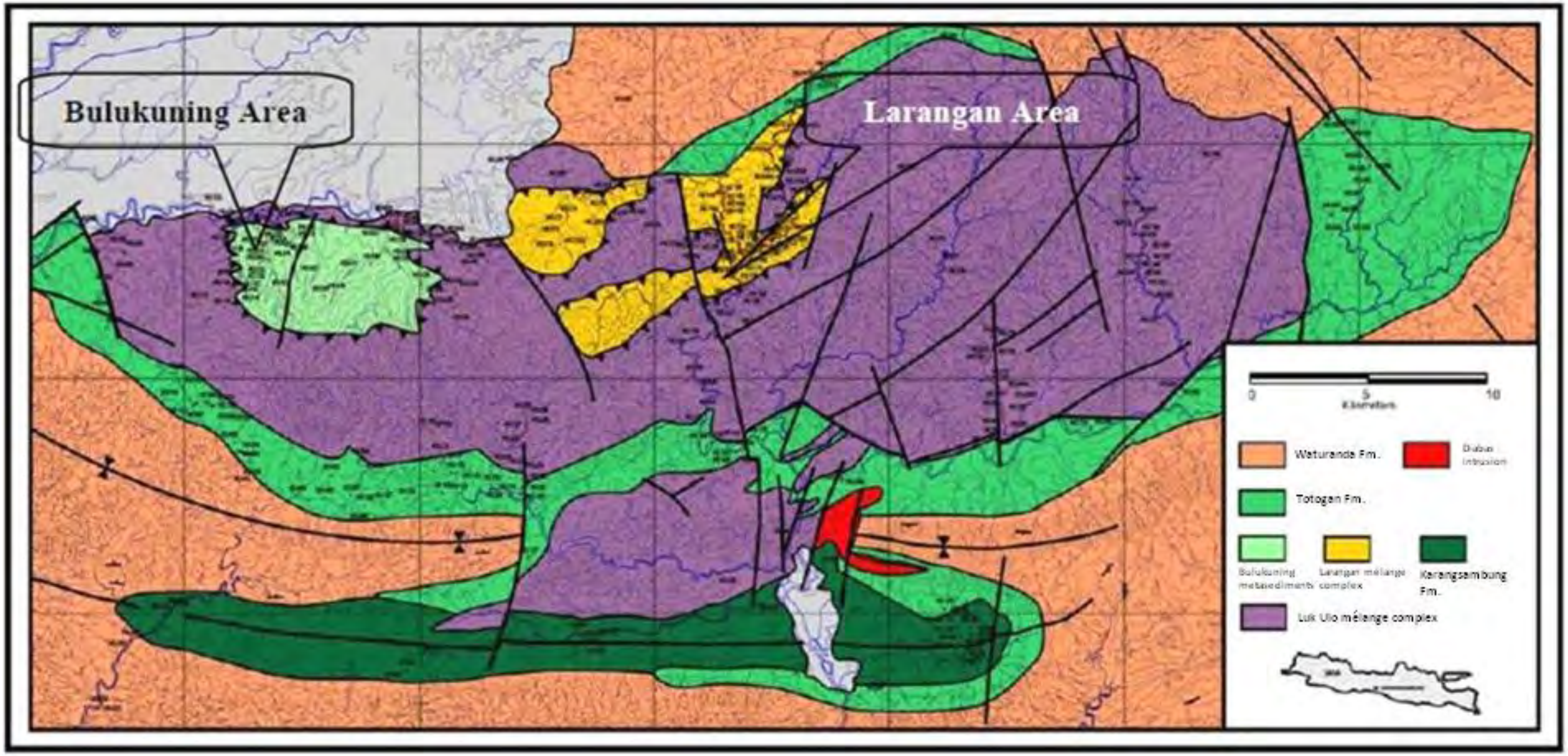


Figure 5 – Simplified and updated geological map of Luk Ulo area, Central Java (after Prasetyadi, 2007). New rock units of Cretaceous accretionary complexes are shown: Bulukuning and Larangan complexes.

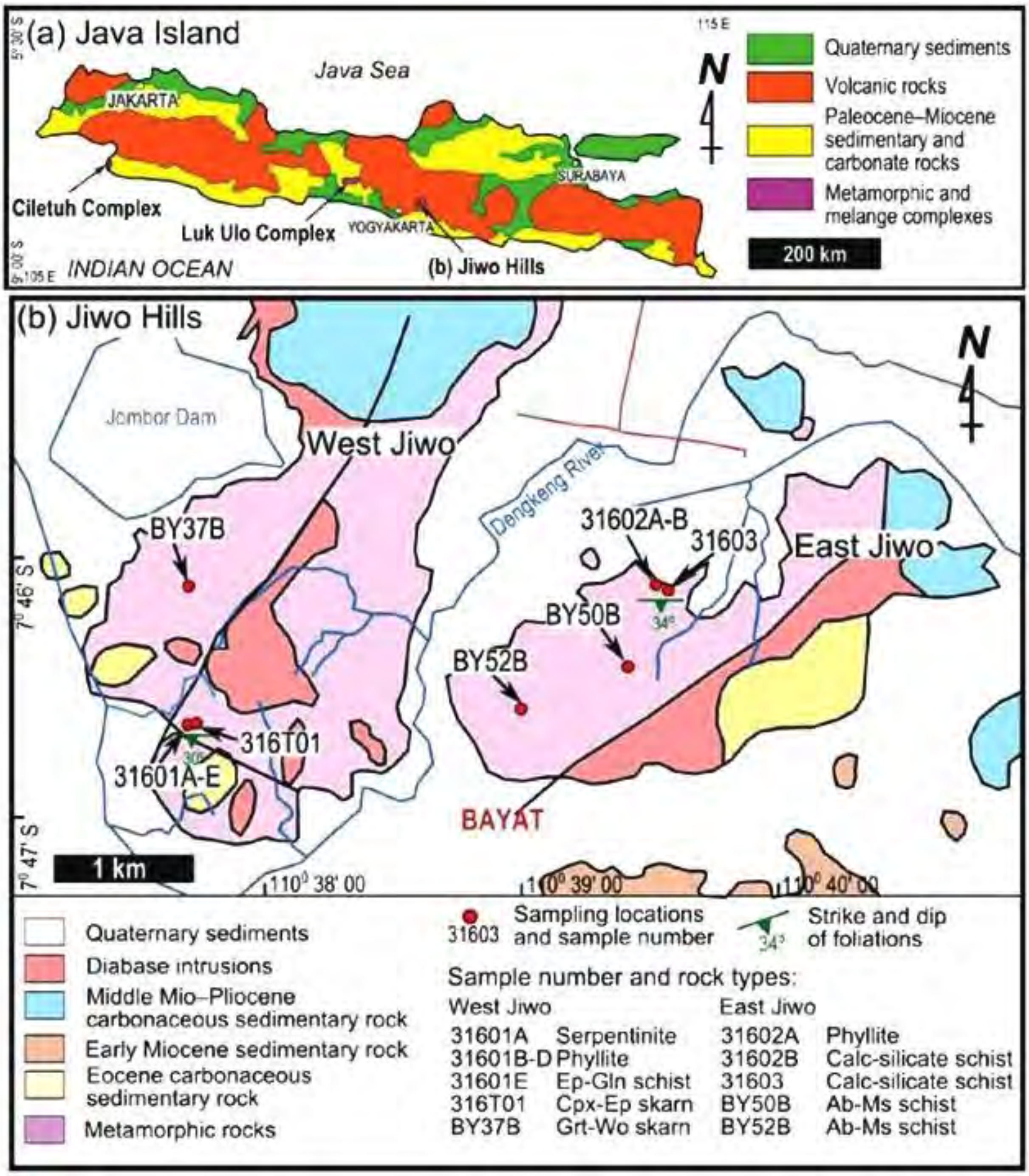


Figure 6 – Simplified geological map of Jiwo Hills, Bayat area, Central Java (after Setiawan et al., 2013).

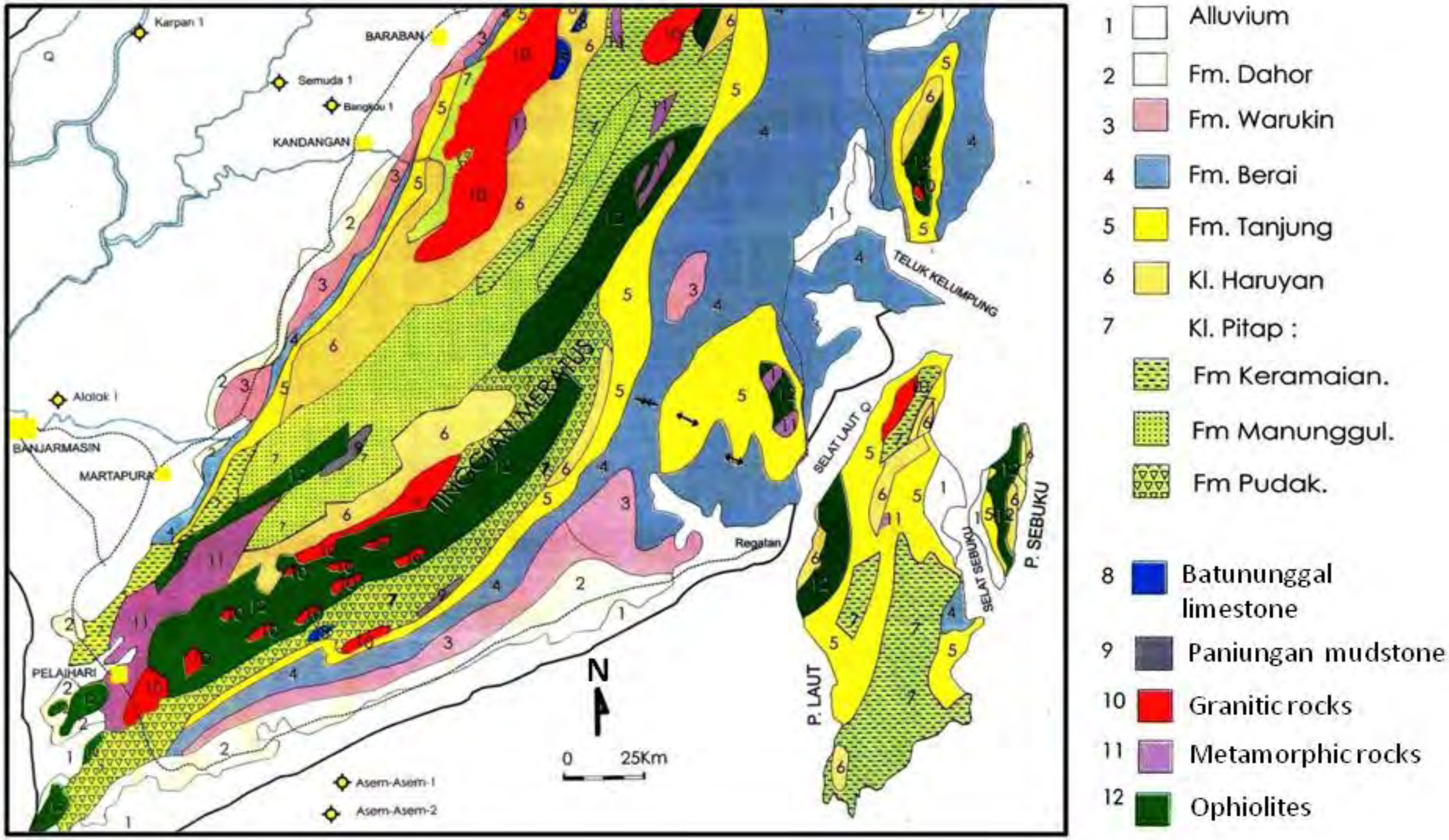


Figure 7 – Simplified geological map of the Meratus Mountains, with new pre-Tertiary stratigraphic subdivisions (after Heryanto, 2010).

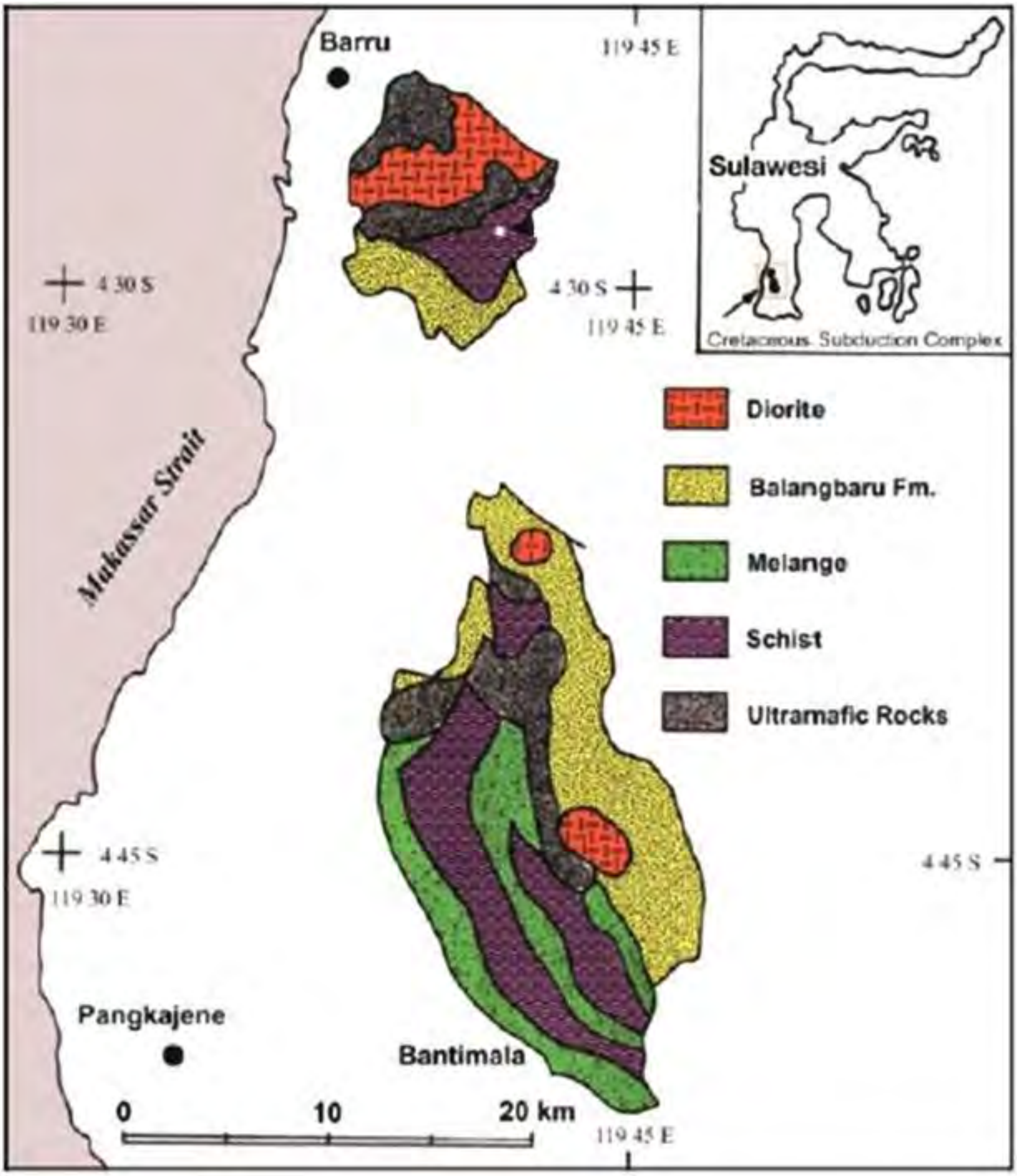


Figure 8 – Geologic map of Cretaceous subduction complex in South Sulawesi, including Bantimala and Barru areas (after Sukamto, 1982, Wakita *et al*., 1996; Munasri, 2013).

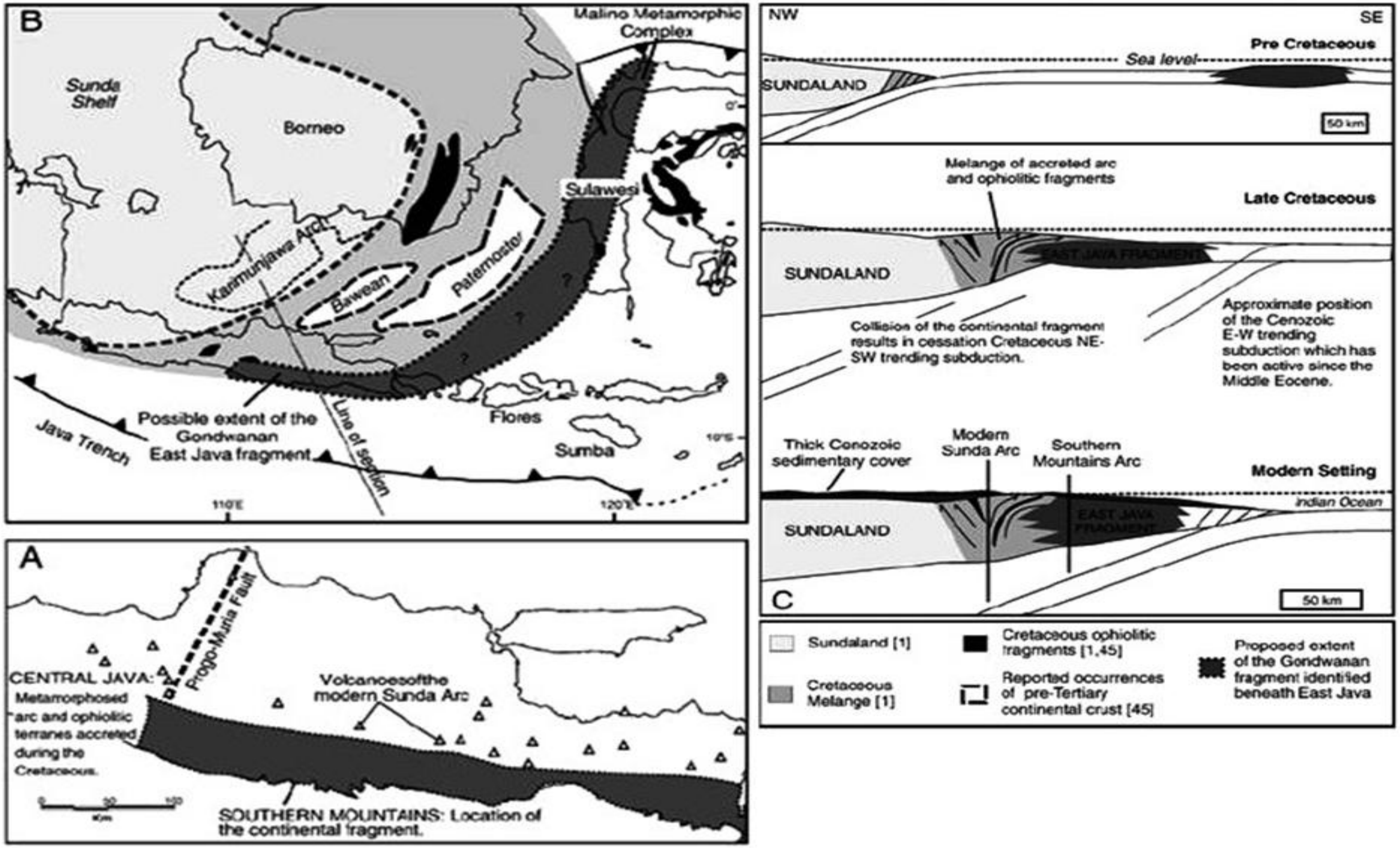


Figure 9 – Character of the crust on the southeastern margin of Sundaland. A. Extent of the continental fragment onshore East Java. B. Map showing the proposed extent of the East Java fragment beneath Sulawesi. C. Sketch cross-section (after Smyth et al., 2007).

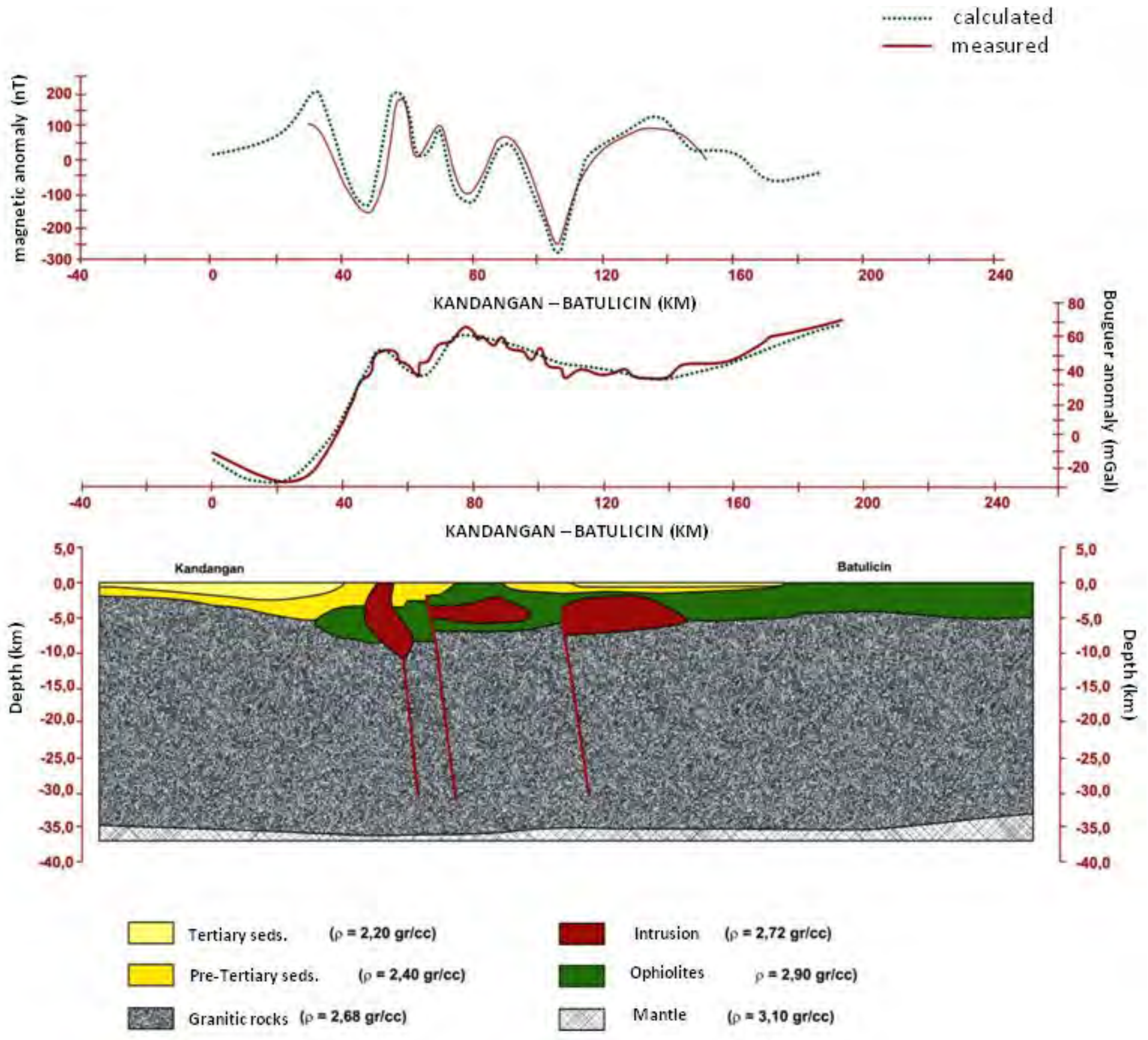


Figure 10 – Gravity and magnetic data and crustal modeling, showing that the ophiolite of the Meratus Mountains is detached slab overlying the Paternoster microcontinent due to obduction (after Satyana and Armandita, 2008).

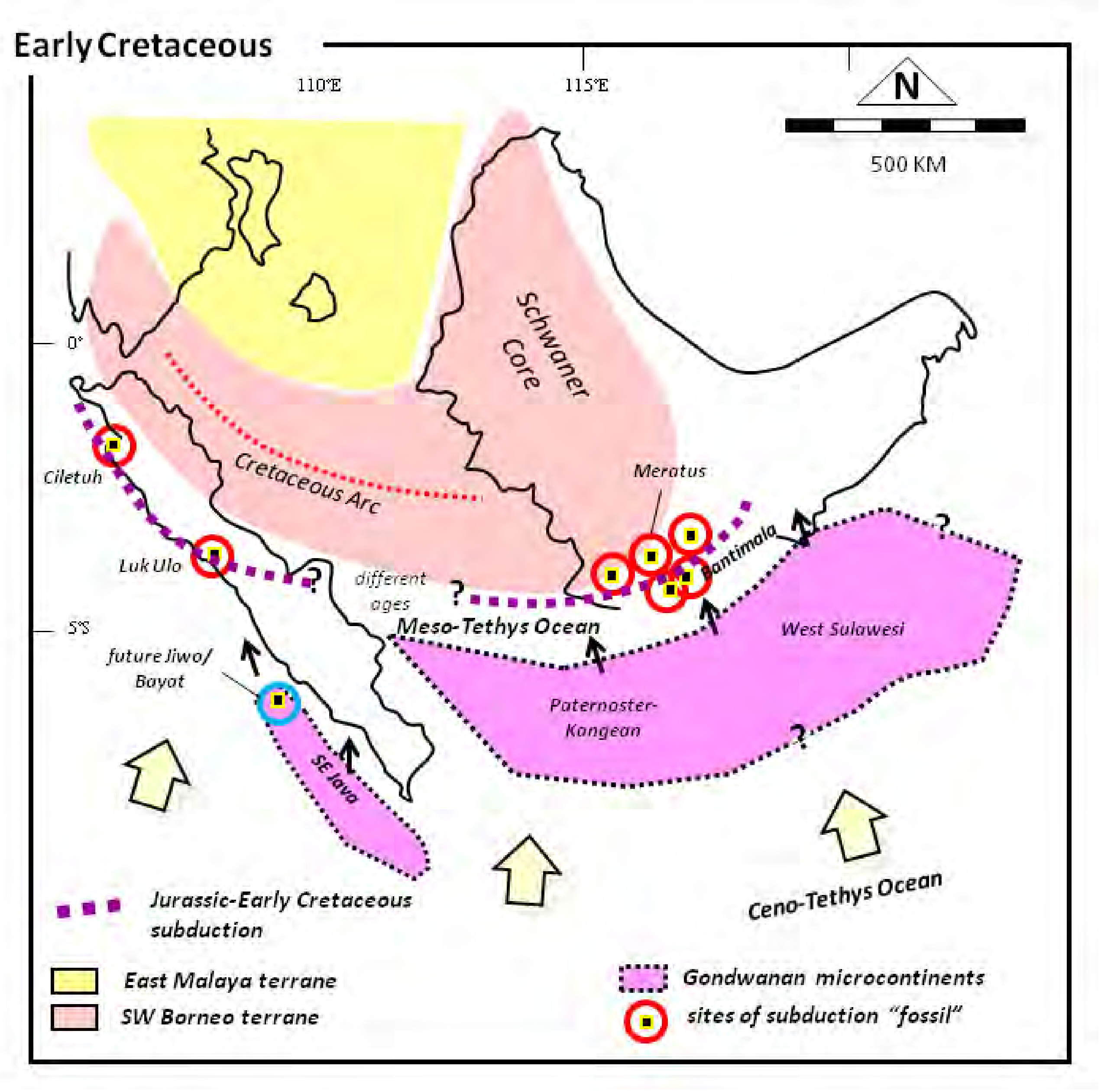


Figure 11 – Paleotectonic setting of Early Cretaceous in southern and southeastern Sundaland. Early Cretaceous subduction occurred in Ciletuh, Luk Ulo, Meratus, and Bantimala, consuming the Meso-Tethys Sea. Bayat was at the front of SE Java microcontinent. Paternoster-Kangean and West Sulawesi microcontinents was about to docking the Meratus and Bantimala Trenches.

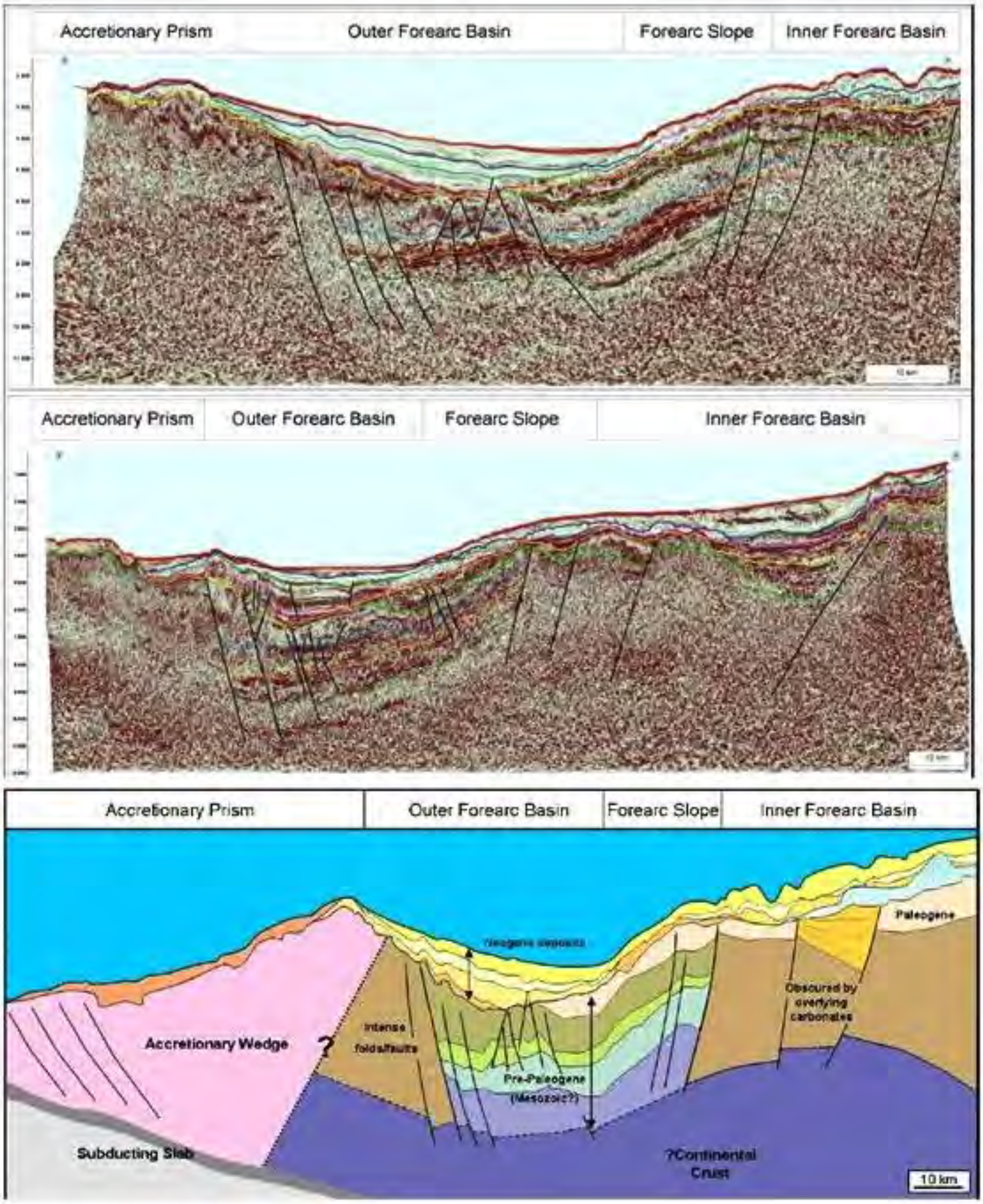


Figure 12 – Dip seismic lines showing main structural units. Location to the south offshore of East Java. The possible Mesozoic section can clearly be seen beneath the outer forearc basin and forearc slope below 5 seconds TWT, while a probable Paleogene half-graben is present beneath the inner forearc basin on the lower section. The presences of Mesozoic bedded horizons open the opportunity of Mesozoic petroleum systems which have been proven in NW Shelf of Australia, from which this microcontinent originated (after Deighton et al., 2011).

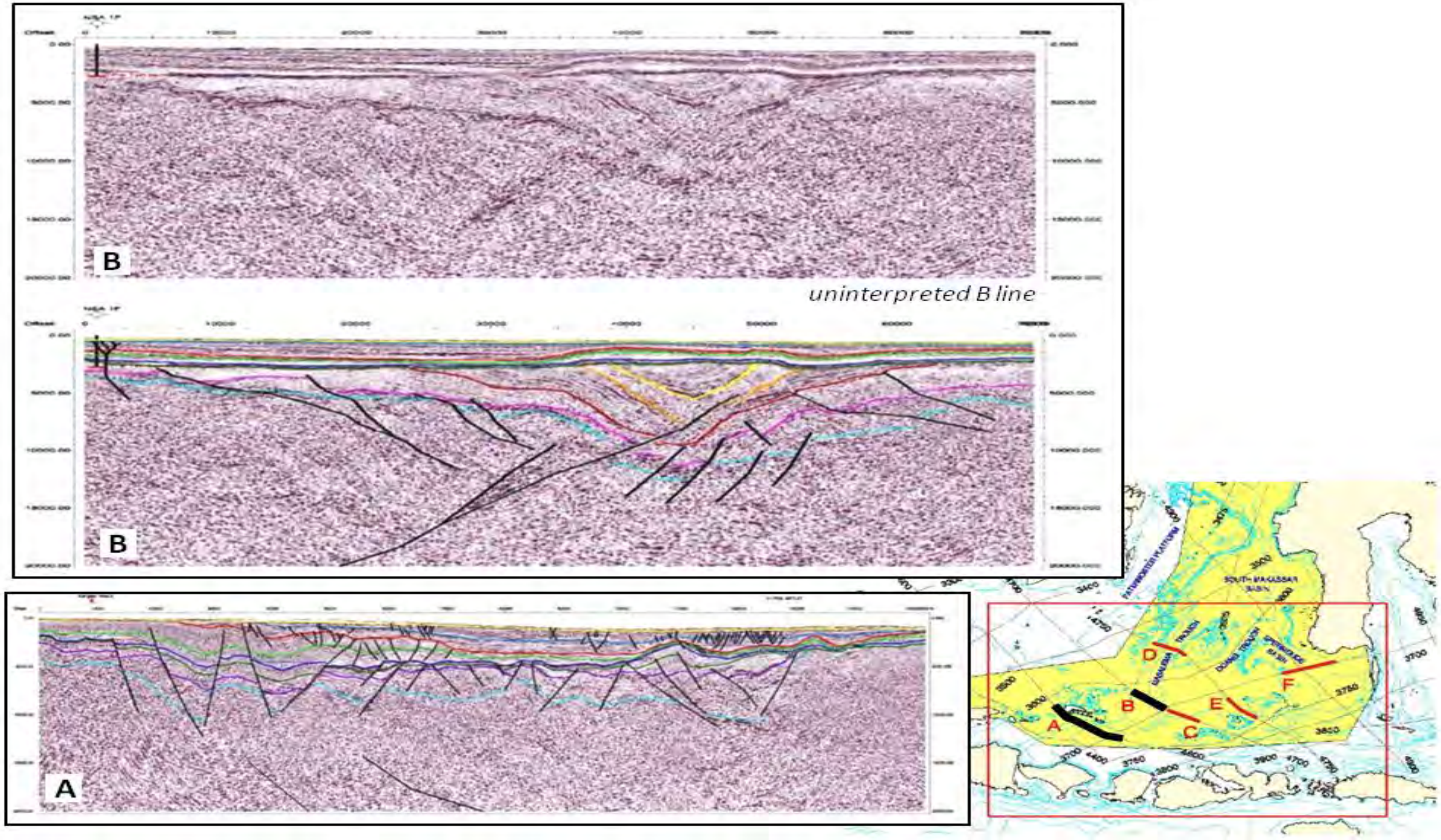


Figure 13 – Two deep seismic lines at southern margin of Kangean microcontinent, showing the presences of bedded horizons until deep. Horizons, from shallowest to deepest; yellow = Late Pliocene, light blue = Late Miocene, red = Early Miocene, light green =Middle Oligocene, dark blue = Late Eocene, dark green = base Middle Eocene, lavender = LateCretaceous? and cyan = crystalline basement (after Emmet et al., 2009). The bedded horizons provided pre-Tertiary petroleum systems like those proven in NW Shelf of Australia, Bintuni, Seram, and Buton.