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# CILETUH SUBDUCTION, SOUTHWEST JAVA – NEW FINDINGS: NATURE, AGE, AND REGIONAL IMPLICATIONS

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## ABSTRACT

Ciletuh, southwest Java has been well known as one of the places in Java where pre-Tertiary basement rocks are exposed (Verbeek and Fennema, 1896; Duyfjes, 1940; van Bemmelen, 1949; Sukamto, 1975). In plate tectonic point of view, Ciletuh has been known as place outcropping melange complex related to pre-Tertiary oceanic plate subduction (Thayyib *et al.*, 1977). Ciletuh subduction regionally has been linked to the Cretaceous subduction zones of Luk Ulo/Karang Sambung (Central Java) and Meratus Mountains (South Kalimantan) (Hutchison, 1973; Asikin 1974; Hamilton, 1979).

Ciletuh subduction however, has not been dated using metamorphic rocks formed in its subduction zone. Its link to Luk Ulo and Meratus subduction zone only based on the presence of melange, which also lacks of data Meanwhile, subduction zones of Luk Ulo and Meratus have been dated and analysed.

We herewith present the results of new field studies and various analyses carried out in the last five years of the Ciletuh subduction complex. The indication of Cretaceous subduction has not found from the date measurement, Ciletuh shows Eocene related subduction. Most of the ophiolites were island-arc tholeiitic or island-arc basalt formed in supra-subduction zone. The overlying olistostrome deposits were younger than previously considered and lasted until early/middle Miocene. Some of the basaltic pillowed lava is considered as part of the ophiolite, while the ones at Gunung Badak is more likely a part of the early Miocene Jampang volcanism. Link of Ciletuh to Early Cretaceous subduction of Luk Ulo is not supported by geochronological data. The new knowledge of Ciletuh subduction implies the pre-Tertiary and Paleogene geology of Java, and petroleum prospectivities of the Paleogene objectives of southern West Java. New problems arise and need more field data and analyses to find out the answers.

## INTRODUCTION

Geologically, Ciletuh, Sukabumi, SW Java is an important place (Figure1). Ciletuh is well known in Indonesian geology as one of the three places in Java Island that expose the oldest rock complex. The other two places are Luk Ulo/ Karang Sambung in Kebumen and Jiwo Hills/ Bayat in Klaten, Central Java (Verbeek and Fennema, 1896; van Bemmelen, 1949). In discussing the plate tectonics of the Indonesian region, Ciletuh and Luk Ulo with their melange complex exposures are concluded as part of the Late Cretaceous to Eocene subduction zone in western Indonesia which also continued to Sumatra and Kalimantan (Hutchison, 1973; Asikin, 1974). Hamilton (1979) also included the Jiwo Hills as a the Cretaceous melange complex.

Luk Ulo, Jiwo Hills, and Meratus Mountains (South Kalimantan) are relatively widely studied and published, while Ciletuh is not. The first detailed study of the Ciletuh melange was published by Thayyib *et al.* (1977), then the geological information about Ciletuh was added by Schiller *et al.* (1991). To date there has been no extensive and detailed publication about Ciletuh after Thayyib *et al.* (1977). Classically, Ciletuh has been positioned in the Cretaceous subduction zone with Luk Ulo, Jiwo Hills, and Meratus Mountains. However, there has been no-age dating performed at the Ciletuh as has been done in three other places.

Satyana (2014a, b) published a new tectonic reconstruction for the southeast Sundaland including a review of the Ciletuh-Luk Ulo-Jiwo Hills-Meratus Mountains Late Cretaceous subduction zone. This reconstruction based on various new data, removed Jiwo Hills from the subduction zone in the absence of the melange complex, similarly as mentioned by

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Asikin (1974), put older subduction zone for Meratus, and added the new Bantimala subduction zone in South Sulawesi. Satyana (2014a, 2014b) connected Ciletuh with Luk Ulo subduction zone based on a geochronological data cited from unpublished study which later the data proved to be wrong. This study corrects the Ciletuh geochronology and presents new data of Ciletuh age-dating based on laboratory analysis.

In the last five years or so, intensive geological research has been carried out in Ciletuh, especially by Faculty of Geological Engineering (FTG), University of Padjadjaran (Unpad). This is related to the proposal of Ciletuh as the Global Geopark and FTG Unpad to become a technical institution to prepare this proposal. Several students from the Magister and Doctoral Programs of the FTG Unpad worked in the Ciletuh geology have published their research reports (Ikhram *et al.* 2018, 2019 and Hardiyono *et al.* *in prep*). In 2018, Pertamina and FTG Unpad conducted surveys and studies at Ciletuh related to the potential for of the Pre-Tertiary hydrocarbons in the Sundaland (referred to Satyana, 2014a, b). These works significantly added the Ciletuh data that has implications for new knowledge of Ciletuh subduction geology, particularly its nature and age.

This paper aims to publish the new knowledge of the Ciletuh geology benefitting new data, which is important to unravel the tectonics and its regional setting.

## METHODS

This study is based on hard data (rock samples) obtained by new geological surveys and latest laboratory analyses. Various analyses were carried out on rock samples, including: petrography, petrochemistry (major, trace, rare earth elements), facies-protolith-thermo-barometric analyses of metamorphic rocks, geochronology of igneous and metamorphic rocks. Previous publications, and new data from the field and laboratory analyses are the main data to construct new interpretations in this study.

## RESULTS

### Melange of Ciletuh: Previous Investigations

Ciletuh area was firstly mapped by Duyfjes (1940) as part of systematic geological mapping of Sukabumi area from 1939 to 1941. Next mapping efforts was by Suhanda (1967), and Sukamto (1975) who had systematically mapped the area at scale of 1:100,000 as part of the Jampang and Balekambang Map Sheets.

The first detailed study of Ciletuh melange was conducted by Thayyib *et al.* (1977, see Figure 2). In Ciletuh, they found an ultramafic to mafic igneous rock complex (ophiolite complex) that consist of: peridotite, gabbro, pillowed lava; sedimentary rocks (red clay, black shale, greywacke, limestone), and metamorphic rocks (serpentinite, schist, phyllite, quartzite). These rocks are tectonically mixed, and the relationship between them cannot be explained by the basic principles of normal stratigraphy, the lateral relationships of each rock unit are often broken (tectonic contact). The rock outcrop map and geological sections show the discontinuities in the shape and distribution of the rock units. Contact between two rock types is often a fault. Sheared, blackish-grey, hard shale appears as a matrix between these rock types. The characteristics of rock complexes like this, both in their variety and in their structural relationships, are often referred to melange complexes as a result of the subduction process of oceanic plate positioned beneath the continental plate.

There are three areas where the melange complex exposed in Ciletuh (Sukamto, 1975; Thayyib *et al.* 1977): Gunung Badak in the north, Gunung Beas-Citisuk-Sodong Parat in the central, and Cibuaya in the south (Figure 2). The Gunung Badak complex on the north coast of Ciletuh Bay exposes: peridotite, gabbro, pillowed basalt, phyllite, serpentinite, greywacke, limestone and shale which is a complex of ophiolite and continental margin (Satyana, 1989). In the Gunung Beas-Citisuk-Sodong Parat complex which also includes Tegal Pamidangan, Tegal Cicalung, Tegal Butak exposed: peridotite, gabbro, pillowed basalt, which is associated with red clays, phyllite, schist, and greywacke. This complex is the widest and most complete melange outcrop of Ciletuh, which represents a group of ophiolite, deep sea sedimentary rocks, continental margin, and subduction zone metamorphic rocks. Sukamto (1975) proposed the name "Pasir Luhur Schist" for this metamorphic rock group in the central part of Ciletuh and the Gunung Beas Formation for its ophiolite group. The southernmost melange outcrops are found along the Cibuaya River to the coast south of Ombak Tujuh Bay. The exposed basalt lava here does not show deformation as found in the north. Sukamto (1975) proposed the name Citirem Formation for this basalt lava outcrop.

Thayyib *et al.* (1977) classified the three areas of Ciletuh melange complex into three groups:

ophiolite and the overlying deep sea sedimentary rocks, continental sedimentary rocks, and metamorphic rocks that formed in the subduction zones. Associated with this rock complex is found sheared shales of a dark, hard, blackish grey colour. These shales function as a matrix of ophiolite fragments, sedimentary rock, and metamorphic. There are no planktonic foraminifera or nannofossils within, so determining the age is difficult. However, in the Ciletuh Formation unconformably covers the melange complex, reworked fossils of planktonic foraminifera aged Upper Cretaceous are found namely *Pseudotextularia sp.* and *Globotruncana sp.* These fossils are thought to come from shales that form a melange matrix, so that the age of the Ciletuh melange is estimated to be Upper Cretaceous or pre-middle Eocene based on the middle Eocene age for the Ciletuh Formation which covers the melange complex.

Schiller *et al.* (1991) published several results of absolute age measurements of Ciletuh ophiolite samples using the K-Ar dating method. Gabbro samples from the tip of Sodong Parat showed an age of 50.9 ± 2.1 Ma (early Eocene). Age measurements were also carried out on the basal fragments of the Ciletuh Formation conglomerate which showed the age of 89.6 ± 3.0 Ma, Upper Cretaceous. This basalt fragment is thought to have originated from pillowed lava ophiolite proposed by Sukamto (1975) as the Citirem Formation.

According to detailed study conducted by Asikin (1974), based on the similarity with the Luk Ulo melange complex located in Central Java, about 370 km to the east, the Ciletuh melange complex is a continuation of the Luk Ulo melange complex (Thayyib *et al.*1977). All works based on this Asikin's study had also considered the same thing.

**New Mapping of Ciletuh**

Together with the proposal of Ciletuh to become a Unesco Global Georpark in 2015, geological works carried out in the area by Faculty of Geological Engineering (FTG) Padjadjaran University (Unpad). These geological studies had enriched the scientific aspects as one of many other requirements in the global-geopark proposal. The Unesco had finally agreed Ciletuh as the Global Geopark in April 2018, along with another geological survey in the central area of Ciletuh conducted by a joint venture between Pertamina Exploration and FTG Unpad. One of the goals of the survey was to confirm reported in the previous investigation done by Thayyib *et al* (1977). Analyses of the collected rock samples from the survey lasted until mid-2018. In addition to this, the Geological Survey of Indonesia conducted more detailed systematic geological mapping at a scale of 1: 50,000 in the Ciletuh area. The new mapping was conducted by FTG Unpad with the map called ~~as~~ the Cikadal-Lengkong map sheet (Rosana *et al.*2019 see Figure 3).

Recent geological investigations mentioned above have significantly added geological data of Ciletuh area. Based on detailed mapping and various rock analyses, there are many significant changes to the geological knowledge of Ciletuh compared to those explained in the previous literatures. Rosana *et al.* (2019) mapped the Ciletuh melange complex as composed of eight rock units, from old to young: (1) Ppsp-Peridotite, serpentinized - early Paleocene, (2) Ppsb -Serpentinite, brecciated - early Paleocene, (3) Ppsea - Schist, epidote - amphibolite – middle Paleocene, (4) Ppskm - Greenschist - late Paleocene, (5) Ppft - Phyllite - late Paleocene, (6) Ppgb -Gabbro, microgabbro - Paleo-Eocene, (7) Ppbsb - Basalt, brecciated - Paleo-Eocene, (8) Ppsc - Scally clay (matrix of melange) - Paleo-Eocene. Younger than this melange complex, the five rock units have been mapped, from old to young: (1) Peccl-Red claystone and sandstone - early Eocene, (2) Pecl - Ciletuh quartz sandstones - middle to late Eocene, (3) Pobm - Ciletuh melange breccia - late Oligocene, (4) Nmbk - Kunti basalt - early Miocene, and (5) Nmbmk - Kunti andesitic breccia - early Miocene. Diorite Intrusion (Di), found to the south of Gunung Badak, is the youngest rock here (upper early Miocene).

Some recent pictures of Ciletuh landscapes, melange rock complex, with the overlying formation, and Jampang volcanics located adjacent each other while some are also overlapping features can be seen on Figures 4 and 5.

**Absence of Blueschist**

Blueschist is metamorphic rock that form in subduction zones at main depths of about 20-35 km, 6-10 kilobars, 200-400° C (high pressure low temperature / HPLT metamorphic rock) (Maulana, 2019). The presence or absence of blueschist is important for explaining subduction zone because it indicates the depth and character of the subduction. Blueschist and eclogite (ultrahigh pressure) have been found in the Cretaceous subduction of Bantimala-South Sulawesi and Luk Ulo (Satyana, 2014a, b). Thayyib *et al.* (1977) reported that blueschist (glaucophane schist) was found extensively in the central part of Ciletuh (Pasir Luhur). The schist shows good foliation, greenish gray color, dominant minerals of mica, plagioclase, and also glaucophane. However, all later field studies in Ciletuh never found the blue schist as reported by Thayyib *et al.* (1977).

Systematic mapping by Sukamto (1975) reported no blueschist was found. The metamorphic of Ciletuh area composed of greenschist, micaschist, amphibolite schist, phyllite, and quartzite. The metamorphic are green and greyish green, contains veinlets of calcite, quartz, and pyrite. The unit is exposed at Pasir Luhur, and in small outcrops alternating with gabbro and peridotite along Cikepuh River.

Schiller *et al.* (1991) stated that the metamorphic rocks in Ciletuh only consist of greenschist, mica schist, amphibolite schist, phyllite, and quartzite. Suparka (1995) and Dirk (1997) reported that metamorphic rocks in Ciletuh are only the rocks formed in cataclastic / dynamic low-grade metamorphism of zeolite and green schists facies. Recent studies have found the same thing. Prasetyo *et al.* (2016) concluded that the metamorphic rocks in Ciletuh indicate low-grade metamorphism in the greenschist-facies. Ikhram *et al.* (2018, 2019) stated the same based on petrographic analysis that the metamorphic rock types found in Ciletuh are greenschist, schistose amphibolite, phyllite, and quartzite. Mapping by Rosana *et al.* (2019) defines the distribution of metamorphic rocks: greenschist, schist-epidote amphibolite, phyllite, and serpentinite.

This study also did not find blue schist in the area that reported to expose the blue schist by Thayyib *et al.* (1977). To confirm this, in 2018 a detailed measured section was carried out on the same river at which Thayyib *et al.* (1977) reported the finding of blueschist outcrops, but our field studies did not find the rocks (Figures 6, 7). What Thayyib *et al.* (1977) described blue schist was actually green schists. Therefore, the absence of the blue schist in Ciletuh area may indicate a shallow subduction.

**Absence of Radiolarian Chert**

Radiolarian chert, which is commonly found in subduction complexes is not found definitely in the Ciletuh area. Its fragments in the polymict breccias of the Ciletuh Formation deposited unconformably above the Ciletuh melange is never found, except fragments of red clays/shales. Rosana *et al.* (2019) mapped the presence of the red clay units (Peccl - early Eocene) although it is very limited and there has been no further research on whether these red clay units are part of the Ciletuh Formation or Ciletuh melange. The field study by Munasri *et al.* (2000) also did not find the radiolarian chert definitely. Thayyib *et al.* (1977) however, reported that they found chert locally to the north of Tegal Pamidangan. Suparka (1995) also reported chert was sometime found in association with basalt. The absence of radiolarian chert in Ciletuh area may indicate a shallow subduction like also supported by the presence of shallow facies of metamorphism. Radiolarian cherts discovered so far in subduction complexes of Indonesia are from Mesozoic age (Munasri, personal communication), this may also relate to the age of subduction in Ciletuh area which is Eocene.

**Ciletuh Greenschist Facies**

Greenschist is the most widely exposed metamorphic rock in Ciletuh (Figure 8). The metamorphic rocks were formed in association with subduction. In a much limited distribution, it is found phyllites and epidote-amphibolite schists. While serpentinite is mostly found to associate with ophiolite suite (peridotite). Greenschist facies is formed in tectonic environment of 10-25 km depth, 300-400 °C, and pressure of 2-6 kilobars (Maulana, 2019). The studies by Prasetyo *et al.* (2016) and Ikhram *et al.* (2018) provide the latest data regarding this metamorphic rock. This study has conducted the absolute age dating of greenschists in order to determine the age of Ciletuh subduction.

Prasetyo *et al.* (2016) conducted field study at Gunung Badak and Tegal Pamidangan. The metamorphic rocks at Gunung Badak consist of Grt-Ms-Qz schist, Ms phyllite, quartzite, and serpentinite. Metamorphic rocks in Tegal Pamidangan consist of Ms-Qz phyllite and slate. These metamorphic rocks show low-grade metamorphism in the greenschist-facies. Protoliths of these metamorphic rocks suggest pelitic (clay), ultramafic, and quartz-rich rocks. The presence of serpentinite among these low-grade metamorphic rocks indicates that the metamorphic environment still correlated with the environment of the oceanic crust or mantle. Low-grade metamorphic rocks develop in near-surface (shallow) subduction system.

Ikhram *et al.* (2018, 2019) observed that greenschists come from two types of protoliths: pelitic (clay-rich) and basic (basaltic igneous rock). Metapelite greenschist contains the following minerals: quartz, plagioclase, muscovite, chlorite, sphene, and magnetite (Figure 8). Graywacke can also source the greenschist. Metabasic greenschists contain minerals: plagioclase, epidote, actinolite, chlorite, calcite, hornblende, opaque minerals. Protoliths can be: metavolcanoclastic, metabasic and metagabbro. It was concluded that the metamorphic rocks in the Ciletuh melange were formed in the metamorphic greenschist facies. The two protolith origins that are continental (clay-rich) and basic (oceanic, metabasic, metagabbro) indicate the environment of the plate convergence (subduction). These low-pressure related metamorphism is usually associated with shallow subduction.

Older field studies by Suparka (1995) and Dirk (1997) reported the same findings that some ophiolite complex of Ciletuh underwent metamorphism in cataclastic /dynamic low-grade metamorphism of zeolite and green schists facies.

**Petrology of Ophiolite Assemblages**

Ophiolite is the main rocks of the Ciletuh melange complex (Figure 9). Mapping by Sukamto (1975) divided Ciletuh Ophiolites into two groups: (1) Ultrabasic Rocks of Gunung Beas consisting of peridotite (initial map: Mgp), serpentine and gabbro (Mgg) which are referred to as intrusive rocks and (2) Citirem Formation (Mcv) which is a volcanic rock in the form of diabase and basalt. Thayyib *et al.* (1977) divided Ciletuh Ophiolite into: (1) peridotite, (2) gabbro, (3) basalt. Suparka (1995) divided Ciletuh Ophiolite into: (1) peridotite, (2) gabbro, (3) diabase, (4) basalt lava. Rosana *et al.* (2019) divided Ciletuh Ophiolite into (1) peridotite, serpentinized-Ppsp, (2) gabbro, microgabbro-Ppgb, (3) basalt, brecciated-Ppbsb. Each rock is bounded by tectonic contact, characterized by brecciation and milonitization.

Detailed petrological and petrographic studies of Ciletuh's ophiolite comes from Rochman *et al.* (1983), Suparka (1995), and Dirk (1997).

Peridotite is unevenly exposed in the northern and middle areas of Ciletuh. These rocks are exposed in Gunung Badak, Tegal Pamidangan, Tegal Butak, Tegal Sabuk, and Sodong Parat, mapped as “Ppsp” and “Ppsb” rock units (Rosana *et al.* 2019). Peridotite outcrops are generally found in hilly areas (Figure 9), which are only covered with grass, making it easy recognizable in the field; characterized by greenish black outcrop, hard, compact, and showing feature of tectonic deformation such as brecciation and milonitization, strong erosion. Almost all of the peridotite rock samples analysed show a fairly strong serpentinization process; characterized by the predominance of antigorite and chrysotile serpentine minerals.

The texture of the rock shows the presence of medium - coarse crystals (up to 4 mm), presence of a mesh and bastite structure indicating the presence of olivine and pyroxene minerals as primary components. Besides olivine and pyroxene relics, spinel and also mineral ores (magnetite) are observed in several samples. Based on the existing primary minerals that have not been altered, the amount of primary minerals can be estimated as follows: olivine 55-60%, pyroxene (orthopyroxene and clinopyroxene) 20-25%, spinel 5-10%, magnetite 5-10%, so the type of peridotite is mainly lherzolite. Presence of harzburgite and wherlite types are also reported.

Serpentinization is another common phenomenon observed in peridotite outcrops, where the peridotite lenses appear to be surrounded by serpentinite as a strongly eroded base mass; this appearance is known as a fish structure. Another secondary feature that is observed is the hydrothermal conversion process to produce secondary minerals, including minerals of clays, epidote, chlorite, prehnite. Serpentine is represented by chrysotile and antigorite; the latter mineral is generally present occupying a large proportion of primary crystals. Chrysotile is present in relatively small numbers, there are filling in fine cracks, forming fine veins; fibrous and needle-like crystal forms with a fiber pattern / needle shapes perpendicular to the direction of the filled fracture. Most of the serpentine is thought to be the result of an alteration of the minerals olivine and pyroxene.

Gabbro outcrops are found at Gunung Beas, and in the Tegal Cicalung area as well as in the Sodong Parat area (Figure 9); in the form of massive outcrops, mapped as “Ppgb” rock unit (Rosana *et al.* 2019). Gabbro dikes in the Citisuk River intrude peridotite, named as rodingite where the gabbro is garnetized (Koesmono, *in* Suparka, 1995). Almost all of the gabbro outcrops found in the field have also underwent changes to produce secondary minerals, including epidote and chlorite/ actinolite, which generally result in greenish coloured rocks. Microscopically, gabbro shows an ophitic and non-ophitic texture; in the latter, this rock sample is characterized by a cumulus - layered texture, consisting of plagioclase, pyroxene, hornblende minerals in addition to secondary minerals such as clay minerals, sericite, prehnite, tremolite/ actinolite, muscovite, calcite, and quartz as a result of the alteration process. Zoisite and almandine are only found in samples from rodingite (Sodong Parat location). Plagioclase is present as the main mineral, characterized by a carlsbad-albite twin with anorthite content ranging from 50-70%. These minerals generally have undergone alteration to produce clay, carbonate, and sometimes-prehnite minerals. The pyroxene in the gabbro sample has often been altered to tremolite / actinolite, and chlorite. Secondary quartz is present in the form of fine veins.

Basalt and diabase are fine-grained mafic rocks of the Ciletuh ophiolite complex. Basalts generally show a pillowed structure while diabase usually present in the form of massive black to grey outcrops, mapped as “Ppbsb” rock unit (Rosana *et al.*2019). These rocks are exposed in several places including Citisuk River and Cibuaya River. Basaltic pillowed lava to the west of Gunung Badak was analysed and dated by Hardiyono *et al.* (*in prep.*) to be not part of Ciletuh ophiolite complex, but it is more likely part of Jampang submarine volcanic of early Miocene in age called as Kunti basalt (Nmbk) by Rosana *et al.* (2019), detailed in specific part below. Basalt is often found in association with red claystone and sometimes chert as well (Suparka, 1995). Like gabbro and peridotite outcrops, both basalt and diabase generally have undergone strong deformation, marked by features of brecciation, milonitization, and also the presence of cracks that have been filled with secondary altered minerals. This alteration process is quite dominant in all basalt and diabase outcrops found in the field. Basalt and diabase represent fine - medium grained mafic rock. Basalt is characterized by fine grain size, textured intergranular - intersertal; some samples showed a porphyritic texture with phenocrysts amounting to not more than 3%. Meanwhile, diabases generally shows the texture of diabases, medium grain size (up to 2 mm). Both basalt and diabase are formed by plagioclase, pyroxene, hornblende as primary minerals which generally have undergone a process of alteration. Secondary minerals that appear in these two rocks are clay minerals, prehnite, chlorite, tremolite. Plagioclase is present as the main mineral besides pyroxene. This mineral shows a carlsbad-albite twin, and most of it has been altered into secondary minerals such as clay, carbonate, and epidote minerals. Pyroxene is greenish in colour, consisting of clinopyroxene and orthopyroxene, both of which have been partially altered into secondary amphibole minerals (tremolite/ actinolite), muscovite, and chlorite. Mineral ore (magnetite) is rarely found in basalt and diabase.

Dirk (1997) mentioned that Ciletuh ophiolite has undergone a metamorphism process in the form of a low degree of cataclastic / dynamic in green schist facies with the appearance of modified secondary minerals. This ophiolite has also been influenced by the low pressure (directed pressure / stress) in the metamorphism process, characterized by the formation of foliation and lineation textures. Because of these characteristics, Dirk (1997) proposed that the Ciletuh ophiolite better be called as the metamorphosed ophiolite complex, not just the ophiolite complex.

**Geochemistry and Tectonic Setting of Ophiolite**

The place where igneous rocks occur or the tectonic setting of igneous rocks, including the ophiolite complex, can be identified by examining the petrochemical characteristics of igneous rocks. Classically, it is generally known that ophiolite complexes in subduction zones originate from ophiolites formed in the mid-oceanic ridge (MOR) which were then carried by moving oceanic plates to the subduction zone and then tectonically is emplaced to the plate margin (definition of 1972’s Penrose conference). However, it was later discovered that ophiolite complexes can also occur in subduction zones (in situ) near volcanic arc systems. Such ophiolite complexes are referred to as supra-subduction zone (SSZ) or volcanic arc ophiolites and have their own petrochemical characteristics that are different from the ophiolite complexes from MOR (Moores, 1982; Dilek, 2003; Dilek and Furnes, 2014; Coleman, 2014). New classification of ophiolite types was proposed by Dilek and Furnes (2014) (Figure 10).

So far, the mafic-ultramafic rocks (ophiolite complex) in the Ciletuh area are considered to have come from a MOR of Indian oceanic plate, Mesozoic in age, which was emplaced due to subduction in the Late Cretaceous (Thayyib *et al.*, 1977; Hamilton, 1979). Petrochemical data of the ophiolite complex and geochronology of the subduction (dated on subduction-related metamorphic rocks) will show the actual origin, nature, and tectonic setting of the ophiolite.

Inorganic geochemical research (petrochemical analysis - major compounds / oxide) of Ciletuh ophiolite rock was first carried out by Panigoro (1981), additional data were from Rochman *et al.* (1983), Suparka (1995), and Dirk (1997). This present study conducted more complete analysis (major compounds, trace and rare earth elements) for the ophiolite. Several data of the most recent and previous petrochemical analysis are included in this publication (Tables 1, 2, 3). Although these analyses have been carried out spanning a long period of time (almost 40 years), the results of the analysis are more or less the same.

Rochman *et al.* (1983) reported that peridotite and gabbro from Citisuk River show very low $K_2O$, $Na_2O$, $TiO_2$, and $Cr_2O_3$. $Mg_2O$ content is quite high. This shows a formation in an arc system. Suparka (1995) reported that both basalt, diabase and gabbro and lherzolite peridotite rocks mostly show island arc tholeiitic affinity; characterized by low $K_2O$ content (0.06-0.95%) and FeO/MgO ratio > 1, only two rock samples showed tholeiitic affinity originating from the MOR (Figure 11).

Dirk (1997) analysed five samples of ophiolite consisting of two samples of peridotite, two samples of basalt, and one sample of gabbro were selected and analysed for their major compounds of oxides. The data from Dirk were also interpreted by Munasri *et al.* (2000). Peridotite rocks in the Ciletuh ophiolite complex is characterized by poor $TiO_2$ but relatively rich in CaO content (1.3-1.5%). This CaO is contained mostly in clinopyroxene. This shows a formation in an arc system which is characterized by poor $TiO_2$, $AI_2O_3$, and $MnO_2$. Rich in CaO elements in peridotite can occur in the process of percolation or impregnation of magma from the mantle wedge in subduction zone. While gabbro rocks are rich in $TiO_2$ (1.48%), $Al_2O_3$ (18.15%), but poor MgO (6.60%) indicating a significant differentiation process occurred in this rock. Basalt from the Ciletuh complex belongs to the calc- alkaline basalt group (Figure 11) characterized by the content of $SiO_2$% 47-50%, $K_2O$ 0.32-0.56%, and poor in $TiO_2$content (0.3-0.8%). Diagram of the main element to MgO% as a function of degree of differentiation shows that gabbro and basalt rocks are more likely to associate with rocks from the arc system than MOR. High alumina ($Al_2O_3$ > 15%) gabbro and basalt are similar to that of high-alumina island arc basalt.

This study analysed serpentinized peridotite, pyroxenite, and gabbro of the Ciletuh ophiolite complex. Based on the modified AFM (alkali-FeO-MgO) diagram from Irvine and Baragar (1971), the gabbro belongs to the magmatic affinity calc – alkaline (subduction related), whereas serpentinized peridotite and pyroxenite are clarified as ultramafic (Figure 11). Calc-alkaline is only found in the orogeneous (subduction) zone (Wilson, 1989). A ternary diagram of the main element, $TiO_2$-MnOx10-$P_2O_5$x10 (Mullen, 1983) shows that the ophiolitic rocks were formed in the Calc Alkaline Basalt tectonic environment (Figure 11). Rocks formed in the archipelagic arc have characteristics of lower $TiO_2$ and MnO values than mid-oceanic ridge basalt (MORB) or oceanic island environments. The results of this diagram is coherent with the AFM diagram (Irvine & Baragar, 1971). To distinguish the affinity of the subduction zone from other zones, other parameters are needed, in this case are trace elements and rare earth elements (REE). Trace elements are used as indicators of petrogenesis, starting with studying their chemical properties on the genesis of igneous rocks relative to partial melting and crystallization. Because of its small abundance in rocks and magma, this trace element is actually very good indicator. Based on the geochemical data presented as trace element data into the spider diagram however, the data show that gabbro sample exhibit a tectonic environment associated with MORB characterized by a decline LREE (low REE) and HREE (high REE) shows an enrichment. Serpentinite sample shows very low depletion and is similar to the chondrite pattern (Figure 12). Spider diagram of the trace elements and REE showing a contribution from MOR, different with plot results from ternary diagram of major oxide which is arc related, may show the presence of ophiolite from MOR in Ciletuh, but later may be overprinted and predominated by arc system petrogenesis. This should be confirmed by more data analyses.

The ophiolite of SSZ (supra-subduction zone) requires a steep Benioff of subducted slab for proto-arc rifting followed by ophiolite petrogenesis above subduction (Dilek and Polat, 2008) (Figure 10). The steep Benioff angle will be related to old subducted slab, it is not known what exactly the slab was in Ciletuh area, the possibility may be a slab attached to one of the Sumatran terranes (West Sumatra block - Barber and Crow, 2003) which continued to West Java. This Jurassic age -slab subducted beneath the proto-Indian oceanic plate at the Eocene and experienced a Benioff zone steepening through a roll back movement, causing a proto-arc rifting above the subduction zone resulting in the petrogenesis of ophiolite with island arc tholeiitic composition (SSZ ophiolite) (Figure 14).

Most of the data show that the Ciletuh ophiolite is mainly formed in the tectonic environment of island arcs tholeiitic affinity, meaning that the ophiolite was formed in the subduction site through the petrogenesis mechanism of SSZ explained above. This ophiolite is in situ, not an emplacement from MOR ophiolite. In this case, the age of the SSZ ophiolite is coeval or relatively younger than the age of subduction. The MOR ophiolite will be much older than the age of subduction because it is originally formed in MOR and carried away from MOR to subduction area and emplaced. It needs some additional time of movement. However, there are few data of ophiolite samples in Ciletuh showing the MOR tholeiitic affinity. There may actually a mixture or overprinting of the ophiolite from MOR and ophiolite from SSZ. The actual extent to which of the two origins in Ciletuh area and how the mechanisms of mixing of the two are not known, but SSZ ophiolite complex is the dominant ophiolite in Ciletuh area.

Volcanism was important during the subduction in Ciletuh, and it was shown by the presence of volcaniclastic sandstone/ tuffs of Gunung Nyalindung. It is located to the south of Kampung Cikadal, which were dated by Schiller et al (1991) as coeval with ophiolite and metamorphic rocks of Ciletuh subduction (middle-late Eocene).

**Geochronology of Subduction and Related Ophiolite**

Age of subduction can be known by dating the metamorphic rocks formed during the subduction. The metamorphic rocks can be originated from protoliths of basic rocks of oceanic plate or pelitic rocks from the continental margin. Depending on the mechanism of subduction, these protoliths will be transformed into metamorphic rocks during subduction at shallow depth, resulting in metamorphic rocks within zeolite or greenschist facies; shallow to middle depth resulting in amphibolite facies metamorphic rocks; and deep subduction resulting blue-schist and eclogite. As discussed earlier, greenschists are dominant metamorphic rocks in Ciletuh area, few amphibolite, and no blueschist or eclogite is found. This indicates a shallow subduction for Ciletuh area.

K-Ar geochronology has been performed on three samples of chlorite-muscovite-schists of the green schist facies of metamorphic rocks in Pasir Luhur area at Citisuk River (Table 3). The analysis was conducted by ActLabs (Activation Laboratories Ltd.) Canada in July 2018. The three samples show the absolute ages of 55.2 ± 2 Ma, 54.7 ± 1.4 Ma, and 37.8 ± 1.5 Ma (early to late Eocene), respectively. This shows that subduction at Ciletuh took place in Eocene time (compare with Luk Ulo subduction at 125 – 101 Ma, upper part of Early Cretaceous). This new age dating corrected the age of 117 Ma put for Ciletuh (Satyana, 2014, cited from unpublished study, dubious source, wrong dating).

One sample of ophiolite was dated, a gabbro from Sodong Parat area, and resulted in age of 42.7 ± 1.6 Ma (middle Eocene) (Table 3). This confirmed the mechanism by which the ophiolite was formed in supra-subduction zone (SSZ) tectonic setting based on the age range of subduction and ophiolite petrogenesis which should be in the similar age range. K-Ar dating of two Ciletuh gabbro samples from Sodong Parat by Schiller *et al.* (1991) show age of 56.0 ± 2.3 Ma and 50.9 ± 2.1 Ma (early Eocene). These age ranges are similar with the age of gabbro dated by the present study. Schiller *et al.* (1991) also dated a sample of basalt pebble from Ciletuh olistostrome which is 89.6 ± 3.0 Ma (Late Cretaceous), this may indicate the presence of older ophiolite in Ciletuh area but it needs other supportive data.

Schiller *et al.* (1991) dated volcaniclastic sandstone/ tuffs at Gunung Nyalindung to the south of Kampung Cikadal as 50.1 ± 2.1 Ma and 33.9 ± 2.1 Ma (middle-late Eocene). This shows an Eocene volcanism occurring contemporaneously with subduction. This indicates that magmatism and volcanism in Ciletuh subduction important in Eocene time.

**Gunung Badak Pillowed Lava Reinterpreted as Part of Jampang Volcanism**

Good coastal exposures of basaltic pillowed lava are located to the west of Gunung Badak, northern part of Ciletuh area (Figures 5, 13). Sukamto (1975) mapped these exposures as Citirem Formation (Mcv), and reported as consists of diabase and basalt, syenite, andesite, and spilite, in the forms of lava flows, partly brecciated, locally with pillow structures, altered and hydrothermal alteration. The age is reported to be Mesozoic. Existing works (such as Sukamto, 1975; Thayyib *et al.*, 1977; Satyana, 1989) included the basaltic pillowed lava of Gunung Badak as part of the ophiolite complex with age of pre-midde Eocene. Differently, Rosana *et al.* (2019) had proposed to exclude the lava from the Ciletuh ophiolite complex based on age dating and petrochemical data and called the lava as Kunti basalt (Nmbk) with age of early Miocene coeval with andesitic and basaltic lava of Ciseureh Member of Jampang Formation (Nmja).

Hardiono *et al.* (*in prep.*) using new data of geochemistry and age-dating discusses the latest findings of pillowed lava in Gunung Badak including the possible origin of the basaltic lava, age range, relationship with ophiolite groups and possible geological setting. Analysis was conducted on 19 basalt samples from pillowed lava outcrop at Gunung Badak (Table 4). Based on Mineralogy compositions, plagioclase is present at most, along with pyroxene, olivine as phenocryst and plagioclase microlites and volcanic glass as its groundmass.

Amphibole and alkali feldspar rarely appear as secondary minerals. Chlorite and clay mineral appears as alteration of olivine, pyroxene and volcanic glass. Geochemically, these samples are trachy-basalts and basaltic trachy-andesites. Based on geochemistry, calc-alkaline magmatic affinities are dominant. Geotectonic diagrams show that magma which produces these rocks originated from subduction related tectonic, specifically island arc tholeiitic. The trace element and REE contents indicate the similar result (Figure 13). Age determination using K-Ar radiometric gives results of 22.4 Ma (early Miocene). These results contradict the existing knowledge that the Gunung Badak pillowed lava formed in the mid-oceanic ridge (MOR) environment during the Cretaceous, and was emplaced to Ciletuh area during subduction. The Gunung Badak basaltic pillowed lava is interpreted as submarine lava formed in situ as part of island arc volcanism. It is not known the nature and age of other basaltic lava exposed in Ciletuh like in the southern area. More sample analysis is required to know this.

Early Miocene Jampang volcanism was very intensive and significant in the southern West Java also regionally along the southern part of Java Island with different name in each area. It was the first significant volcanic arc of the Java. The volcanism was mainly submarine and including various volcanic lithologic products: volcanic breccias, lavas, and tuffs. Jampang basaltic-andesite lava of Ciseureuh Formation partly also shows pillowed structure like that of Gunung Badak. The Jampang volcanics intercalated with marine siliciclastic sediments like sandstones and clays. If Gunung Badak pillowed lava is part of the Jampang volcanism, meaning that part of the arc was positioned on the older subduction trench, and has similar geochemical characteristics with the ophiolite (Figure 14).

**Ciletuh Olistostrome Deposits**

Basal conglomerates (Thayyib *et al.* , 1977) or polymictic breccias (Sukamto, 1975) with fragments such as phyllite, gabbro, peridotite, basalt, sandstones, red clays, are found to the west of Gunung Badak in an area called Pulau Kunti (a rock point) with its sea cave nearby (Figure 5D). The sea cave Kunti is made up of this deposit and so typical for this locality. The deposits have been included into the lower part of Ciletuh Formation, the earliest formation overlying the melange. Fragments composing the conglomerates/ breccias were mainly sourced by the melange complex. The melange complex was uplifted, eroded, and resulting in this deposit. The deposit is poorly sorted with sedimentary matrix, and it is interpreted as olistostrome deposit formed at the trench slope of subduction zone.

Olistostromes (sedimentary melanges) represent the products of ancient submarine mass transport processes (Festa *et al.* 2016). As firstly introduced by Flores (1955), olistostrome is sedimentary deposits with non- true internal bedding, and that they can be differentiated in a matrix (“binder”), which consists of “prevalent pelitic, heterogeneous material”, and dispersed “bodies of harder rocks” (“from pebbles to boulders up to several cubic km”). Subsequently, the term olistostrome has been used extensively by international geological communities in reference to stratally disrupted, chaotic complexes and exotic sedimentary packages, resulted from various mass transport events. The general physiography and tectonic setting of their depocenters, the nature, scale and rate of downslope transformation mechanisms, and global climatic events are the main factors controlling the internal structure and stratigraphy of olistostromes. Based on the tectonic settings of their formation olistostromes can be classified as: (i) passive margin, (ii) convergent margin and subduction-accretion, and (iii) collisional and intra-collisional types (Festa *et al.* 2016). Ciletuh olistostrome is classified to the type of convergent margin and subduction-accretion since Ciletuh recorded plate margin convergence in Eocene time.

Ciletuh olistostrome deposits overlying the Ciletuh melange, has been interpreted to be Eocene in age (Sukamto, 1975; Thayyib *et al.* 1977) considering the melange which sourced the fragments of olistostrome is pre-middle Eocene in age. However, due to this study found that the subduction of Ciletuh was in early to late Eocene, meaning the processes of melange formation was contemporaneous with subduction or sometime after it, the process of olistostrome deposition should be younger than Eocene since most of olistostromal fragments were sourced by uplifted melange. The younger age of the olistostrome is shown by recent findings of some fragments like Eocene *Nummulitic*-bearing limestone fragment, and an early Miocene andesitic fragments like Jampang volcanics. This indicate that the olistostrome can be as young as middle Miocene (but there is no K-Ar dating of the volcanic fragment). New mapping of Ciletuh put the Kunti olistostrome (Nmbk) into the age of early Miocene (Rosana *et al.* 2019). The range of age from late Eocene to early/middle Miocene of the olistostrome may show that Paleogene trench of Ciletuh as a basin for olistostrome deposition existed longer in age than previously considered. The relation of Ciletuh subduction trench to later Jampang volcanic arc in early Miocene also partly in similar space and time (Figure 14).

Gunung Badak pillowed lava dated as early Miocene (Jampang equivalent, - Hardiono *et al., in prep*.) located just to the east of Kunti olistostrome deposit, it may show that subduction trench where olistostrome was deposited ~~was~~ in one time and one place with early Miocene volcanism. Age dating of some olistostrome fragments may contribute to the tectonic relationship between olistostrome and Jampang volcanism in Ciletuh area.

**Geological Evolution of Ciletuh Subduction**

The first geological process dated at Ciletuh was at the Eocene time (56-37.8 Ma) when the subduction occurred (Figure 14). Oceanic plate that subducted is considered was part of Woyla oceanic slab, regionally attached to the West Sumatra terrane (Barber and Crow, 1983). This slab and terrane continued into West Java. Woyla slab subducted beneath proto Indian oceanic plate in Eocene (Figure 14). It is not known the possibility of existence of Early Cretaceous slab in Ciletuh as that in Luk Ulo. Old slab steeply subducted is required for the formation of ophiolites in SSZ (supra-subduction zone). This slab is considered the Woyla oceanic plate, not the proto-Indian oceanic plate which was young at the time of subduction and would not subduct steeply due to young age. The petrogenesis of SSZ ophiolite needs a subduction roll back and a rifting of the overriding plate. This is fulfilled by roll back movement of old Woyla slab (Jurassic) steeply subducted (Figure 14). The process of magmatism and volcanism in the subduction zone is also shown by the Eocene tuff deposits (dated 50.1-33.9 Ma, Schiller *et al.*, 1991) found on Gunung Nyalindung to the southeast of Gunung Badak.

In the late Eocene to Oligocene, melange formation took place with the composition of metamorphic rocks, ophiolite, deep sea sediments and continental margin sediments. Thrusting was contemporaneously taking place, and also olistostrome deposition as submarine slides into the trench slope sourced by uplifted melange (Figure 14). The progressive melange formation and thrust migration had slowed down and finally stopped the movement of the proto-Indian oceanic plate, which then initiated the plate to subduct beneath the accreted terrane since then. A reversal of subduction took place. The subduction in early Miocene resulted in island arc tholeiitic volcanism, occurred again in SSZ like Gunung Badak basaltic pillowed lava, which located still in Eocene subduction site. Uplift, deformation, and continuous subduction occurred contemporaneously in middle Miocene and onward. Several episodes of uplift took place and one time in the Plio-Pleistocene it was compensated by a gravity collapse of Ciletuh Block forming the Ciletuh Amphitheater. Final uplifts related to subduction of Indian oceanic plate beneath West Java eventually exposed the Ciletuh and Jampang Plateau areas as can be seen today.

**Regional Implications to Southeast Sundaland Cretaceous Subduction**

Ciletuh subduction and melange considered as pre-Tertiary (Cretaceous) in age has been linked to the other contemporaneous subduction in western Indonesia (Luk Ulo, Meratus, Bantimala subduction) (Hutchison, 1973; Thayyib *et al.*, 1977; Hamilton, 1979) and many others based on these references, also by Satyana (2014a, b) based on the age of subduction schist of Ciletuh as 117 Ma - later was known that this age is wrong, cited from dubious source). However, this study presents new results of age dating of subduction complex of Ciletuh based on metamorphic rocks and ophiolite complex which range in age from 55.2 ± 2 Ma to 37.8 ± 1.5 Ma (early to late Eocene). Similar results were also shown by Schiller *et al.* (1991) which dated the gabbro ophiolite formed in SSZ as 56.0 ± 2.3 Ma and 50.9 ± 2.1 Ma (early Eocene). Table 5 put petrotectonic characteristics and ages of the key areas of subduction and collision sites in Java, Kalimantan, Sulawesi. Regional implications of Ciletuh to other subduction sites in Southeast Sundaland is based on this table (Figure 15).

Would it be possible to have older subduction in the Ciletuh as Luk Ulo (Early Cretaceous subduction 125 -101 Ma)? This study has not found any evidences of the pre-Tertiary subduction at Ciletuh. The ophiolite in Ciletuh is dominated by in situ ophiolite formed by supra-subduction mechanism with geochemical characteristics of island arc tholeiitic. Is there subduction-unrelated transported MOR (mid-oceanic ridge) ophiolite in Ciletuh. There are some ophiolites that geochemically indicate MOR (Suparka, 1995however there are no age data for this. Schiller *et al.* (1991) found the basalt pebble in the Ciletuh olistostrome dated as 89.6 ± 3.0 Ma (Late Cretaceous), if this is a part of the ophiolite, it may indicate the presence of older ophiolite in the Ciletuh area. However, there have been none of the geochemical data on this study to further evaluate its tectonic setting.

The absence of high pressure metamorphic rock (blue schist) and the absence of radiolarian chert in melange complex of Ciletuh, may indicate that the subduction of oceanic plate at Ciletuh was shallow and has a low-angle dip Benioff zone, resulting in metamorphic sole. Luk Ulo subduction has been dated ~~as~~ Early Cretaceous (101-125 Ma). It has blue schist and eclogite, showing deep and steep Benioff zone. The ophiolites are MOR-associated (Suparka, 1988). Cretaceous radiolarian cherts were part of the Luk Ulo melange. The oceanic plate subducting at Luk Ulo was Meso-Tethys oceanic plate, the subduction ceased in mid-Cretaceous time when a terrane called Southeast Java microcontinent collided the subduction zone (Satyana, 2014a, b) (Figure 15). Different in age and nature between Luk Ulo and Ciletuh subductions show the two areas did not compose similar subduction zone.

When Meso-Tethys oceanic plate subducted at Luk Ulo trench in Early Cretaceous time, it is not known what was happening in Ciletuh, no data as old as Early Cretaceous has been dated for geologic process in Ciletuh. There is a 134 Ma (Early Cretaceous) granitic pebble in the conglomerate fragment of the Ciletuh Formation (Schiller et al, 1991), but it does not indicate the age of the geological process in Ciletuh, it is the age of the granite at its source which is thought to be in the north of Java Island and became fragment of the Ciletuh conglomerate in the Eocene. When subduction at Luk Ulo ceased at mid-Cretaceous, it is also not known what was happening to Ciletuh because no data of the age has been dated for the geological process in Ciletuh. Based on this, regionally Ciletuh did not link to Luk Ulo. Regional continuation to where of both Early Cretaceous Luk Ulo subduction and Eocene Ciletuh subduction is not known (Figure 15).

**Petroleum Implications**

Pre-Tertiary (Mesozoic and Late Palaeozoic) petroleum prospectivity of the Southeast Sundaland was proposed by Satyana (2014a, b) related to new tectonic reconstruction during Mesozoic in this area. The Mesozoic petroleum possibilities of the southeastern part of Sundaland related to the presence of some Australian-origin microcontinents. Deep seismic data in the southern offshore East Java, eastern East Java Sea, and South Makassar Strait show the presence of Mesozoic-Palaeozoic bedded horizons overlying the Southeast Java and Paternoster-Kangean microcontinents. The seismic characters of the horizons show the typical of basins in the NW Shelf of Australia which are well known to be productive. The petroleum prospectivity was discussed in more detail by Satyana (2016) showing that the Mesozoic petroleum system is proven to be actively generating hydrocarbons such as oils trapped in the Sepanjang field, Kangean area, which is proven geochemically sourced by Early Cretaceous marine shales deposited overlying the Paternoster-Kangean microcontinent. Satyana (2017, 2019) in discussing future regional petroleum play types of Indonesia and possible future giant fields of Indonesia, included the Mesozoic play type of Southeast Sundaland microcontinent in Northeast Java Sea and South Makassar Strait, called as Gondwanan Mesozoic sections of Makassar Straits play type. Recently, in 2020 Pertamina national oil company acquired new seismic lines in South Makassar Strait to further explore this play type.

The new interpretation of Ciletuh subduction does not change the Mesozoic petroleum prospectivity summarized above due to the prospective areas are located to the east of Meratus and Luk Ulo Cretaceous subduction. The argument that Ciletuh is not part of Cretaceous subduction, does not imply the Mesozoic play type. The new interpretation of Ciletuh subduction will imply the knowledge of geological evolution of West Java and Java in the Paleogene. If there is petroleum prospectivity in the Paleogene objectives of southern part of West Java, new interpretation of Ciletuh will significantly affect the petroleum prospectivity.

**New Problems Arise**

New data, findings, and interpretation of Ciletuh which significantly are different from the existing/ classical knowledge of Ciletuh (Thayyib *et al.* , 1977 and many literatures cited this), also raise several problems that has not currently been answered due to lack of data and analysis. The followings are the problems in the Ciletuh area that must be worked on in the future.

1. Pre-Eocene subduction in Ciletuh remains unknown, whether there was a subduction during the Luk Ulo time in the Early Cretaceous Meso-Tethys oceanic plate subduction, or a little bit later in the Late Cretaceous Ceno-Tethys oceanic plate subduction, or not visible since it was then overprinted by the Eocene subduction? The extent of Meso-Tethys and Ceno-Tethys oceans between Luk Ulo and Ciletuh during the Cretaceous to Paleogene is also unknown. Available paleo-tectonic map of Meso- and Ceno-Tethys of the Southeast Asia from Metcalfe

(2013) can be used as the starting point to evaluate this puzzle.

2. Would the ophiolite possibly be formed in the MOR where it was re-emplaced to Ciletuh as the ophiolite should be older than the SSZ ophiolite formed in the Eocene's SSZ? If so, how far the extent of MOR ophiolite in relation to the SSZ ophiolite, whether the SSZ ophiolite overprinted the MOR ophiolite, or not? Suparka (1995) reported the presence of MOR ophiolites in the Ciletuh area based on its petrochemistry.

3. Gunung Badak basaltic pillowed lava that has been considered as part of the pre-Tertiary ophiolite, according to the geochemical and age data is more likely to be part of the early Miocene Jampang volcanism. The extent of the Jampang volcanism distribution in the Ciletuh area remains unknown. The main distribution of Jampang volcanic is to the east of Ciletuh on the Jampang plateau and further to the east.

4. Olistostrome deposition on the slopes of the Ciletuh trench seems to have lasted a long time from Eocene to early/middle Miocene. In the early Miocene, part of the Ciletuh area became a place for the Jampang volcanic arc. The evolution of Ciletuh from the subduction trench to become a site for volcanic arc remains unknown.

The problems could be answered if the area studied and the samples analysed are more comprehensive.

**CONCLUSIONS**

Ciletuh subduction complex is known largely by the first publication discussing its melange complex (Thayyib *et al.,* 1977). Ciletuh has been scarcely studied after this, there were several studies but unpublished or limitedly known. In the last five years, there have been a lot of works to do in the Ciletuh area in relation to its proposal becoming one of the Unesco global geoparks. New mapping and various petrologic, petrographic, petrochemical analyses were conducted, including absolute dating of melange complex and its overlying deposits. The results are surprisingly different from the previous/classical knowledge of Ciletuh. The following are important things about the new Ciletuh.

1. Melange complex of Ciletuh consists of fragments of: ophiolite suite (serpentinized peridotite, gabbro, diabase, basalt), continental sedimentary rocks (shale and graywacke), pelagic sediments (red clay), metamorphic rocks (greenschist), in matrix of scaly clay. No blueschist, eclogite, radiolarian chert is found.
2. Subduction of Ciletuh based on age-dating of metamorphic rocks formed during subduction was in the early to late Eocene (55.2 ± 2 Ma to 37.8 ± 1.5 Ma). No Cretaceous subduction is dated.

3. Petrochemistry of ophiolite (serpentinized peridotite, gabbro, basalt) show dominantly of island arc tholeiitic (SSZ – supra-subduction zone generation) – in situ, dated 56.0 ± 2.3 Ma to 42.7 ± 1.6 Ma (early to middle Eocene). The process of magmatism and volcanism in the subduction zone is also shown by the Eocene tuff deposits (dated as 50.1-33.9 Ma, Schiller *et al.*, 1991). Some MOR/ midoceanic ridge formation (transported) samples are found (Suparka, 1995) but no age-dating data. The formation of SSZ ophiolite is considered to be related to proto-arc rifting due to roll-back subduction of the old Woyla slab attaching to a Sumatran terrane (West Sumatra Block) that continued to West Java when it subducted beneath the proto-Indian oceanic plate in Eocene time.

4. Based on the nature and age, there is no reason to keep any longer the link of Ciletuh subduction to Lower Cretaceous Luk Ulo subduction. When Meso-Tethys oceanic plate subducted at Luk Ulo from 125 to 101 Ma (Lower Cretaceous), it is unknown what was happening in Ciletuh since no pre-Tertiary age dating of geological process in Ciletuh.

5. Olistostrome of Ciletuh Formation contains various olistoliths of melange fragments and overlying sediments. The age of it is from the late Eocene to early/middle Miocene, is later and longer in age than previously considered. indicating that the trench where olistostrome was deposited existed in a longer time.

6. Based on the recent analyses of petrochemistry, the basaltic pillowed lava of the Gunung Badak has been considered as part of the Ciletuh ophiolite. The age dating shows it is subduction related-lava, submarine, island-arc tholeiitic of the early Miocene in age (22.4 Ma). It may be part of the early Miocene Jampang volcanism that situated close to the Ciletuh subduction trench. Since the Eocene time, volcanism in the subduction site of Ciletuh was significant and there were two episodes of it: the Eocene Ciletuh

volcanism (Gunung Nyalindung tuffs) and the early Miocene Jampang volcanism.

7. New geochronology and nature of the Ciletuh subduction will imply the geological evolution of Java and especially West Java during the pre-Tertiary and Paleogene time. If there are petroleum prospects in southern West Java with objectives of Paleogene age, the geological setting of the prospects regionally will be implied by new setting of Ciletuh subduction.

8. Field studies, various petrologic analyses, and age dating results in new knowledge of Ciletuh subduction significantly different with the classic knowledge which has not been supported by various petrologic analyses and age dating. However, this new knowledge also raises several new problems that the answers could potentially be known if the area studied and the samples analysed are more comprehensive.

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**TABLE 1. PETROCHEMISTRY ANALYSES (MAJOR OXIDES) OF CILETUH ROCK SAMPLES (OPHIOLITE AND METAMORPHIC) FROM THIS STUDY AND FROM PREVIOUS STUDIES.**

| MAJOR OXIDES | CLTH (%) | 156 (%) | 171 (%) | 159 (%) | 150 (%) | 166 (%) | CKP (%) | CL-01 (%) | CL-05 (%) | CL-09 (%) | CL-22 (%) | DI (%) | CL-27 (%) | CBG-2 (%) | CLH-07 (%) | 2 (%) | 4 (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 43.03 | 66.76 | 58.61 | 70.61 | 40.69 | 53.86 | 39.72 | 47.87 | 48.86 | 47.45 | 43.19 | 50.40 | 43.75 | 49.25 | 50.50 | 30.10 | 54.95 |
| $Na_2O$ | 2.98 | 1.58 | 2.91 | 1.53 | 0.11 | 4.20 | 0.14 | 2.72 | 3.39 | 2.83 | 0.02 | 2.65 | 0.02 | 1.39 | 2.43 | 0.20 | 4.50 |
| $K_2O$ | 0.10 | 1.69 | 0.62 | 2.51 | 0.04 | 0.77 | <0.01 | 0.32 | 0.32 | 0.61 | 0.01 | 0.56 | 0.01 | 0.06 | 0.49 | - | 0.69 |
| $Al_2O_3$ | 13.96 | 14.45 | 14.32 | 12.98 | 1.7 | 14.97 | 12.46 | 24.22 | 22.84 | 18.15 | 1.54 | 19.50 | 1.35 | 24.87 | 24.84 | 5.45 | 9.12 |
| CaO | 14.17 | 0.52 | 4.36 | 1.27 | 0.54 | 8.79 | 18.92 | 12.32 | 13.56 | 8.84 | 1.51 | 11.20 | 1.32 | 7.73 | 4.64 | 1.15 | 7.12 |
| $Fe_2O_3$ | 9.19 | 7.87 | 7.47 | 5.74 | 8.58 | 5.92 | 5.21 | 4.97 | 3.81 | 5.03 | 0.90 | 2.70 | 0.78 | 5.27 | 6.24 | 2.50 | 1.40 |
| MgO | 5.52 | 2.61 | 6.73 | 2.19 | 35.24 | 8.33 | 16.61 | 4.54 | 2.95 | 6.60 | 38.10 | 4.45 | 38.40 | 3.53 | 2.75 | 42.30 | 9.15 |
| $Cr_2O_3$ | 0.05 | 0.04 | 0.05 | 0.01 | 0.59 | 0.10 | 0.18 | - | - | - | - | - | - | - | - | 4.78 | - |
| $P_2O_5$ | 0.226 | 0.123 | 0.125 | 0.133 | 0.016 | 0.020 | 0.018 | 0.03 | 0.07 | 0.13 | 0.08 | 0.15 | 0.07 | 0.12 | 0.04 | - | - |
| MnO | 0.14 | 0.06 | 0.15 | 0.12 | 0.14 | 0.14 | 0.11 | 0.13 | 0.15 | 0.23 | 0.23 | 0.16 | 0.20 | 0.12 | 0.07 | - | - |
| $TiO_2$ | 1.35 | 0.88 | 0.78 | 0.58 | 0.03 | 0.44 | 0.22 | 0.30 | 0.36 | 1.48 | 0.00 | 0.80 | 0.00 | 0.92 | 0.95 | 1.89 | - |

CLTH schist -epidote amphibolite
156 schist -musccovite chlorite
171 schist -musccovite chlorite
159 schist -musccovite chlorite
150 serpentinite
166 gabbro
CKP pyroxenite
*this study*

CL-01 basalt
CL-05 basalt
CL-09 gabbro
CL-22 peridotite
DI basalt
CL-27 peridotite
*Dirk (1997)*

CBG-2 basalt
CLH-7 basalt
*Suparka (1995)*

2 serpentinite
4 basalt
*Rochman et al. (1983)*

## TABLE 2. PETROCHEMISTRY ANALYSES (TRACE ELEMENTS & RARE EARTH LEMENTS) OF CILETUH ROCK SAMPLES (OPHIOLITE AND METAMORPHIC).

| Element | CLTH (ppm) | 156 (ppm) | 171 (ppm) | 159 (ppm) | 150 (ppm) | 166 (ppm) | CKP (ppm) |
|---|---|---|---|---|---|---|---|
| Al | 66600 | 76400 | 75700 | 70700 | 9620 | 79700 | 64700 |
| Ca | 90500 | 3450 | 30600 | 8850 | 3600 | 65700 | 124000 |
| Cr | 334 | 298 | 245 | 83 | 2790 | 451 | 697 |
| Cu | 13 | 29 | 48 | 92 | 25 | 16 | 72 |
| K | 650 | 14000 | 5240 | 21600 | 360 | 6480 | 50 |
| Mg | 28500 | 16100 | 41500 | 13500 | 204000 | 52700 | 98400 |
| Mn | 897 | 428 | 996 | 840 | 921 | 895 | 727 |
| Na | 20500 | 11800 | 22200 | 11900 | 1240 | 32300 | 1220 |
| Ni | 142 | 105 | 302 | 59 | 2130 | 100 | 416 |
| P | 850 | 530 | 530 | 590 | <50 | 60 | <50 |
| S | 230 | 1100 | 630 | 1430 | 100 | 150 | 140 |
| Sc | 23 | 15 | 20 | 13 | 13 | 39 | 24 |
| Ti | 6290 | 3410 | 4390 | 3490 | 271 | 2420 | 1190 |
| V | 116 | 115 | 131 | 93 | 65 | 171 | 86 |
| Zn | 129 | 102 | 102 | 83 | 70 | 51 | 54 |
| Ag | 0,4 | 0,5 | <0.1 | 0,2 | <0.1 | <0.1 | 0,5 |
| As | 2 | 8 | 1 | 3 | <1 | <1 | 3 |
| Ba | 79 | 185 | 113 | 271 | 14 | 188 | 37 |
| Be | 0,5 | 1,2 | 1,1 | 1,4 | <0.5 | <0.5 | <0.5 |
| Bi | <0.05 | 0,21 | 0,24 | 0,21 | 0,05 | 0,06 | 0,22 |
| Cd | 0,17 | 0,08 | 0,1 | 0,25 | <0.05 | 0,1 | <0.05 |
| Co | 34 | 16 | 33 | 20 | 109 | 31 | 40 |
| Cs | <0.1 | 1,7 | 0,2 | 0,8 | <0.1 | 0,2 | 0,2 |
| Ga | 13,2 | 17,6 | 18,2 | 13,9 | 1,9 | 12,9 | 7,6 |
| Ge | 0,5 | 1,2 | 1,1 | 1,4 | <0.5 | <0.5 | <0.5 |
| Hf | 0,4 | 0,4 | 0,1 | 0,1 | <0.1 | 0,3 | 0,3 |
| In | 0,05 | 0,06 | 0,06 | 0,15 | <0.05 | <0.05 | <0.05 |
| Li | 3,9 | 29,5 | 18,6 | 15,7 | 2,7 | 10,8 | 7,7 |
| Mo | 0,3 | 0,9 | 0,5 | 0,8 | <0.1 | 0,1 | 0,9 |
| Nb | 12 | 4,2 | 4,8 | 5,6 | 0,4 | 0,6 | 1,7 |
| Pb | 683 | 396 | 97 | 66 | 65 | 194 | 240 |
| Rb | 1,3 | 63,6 | 15,6 | 75,9 | 1,3 | 12,7 | 4,2 |
| Re | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 |
| Sb | 1,7 | 1,4 | 0,5 | 1,1 | 0,3 | 0,7 | 1,3 |
| Se | <1 | 2 | <1 | <1 | <1 | <1 | <1 |
| Sn | 1,4 | 1,5 | 1,5 | 2 | 0,7 | 0,9 | 3 |
| Sr | 180 | 89,5 | 233 | 86 | 12,3 | 229 | 36,2 |
| Ta | 1,2 | 0,31 | 0,35 | 1,25 | 0,21 | 0,33 | 1,74 |
| Te | <0.1 | <0.1 | <0.1 | 0,1 | <0.1 | <0.1 | 7,3 |
| Th | 1,07 | 2,93 | 3,07 | 3,78 | 0,24 | 0,28 | 1,29 |
| Ti | 0,03 | 0,29 | 0,09 | 0,6 | <0.02 | 0,06 | 0,21 |
| U | 0,19 | 0,64 | 0,92 | 1,17 | <0.05 | <0.05 | 0,44 |
| W | 0,5 | 0,9 | 0,5 | 2,4 | 0,3 | 3,1 | 2,1 |
| Y | 14,9 | 10 | 21,1 | 17,7 | 1,1 | 11,8 | 6,1 |
| Zr | 10,1 | 27,9 | 5,1 | 6,4 | 1,8 | 17,7 | 8,8 |
| Ce | 21 | 45,1 | 32,6 | 34,6 | 1,3 | 3,2 | 6 |
| Dy | 2,8 | 2,2 | 3,6 | 3,9 | 0,2 | 2,1 | 4,1 |
| Er | 1,6 | 1 | 2,3 | 2,1 | 0,1 | 1,4 | 1,2 |
| Eu | 0,8 | 0,9 | 0,9 | 1,1 | <0.1 | 0,4 | 0,9 |
| Gd | 3,1 | 3,4 | 4 | 4,8 | 0,2 | 1,8 | 5,9 |
| Ho | 0,6 | 0,4 | 0,7 | 0,8 | <0.1 | 0,4 | 0,9 |
| La | 9,9 | 21,5 | 15,4 | 16,8 | 0,6 | 1,2 | 5,1 |
| Lu | 0,15 | 0,13 | 0,24 | 0,18 | <0.05 | 0,18 | 0,21 |
| Nd | 10,6 | 19,6 | 15,9 | 16,5 | 0,7 | 2,8 | 4,1 |
| Pr | 2,51 | 5,15 | 3,91 | 4,88 | 0,17 | 0,52 | 4,2 |
| Sm | 2,6 | 4,1 | 3,6 | 4,4 | 0,2 | 1,1 | 3,9 |
| Tb | 0,45 | 0,43 | 0,57 | 0,74 | <0.05 | 0,29 | 0,83 |
| Tm | 0,2 | 0,1 | 0,3 | 0,6 | <0.1 | 0,2 | 0,6 |
| Yb | 1,3 | 0,9 | 1,9 | 1,7 | 0,1 | 1,2 | 0,9 |

**CLTH schist-epidote amphibolite, 156 schist-muscovite chlorite, 171 schist-muscovite chlorite**

**159 schist-muscovite chlorite, 150 serpentinite, 166 gabbro, CKP pyroxenite**

**TABLE 3. ABSOLUTE K-AR AGE-DATING OF CILETUH OPHIOLITE AND METAMORPHIC ROCKS.**

| Clients ID | Actlabs ID | K % ± σ | $^{40}$Ar rad (ng/g) % | $^{40}$Ar air | AgeMa | Error 2σ |
|---|---|---|---|---|---|---|
| **156** | A18-06394-4 | 0.850±0.015 | 3.306±0.016 | 19.7 | **55.2** | 2 |
| **171** | A18-06394-5 | 0.555±0.010 | 1.471±0.011 | 31.3 | **37.8** | 1.5 |
| **166** | A18-06394-8 | 0.674±0.010 | 2.02±0.0200 | 44.1 | **42.7** | 1.6 |
| **159 B** | A18-06394-9 | 1.60±0.0200 | 6.16±0.0300 | 21.2 | **54.7** | 1.4 |

***156, 171, 159B – schist, muscovite-chlorite; 166 - gabbro***

**TABLE 4. PETROCHEMISTRY ANALYSES (MAJOR OXIDES) OF GUNUNG BADAK PILLOWED LAVA SAMPLES (HARDIYONO *ET AL. IN PREP.*)**

| MAJOR OXIDES | SAMPLE CODE | | | | | | |
|---|---|---|---|---|---|---|---|
| | STA 01 | STA 04 | STA 05 | STA 06 | STA 09 | STA 13 | STA 14 |
| $Al_2O_3$ | 17.15 | 16.52 | 16.42 | 18.02 | 16.54 | 16.44 | 17.26 |
| CaO | 7.46 | 4.83 | 4.82 | 6.03 | 3.49 | 4.36 | 3.83 |
| $Fe_2O_3$ | 9.59 | 9.17 | 9.24 | 8.77 | 7.39 | 9.04 | 9.78 |
| $K_2O$ | 0.81 | 1.07 | 1.06 | 0.36 | 0.52 | 0.96 | 0.48 |
| MgO | 4.45 | 4.61 | 4.88 | 6.33 | 4.45 | 4.43 | 6.05 |
| MnO | 0.17 | 0.13 | 0.14 | 0.21 | 0.15 | 0.14 | 0.16 |
| $Na_2O$ | 4.84 | 6.10 | 5.92 | 5.06 | 7.40 | 6.59 | 6.17 |
| $P_2O_5$ | 0.22 | 0.23 | 0.23 | 0.26 | 0.24 | 0.22 | 0.23 |
| $SiO_2$ | 52.39 | 53.88 | 53.23 | 51.10 | 56.56 | 53.81 | 51.80 |
| $TiO_2$ | 1.15 | 1.13 | 1.12 | 1.25 | 1.11 | 1.11 | 1.16 |
| LOI | 1.70 | 2.21 | 2.91 | 2.52 | 2.01 | 2.79 | 3.02 |
| Total | 99.92 | 99.89 | 99.98 | 99.93 | 99.88 | 99.89 | 99.95 |
| FeO | 6.04 | 5.77 | 5.82 | 5.52 | 4.66 | 5.70 | 6.16 |
| $FeO+Fe_2O_3$ | 15.63 | 14.94 | 15.06 | 14.29 | 12.05 | 14.74 | 15.94 |
| $Na_2O+K_2O$ | 5.65 | 7.17 | 6.98 | 5.43 | 7.93 | 7.55 | 6.66 |

**TABLE 5. PETROTECTONIC CHARACTERISTICS AND AGES OF THE KEY AREAS OF SUBDUCTION AND COLLISION SITES IN JAVA, KALIMANTAN, SULAWESI (MODIFIED FROM SATYANA, 2014A, 2014B).**

| | CILETUH, WEST JAVA | LUK ULO, CENTRAL JAVA | JIWO HILLS/BAYAT, CENTRAL JAVA | MERATUS, SOUTH KALIMANTAN | BANTIMALA, SOUTH SULAWESI |
|---|---|---|---|---|---|
| Rock assemblages | ophiolite (peridotite, gabbro, diabase, pillow basalt), graywacke, limestone, tuff, red shales, serpentinite, phyllite, greenschist, Ophiolite is mostly not MOR, but subduction-generated. Gn. Badak pillow basalt is considered not ophiolite but it could be Jampang volcanics (22.4 Ma). | ophiolite (pillow basalt, diabase, gabbro, sepentinized peridotite); quartz porphyry - rhyolitic tuff; chert, siliceous shale, red limestone; sandstones , pebbly shale, basaltic conglomerate; phyllite, blueschists, eclogite, gneiss, quartzite, marble | phyllite, slate, marble, mica schist | ophiolite (serpentinized peridotite, pyroxenite with gabbro and plagiogranite intrusions, basalt); limestone, chert, clastic and carbonate sediments; phyllite, greenschists, blueschist; granite, tonalite, trondhjemite, diorite | ophiolite (serpentized peridotite, basalt); sandstone, shale, conglomerate, chert, siliceous shale; blueschist, schist breccia, eclogite, and felsic intrusives & rhyolitic tuff |
| Nature of rocks | tectonic blocks, mélange | tectonic blocks, mélange | no tectonic block, no mélange | tectonic blocks, mélange | tectonic blocks, mélange |
| Age of subduction schists or eclogites (Ma) | 55 – 38 (on greenschist) | 124-102 | 98 | I. 119-108<br>II. 180-165 | 137-111 |
| Age of radiolaria | *no radiolarian chert is found* | Early Cretaceous-late Latest Cretaceous | *no radiolarian chert is found* | late Early Jurassic-late Early Cretaceous | mid-Cretaceous (late Albian-early Cenomanian) |
| Overlying formations, age | slope deposits, Ciletuh Fm., ?middle Eocene - ?mid Miocene | 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 |

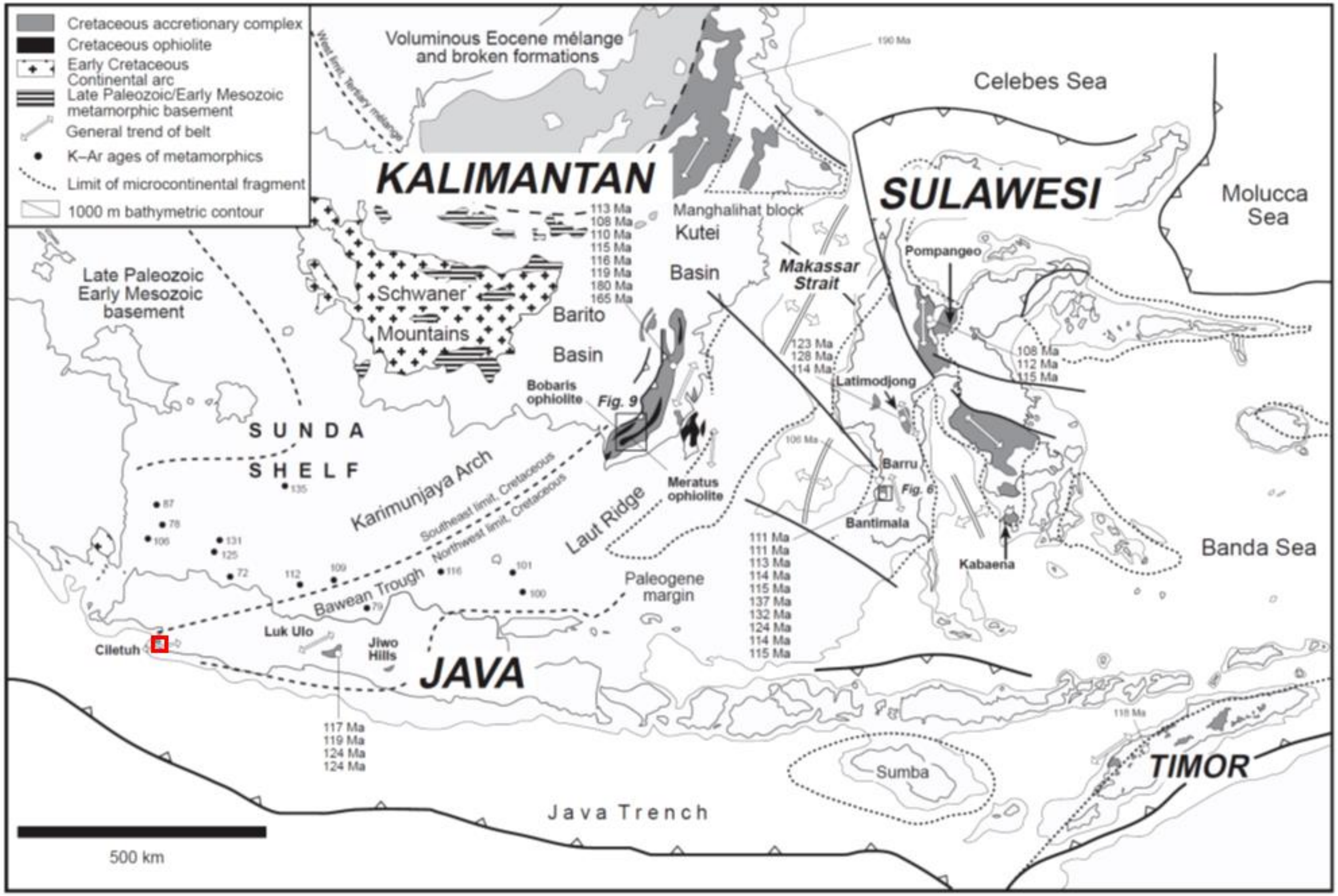



**Figure 1 -** Distribution of Mesozoic rock complexes in the central Indonesia region (Parkinson *et al.*, 1998). Ciletuh is marked by red box at Southwest Java.

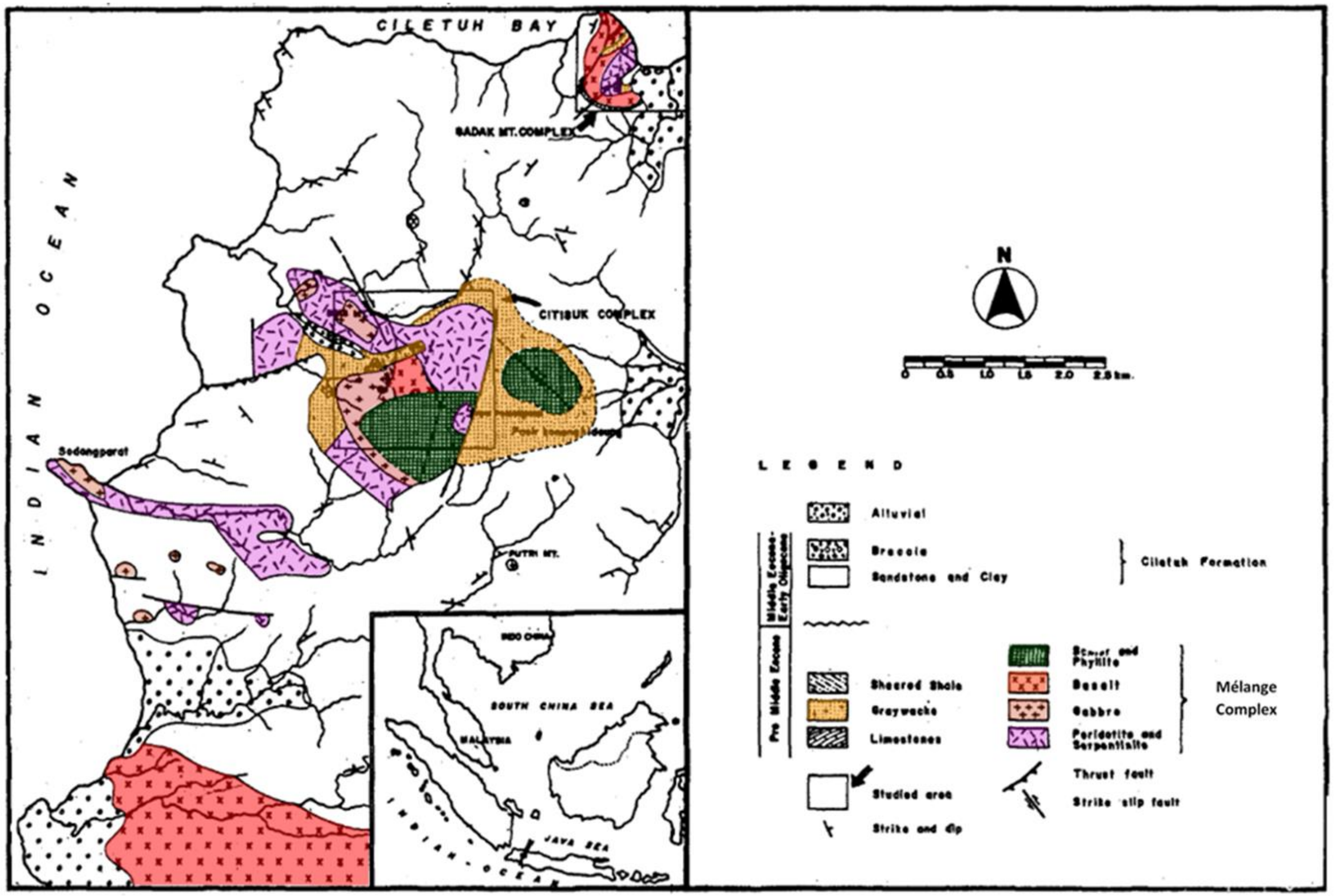



**Figure 2** - Geological map of Ciletuh area (Thayyib *et al.*, 1977).

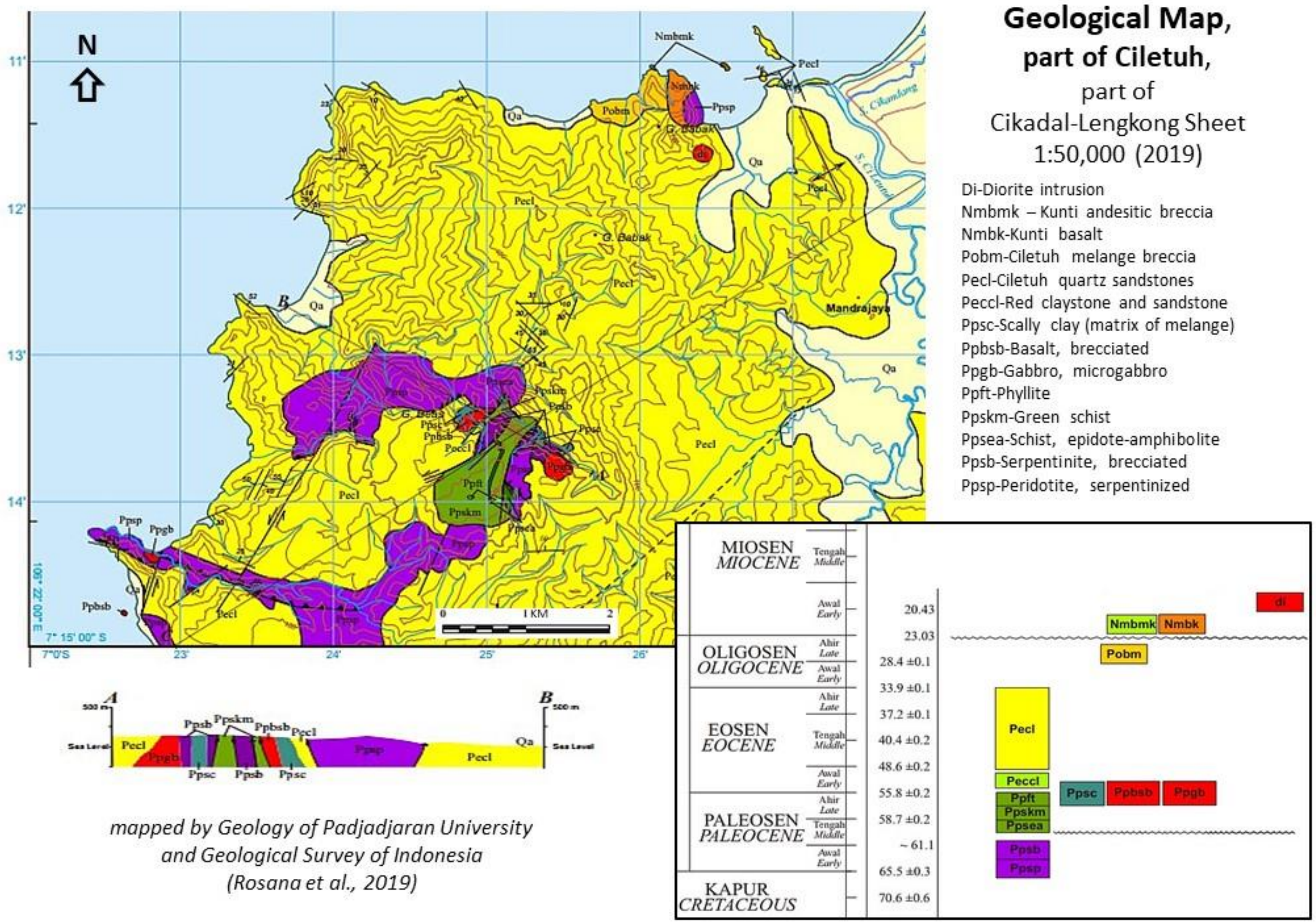



**Figure 3 -** Geological map of part of Ciletuh area (Rosana *et al.*, 2019).


**Figure 4 -** Pictures from Ciletuh area. A) 3D DEM area of Ciletuh, showing an amphitheatre morphology of Ciletuh to the west of Jampang Plateau. B) Ciletuh Amphitheatre landscape seen from Panenjoan site. C) Ciletuh Bay seen from Darma Peak. D) Outcrop of Eocene well-bedded, turbiditic, quarzitic sandstones of Ciletuh Formation. E) Cimarinjung Waterfall, crossing an early Miocene sandy tuff of Cikarang Formation, western margin of Jampang Plateau.


**Figure 5 -** Outcrops at northern and western margin of Ciletuh area. A) Basaltic pillowed lava to the west of Gunung Badak. B) Basaltic pillowed lava to the west of Gunung Badak, early Miocene in age. C) Gabbro of Sodongparat Cape, Eocene in age. D) Sea cave of Kunti Island, composed of olistostromal deposits with various olistoliths coming from ophiolite and its overlying sedimentary rocks, Eocene to middle Miocene in age.

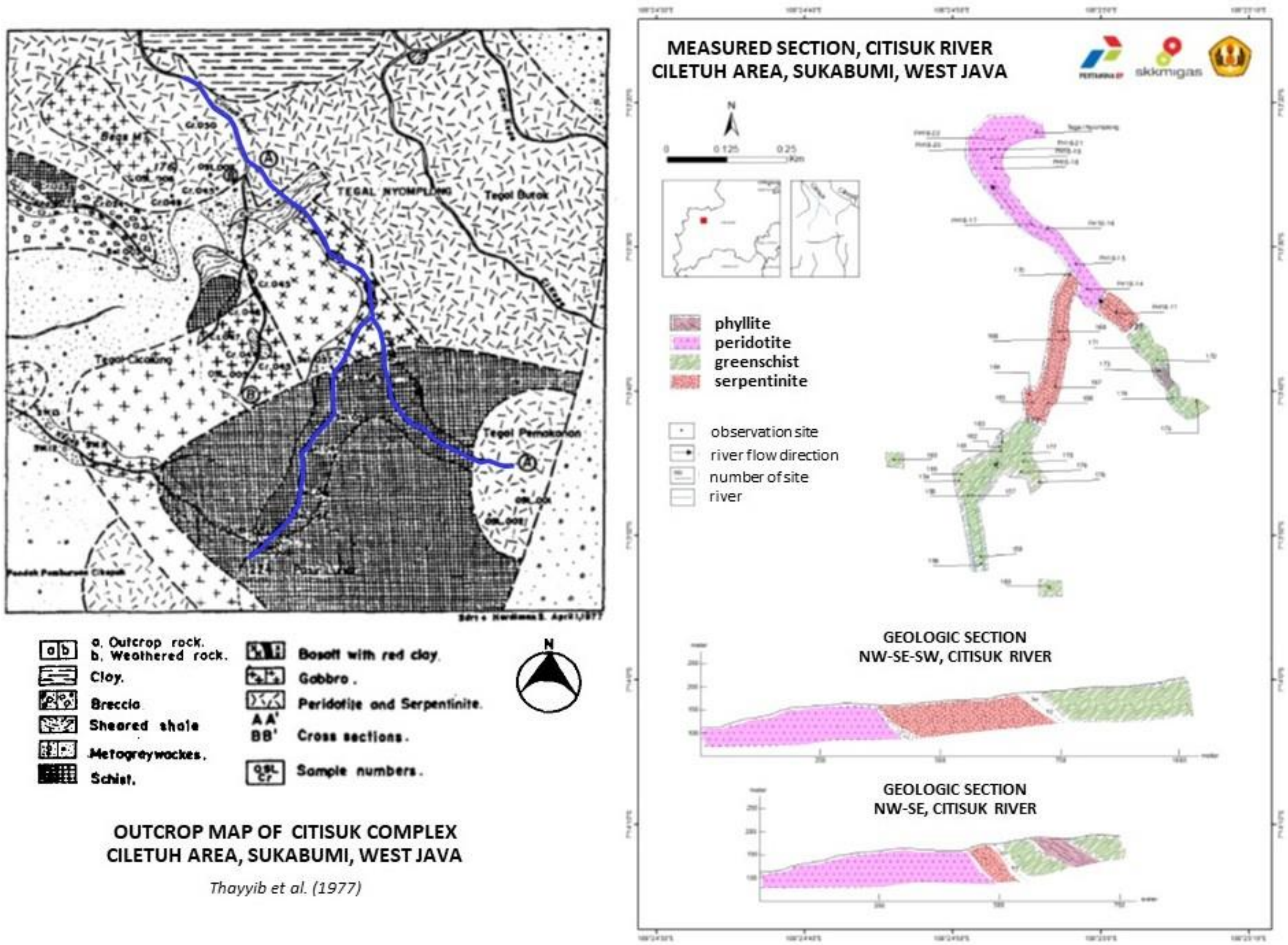



**Figure 6 -** Resurvey of Citisuk River in searching of the blue schist reported by Thayyib *et al.* (1977) (left figure). No blueschist is found, the blueschist reported is greenschist (right figure). The Citisuk River exposes well the melange of Ciletuh as can be seen on the variety of rock units exposed in mixture including: greenschist, phyllite, peridotite, serpentinite.

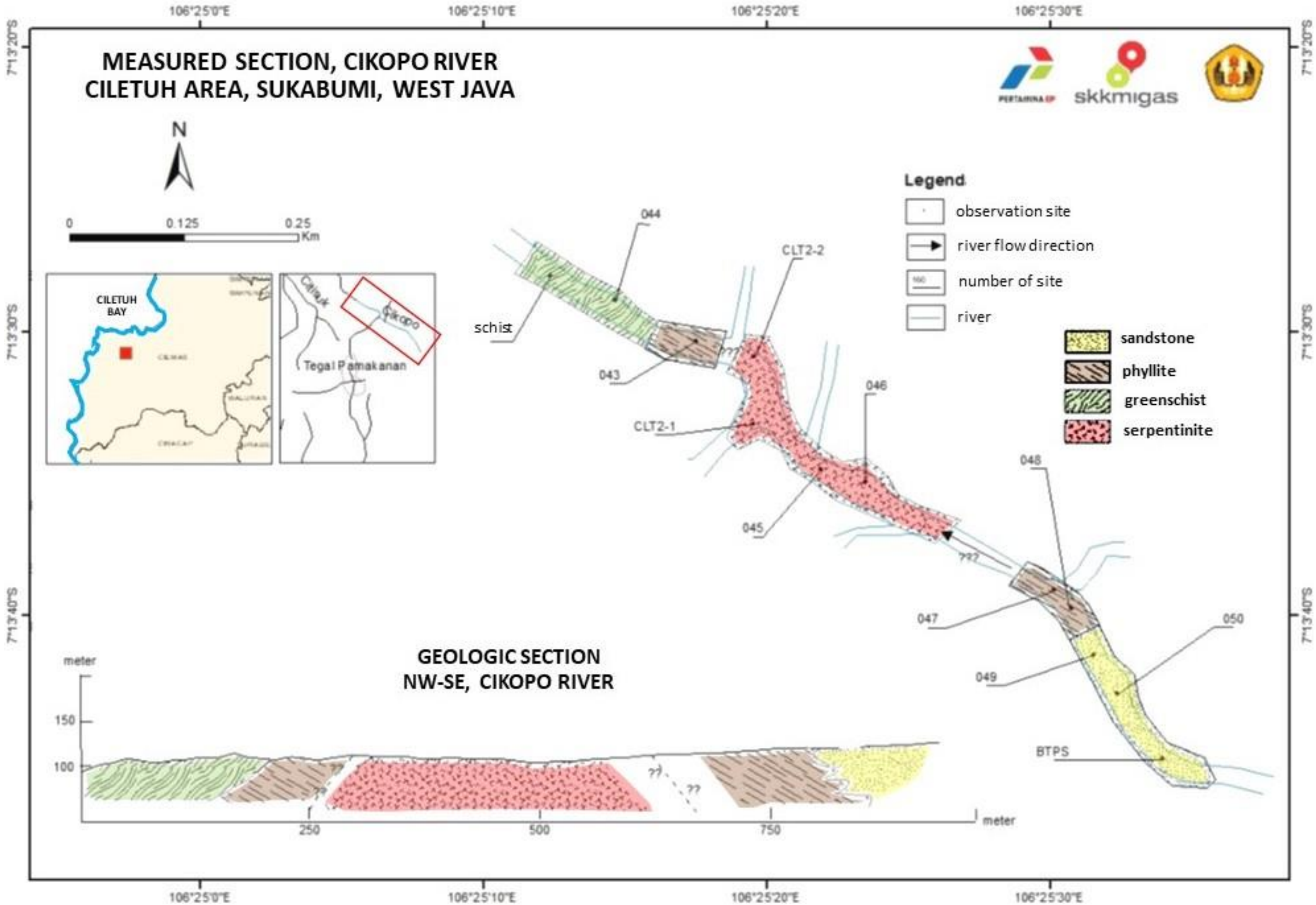



**Figure 7 -** Measured section at Cikopo River, exposing well the melange of Ciletuh, composed of greywacke sandstone, greenschist, phyllite, and serpentinite, contact areas between units are generally blank area in measured section showing a fault contact.

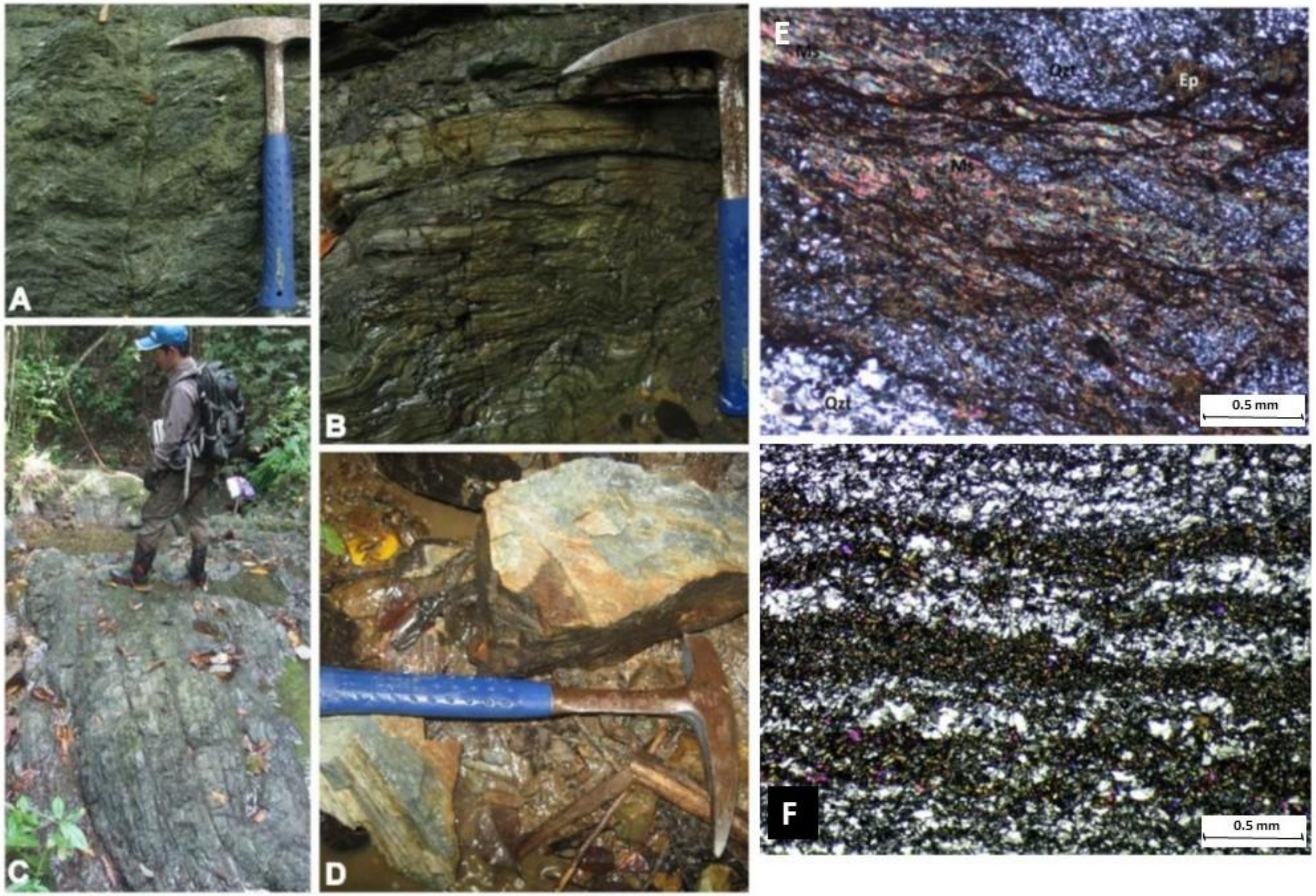



**Figure 8 -** Greenschist metamorphic facies of Ciletuh area. A) and B) Greenschist outcrops at Citisuk River. C) Greenschist outcrop at a river to the north of Tegal Pamakanan. D) Outcrop of phyllite with layers of quartzite at a river to the southwest of Tegal Pamakanan. E) Microscopic photography of muscovite epidote schist (Qtz -quartz, Ep-epidote, Ms-muscovite). F) Microscopic photography of muscovite epidote schist, showing a well-developed schistosity, alternations of muscovite epidote and quartz. Pictures A to E from Ikhram *et al.* (2019).

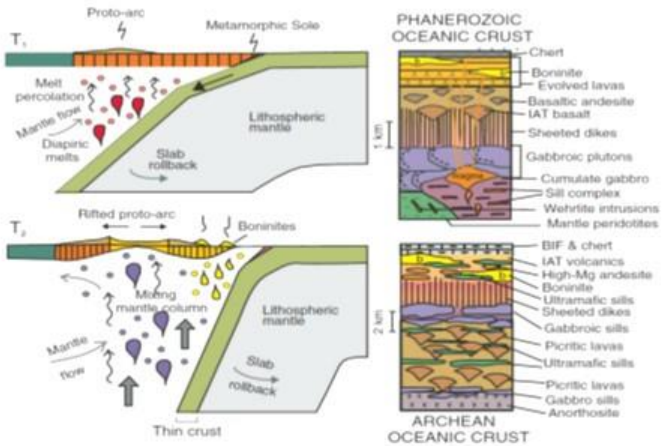

**Figure 9 -** Outcrops of Ciletuh ophiolite. A) Gabbro at Sodongparat. B) Layered gabbro intruded by plagiogranite, whitish in colour, Cikepuh River near to Sodongparat. C) Hilly area composed by peridotite, Tegal Panglayugan, central part of Ciletuh.

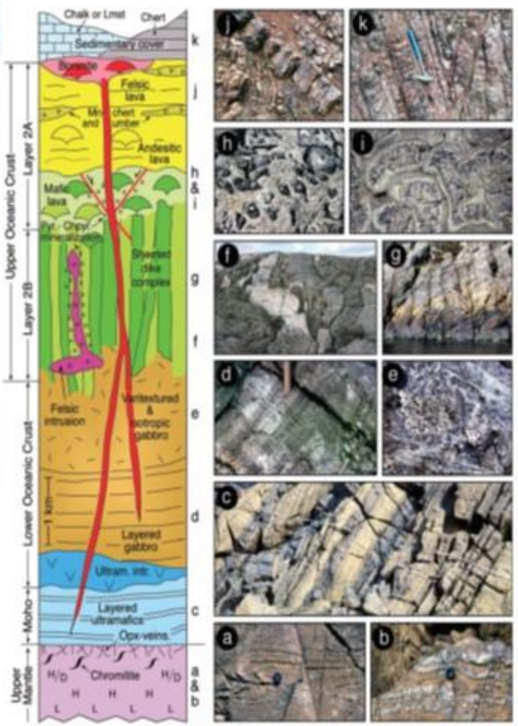
| Ophiolite Types & Their Tectonic Settings | | | Ophiolite/Modern Examples | Geochemical Affinities | Crystallization Order of Minerals |
|---|---|---|---|---|---|
| Subduction-unrelated | Continental margin type | | Ligurian and Western Alpine ophiolites; Jormua (Finland) | N-MORB, E-MORB, P-MORB & C-MORB lavas | Olivine + plag + cpx |
| | Mid-ocean ridge types | Plume-distal MOR | Macquarie Ridge; Masirah (Oman) | N-MORB (DMM) to E-MORB lavas | Olivine + plag |
| | | Plume-proximal MOR | Iceland | N-MORB and P-MORB lavas | Olivine + plag ± cpx |
| | | Trench-proximal MOR | Taitao (Chile) | N-MORB, E-MORB ± C-MORB lavas | Olivine + plag + cpx |
| | Plume-type | | Nicoya (Costa Rica); Bolivar (Colombia) | P-MORB lavas | Olivine + plag + cpx ± opx |
| Subduction-related | Suprasubduction zone types | Forearc | Troodos (Cyprus); Kizildag (Turkey); Semail (Oman); Betts Cove (Canada) | FAB (MORB-like), IAT to boninite lavas | Olivine + plag + cpx + opx and Olivine + cpx + plag |
| | | Backarc (continental & oceanic) | Rocas Verdes (Chile); Solund-Stavfjord (Norway) | BABB lavas | Olivine + plag + cpx and Olivine + cpx + plag |
| | Volcanic arc type | | Smartville (California); Itogon (Philippines) | IAT to CA lavas; middle crust with tonalite, diorite | Olivine + plag + cpx and Olivine + cpx + plag |

BABB = back-arc basin basalt; CA = calc-alkaline; C-MORB = contaminated MORB; DMM = depleted MORB mantle; E-MORB = enriched MORB; FAB = forearc basalt; IAT = island-arc tholeiite; MORB = mid-ocean ridge basalt; N-MORB = normal MORB; P-MORB = plume-influenced MORB

**OPHIOLITE TYPES AND REPRESENTATIVE EXAMPLES, WITH THEIR GEOCHEMICAL AFFINITIES AND MAJOR MINERAL PHASES** *Dilek and Furnes (2014)*

**SSZ EVOLUTION OF PHANEROZOIC OPHIOLITES** *Dilek and Polat (2008)*




*Dilek and Furnes (2014)*

(**LEFT**) Columnar section showing the upper mantle and crustal components of a generalized suprasubduction zone ophiolite. (**RIGHT**) Field photographs; a photo illustrating a component of a given unit has the same letter as the unit in the section. Photos (**a**) and (**b**) banded and folded harzburgite (olivine+orthopyroxene); (**c**) layered cumulates of dunite (yellow) and wehrlite (olivine + clinopyroxene; dark); (**d**) layered and folded gabbro; (**e**) varitextured gabbro; (**f**) gabbro cut by basaltic and felsic intrusions; (**g**) sheeted dike complex; (**h**) volcanic breccia with a hyaloclastic matrix; (**i**) pillow lava; (**j**) massive andesitic lava fl ow; (**k**) folded chert layers. Locations of photos: (a–c, i): Leka ophiolite, Norway; (d): Karmøy ophiolite, Norway; (e–h): Solund-Stavfjord ophiolite, Norway; (j, k): Mirdita ophiolite, Albania. Chpyr = chalcopyrite, H/D = harzburgite/ dunite, H = harzburgite, L = lherzolite, Lmst = limestone, Opx veins = orthopyroxenite veins, Pyr = pyrite.

**Figure 10 -** Ophiolite types, characteristics, and their tectonic settings. Dilek and Furnes (2014) subdivided ophiolite into two tectonic types: subduction-related and subduction-unrelated (MOR type). Ciletuh is dominated by subduction-related SSZ (suprasubduction zone) type. The mechanism of formation is explained on bottom left figure (Dilek and Polat, 2008), and the ideal order of the SSZ ophiolite is shown on right figure (Dilek and Furnes, 2014).

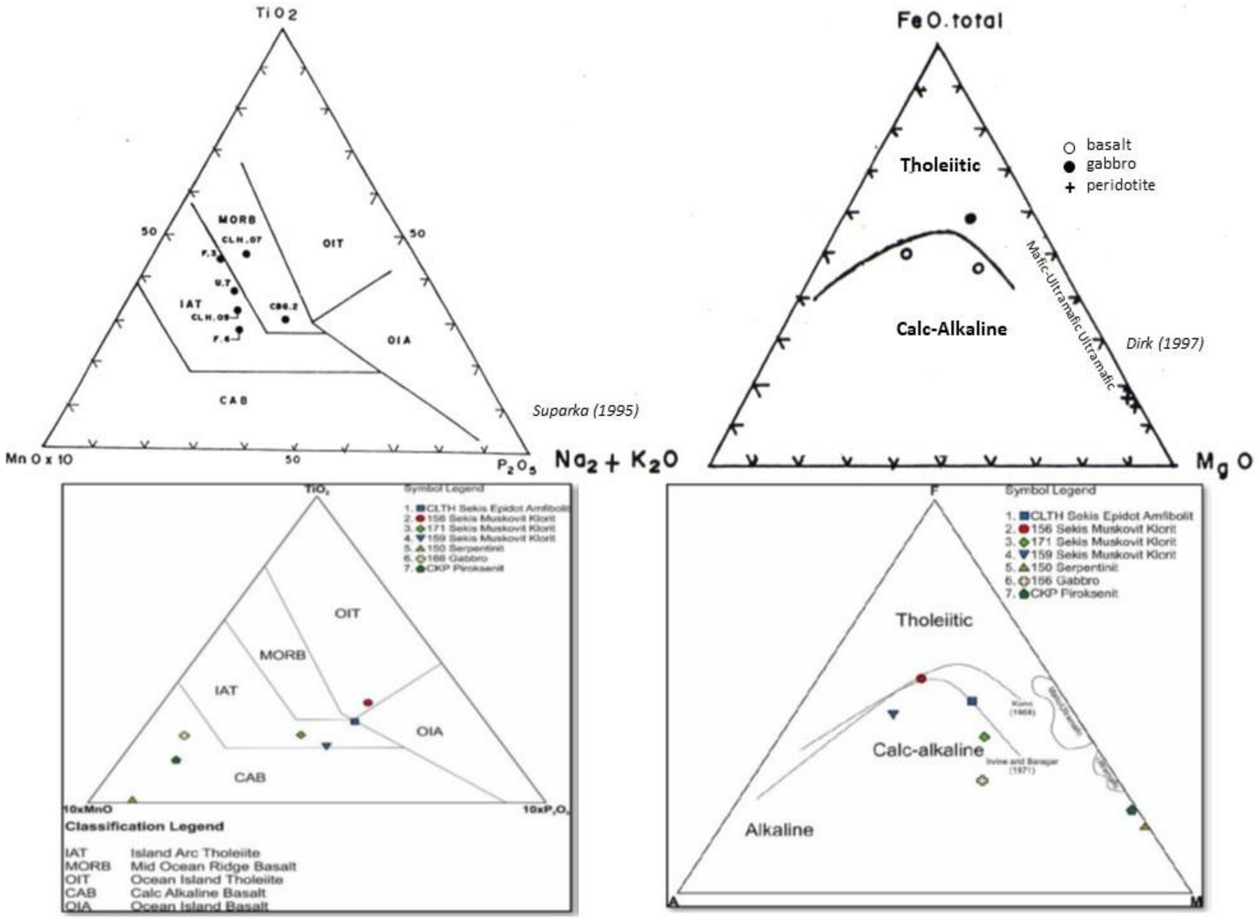
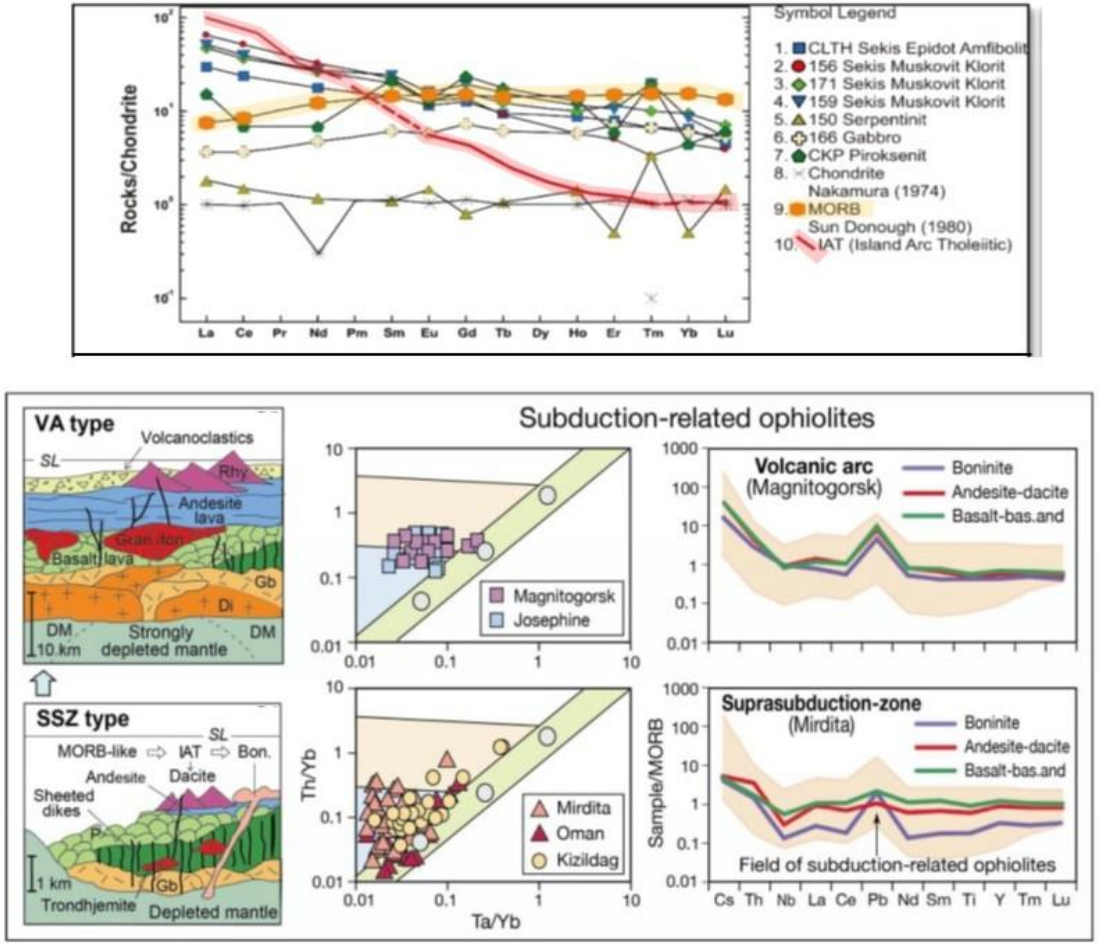



**Figure 11 -** Triangular plots of major oxides of ophiolite and metamorphic rocks of Ciletuh to know the petrotectonic setting of rock formation (petrogenesis). Top figures are plot of ophiolite from previous studies (Suparka, 1995) and Dirk (1997) on plot of Mullen (1983) and AFM diagram of Kuno (1968), respectively. Bottom figures show plots of this study based on Mullen (1983) and AFM diagram of Kuno (1968) and Irvine and Baragar (1971). Most of the rocks fall under the group of island arc tholeiitic (IAT) or calc-alkaline basalt (CAB), showing petrogenesis of subduction-related or suprasubduction zone (SSZ) ophiolite. Some samples from Suparka (1995) show a MOR (midoceanic ridge) ophiolite.




Bon. = boninite; Gb = gabbro; IAT = island arc tholeiite; P = pillow lava; **SSZ type = supra-subduction zone type.** Di = diorite; DM = depleted mantle; Gb = gabbro; Gran/ton = granodiorite/ tonalite; Rhy = rhyolite; **VA type = volcanic arc type**. Bas. and = basaltic andesite.

*Dilek and Furnes (2014)*

**Figure 12 -** Top. Spider diagram of trace elements and REE, normalized, for metamorphic and ophiolite rocks of Ciletuh, plotted are trend of chondrite, MORB, and IAT. All of metamorphic rocks show trend of IAT. Gabbro sample shows trend of MORB, pyroxenite shows a combination of IAT and MOR. This confirms the petrogenesis of metamorphic rocks at subduction zone, and there is possibility of MOR ophiolite (gabbro). Bottom. Characteristics of ophiolite petrogenesis in subduction-related setting of SSZ (suprasubduction zone) or VA (volcanic arc) based on Dilek and Furnes (2014).

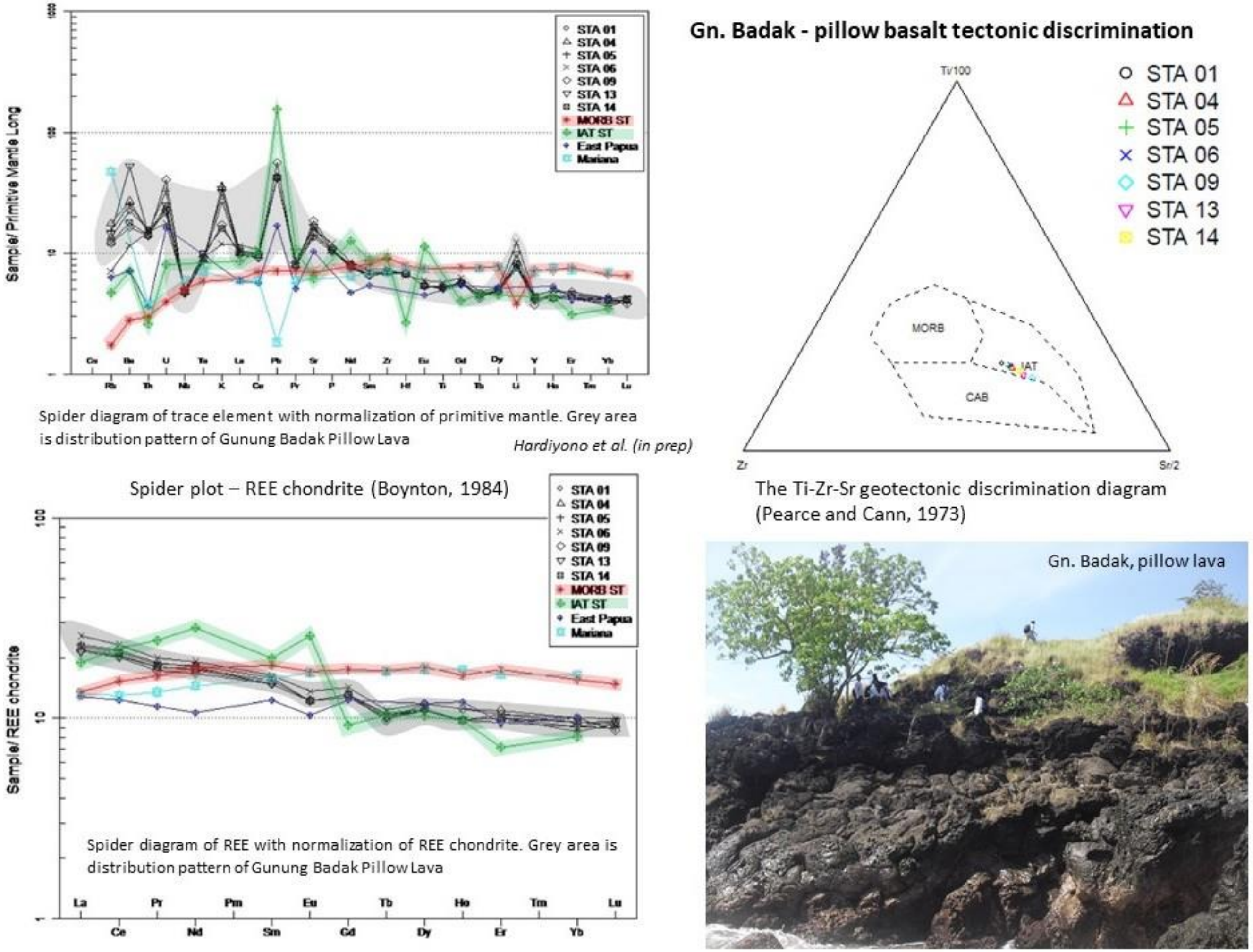



**Figure 13 -** Petrotectonic setting of Gunung Badak basaltic pillowed lava based using trace elements and REE. Grey shaded at spider diagram are data coverage of Gunung Badak samples, green shaded is trend of IAT (island arc tholeiitic) setting, red shaded is trend of MOR (midoceanic ridge) setting. Gunung Badak samples based on trace elements and REE show island-arc tholeiitic setting.

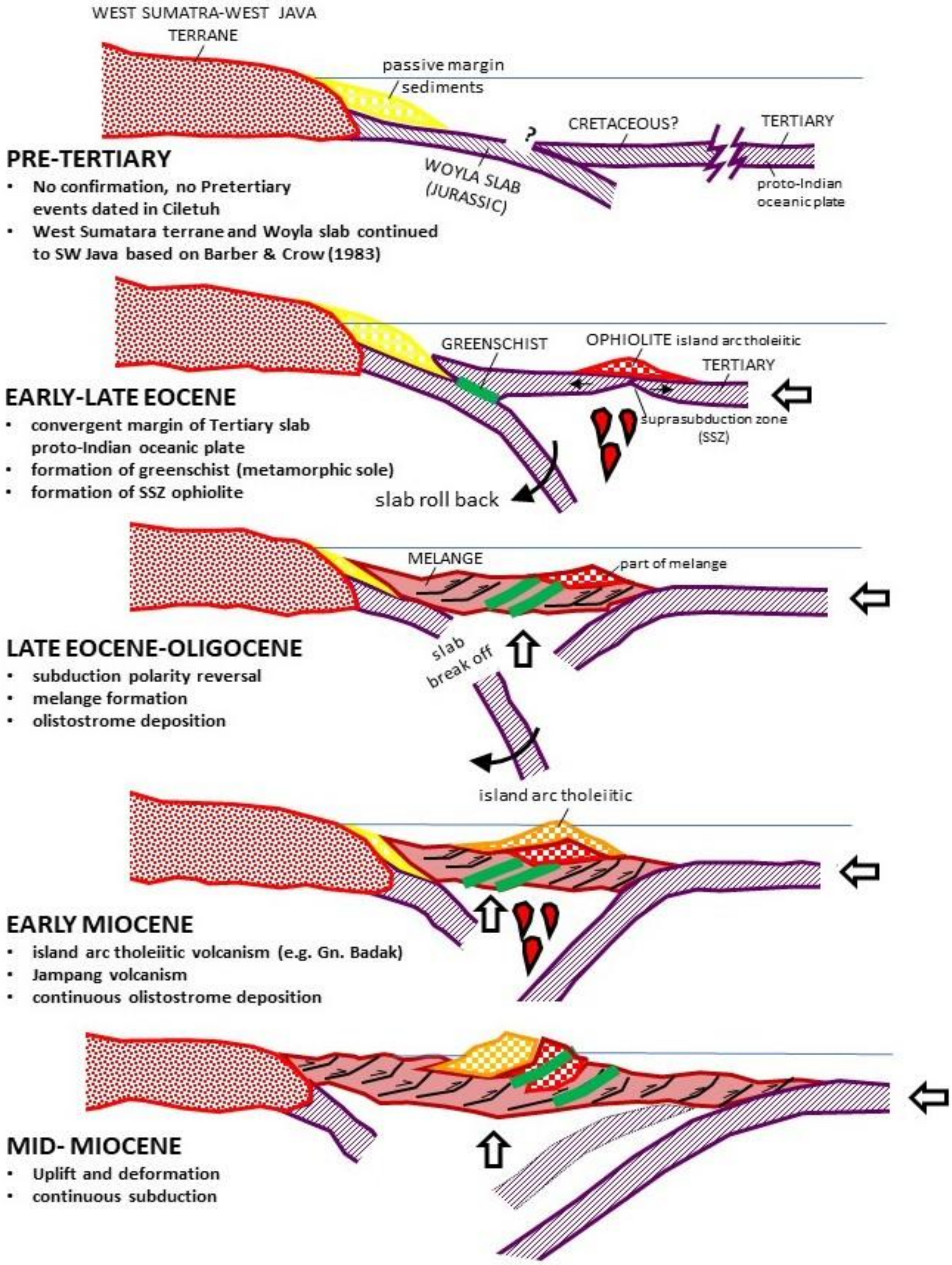
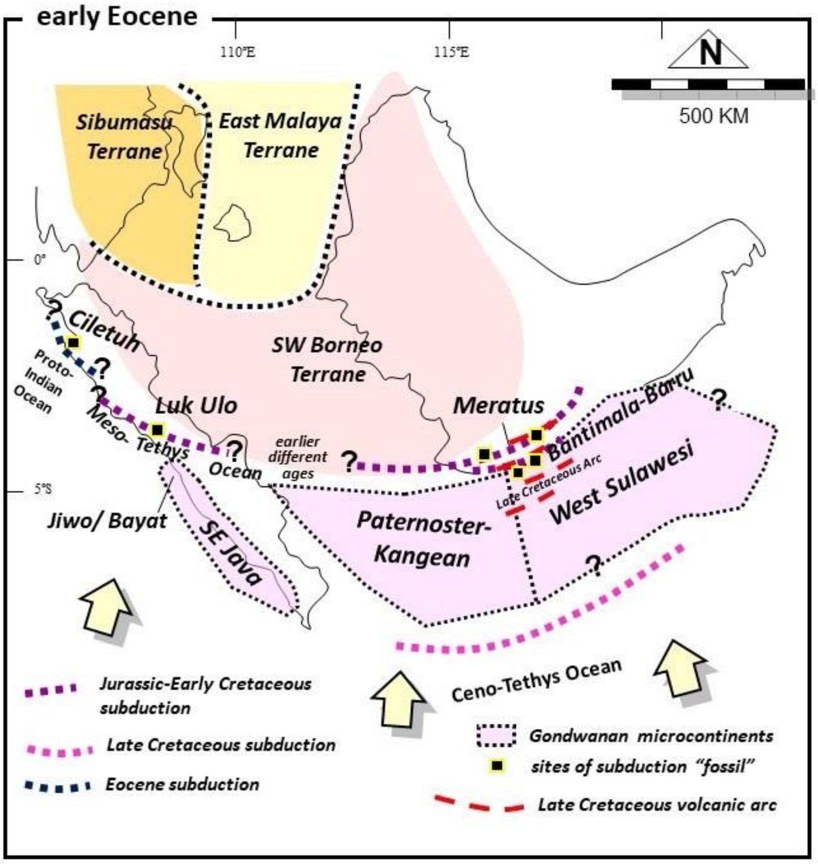



**Figure 14** – Schematic sections showing tectonic evolution of Ciletuh subduction. The presence of SSZ ophiolite in Ciletuh geochemically characterized by island arc tholeiitic required a petrogenesis at rifted overriding oceanic plate by roll back subduction of old slab. Melange formation occurred right after metamorphic and ophiolite petrogenesis, also involved continental margin sediments and slab segment. New reversed subduction took place in the late Eocene to Oligocene coeval with melange formation and thrusting. The accreted terrane stopped the movement of the proto-Indian oceanic plate and became subduction margin since then. Island arc tholeiitic volcanism occurred again in early Miocene like Gunung Badak basaltic pillowed lava still in Eocene subduction site. Uplift, deformation, and continuous subduction occurred during middle Miocene and onward.




**Tectonic events from Jurassic-Eocene**

- Early-Middle Jurassic: subduction of Meso-Tethys in Meratus trench (180-165 Ma Hauran schists; Middle Jurassic radiolaria.
- Subduction took place in Barru-Bantimala in Early Cretaceous (137 Ma Bantimala eclogite). Subduction resumed in Meratus (131-101 Ma) and continued in Bantimala (113 Ma).
- Subduction took place in Early-mid Cretaceous in Luk Ulo (124-102 Ma).
- 112 Ma: collision of West Sulawesi microcontinent onto Bantimala trench. Post-collision Bantimala radiolarian chert
- 110-90 Ma: collision of Paternoster-Kangean onto Meratus trench.
- 98 Ma: docking of SE Java microcontinent to the east of Luk Ulo. Bayat/ Jiwo Hill metamorphism.
- Late Cretaceous subduction behind Paternoster-Kangean/ Paternoster trench (vocaniclastic Haruyan & Pitap Group in Meratus, 83-66 Ma).
- Eocene (55-38 Ma) Ciletuh subduction, dominant suprasubduction ophiolite

**Figure 15** – Early Eocene tectonic reconstruction of Java, Kalimantan, western Sulawesi or collectively called as Southeast Sundaland, modified from Satyana (2014a, b). Tectonic events from Jurassic to Eocene are listed based on available absolute age dating. Subduction in Ciletuh is the last event dated 55-38 Ma. or early to late Eocene from proto-Indian oceanic plate. The Early Cretaceous subduction of Meso-Tethys oceanic plate at Karangsambung (124-102 Ma) has no evidence continued into Ciletuh area.