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8 Ultrahigh-Pressure Metamorphic Rocks in the Bantimala Mélange Complex and Its Implication to Cretaceous Tectonics in the South Arm of Sulawesi

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Abstract. Bantimala Mélange Complex is about 75 Km to the North of Makassar, the capital city of South Sulawesi Province. The presence of High-pressure Metamorphic Rocks, and Ultrahigh Pressure in the Bantimala Mélange Complex, has been known and studied by a number of geologists. Eclogite and Blue Schist are Ultrahigh, and High-pressure metamorphic rocks in the Bantimala Mélange Complex which have important significance in explaining the Cretaceous tectonics in this area. Furthermore, Bantimala Eclogite is the only Ultrahigh-pressure metamorphic rock known to be exposed in Sulawesi. The results of thin section analysis of Eclogite show the presence of Omphacite Minerals, and Coesite as an index mineral for Ultrahigh pressure metamorphic rocks. While in Blue Schist with Glaucophane Minerals are found which are partially replaced by Chlorite which indicates the presence of Poly-metamorphism as a result of retrogradation from Ultrahigh pressure to High pressure and to Medium pressure metamorphic rocks. Radiometric age dating using the Ar^{40}/Ar^{39} method shows an age spectrum of 100 Ma -114 Ma (Early Cretaceous). The 114 Ma, age is interpreted as the age of Eclogite's Ultrahigh pressure metamorphic rocks formation with respect to the peak of subduction tectonics. Whereas the age of 100 Ma before now is interpreted as the age of exhumation or collision as the end of the Cretaceous tectonic subduction in the South Arm of Sulawesi or in the East or Southeast of Sundaland.

1. Introduction

Sulawesi Island has a unique shape and has or there are at least nine metamorphic complexes. Is the mainland or lithosphere with the most metamorphic rock complexes in the world [1]. Bantimala Mélange Complex is one of them, also known as the accretionary complex, is about 75 Km to the Northeast of Makassar, the capital city of South Sulawesi Province (Figure 1). It stretches relatively North to South along approximately 55 Km with a width of about 15 Km [2].

The Bantimala Mélange Complex consists of two blocks namely the Bantimala Block in the south and the Barru Block in the North [3]. High and Ultrahigh-pressure metamorphic rock outcrops associated with Mélange, well exposed at a number of locations in this complex. So far as much research has been done both in relation to the presence of mélange, and related to tectonics event and metamorphic rocks which are very varied. A number of geologists who have conducted research in this area, including [2, 3, 5-13].

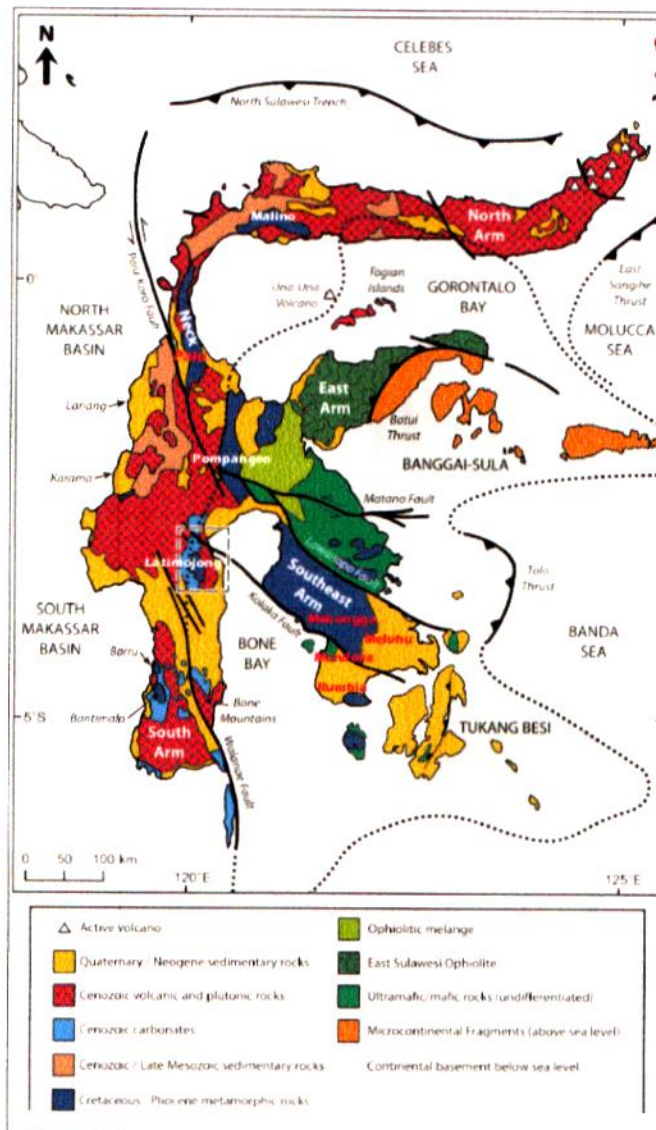


Figure 1. Geological map of Sulawesi Island (Modified from [4])

2. Research location

The research location is about 75 Km to the north of Makassar City, the Capital City of South Sulawesi Province (Figure 2). This area can be reached by vehicles for approximately 1.5 hours from Makassar City or one hour from Hasanuddin International Airport in Maros, South Sulawesi.



Figure 2. Research location (Bantimala Mélange Complex). The red square is Bantimala Mélange Complex.

3. The aims and objectives of the study

The purpose and objective of this research are to know and understand the Cretaceous tectonics in the South Arm of Sulawesi and/or Southeast Sundaland based on metamorphic rock data.

4. Geology of the Bantimala Mélange Complex

In the Sulawesi Island, there are at least nine segments of the accretionary complex [1], one of which is the Bantimala Complex [5-8]. Other accretion complexes namely the Pompango Complex in Central Sulawesi [9, 10], Latimojong Complex in the Northern part of the South Arm [2, 4, 11], Mekongga, Umbia, Mendoke and Meluhu Complex in the Southeast Arm of Sulawesi [1, 12, 13], Malino Complex in the Western part of the North Arm of Sulawesi [14], and the Palu Complex in Western part of Central Sulawesi [15].

It is noted that between the Bantimala Mélange Complex in South Sulawesi and the Meratus Complex in South Kalimantan it is assumed to be the Cretaceous accretion complex that merges before the Makassar Strait opening in Paleogen [2, 6, 16]. This assumption explains that both complexes are part of the same accretion complex in Southeast Sundaland. This can be seen from the appearance of spatial distribution, and between the two complexes there is the Paternoster Platform [2]. The Paternoster platform was reported as a continental fragment that moved to North after detachment from Gondwanaland during the opening of Meso-Tethys [2, 17-19]. Other researchers explain that Bantimala mélange complex is the same accretion pathway as the Karang Sambung accretion complex in Central Java [2].

4.1. Lithology Unit of Bantimala Complex

The Bantimala Complex is composed by Mesozoic basement which is overlain unconformably of Late Cretaceous sedimentary rock formations to Cenozoic sedimentary and volcanic rocks [2]. Mesozoic rocks as a basement exposed in the South Arm of Sulawesi especially in the Bantimala Complex consist of ultramafic, metamorphic rocks, and Mélange [2, 3, 6, 8]. At the top of the basement, the Cretaceous sedimentary rocks are overlain the same direction as the intersection between re-crystallized sandstone and shale. This unit is known as the Balangbaru Formation with a thickness at least 2500 m [2, 8].

4.1.1. Mesozoic Metamorphic Basement Rocks

The Mesozoic metamorphic rock unit in the Bantimala Mélange Complex consists of eclogite, glaucophane schist, garnet schist, amphibolite schist, muscovite schist, quartz-feldspar gneiss [2, 3, 8]. This unit exhibits medium to ultra-high pressure and medium-grade metamorphisms [8, 18, 19, 20]. Experienced metamorphism under pressure conditions 16- 17 Kbar and 24-27 K-bar, and temperatures 580-620°C and 580-650°C [20].

4.1.2 Mélange

Mélange outcrops consist of deformed sandstones, shales, conglomerates, diorites and schist breccias. The lithology unit is classified as mélange [2, 3, 8]. The stratigraphic relationship between its components is not clear, between unit contact cannot be defined. Foliation tends to tilt to the northeast and southwest. The thickness of this unit is estimated to be not less than 1,750 m [2, 8]. The Breccia-schist overlies with metamorphic schist at the top the schist-breccias develops into sandstones which are crushed by radiolarian chert. Radiolarian chert is conformably overlain by shales alternating with sandstones with conglomerate intercalation. Chert and limestone which are components in mélange were deposited in the Cretaceous Period [2, 21, 22].

4.1.3 The Late Cretaceous Sediment

Sedimentary rock units which are in the Late Cretaceous, are shown by flysch-type deep-sea sediments and turbidite sediments consisting of solid and shale sandstone intercalations. This lithology unit is known as the Balangbaru Formation. Deposited unconformably above the Bantimala Mélange Complex in the Late Cretaceous [2]. Paleo-current studies show that the Balangbaru Formation originated from the west highlands to the northwest [10]. In the upper reaches of the Bontoriu River, this unit serves an imbrication between the blueschist and greenschist and is considered a crystalline basement which proposed as a Jurassic Paremba Sandstone [8]. The Balangbaru Formation intercalated with the Marada Formation which was deposited in the shallow marine during the Late Cretaceous Period [2]. Volcanic activity at that time was responsible for the presence of volcanoclastics intercalations between the Marada Formation and the flysch sediments of Balangbaru Formation [2, 8, 10].

4.1.4 Tertiary Sediment and Volcanic

Tertiary sediment deposits on the top of the Pre-Tertiary rocks are represented by sedimentary and volcanogenic rocks, which are separated into two groups representing different events. The first is the sedimentation and volcanic activity during Paleogene to the Lower Miocene when compression and orogens occur in the South Arm of Sulawesi. This event was shown by Langi volcanic with Calc-alkaline affinity and some shallow marine sediment sequences in the paralic environment namely the Malawa, Tonasa and Salo Kalupang Formations [2, 7, 8, 23, 24]. During the Oligocene - Early Miocene period, important tectonic events occurred which were followed by the emplacement of the Kalamiseng Formation as the Back-Arc Basalt associated with oceanic crust obduction in the South Arm of Sulawesi at the end of subduction in this region [2, 24]. The second is sedimentation and volcanic activity after the Early Miocene when extensional regimes dominated in this region. Miocene sedimentation in the South Arm of Sulawesi, dominated by volcanic activity. The Camba Formation, which occurred during this area, consisted of marine sediments intercalation with volcanic rocks. K-Ar dating of wall rocks alkaline basal, dacite, andesite and basaltic rocks from the Camba Formation obtained age 17.7 Ma; 8.93 Ma; 9.29 Ma and 6.2 Ma [24, 25]. It was explained that the volcanic rocks older than the Middle Miocene were of an orogenic type, while the younger ones of the Middle Miocene were said to be unrelated to subduction. It seems that the magmatic arc formed from partial melting after collision due to thickening crust [25].

In the Middle Miocene to the Pliocene in this region, it shows the spread of the Walanae Formation in the north and east and laterally in the form of thicker limestone and is known as the Tacipi Formation. During the Miocene, volcanic and plutonic rocks predominantly formed in the Southern Arm of Sulawesi. In this case, such as Baturape and Pare-Pare volcanic rocks [2]. This is interpreted as a

Magmatic belt produced by the development of volcanic arcs associated with subduction [6, 8]. While Yuwono, et.al [25] interpret the magmatic arc as in this context of plate dimensions during Tertiary subduction, which ended before the main volcanic period. Other researchers suspect that magmatic arcs result from melting of the lithosphere due to collision [26].

4.2. Metamorphic Rocks of Bantimala Mélange Complex

As explained earlier that high pressure metamorphic rocks (glaucophane schist) and ultrahigh-pressure (eclogite) in the Bantimala Mélange Complex are found in the Koraja-Cempaga River, Bontoriu, Tinjau Bali, Elle and Patetayang. Consisting of amphibole eclogite, amphibole eclogite epidote, epidote eclogites; zoisite blueschist, tourmaline blueschist, lawsonite blueschist, epidote blueschists; Phyllitic blueschist, greenschist, phyllitic greenschist, piemontite phyllite and graphite phyllite [2, 8].

Eclogite is commonly found as a boulder, and some show it has been retrogradation to glaucophane schist and chlorite schist. Some of the eclogite is the result of a prograde and finally after the peak of metamorphism, followed by retrogradation [2]. This is reflected in the replacement as omphacite minerals by glaucophane and lawsonite. Furthermore, by chlorite and epidote. Eclogite as lenses of dimensions from a few centimeters to several meters. Boulder eclogite is found along the Patetang River and Elle River, with a diameter of up to 3 meters (Figure 3).

4.3 Methodology

This research includes survey and rock sampling, petrographic analysis and radiometric age dating. Survey and sampling of high and ultrahigh-pressure metamorphic rocks (glaucophane schist and eclogite) were collected from the Cempaga River, Patetang River and Pangkajene River where various eclogite and glaucophane schists. Subsequently, the samples collected were analyzed by petrography using a polarizing microscope at the Department of Geology, Faculty of Engineering, Hasanuddin University. Whereas radiometric age dating used $^{40}\text{Ar}/^{39}\text{Ar}$ in collaboration with the Research School of Earth Sciences, The Australian National University, Canberra, Australia.

Dating $^{40}\text{Ar}/^{39}\text{Ar}$ is very good for the study of the evolution of metamorphic rocks because this method can detect the possibility of contamination. In particular, ^{40}K isotopes can also form ^{40}Ca isotopes and ^{40}Ar isotopes. Therefore, although the K-Ar dating method has so far contributed to radiometric age data that are known to have a half-life of 1,250 years, a number of weaknesses and weaknesses are now being discovered. However, the $^{40}\text{Ar}/^{39}\text{Ar}$ method is based on the ^{40}K isotope or in other words, K-Ar is the basis for developing the $^{40}\text{Ar}/^{39}\text{Ar}$ dating method.

4.3.1 Field data

The geological survey and rock sampling were carried out in the Bantimala Complex namely in the Pangkajene River, Patetang River and Cempaga River. Field data show that high to ultrahigh-pressure metamorphic rocks were found in bolder form along the Pangkajene River. Large bolder of more than 3 meters is found in Cempaga and Patetang River. Eclogite is found in various types including garnet eclogite, lawsonite-glaucophane eclogite, glaucophane eclogite, tourmaline-glaucophane eclogite. In some spots showing omphacite minerals replaced by glaucophane to chlorite. Also found outcrops with an abundance of garnets with relatively fine crystal sizes forming an orientation measuring 0.5-2 mm. While garnet crystals up to 2 cm in size, show relatively euhedral crystalline shapes and spread in rocks as porphyroblasts that are present between omphacite, tourmaline and glaucophane crystals. Eclogite, which is present with partial replacement of omphacite minerals by glaucophane and/or chlorite, exhibits polymetamorphism symptoms. This condition is found and is well exposed near the branches of the Cempaga River and Patetang River. Visually eclogite outcrops and glaucophane schist can be seen (Figure 4). It appears that eclogite cannot be mapped on a regional scale. Eclogite exists as a subordinate of metamorphic rocks. However, the existence of eclogite provides important significance in the history and tectonic evolution of the Bantimala Mélange Complex and/or in the South Arm of Sulawesi.

The distribution of ultrahigh-pressure metamorphic rocks in the Bantimala Mélange Complex, appears to be located or subordinated to metamorphic rocks of high-pressure (glauco-phane schist) and medium pressure (chlorite schist) and mélange. The geology of the Bantimala Mélange Complex is shown in the geological map of the western part of the South Arm of Sulawesi (Figure 5).

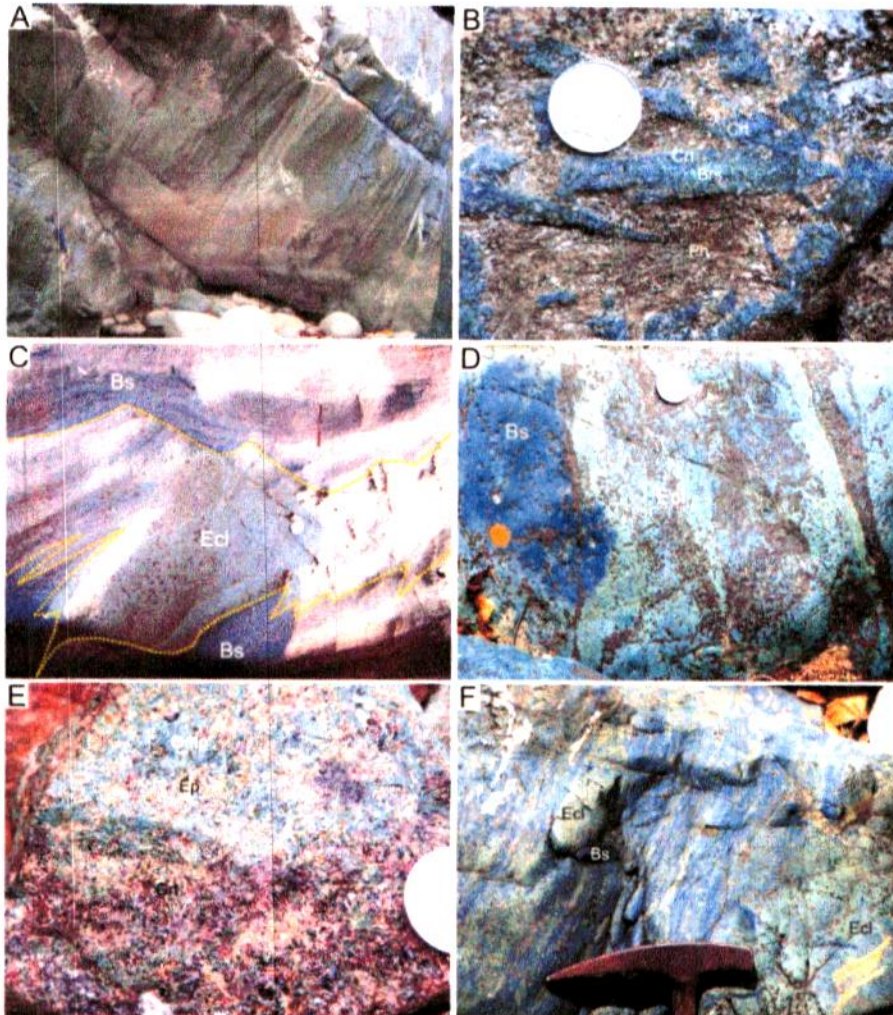


Figure 3. Outcrop of eclogite at Koraja River (all except E) and at Tinjau Bali River (E). This eclogite outcrops are common along Station BTM 134 until BTM 142 at Koraja River. Eclogite lenses are commonly found inside blueschist (C and F) while in some part remnant of blueschist is still preserved during prograde toward eclogite facies (D). Figure E is epidote eclogite at Tinjau Bali River (After [2])

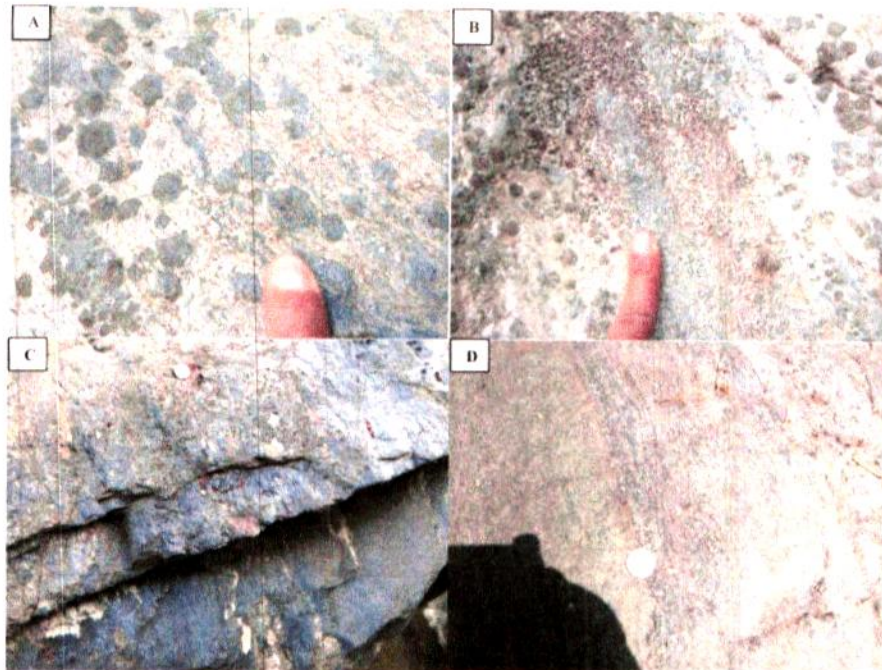


Figure 4. Eclogite outcrop at Cempaga River; (A) Garnet-tourmalin Eclogite with big garnet porphyroblasts, and some of garnet wrap by chlorite; (B) Garnet-Eclogite with small garnet forming layers; (C) Glaucophane schist with small garnet, and some showing glaucophane replaced omphacite; (D) Glaucophane schist showing glaucophane and chlorite replaced ophacite

4.3.2 Petrography Analysis of High and Ultrahigh-Pressure Metamorphic Rocks

A total of 5 eclogite and 5 glaucophane schist samples were prepared using a thin section (0.01 -0.03) mm. Then observed and analyzed using a polarizing microscope. Petrographic observations and results show various types of eclogite namely: Garnet Eclogite, Garnet-tourmaline Eclogite, Garnet-glaucophane Eclogite, Epidote-glaucophane Eclogite and Tourmaline-hornblende Eclogite. Some exhibit mortar textures which are interpreted regarding the event of enlargement and deformation after the metamorphism phase. Five variants of eclogite can be grouped based on the specific abundant minerals found. Eclogite with abundant epidote; epidote-amphibole; amphibolite; quartz (coesite) and lawsonite. Common mineral assemblages of eclogites in the Bantimala Complex are garnet + omphacite + phengite + rutile + glaucophane + small amounts of quartz with several epidemics ± tremolite-actinolite ± titanite ± zoisite ± clinozoisite ± lawsonite and opaque minerals. Eclogite variations seem to reflect that most eclogites in the Bantimala Complex experience polymetamorphism. Also enhanced is the local presence of high temperature metamorphic rocks (Amphibolite and Amphibolite-Chlorite schist). It can be interpreted that the polymetamorphism occurs with regard to the decrease in pressure and temperature accompanying the end of the subduction event at the Bantimala Complex followed by collision and exhumation events. This can be proven by the presence of medium to low pressure minerals replacing ultrahigh-pressure and high-pressure minerals. Likewise, high temperature minerals by medium temperature minerals. Visually shown in (Figures 6 and 7).

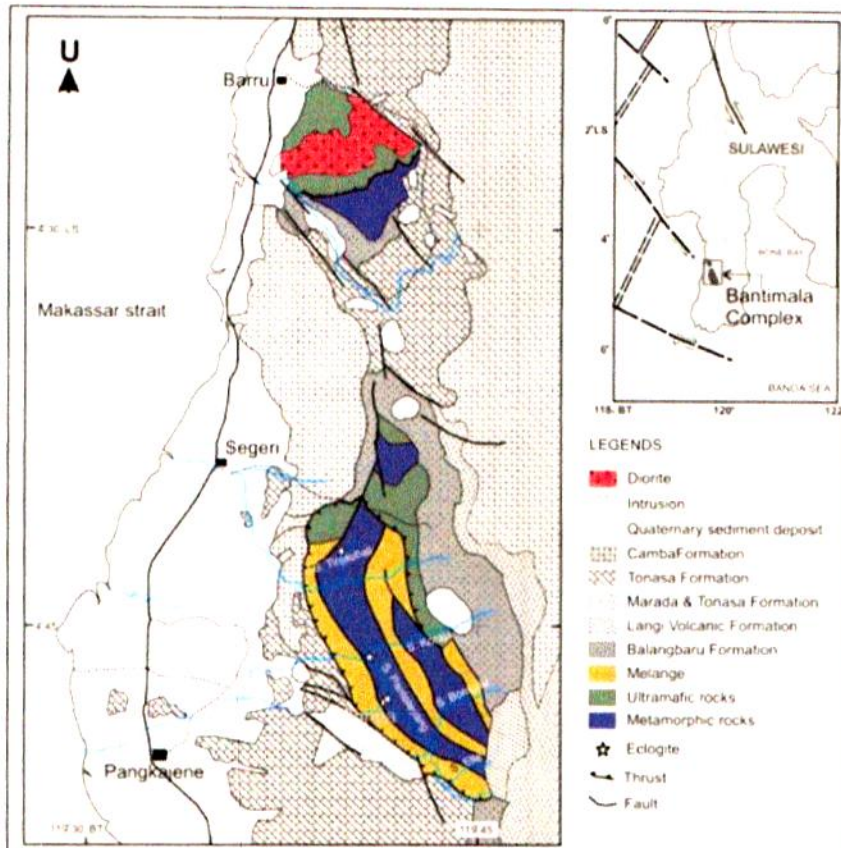


Figure 5. Geological map of Western part of South Sulawesi Indonesia shows metamorphic and ultramafic units are surrounded by Cretaceous sediment and Tertiary [2]

Glaucophane are common mineral in eclogite and blueschist of the Bantimala Melange Complex, either present as inclusion or matrix. Its lavender blue to blue color is typical for glaucophane mineral. Besides present in matrix of eclogite, some glaucophane also present as an inclusion in garnet.

4.4 Geochronology and Cretaceous Tectonics

Radiometric age dating results for metamorphic rocks of high pressure and ultrahigh-pressure of the Bantimala Mélange Complex from various methods can be described as follows:

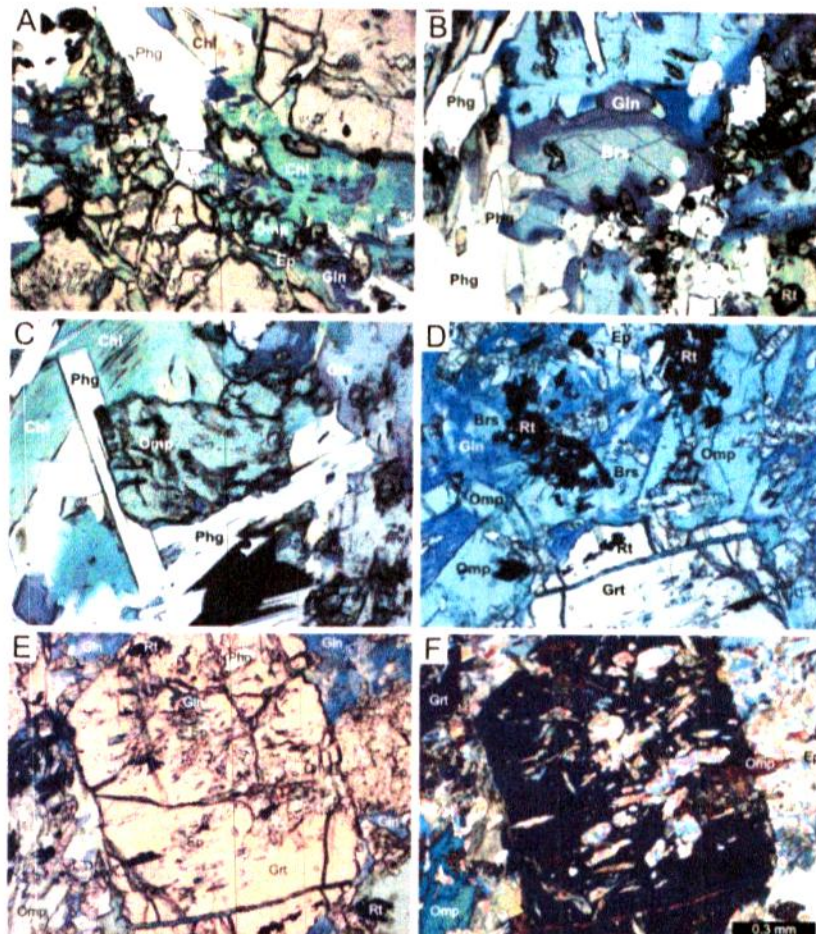


Figure 6. Microphotograph of eclogites taken from the Bantimala Melange Complex. A, B and C are taken from Epidote Amphibole Eclogite of BTM 134A while D and E are taken from Amphibole Eclogite of BTM 140A. F is cross polar of Figure E. Assemblage of garnet-omphacite- phengite-rutile-glaucophane designate this rock. Inclusions of Ph, Crt, Rt, Ep, Qz are common. Chlorite present as replacement of amphibole and garnet (After [2])

4.4.1 K-Ar Dating

K-Ar age dating of phengite minerals from blueschist and eclogite [21, 28], indicates Valanginian age through the Cretaceous Aptian age. Whereas K-Ar on the muscovite mineral from blueschist yielded 111 Ma [27]. The most recent K-Ar age data taken from phengite minerals of garnet-glaucophane schist from Barru Blok provide age spectrum 132 ± 7 Ma, 124 ± 6 Ma, 115 ± 6 Ma, and 114 ± 6 Ma and 106 ± 5 Ma [28]. Whereas the eclogite collected from Bantimala produced K-Ar age of 137 ± 3 Ma [18].

4.4.2 U-Pb Zircon SHRIMP

Radiometric age dating of U-Pb from zircon minerals by the *SHRIMP* method gives results of 819.4 ± 9.3 Ma, 758.8 ± 8.7 Ma, and 296 ± 2 Ma [2]. In detail the *SHRIMP U-Pb Zircon* age spectrum can be shown in Figure 8.

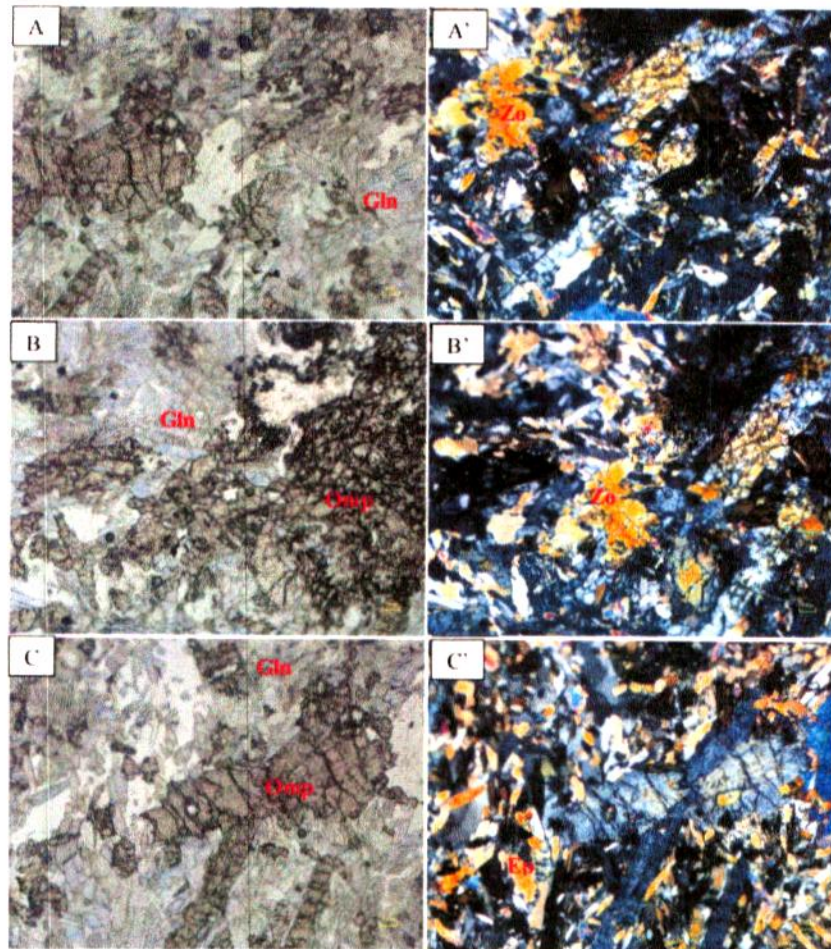


Figure 7. Microphotograph of thin section of Eclogite from Cempaga river. Parallel nicol (PPL) in left, and Cross nicol (XPL) in right. It appears that the mineral Omphacite (Omp) was partially replaced by Glaucophane (Gln) and the zoisite and epidote (Ep). The conditions reflect polymetamorphism from ultrahigh-pressure to high-pressure - medium temperature.

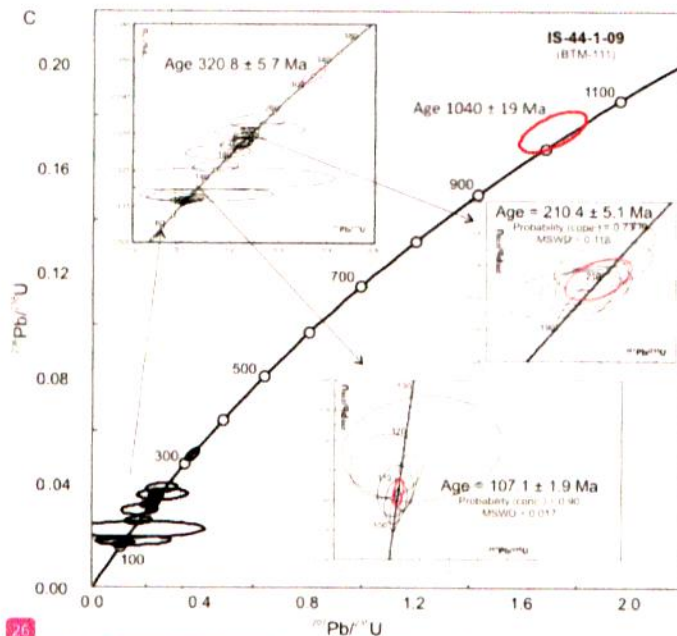


Figure 8. Concordia diagram with U-Pb SHRIMP analysis of zircon from the Bantimala Melange Complex. Eclogite is MORB geochemistry (above left). Diorite block in mélange (above right). Below is detrital zircon of the Balangbaru sandstone. Some zooms are made to display the detail concordant ages (After [2]).

4.4.3 $^{40}\text{Ar}/^{39}\text{Ar}$ Geochronology

$^{40}\text{Ar}/^{39}\text{Ar}$ age dating of white mica (phengite) from samples of phenocrysts with a crystal size of 150 >250 μm . Dating results gives an age spectrum of 114 Ma - 100 Ma. The age of 114 Ma can be interpreted as the age of eclogite formation which is the peak of metamorphism or as the final or maximum subduction. Whereas the age of 100 Ma can be interpreted as the age of exhumation or collision as the end of subduction tectonics in the Bantimala Complex.

5. Conclusions and Discussion

Based on the results of radiometric age dating and petrographic analysis of high and ultrahigh-pressure metamorphic rocks, that in the Cretaceous Period in the Bantimala Complex has experienced subduction and collision tectonics followed by exhumation. This event, allegedly occurred in the South Arm of Sulawesi, or in the Southeastern part of Sundaland, which caused Sundaland to increase. This tectonic phase occurred in the Cretaceous Period (137-100 Ma). Collision occurred at around 100 Ma which is interpreted as the age of exhumation or collision regarding the end of subduction tectonics in the South Arm of Sulawesi for the tectonics of Cretaceous Period. The results of the U-Pb Zircon SHRIMP 819.4 \pm 9.3 Ma, 758.8 \pm 8.7 Ma originating from zircon detrital in the Balangbaru Formation, were interpreted as zircon detrital originating from the Gondwana Continental and experiencing transportation and deposition with the Balangbaru Formation during the Cretaceous Period. Whereas zircon ages 320.2 \pm 5.7 Ma and 210.4 \pm 5.1 are interpreted as zircon magmatism before or during the initial phase of subduction tectonics, regarding the disappearance or consumption of the Tethys Ocean under the Eurasian Continent.

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