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Fracture Characteristics of Mélange Complex Basement in Bantimala Area, South Sulawesi, Indonesia

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Abstract - A detailed geological mapping and fracture characterization had been performed in Bantimala area, South Sulawesi, Indonesia. The geology of the studied area is composed of pre-Tertiary metamorphic, sedimentary, and igneous rocks which tectonically mixed forming a mélange complex. Located on the southeastern margin of Sundaland, the tectonic strongly influences the fracture occurrences in the studied area. A total of 3,841 fractures comprising shear fractures, extension fractures, veins, and joints have been measured and analyzed. The common fracture orientations are NW - SE, W - E, NNE - SSW, and ENE - WSW trends. Fractures developing in Bantimala have clearly been controlled by lithology and structure position (*i.e.* fault zones and fold hinge). The orientation of fractures in Bantimala area is different on each lithology, showing that the fracture system was complex. Fracture intensity in schist is higher compared to the other lithologies. The 3D fracture modeling through 3D geocellular modeling was generated using the result from field data measurements and analyses. Discrete Fracture Network (DFN) was built by fifty-one fracture sets that were analyzed from field measurement data. However, the estimation of average fracture porosity from modeling varies significantly depending on lithology. The value of fracture porosity is relatively small, varied from 0.0004 to 0.0029 %. A high fracture porosity number is observed in an area with a significant fracture intensity and most crosscutting of fracture which in turn is controlled by faults and lithology. A mélange complex can have high potential as a basement fractured reservoir target, where fracture distributions and their attributes will vary depending on the lithology as well as local deformation.

Keywords: Bantimala Mélange Complex, basement fractured reservoir, Discrete Fracture Network, 3D Geocellular Modeling

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Introduction

Naturally, a fractured reservoir is proven as a productive reservoir in numerous oil fields. A basement is one of lithologies that performs as a naturally fractured reservoir. A number of fractured basement reservoirs have been discovered in the world (Koning, 1985; Koning and Darmono, 1989; Nelson, 2001; Sapiie *et al.*, 2014). A recent oil and gas exploration in the offshore of the northern Madura Island discovered gas within the basement rocks. The basement lithology was made of various rocks which are interpreted as part of the Cretaceous accretionary complex developed as mélange. Mélange complexes are widely distributed in the Indonesian archipelago but exposed in

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a few localities (Figure 1). However, until recent years, fractured mélange basements have not well been understood. Bantimala area is one of well-known places where the pre-Tertiary Mélange

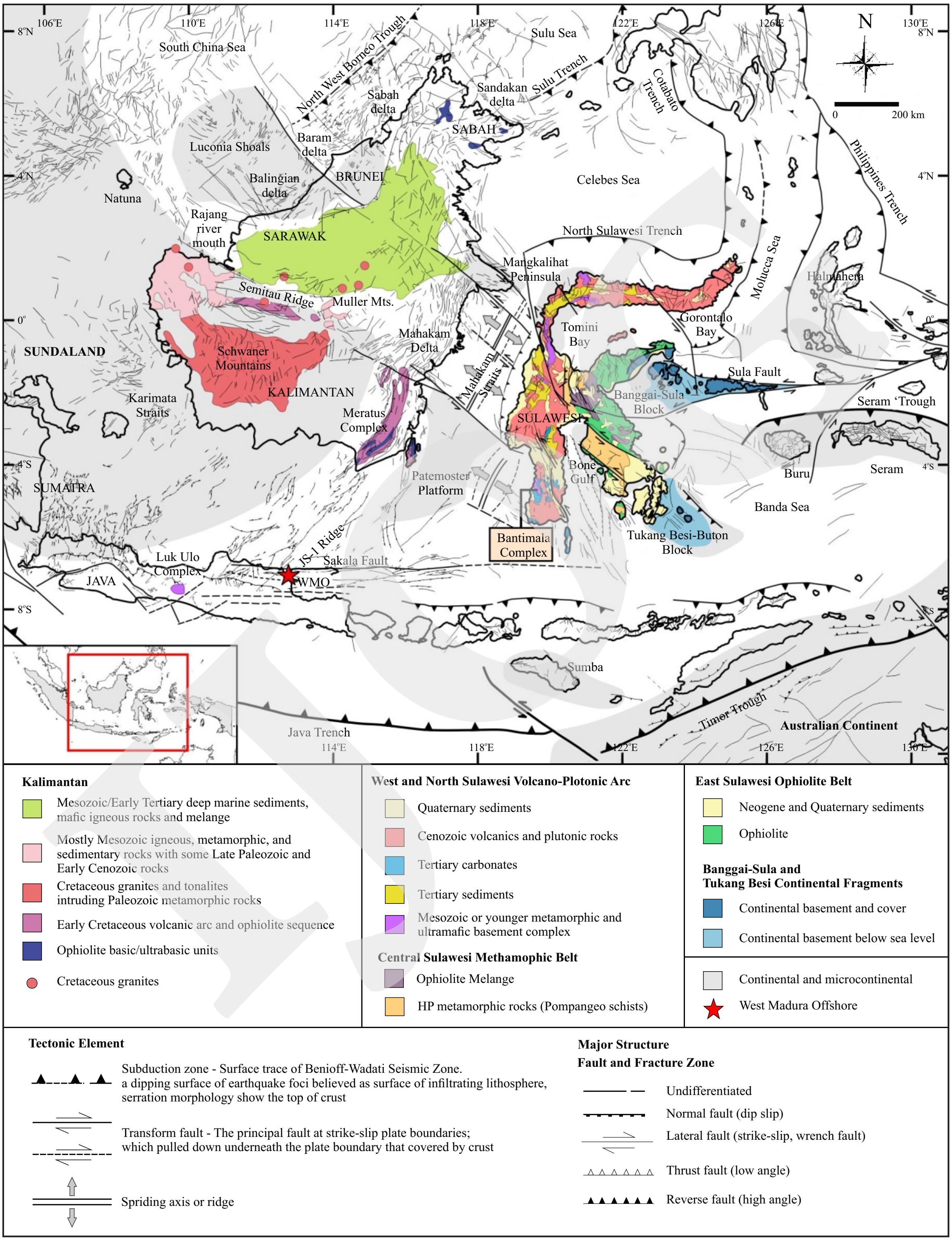

Figure 1. Tectonic and location map of studied area at Bantimala Complex, South Sulawesi, showing structural pattern and tectonic units. West Madura Offshore is an oil and gas field where well penetrates basement with similar rock types exposed at Bantimala area (modified from various sources).

Complex basement is exposed along river beds. The area lies in the south arm of Sulawesi in the southeastern margin of Sundaland. The Bantimala Mélange Complex is excellent for understanding a mélange complex basement reservoir since it is well exposed in a river in Pangkep-Bone-Barru Regency, South Sulawesi.

The study was concentrated in Bantimala and surrounding areas. Administratively, the area includes Pangkajene and Kepulauan (Pangkep), Bone, and Barru Regencies in South Sulawesi Province, Indonesia. In the UTM coordinate system, the studied area is located in the zone of 50S 9460700 - 9488700 mN and 789000 - 809000 mE. The Bantimala Complex is a pre-Tertiary mélange tectonic complex, and also performs as basement rocks in the south arm of Sulawesi. According to its location that has strongly been affected by younger tectonics, the basement is well predicted to be the home of high intensive fractures. The main purpose of this study is to understand the fracture distributions and characteristics in the basement outcrop of mélange complex rocks. In addition, this study will develop a fracture model and characterize the relationship between lithology and fracture distribution in the mélange complex basement.

Furthermore, the result of the study hopefully can be used as an analog model for basement fractured reservoir exploration activity within the oil field in West Madura Offshore (WMO) at the East Java Basin (Figure 1). The regional reconstruction shows that both Bantimala and WMO areas are located on the southeastern margin of Sundaland and share a similar geological setting, particularly during the Cretaceous time. Considering this idea, the fracture interestingly shares similar characteristics. Thus, the result of this study in Bantimala can be a preliminary reference for further and advanced basement exploration in WMO.

Materials and Methods

This study presents a comprehensive method regarding the fracture distribution in the mélange complex basement. In order to understand the fracture characteristics of this kind of lithology, the study involves fieldwork activity and subsurface modeling as well. Several stages of this research are as follows.

Geological Mapping

The geological mapping covered an area of about 560 km2 (20 km x 28 km) in the Bantimala area. The objectives of the geological mapping are to convey information of the structure and stratigraphy within the area. It is also to determine where the most suitable areas are for conducting the scan line sampling in the studied area. At this stage, the primary data were collected from the field observation while satellite images and literatures from previous researchers were also used as secondary data. Laboratory activities such as petrographic and micro-paleontology analyses had also been conducted to support the geological interpretation. The analysis of fracture data is needed to know the characteristics of the fracture system in the studied area. The interpretation was conducted to investigate factors controlling the fracture distribution in the mélange complex basement (*e.g.* lithology, structure).

Scan Line Sampling for Fracture Characteristics

The scan line sampling was employed in the Bantimala Mélange Complex and some Cretaceous to Tertiary rocks. There were forty-seven locations of scan line which was successfully conducted during the study. Fracture data were collected by the 1D scan line method. The data that were observed using the scan line sampling are fracture types, orientation, length, aperture, spacing, and filling material (Figure 2). Fracture data collected from the field observation were then processed into the tables, diagrams, graphs, and were analyzed in order to understand their characteristics. The result of this step will then be used as a guidance in the next fracture modeling step.

Fracture Modeling

The fracture modeling was constructed to perform conceptual visualization using DFN

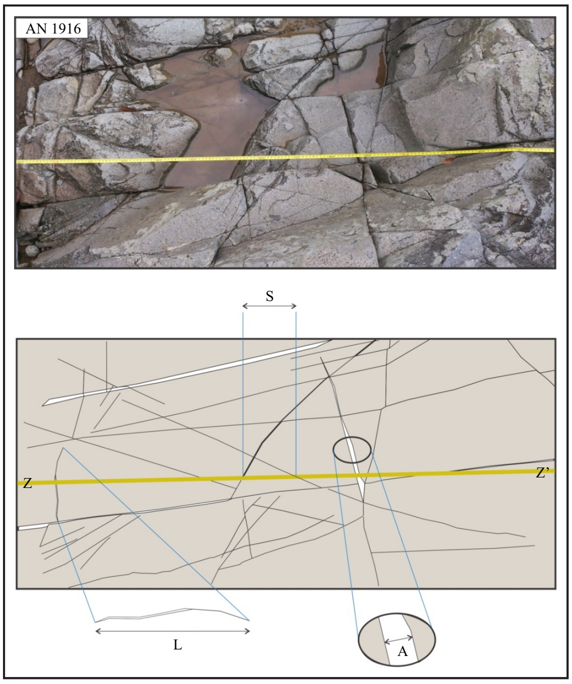

Figure 2. Scan line sampling method showing measurement of fracture attributes such as fracture length, aperture, and spacing. Z-Z' is the length of scan-line measurement; A is the aperture size of the fracture; S is the spacing between adjacent fractures; and L is the trace length of the fracture.

(Discrete Fracture Network) algorithm (Winberg *et al.*, 2003). The DFN approach is a modeling methodology that aims to describe the fractures in statistical calculation by generating a series of discrete fracture objects based on field observations of fracture properties, such as size, orientation, and intensity. Reliable data are needed to make a good fracture model. Data such as aperture, length, and type of fracture will guide the distribution of fracture. Furthermore, these data will be used to determine other properties, such as fracture porosity.

Regional Geology

Tectonic Setting

Sulawesi is located within a critical position in the Indonesian archipelago. Tectonically, it is situated between a number of major lithospheric plates; *i.e.* the northward moving Indo-Australian Plate, the westward-moving Pacific Plate, and the south - southeastward moving Eurasian Plate (Hall and Smyth, 2008). Tectonic evolution of the southwestern part of Sulawesi is related to the collision between Eurasia and East Java Microplate during Late Cretaceous forming the last boundary of Sundaland margin (Figure 3).

Sulawesi and its surrounding islands can tectonically be divided into four belts. Each belt shows characteristic lithological association and tectonic environments. Those are Western Sulawesi Volcano-Plutonic Belt, Central Sulawesi Metamorphic Belt, Eastern Sulawesi Ophiolite Belt, and Banggai-Sula Microcontinent Platform (for detail see Figure 1).

The studied area is located in the Western Sulawesi Volcano-Plutonic Belt. This belt can be divided into two north - south trending mountain chains, the Western Divide Mountains and the Bone Mountains. The Walanae River runs in a graben-like structure, known as the Walanae depression, which occupies the area between these two mountain chains. This structure forms a major north to northwest trending fault zone (Walanae Fault Zone). This depression appears to structurally separate South - West Sulawesi from the rest of the western arc. The structural and tectonic pattern of this region is strongly influenced by the Walanae Fault Zone, which is manifested as a major N - S low bounded on the east and west by major sinistral wrench faults (Figure 4).

The Walanae Fault Zone divided the South Sulawesi into two parts. To the west of the fault zone it is an uplifted area, dominated by a mountainous belt of Late Tertiary volcanic rocks known as Camba Volcanics. The Bantimala Complex and the overlying Cretaceous sediments were intensively faulted during the Plio-Pleistocene times as a result of the northward movement of the Banda Sea Microplate with respect to western Indonesia (Berry and Grady, 1987).

Stratigraphic Setting

Regional stratigraphy in this study referred to the stratigraphy of Western South Sulawesi by previous researchers and compared to this study as shown in Figure 5.

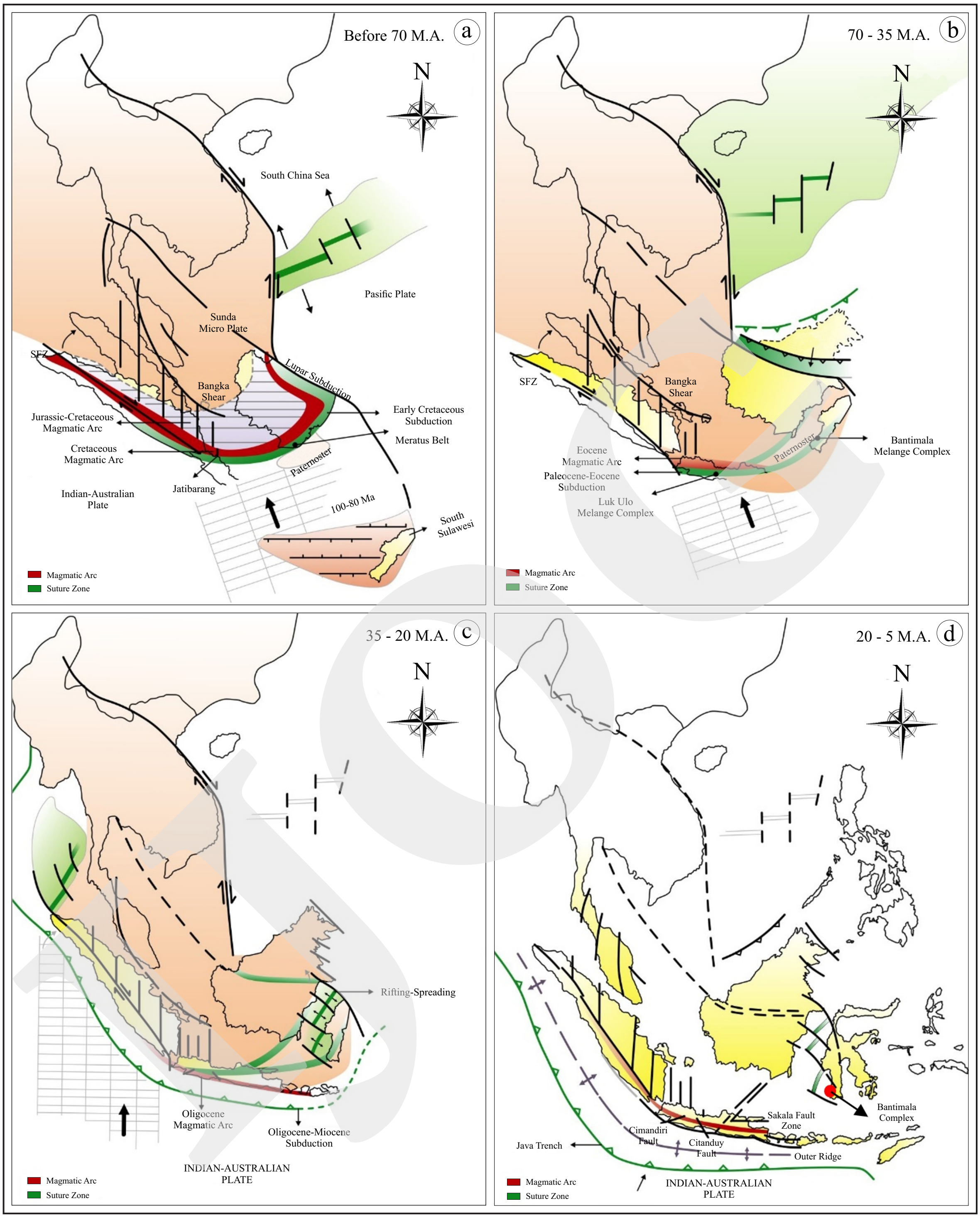

Figure 3. Tectonic evolution of Eastern Sundaland margin during Cretaceous–Pliocene showing evolution of Bantimala Mélange Complex (studied area) as part of the collision between Eurasia and East Java Microplate (modified from Sribudiyani *et al*., 2003).

Bantimala Tectonic Complex

The Bantimala Complex is a tectonic assemblage of various lithologies ranging in age from Jurassic to Cretaceous. The main components of the Bantimala Complex are sandstone, shale, conglomerate, chert, siliceous shale, basalt, ultramafic rocks, schist, and metamorphic breccia. The stratigraphic relationships among the com-

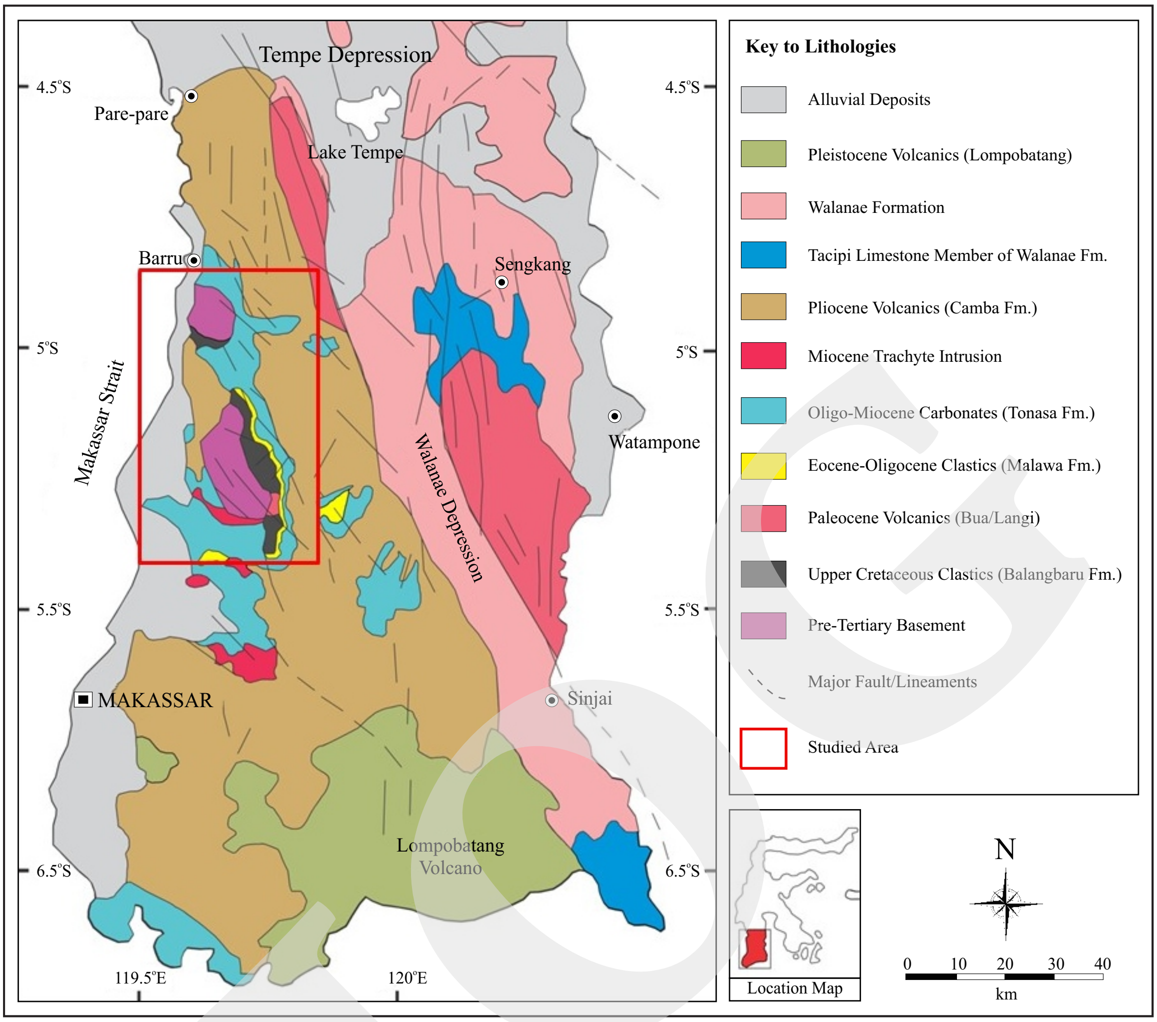

Figure 4. Regional geology and structure map of Southwest Sulawesi region modified from various sources showing rock units and major structures as well as location of the studied area pre-Tertiary basement known as Bantimala complex (red box).

ponents are mostly unclear because of their fault contacts with each other. All the components are surrounded by sheared claystone matrix.

Balangbaru Formation

Balangbaru Formation consists of flysch sequences that are deposited in a deep-water environment (bathyal - abyssal). The Balangbaru Formation is widely distributed in northeast and north of Bantimala area. These Cretaceous flysch sediments are predominantly interbedded sandstone and silty shale with subsidiary conglomerates, pebbly-sandstone, and conglomeratic-breccia. The sediment was unconformably deposited on the Bantimala subduction complex and unconformably overlain by Eocene sediments (Coffield *et al*., 1997).

Paleocene Volcanic Rocks

They consist of andesitic lava and pyroclastic deposits with trachyandesite composition and have intercalations of limestones and shales. Paleocene volcanic rocks in the Biru area are called Langi Volcanics, while in the southeast Bantimala, are known as Bua Volcanics (Yuwono *et al*., 1988). Sukamto (1982) called the unit as a prophylitized volcanic rock because of its strong alteration. In a more detailed mapping, volcanic rocks in eastern Bantimala are called Alla Formation (Sukamto, 1986). These Paleocene volcanic rocks were unconformably deposits out at the top of Balangbaru Formation.

Malawa Formation

The Malawa Formation consists of sandstone (arkose), siltstone, claystone, marl, and conglomerate

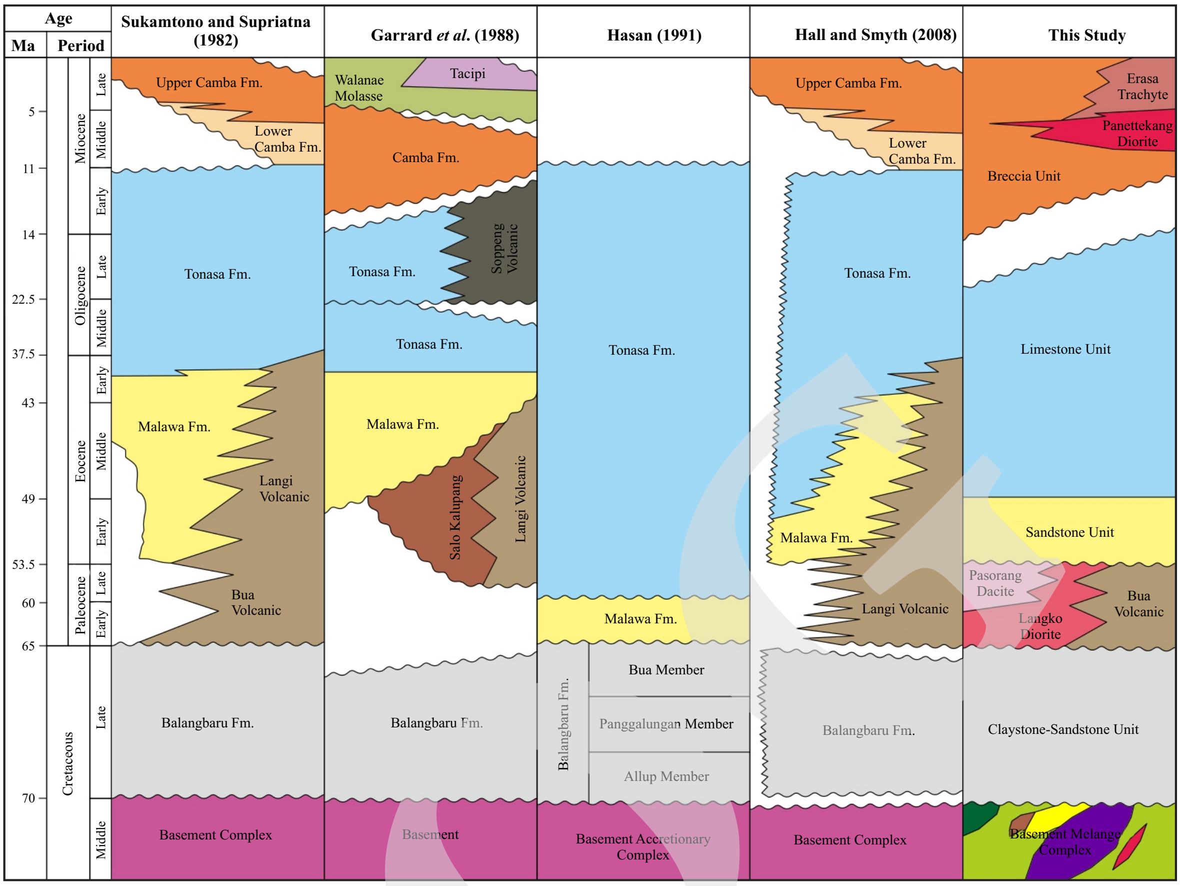

Figure 5. Regional stratigraphy of South Sulawesi area showing comparison of several previous study and this study (see text for detail).

interbedded with layers of coals and limestone. This formation is thought to be deposited from terrestrial to shallow marine environment. This Eocene transitional sequence is located in the western part of South Sulawesi and is generally dominated by quartz-rich sandstones. In addition, this formation has unconformably overlain the Balangbaru Formation and interfingering with the Paleocene volcanics.

<u>Tonasa Formation</u>

The Tonasa Formation consists of limestone, marl, sandstone, siltstone, and claystone which were deposited in Late Eocene-Miocene (van Leeuwen, 1981). The formation was deposited conformably over Toraja Formation (Malawa Formation) and Langi Volcanics. This formation is widespread in the western part of South Sulawesi, where this formation is not exposed in the eastern part of the Walanae Valley.

<u>Camba Formation</u>

The Camba Formation is located in the western part of South Sulawesi, and it comprises volcanic breccia, conglomerate, lava, and tuff, interbedded with marine sedimentary rocks. The formation is alkaline due to upper mantle partial melting that has incompatible elements-rich with metasomatism. This may be related to the previous subduction in the Early Miocene in the context of intraplate extension. Alkaline nature is thought to be caused by an excessive assimilation of melted old limestone and joining the continental material into the volcanic arc subduction (Yuwono *et al*., 1988).

Geology of The Studied Area

A detailed geological mapping during the fieldwork activity in Bantimala area, resulting in a detailed geology map. This was done not only to understand the geological setting of the studied area, but also with the aim to determine where the most suitable locations for conducting scan line sampling method as well. Figure 6 shows a detailed geological map of the studied area.

Mélange Complex Unit, Claystone-Sandstone Unit, Andesite Lava-Tuff Unit, Pasorang Dacite Intrusion Unit, Langko Diorite Intrusion Unit, Sandstone Unit, Limestone Unit, Breccia Unit, Erasa Syenite Intrusion Unit, Panettekang Diorite Intrusion Unit, Collovial Deposit Unit, and Alluvial Deposit Unit underlie the Bantimala area.

Bantimala Mélange Complex Unit

The Mélange Complex Unit is the oldest rock in the studied area and composed of a tectonic assemblage of slabs and blocks consisting of sandstone, schist, ultramafic rocks, metamorphic breccia, chert, basalt, and conglomeratic sandstone (Figure 7). The tectonic slabs are oriented NW - SE and dip steeply to the east. Stratigraphic and structural relationships among the components are unclear. Each block is bounded by fault which is a kind of a structure boundary.

Matrix Mélange

The matrix of the Mélange Complex Unit is sheared claystone. The matrix is widely distri-

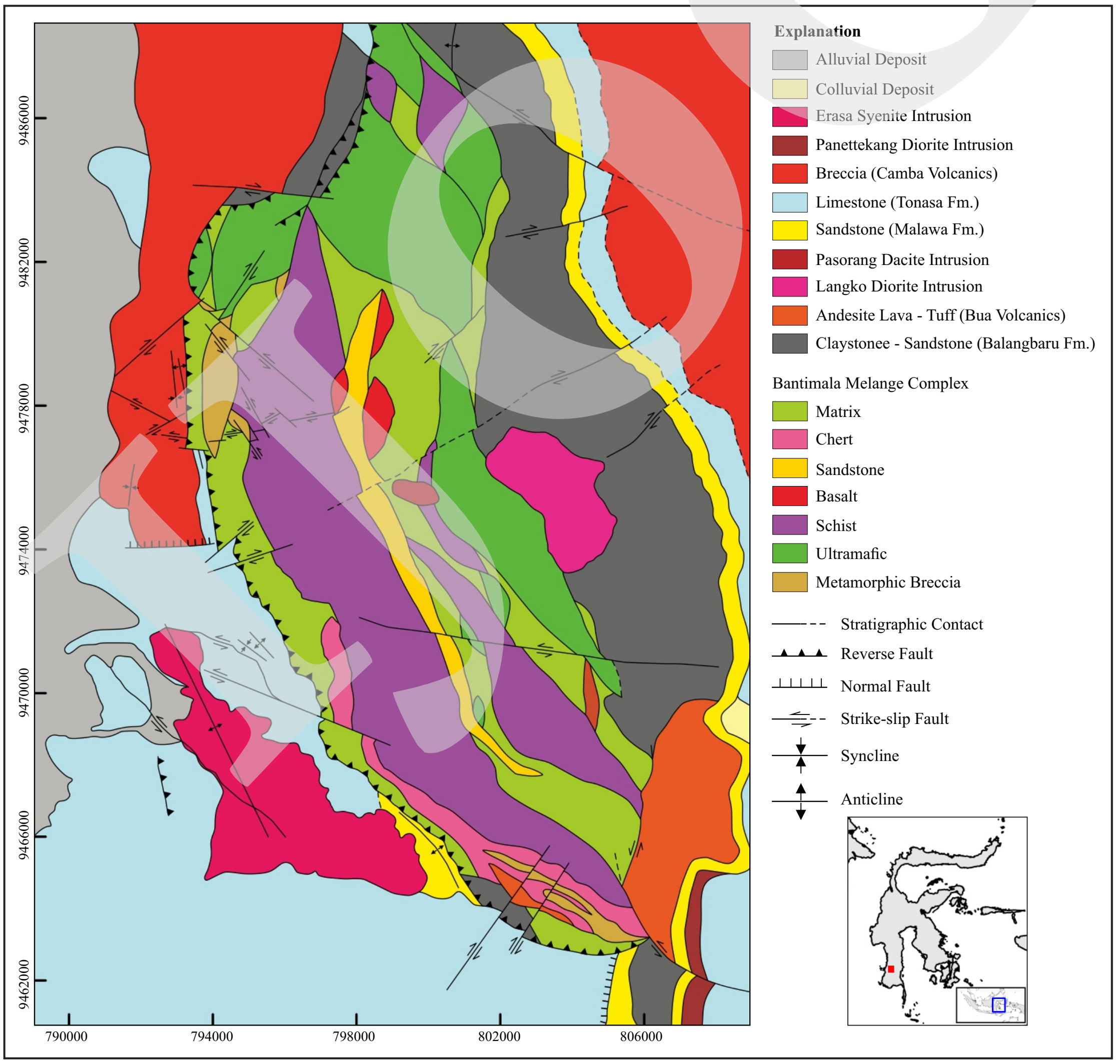

Figure 6. A detailed geological map of Bantimala complex resulting from fieldworks showing various rock units and major structural boundaries. The equivalent formation name refers to regional stratigraphic nomenclatures as presented in previous figure.

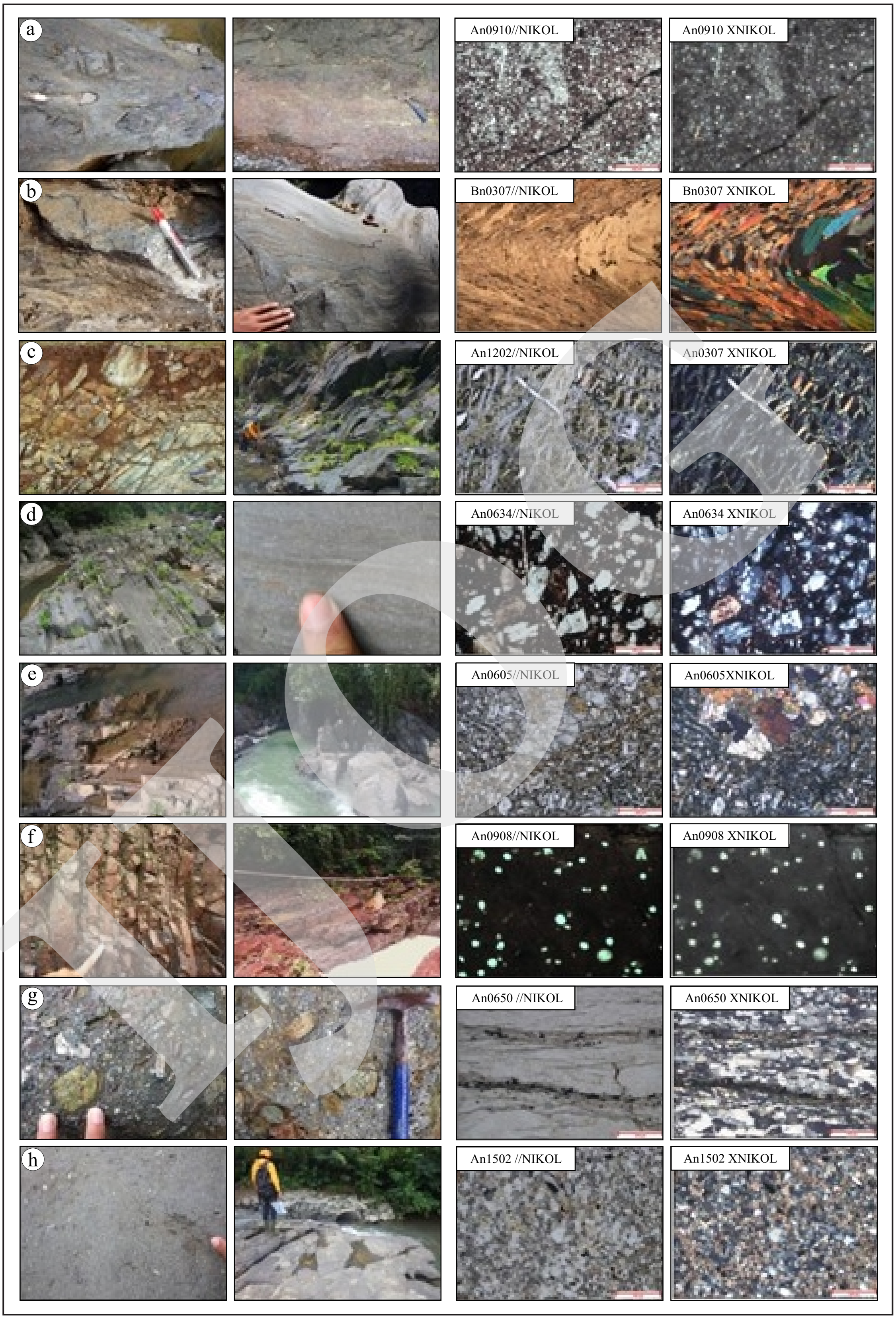

Figure 7. Some field photos of various mélange blocks found in the studied area showing their lithology characteristic and structures. The third and fourth columns are microphotographs thin section of the blocks of the first and second columns. (a) claystone of matrix mélange; (b) blueschist; (c) ultramafic rocks; (d) greywacke sandstone; (e) basalt; (f) chert; (g) breccia; (h) conglomeratic sandstone blocks.

buted in the Mélange Complex Unit. In the matrix, there would be tectonic clasts but in small sizes. The most distinct outcrops of the matrix and small size blocks occur near the junction of the Pangkajene River, Pateteyang River, and Cempaga River. Also, the major clasts in this mélange are metamorphics, sandstone, chert, ultramafics, and basalt. The clast sizes range from several millimeters to several hundred meters. The clasts are locally in boudinage structures, sometimes showing a chaotic orientation (Figure 7a).

Schist Block

The Schist Blocks are located in the central part of the Mélange Complex Unit. The schist blocks are mainly composed of green schist, blue schist, phyllite, locally eclogite quartzite, and gneiss. The schist blocks well outcrop in Pateteyang, Bontorio, and Cempaga River. The blueschist block is locally brecciated. This block is commonly foliated northwest-southeast by the trend and 34° to 48° by the dip angle. The result of petrographic analysis shows the lithology in schist block is glauchophane-mica-garnet schist, quartz-mica schist, and glaucophane-mica schist (Figure 7b). K-Ar radiometry has been conducted from mica components of schist in Bantimala with an age range of 132 to 113 Ma (Wakita, 2000).

Ultramafic Block

Ultramafic rocks of the Mélange Complex Unit are mainly distributed in the northern and eastern part of the complex. The ultramafic rocks are mostly serpentinized peridotite and serpentinite, generally dense, pale green to bluish green rocks, with a waxy luster and tend to be slickensided in the hand specimen. The rocks are commonly found disrupted, fractured, and sheared as shown in Figure 7c. The petrographic analysis shows that this block has the sea and island texture constructed by olivine and serpentine.

Sandstone Block

The Sandstone Block is located in the central part of the Mélange Complex Unit, well outcrops in Paremba River (Figure 7d). This block is composed of thinly bedded sandstone and shale. Some sedimentary structures such as parallel lamination and cross lamination can still be recognized in this unit. The sandstone in this block is grey, medium to fine-grained, subrounded - subangular grain shapes, well sorted, and compact. This sandstone beds have a range of dip angles varying from 16° to 48°, striking N - S to NW - SE. The petrographic analysis shows that the sandstone in this unit could be classified as lithic-wacke. Based on lithology characteristics, the sandstone unit is equivalent to Paremba Sandstone (Sukamto, 1986). Sukamto and Westermann (1993) reported that sandstone in Bantimala Mélange Complex yielded Early to Middle Jurassic age based on the fossil presence, which were Ammonites (*e.g.* Liassic fuciniceras), gastropods, and brachiopods. Fractures in this unit commonly present as shear fractures, which are dominantly to be oriented in NNW - SSE direction.

Basalt Block

The Basalt Block is distinctly exposed in Dengeng-dengeng River and Paremba River, as can be seen in Figure 7e. The basalt is very dark grey to black and massive structure. Petrographically, it shows that these basalts have an intergranular texture and consist of pyroxene and plagioclase.

Chert Block

The Chert Block is located in the southeastern of the Mélange Complex Unit. The block is well exposed in the Baruttung River. The chert layers range from 1 - 20 cm thick, and are sometimes intercalated with thin shale. The bedded chert is mostly red or reddish brown. The chert is mainly composed of radiolarian skeletons and fragments. Quartz and calcite veins usually fill the extension fractures in the chert unit (Figure 7f). Fractures in this unit commonly present as shear fractures that have an E - W orientation.

Breccia Block

Breccia is a sedimentary rock consisting mainly of metamorphic rock fragments. The block is mostly distinct in the southwestern of the Mélange Complex Unit in Baruttung River, while the distribution also occurs in the northwestern of the Mélange Complex Unit. The main component of this breccia is schist with 5 - 125 cm sized, angular - subangular, bad sorted, and coarse sand matrix. Quartzite also composes as fragments in this breccia (Figure 7g).

Conglomeratic Sandstone Block

The Conglomeratic Sandstone Block is situated in the eastern part of the Mélange Complex Unit. The block is distinctly exposed in Kambotti River. The sandstone colour ranges from grey to dark grey, pebbly - coarse sand grain size, subangular - subrounded, medium sorted, and polymict. The fragments are schist, basalt, marble, quartz, and sandstone (Figure 7h).

Pre-Tertiary and Tertiary Rocks

The Claystone-Sandstone Unit (Balangbaru Fm.) lies unconformably on the Bantimala Mélange Complex Unit. This unit was deposited in a marine fan environment during the Late Cretaceous (Hasan, 1991). The volcanic activity occurred during Paleocene resulting in Andesite Lava-Tuff Unit (Bua Volcanics) in the Bantimala area. This unit has unconformable stratigraphic relationship with the Claystone-Sandstone Unit. The other volcanic products during Paleocene are Pasorang Dacite Intrusion Unit and Langko Diorite Intrusion Unit. Both of them intrude the Mélange Complex Unit.

During Eocene, Makassar Strait rifting took place and caused the deposition of Sandstone Unit (Malawa Fm.). This unit was deposited in the fluvial - transition environment, recognized by coal seam and limestone particularly. Followed the rifting events, Limestone Unit (Tonasa Fm.) was deposited during Late Eocene - Middle Oligocene where sagging tectonic events began. Tonasa Limestone was widely spread as karst hill landscape in the south arm of Sulawesi. In Bantimala area, this limestone has Late Eocene - Middle Oligocene in age.

The volcanic activity became active for the second time in Late Miocene. This volcanic product is well known as Camba Formation. The Camba Formation is composed of marine volcanic and sedimentary rocks (Bergman *et a*l., 1996). In the Bantimala area, the Camba Formation Unit could be mapped into detailed units as Breccia Unit, Erasa Trachyte Intrusion Unit, and Panettekang Diorite Intrusion Unit.

Quaternary alluvial deposits are mostly situated in the western part of the Bantimala area. This unit consists of various unconsolidated material sizes ranging from clay to gravel. The material originated from the oldest rock, which widely spread at the upstream side in the eastern part of the studied area.

Fracture Characterization

Fracture is a general term for material failure on brittle condition (Koestler *et al.*, 1995). In this research, the definition of fracture is more underlined for naturally formed fractures. The other definition is by Nelson (2001), that reservoir fracture is natural macroscopic discontinuity plane on rocks, which is formed by deformation or physical diagenesis.

According to the direction of movements, fractures in rock are classified as extension and shear fractures. Shear fracture involves parallel movements of a fracture plane, while the movement of extension fracture is perpendicular to the fracture plane. Fossen (2010) illustrates various types of fracture as seen in Figure 8a. The fracture type that was observed in the Bantimala area consisted of fault/shear, gash/vein, extension fracture, and joint (Figure 8b).

Fracture characterization in this study is conducted using surface fieldwork and subsurface modeling. Geological mapping and scan line sampling are the first fieldwork activities to collect geological and fracture data from the Bantimala and surrounding area. Thus, those fracture data are sorted in order to divide the fracture system into several fracture set and to obtain fault-related fractures. After all, the subsurface model will be generated using data observed from the field.

Fracture types, distribution including orientation, density and intensity vary in each lithology

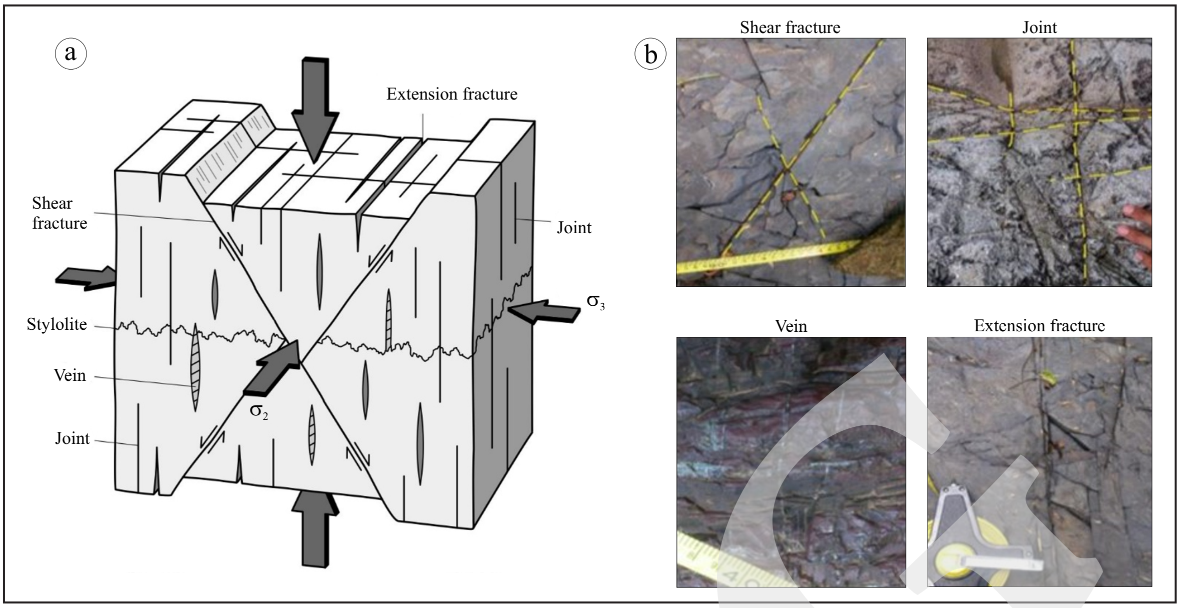

Figure 8.Types of geological fractures observed and mapped in the studied area. a) shear fractures (SF) and extension fractures (EF) including joint (JT) and vein (VE) (modified from Fossen, 2010). b) Types of fractures observed.

within mélange blocks in the Bantimala complex (Figure 9). A total of 3,841 fractures is measured in the studied area from various locations and lithology, particularly concentrated in different mélange blocks. Strike and dip orientation are different in each lithology, especially in mélange complex block units (Figure 10). Based on statistical analyses using both lower hemisphere stereographic projections and rose diagram of fracture orientations it indicates various fracture trends. The main orientations are relatively NW - SE, N - S, and NE - SW trendings (Figure 11). The fracture intensity is defined as the number of fracture per length unit, and it becomes an essential attribute of a fracture pattern. The field observation and measurement indicated that fracture intensity in schist is the most intensive fractured spot in The Bantimala Mélange Complex. This fracture intensity that has been measured from the field is used for subsurface modeling in the further step.

Fracture Modeling

The main purpose of this study is to understand fracture distribution) in basement rocks for helping to develop fracture modelings in subsurfaces. One of the problems in exploring natural fracture reservoirs is to distribute fractures in 3D rock volume. The fracture modelings were directed to build a discrete fracture network from field data, and furthermore to determine the fracture porosity. Fault geometry, lithology distribution, and geological cross section are the main components used for constructing a geometrical model of the studied area. Fractures modeling (3D Geocellular modeling) in this paper was build using Petrel 2016 software from Schlumberger with workflow presented in Figure 12.

Grid and 3D Cube

Due to the complexity of the relationship with the mélange unit, structural gridding was used in this modeling (without pillar gridding). The three-dimensional cube was generated by combining the SRTM (Shuttle Radar Topographic Mission) image and surface geology with constant depth of 1,000 m below sea level. The complex structure of the mélange complex causes problems for common geometry modeling. Stair-step faulting is used for the modeling of complex fault relationship. The complex rela-

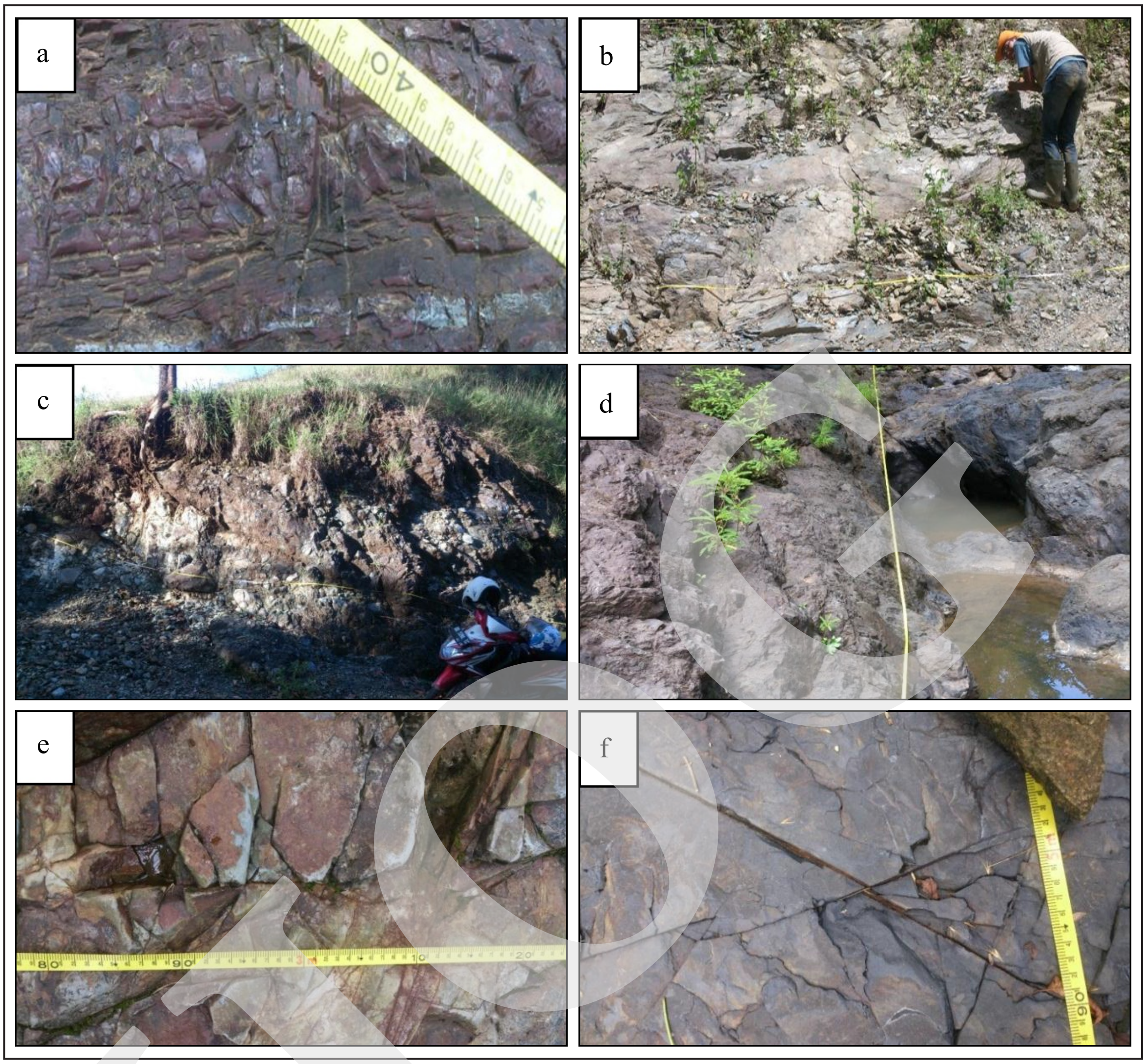

Figure 9. Outcrop photographs showing types of fractures observed in the studied area: (a) quartz VE observed in interbedded chert and red limestone; (b) SF in schist; (c) SF in ultramafic rocks; (d) SF and JT in clay matrix; (e) SF in sandstone; (f) SF in mudstone. VE= vein; SF= shear fractures; JT= joint.

tionship of each block in the mélange complex unit is properly modeled using stair-step faulting process. Stair-step faults are created based on fault geometries, which have been defined in the structural framework. Stair-step faulting would convert a fault model into stair-step faults making them into stair-step form. The lithology was distributed using facies modeling according to a polygon and point that was created based on the geological map and cross section. The rock units are vertically dipping with the aim to make model simpler (Figure 13). The grid size (in meter) used in the model is 100x100x65 with the total cell of 1,288,000.

Fracture Guide Model

Several parameters such as distance to the fault, distance to the surface, and lithology are measured to ascertain the structure control of fracture distribution. These three properties were created on geometrical modeling, with some calculation to approach the real number. Distance to the surface is a linear function, while the distance to fault was calculated using equation between distance and fracture intensity. Distance to the surface also plays a role in the fracture distribution, as well as lithology. Distance to a fault, distance to the surface, and lithology are used as a fracture intensity guide to distribute the fracture

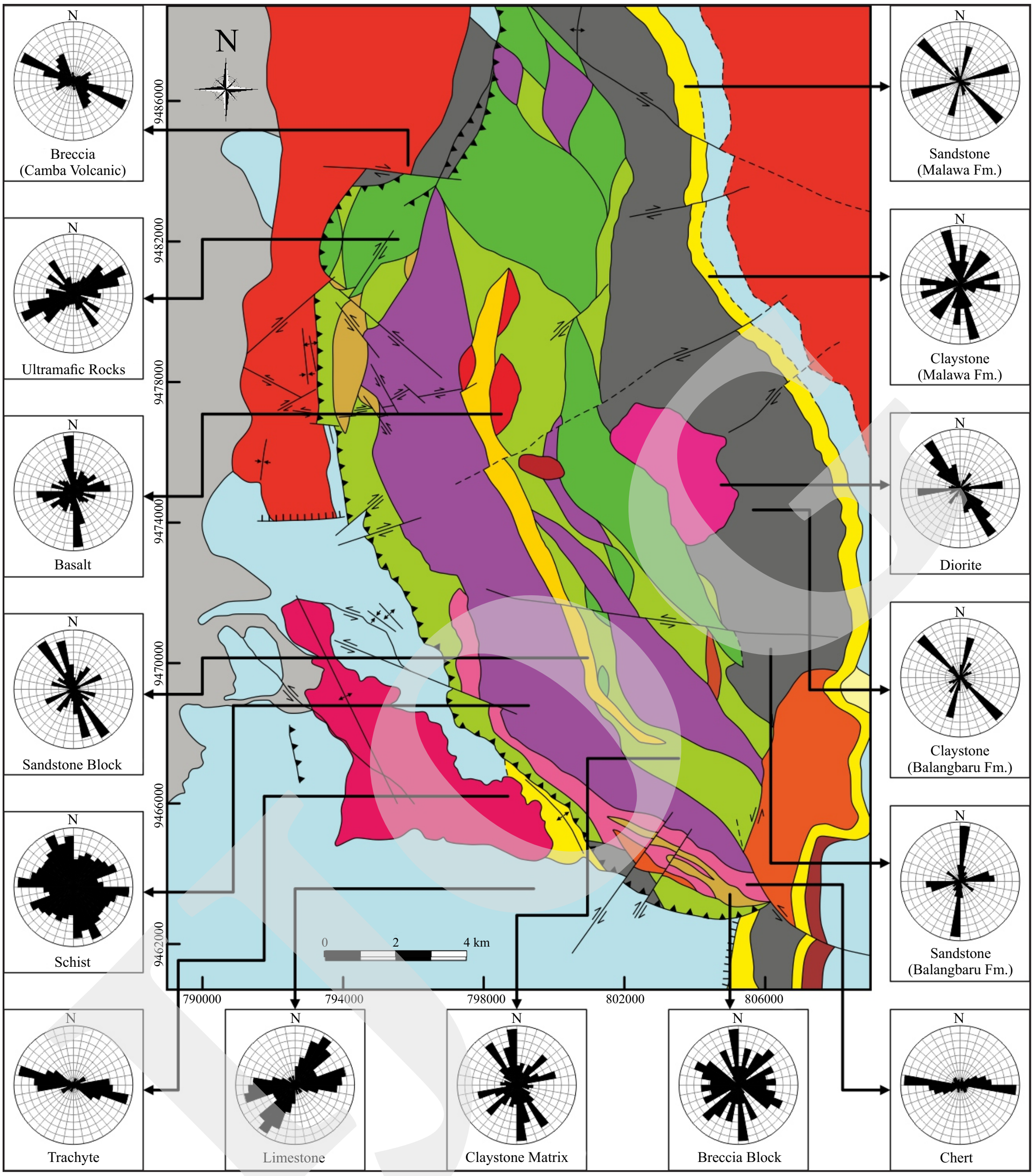

Figure 10. Distributions of fracture orientation of each lithology (mélange blocks) in Bantimala Area showing various orientations with three major trends: NW–SE, N–S, and NE–SW. This trending variation is interpreted due to different ages, deformations history, and environment of formations of the blocks (see text for detail).

intensity. Basically, modeling can be conducted with a limited number of good data that assume from the scan line traverse. The Bantimala Mélange Complex is composed of various tectonic blocks which come from different ages and environments. Therefore, each block has different characteristics and indicates that lithology also controls the fracture distribution. All structure and lithology controls are set up as parameters to build a fracture intensity guide. The fracture intensity guide will be used in distributing fracture intensity throughout the studied area.

Fracture Intensity Model

The Fracture Intensity Model is the intensity of fracture that is inferred from scan line data

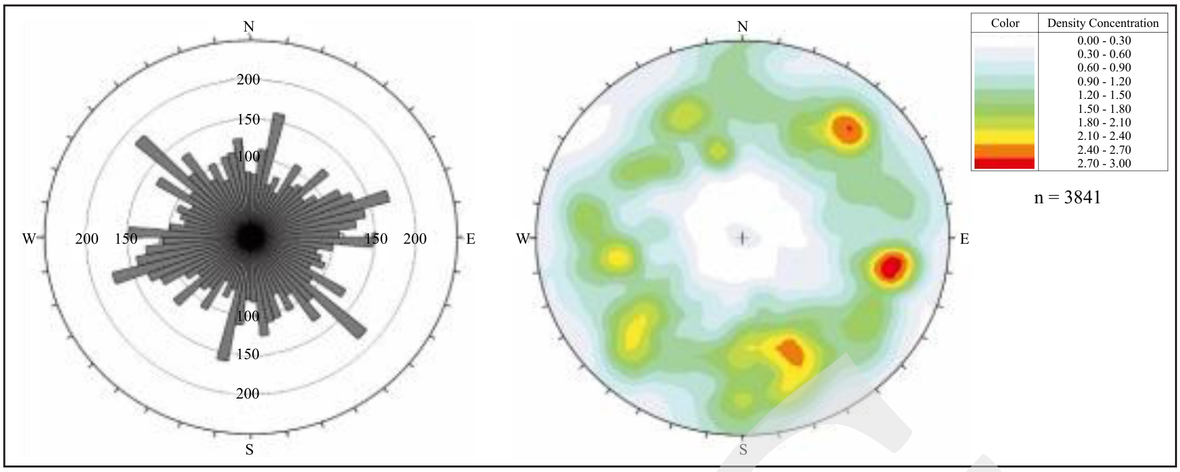

Figure 11. Total of 3841 fractures are delineated from field observation. Fracture orientation is commonly NW-SE, W-E, NNE-SSW, and ENE-WSW. This trending variation is interpreted due to different ages, deformations history, and environment of formations of the blocks (see text for detail).

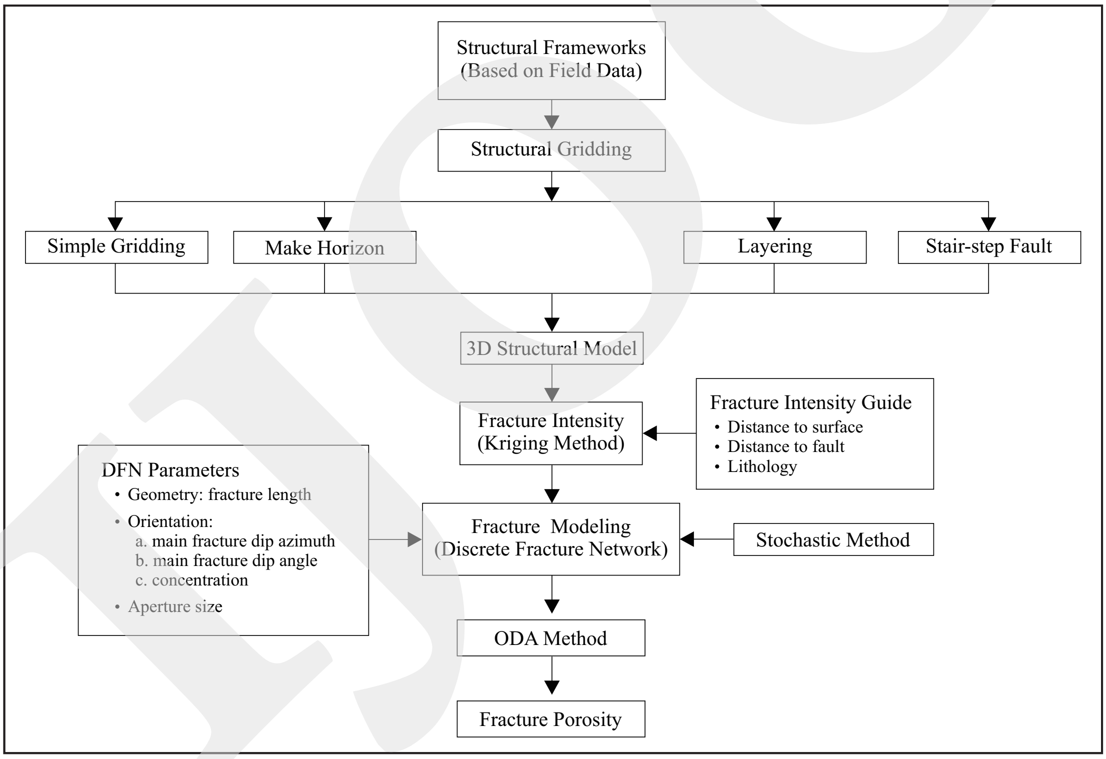

Figure 12. 3D fracture modeling work flow used in this study using PETREL.

and scaled up into grid model. The fracture intensity model was generated from the guidance of fracture guide that was generated beforehand. The modeling result shows that the most populous fracture will occur on the red coloured zone and the less fracture appeared on the turquoise coloured zone (Figure 14). The main controls on this distribution of intensity model are the distance to the fault, distance to the surface, and their intensity.

Discrete Fracture Network

Discrete Fracture Network (DFN) is a method that can describe the fracture network in the field as a model (Dershowitz *et al.*, 2002). The main idea to make this concept is by using

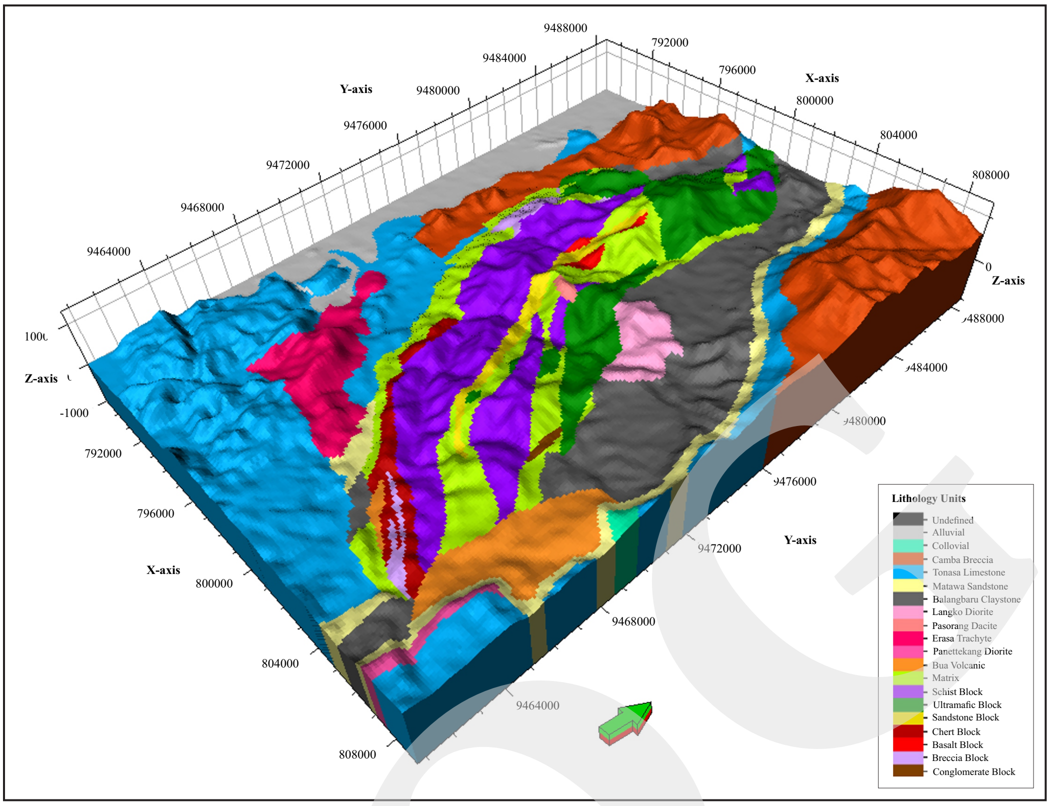

Figure 13. 3D geological model of Bantimala Complex showing lithology distributions and structural relationship. The model was generated based on field mapping (see text for detail).

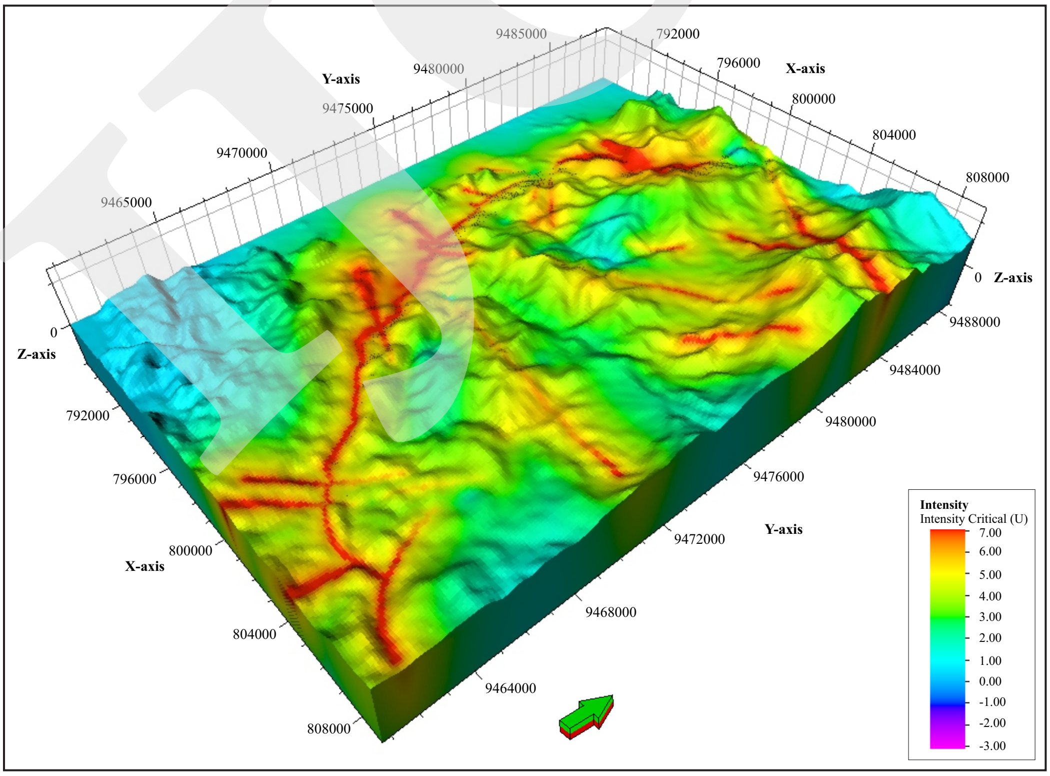

Figure 14. 3D fracture intensity model that is built and guided from both structure and lithology control showing high intensity fracture area is strongly controlled by faults.

some limited data, such as a fracture from a scan line mapping and distribute it by using some fracture guidance and several parameters. In a 3D Geocellular DFN model (Petrel software), the fractures and faults, and their properties are generated directly from that cell-based information. The guidance consisted of distance to the fault, distance to the surface, and lithology intensity. The orientation of fracture in Bantimala area is different on each lithology, showing that the fracture system was complex. The distribution of fracture orientation is guided by lithology. There are fifty-one fracture sets, which is distributed in the discrete fracture network model using the stochastic method. All of the fracture set orientation were generated by the Fisher method (Fisher *et al.*, 1987; Allmendinger *et al.*, 2012). The Fisher method describes the distribution of fracture angles in much the same way as for continuous variable. The Fisher model method gives more isotropic data for fracture deviation. The length and aperture are both fracture geometry, which would be parameters for generating DFN. The length of fractures is distributed using the power law. The aperture of fractures has a range from 0 - 1 mm, and is also distributed using the power law. All parameters are generated to produce a discrete fracture network model as seen in Figure 15. As an example, a zoomed-in fracture set in claystone matrix shows domination of two sets of fracture system (Figure 16).

Fracture Porosity

The secondary porosity or fracture porosity was playing an important role in rocks, because it could provide an economic value. Scaling up the DFN model using scale up fracture network properties generates a fracture porosity model (Oda, 1985). The value of porosity varies from 0.0004 to 0.0029 %. The high fracture porosity number is found in an area with a significant fracture intensity and most crosscutting of fracture which is controlled by faults and lithology (Figure 17).

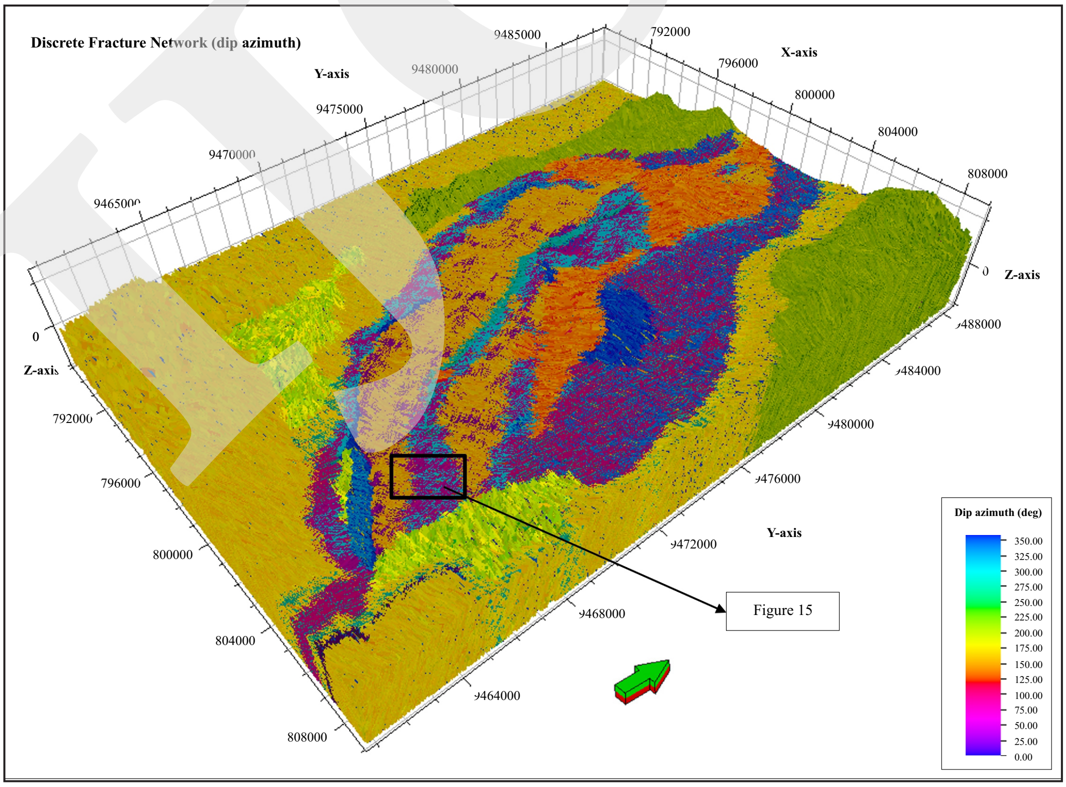

Figure 15. Discrete Fracture Networks (DFN) modeling of the Bantimala Mélange Complex (Dip Azimuth) using 51 fracture sets resulted from field measurements.

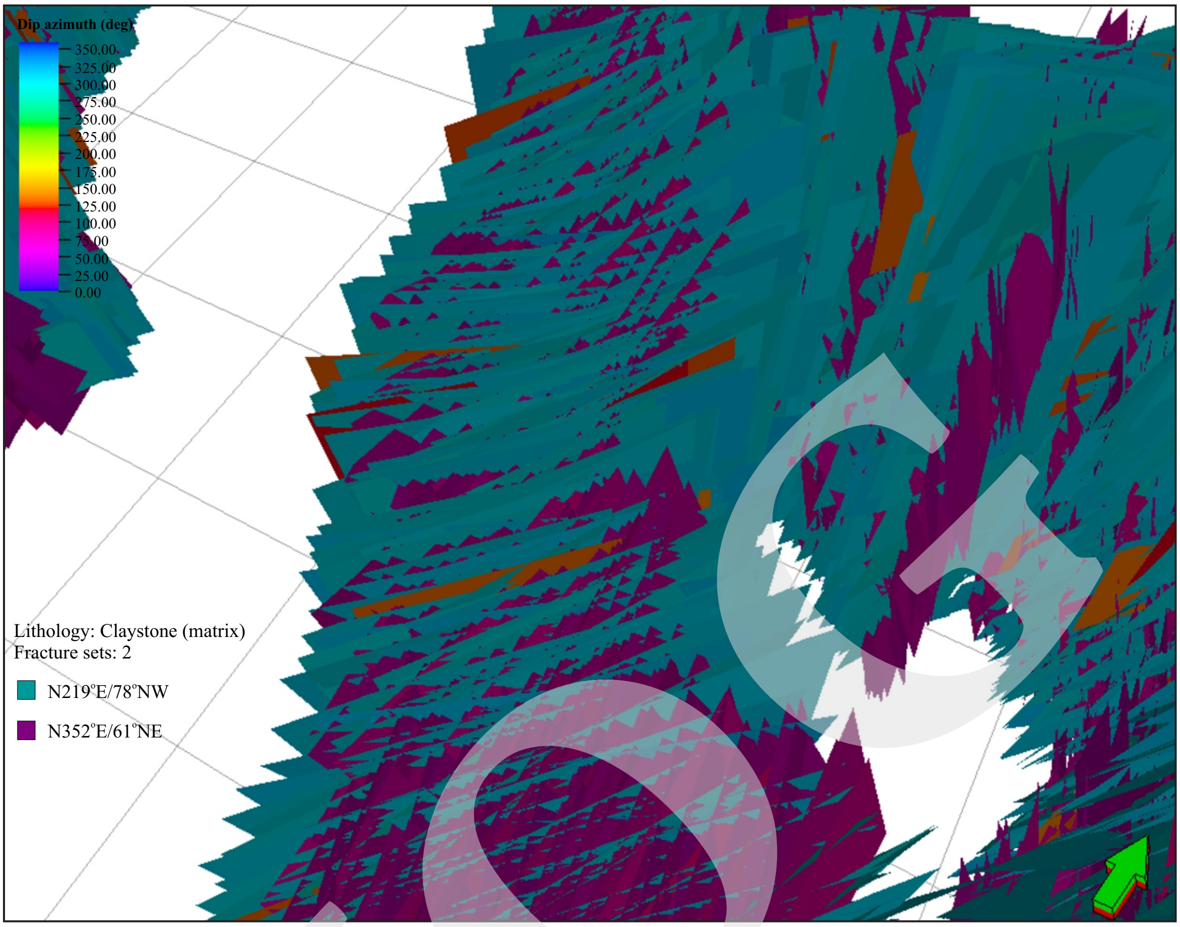

Figure 16. Example of zoomed-in fracture sets in claystone matrix from Discrete Fracture Networks (DFN) model as presented in Figure 15.

Analysis and Discussion

The Bantimala Mélange Complex consists of an assemblage of metamorphic, igneous, and sedimentary rocks, which were tectonically mixed. Each block came from different ages and environments. Considering the various natural forming of each block, they will have different characteristics in any circumstances as well. This study has shown that fractures in the Bantimala Mélange Complex are strongly controlled by lithology and fault zones. A fractal analysis is the first important step in order to determine the fracture distribution. The fracture intensity shows a comparative frequency of fracture presence on a certain distance interval. In the Bantimala area, the fracture intensity is dominantly controlled by lithology. The number of fracture intensity is increasing to the brittleness of rocks. The field evidence indicated the Bontorio Metamorphic Rocks and Jurassic Paremba Sandstone blocks have an intensive fracture since they are the most brittle unit among others. The structure position in a particular fault also has the control in fracture distribution, where the fracture intensity increases towards the structure boundary.

The result of this modeling can be used for conducting basement fractured reservoirs in the West Madura Offshore (WMO), in particular designing drilling targets. Using this modeling result, exploration wells should be drilled slightly incline toward the SE direction in order to penetrate a maximum fractured area. Certainly, detailed reservoir geomechanic works need to be done in WMO field to have a better understanding concerning subsurface stress condition. Applying results from geomechanic to fracture distributions, exploration well can be directed

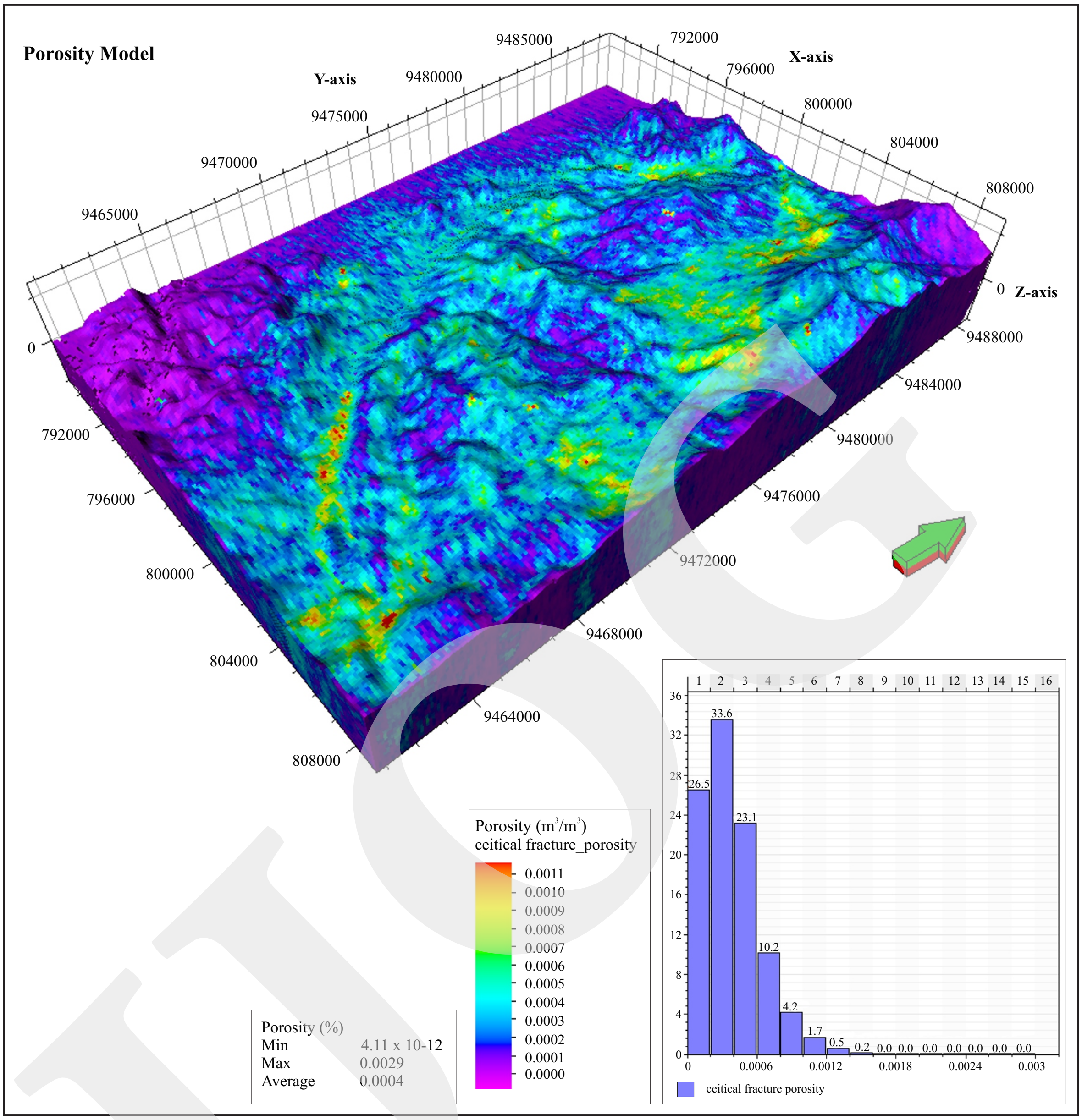

Figure 17. Fracture porosity distribution model showing high porosity area is controlled by fault, fracture intensity, and lithology (see text for detail).

to cut critically stress fractures which will have better permeability.

Conclusions

Structural factors as well as lithology types played a critical role in the development of basement fractured reservoirs in the Bantimala Mélange Complex. Detailed structural mapping in the area revealed the following points:

1. The fracture type that was observed in the Bantimala area consists of fault, shear fracture, gash fractures (vein), extension fractures, and joints.
2. A total of 3,841 fractures are measured from various different mélange blocks. Strike and dip orientation are different in each lithology where the main orientations are relatively NW - SE, N - S, and NE - SW trendings.
3. The orientation of fracture in Bantimala area is different on each lithology, showing that the

fracture system was complex. The fracture intensity in schist is higher compared to the other lithology in the Bantimala Mélange Complex.
4. Discrete Fracture Network (DFN) model was generated using fifty-one fracture sets from field measurements, which are distributed using the stochastic method.
5. The value of the fracture porosity is relatively small, varied from 0.0004 to 0.0029 %. The high fracture porosity number is observed in an area with a significant fracture intensity and most crosscutting of fracture which in turn is controlled by faults and lithology.

The conclusion is that the Mélange Complex can have high potential as a basement fractured reservoir target, where fracture distributions and their attributes vary depending on the lithology as well as local deformation. It is believed that the recognition of fracture styles, distribution, and intensity in each mélange block is an essential factor in exploring their potential, particularly for planning exploration well location. Integrated fieldwork and 3D geocellular modeling results are proven as a powerfull approach to help understanding the fracture distributions in space.

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