PROCEEDINGS, INDONESIAN PETROLEUM ASSOCIATION
Forty-Fifth Annual Convention & Exhibition, September 2021

Trilogy of Southeast Sundaland Terranes: Re-Uniting Drifted Terranes of Southeast Sundaland Using Common Marker of the Late Cretaceous Volcanics to Volcanic-Clastics of the Meratus Mountains, South Sulawesi, and Sumba - Implications for Petroleum Opportunities

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ABSTRACT

Amalgamation and dispersion of terranes characterized the growth and slivering of Southeast Sundaland into the present configuration of central Indonesia.

Amalgamation of the Paternoster-West Sulawesi terrane which docked, in mid-Cretaceous time, onto the Southwest Borneo terrane, thus closed the Meso-Tethys Ocean at the Meratus suture. This made Sundaland expand its area to the east and southeast. In the Late Cretaceous time, the Ceno-Tethys oceanic plate subducted beneath Southeast Sundaland, giving rise to coeval volcanism in the Meratus Mountains and the surrounding areas. Dispersion of some terranes in Southeast Sundaland occurred in the Paleogene through successive rifting and the opening of the Makassar Straits and the Flores Sea, with an eastern drift of South Sulawesi and Sumba away from Southeast Kalimantan to their present positions. Prior to the dispersion, the Meratus Mountains, South Sulawesi, and Sumba (called here the Trilogy of Southeast Sundaland) were united or adjacent to each other and underwent similar Late Cretaceous volcanism. The Late Cretaceous Volcanics and/or Volcanic-Clastics are therefore the common marker of their union.

Our field studies in 2018-2019 at Sumba, South Sulawesi, and the Meratus Mountains (South Kalimantan) in the program, called the "Trilogy of Southeast Sundaland Terranes," sampled the Late Cretaceous volcanics/ volcanic-clastics in these areas to prove that they were once united. Petrographic, petrochemical, isotopic, and geochronological data of the rock formations, based on the recent and previous analyses, show that these rocks, in the three terranes, are co-genetic spatially and temporally thus indicating their previous unity.

The paired Paleogene dispersions of South Sulawesi from South Kalimantan, and successively Sumba from South Sulawesi, had resulted in rifted structures in the present Makassar Straits, the Flores Sea, and offshore Sumba. The rifted structures contain source rocks, reservoirs, seals, and structural-stratigraphic traps. Oil has been discovered therein, so further exploration is required since these objectives have not been sufficiently explored in the past and are thus still interesting.

INTRODUCTION

As a continental margin, based on terrane tectonic theory, with terrane defined as a distinct lithospheric block Southeast Sundaland has undergone growth by the amalgamation/ unity of terranes, and slivering by the dispersion of terranes during the Cretaceous and Paleogene. The amalgamation of terranes occurred by subduction, accretion, and terrane collision. While the dispersion of terranes occurred through basement rifting and major strike-slip faulting.

Related to this, the areas of Meratus-South Kalimantan, South Sulawesi, and Sumba Island are interpreted to have been united as an amalgamation of terranes in the mid-Cretaceous (Satyana, 2003; 2014). In the Late Cretaceous, magmatism and volcanism, associated with the subduction of Ceno-Tethys oceanic plate beneath Southeast Sundaland, developed relative to these terranes. Starting in the middle Eocene, a tectonic escape, as a response to far-field stress from the India-Eurasia collision, took place in Southeast Sundaland. Dispersion of South Sulawesi and Sumba from South Kalimantan occurred by the opening of the Makassar Straits and Flores Sea, respectively.

To prove that South Kalimantan, South Sulawesi and Sumba were once united or close to each other in the Late Cretaceous, we carried out field work at Sumba Island, South Sulawesi, and the Meratus Mountains in 2018-2019 (Figure 1). The common marker that they were united is Late Cretaceous volcanics and/or their related volcanic-clastics. The three areas of the three terranes, where the common marker is exposed, were visited (Figure 2), namely: Lapopu and Masu (South and East Sumba), Celebes Canyon (South Sulawesi), Amandit River-Loksado (Meratus Mountains). The rock samples from the three areas were analysed (Tables 1-3). These results were integrated with previous analyses that had been conducted separately. So, a synthesis and interpretations were made.

The dispersion of South Sulawesi and Sumba from South Kalimantan in the Paleogene had formed rifted structures in the present North Makassar Strait, South Makassar Strait, and the Flores Sea. These rifted structures have potential for petroleum accumulation and have been proven in some places but need further exploration.

This study discusses the following: (1) the evidence, based on petrography, petrochemistry, isotopic, sedimentologic, and geochronological data, that South Kalimantan (Meratus Mountains), South Sulawesi, and Sumba terranes were united as Southeast Sundaland in the Late Cretaceous time; (2) the reconstruction of amalgamation and dispersion of the terranes; and (3) implications for petroleum potential.

METHODS

This study is based on data obtained from fieldwork and sample analyses (petrography, petrochemistry, isotope, sedimentology, geochronology). Previous published and unpublished literatures were studied, together with the results of fieldwork and data analyses. All these results provided the basis for a comprehensive data synthesis and our subsequent interpretations. Seismic data and exploration wells in the Makassar Straits, Flores Sea and Sumba areas are the basis for evaluating petroleum potentials.

RESULTS

Trilogy of Southeast Sundaland Terranes

Trilogy's definition in Merriam-Webster dictionary is “a series of three dramas or literary works or sometimes three musical compositions that are closely related and develop a single theme” (Merriam-Webster online dictionary). We in this paper presume a geological condition that involved three inter-related stories, namely a drama of three terranes that were once united and then separated. We re-unite their stories. Our Trilogy of Southeast Sundaland terranes are the three terranes located at the far southeastern portion of Sundaland, including: the Meratus Mountains, South Sulawesi, and Sumba Island (Figure 1). Those three terranes are now located separately but, in their geologic history, we postulated, they had been united, or close to each other, undergoing similar geologic processes at their time of close proximity., To establish this hypothesis, we needed to find a common marker or some commonality, as evidence that the Trilogy were once united. The common marker/ commonality is Late Cretaceous volcanics/volcanic-clastic sediments. The Trilogy underwent a demonstrable, contemporaneous volcanism and had coeval, interrelated processes.

Their separation during the Paleogene had formed via basement faulting due to extension and strike-slip faulting, thus opening basins into which sediments were rapidly deposited. We further postulate said sediments would become potential petroleum system elements as seen in nearby areas of current Southeast Sundaland.

Accretion and Dispersion of Southeast Sundaland

Occupying the position of an active continental margin, Sundaland had a recorded history of growth and slivering of a continent by accretion/ amalgamation and dispersion, respectively. Satyana (2003) discussed the tectonic processes of the growth and slivering of Southeast Sundaland, the most complicated part of the Sundaland. The growth of Southeast Sundaland occurred during Jurassic to Late Cretaceous (180-70 Ma) through subduction, accretion, and collision (Satyana, 2014). Related to this growth are: the Meso-Tethys Ocean which was sutured to become the Meratus Mountains, South Kalimantan by collision of Paternoster terrane, South Sulawesi, and Sumba forming accreted terranes. In the Late Cretaceous these accreted terranes including the Meratus suture became the area of volcanic arc/ volcanism and its associated sedimentation when the subduction of the Ceno-Tethys oceanic plate took place beneath Southeast Sundaland.

Starting at around 50 Ma or within the Middle Eocene, some of the accreted mass of Southeast Sundaland rifted and drifted eastward and southeastwardly slivering said continental margin. The dispersion of SE Sundaland is regionally considered to relate with some tectonic mechanisms such as: separation by mantle upwelling, far-field tectonic escape related to the India-Eurasia collision, marginal basin spreading of Southwest Pacific areas, and the sea-floor spreading of the Sulawesi Sea. The dispersed terranes included South Sulawesi through the opening of the Makassar Strait, Flores Sea Islands, and Sumba Island. This dispersion had caused the segmentation of the basement fabric by forming of rifted structures of horsts and grabens.

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So in part, the Pre-dispersion, which was during the Late Cretaceous, the terranes of South Sulawesi and Sumba Island were adjacent to South Kalimantan. These had a subsequent period of Late Cretaceous volcanism and related sedimentation. This is based on common markers of Late Cretaceous volcanism and related sedimentation.

Field Work in Lapopu, Sumba Island

Field work at Sumba Island was carried out in April 2018 to the area called as Lapopu, South Sumba, where sampling was carried out on rocks of the Lasipu Formation (Late Cretaceous) (Figures 1, 2).

Sumba Island is a terrane presently situated in the forearc setting of the Neogene-Quaternary Sunda-Banda volcanic arc. Sumba is considered a microcontinent and its origin has been a matter of debate for a long time. Satyana and Purwaningsih (2011) studied various considerations from previous authors and presented a new interpretation and synthesis based on multidisciplinary methods including: stratigraphic succession, geochronology-geochemistry of magmatic rocks, paleomagnetism, isotope geology, and Eocene large foraminifera. These studies concluded that Sumba was part of or adjacent to South Sulawesi before dispersion to its present position.

Satyana and Purwaningsih (2011) showed that the Paleogene stratigraphy of Sumba is similar to that of South Sulawesi. The Late Cretaceous extruded magmas exposed in Sumba show the characteristics of typical island arc setting at the margin of Sundaland. Paleomagnetic data of Sumba show the position close to Southeast Sundaland in the Late Cretaceous and has occupied the present position since early Miocene. Isotope data of Pb-Nd from Sumba display isotopic signatures and affinities similar to rocks from Sundaland. Sumba also contains typical Eocene low-latitude Sundaland large foraminifera of "APB" fossils of *Assilina*, *Pellatispira*, and *Biplanispira* and no Eocene high latitude Australian large foraminifera of *Lacazinella*.

Two formations of Late Cretaceous Volcanics are exposed at East (Masu Formation) and South Sumba (Lasipu Formation). The products of the Masu Formation of East Sumba (Effendi and
Apandi, 1994) consist of an assemblage of pyroclastic breccias, tuffs and lava flows, intruded by granodiorite. The magmatic rocks exposed in the Tanadaro area, in East Waikabubak, and South Sumba coastal area are included in the Lasipu Formation. These rocks include mostly granodioritic and dioritic intrusions and volcanic units of chiefly basaltic composition (basalts and minor basaltic andesites).

A field check and sampling of the Lasipu (Late Cretaceous) Formation in the Lapopu area (Figure 2), South Sumba was carried out on volcanic turbidite deposits, with analysesalso conducted on porphyritic andesite lava (Figure 3) under the hypothesis that said rock is part of common marker of the trilogy of Southeast Sundaland (Late Cretaceous volcanic and related sediments). The outcrops of Lapopu area show the first sedimentary cycle (Late Cretaceous-Palaeocene) in Sumba (Abdullah, 2000), represented by marine turbidites of the Lasipu Formation, which was accompanied major Late Cretaceous calc-alkaline magmatic episodes from Santonian to Thanetian episode (86-56 Ma).

Chamalaun et al. (1981) found that the oldest (Mesozoic) sediments of Sumba are typically carbonaceous siltstones with volcanogenic mudstones, sometimes showing signs of low-grade metamorphism, interbedded with sandstones, conglomerates, limestones and volcaniclastic debris. Burollet and Salle (1981) reported microfossil assemblages in some samples of the Lasipu Formation indicate Coniacian to Early Campanian ages (mid to Late Cretaceous). The detrital materials suggest either a continental origin, or an island arc environment; essentially a Mesozoic submarine fan with shallow-water deposits or an open marine bathyal environment.

Field Work in Celebes Canyon, South Sulawesi

Field work in South Sulawesi was carried out in February 2019 in the area called as Celebes Canyon, between Maros and Parepare (Figures 1, 2). Here there is rock outcrop of the Balangbaru Formation (Late Cretaceous).

Sukamto (1982) in mapping the area of Pangkajene and western part of Watampone described the Late Cretaceous Balangbaru Formation as flysch type-sedimentary rocks, sandstones interbedded with siltstone, claystone and shale. The formation is intercalated with conglomerate, conglomeratic sandstone, tuff and lava. The sandstones are composed of greywacke and arkose, partly tuffaceous and calcareous; generally, show turbiditic structure; in place conglomerate with components of basalt, andesite, diorite, shale, silicified tuff, schists, quartz. Generally, the rocks are dense and part of the shale is silicified. Microscopically the sandstone and siltstone show fragments of igneous, metasediments, and radiolarian chert. The northwestern part of the area contains more sandstone, and the southeastern part contains more claystone and shale, indicating the provenance from the northwest area.

Hasan (1991) studied in detail the turbiditic/flysch succession of the Balangbaru Formation. The sediments were deposited by sediment gravity flows, including high- and low- density turbidity currents, and debris flow processes in a submarine fan environment, ranging from lower bathyal to abyssal environments. Hasan (1991) divided the Balangbaru Formation into three members based on lithostratigraphy and sequence. From bottom to top: (i) the Allup Member, characterised by a chaotic fabric of debris flow deposits representing an inner-fan facies association; (ii) the Panggalungan Member, characterised by 'distal turbidite' features representing an outer-fan to basin plain facies association; (iii) the Bua Member, characterised by 'proximal turbidite' features representing a mid-fan facies association. The composition of the sediment in the Balangbaru Formation shows progressive changes with time from the lower to upper part of the succession. Petrographic, heavy mineral and geochemical studies suggest that the sediments in the lower part were mainly derived from erosion of the basement accretionary complex, but the upper part was more influenced by a magmatic arc provenance. The paleocurrent of the flysch succession of the Balangbaru Formation were predominantly from north to south, and northwest to southeast, with subsidiary flows from east to west. Thus, most of the clastic detritus was probably derived from two general source areas in the northwest to north of the basin (southeast Kalimantan), which agree with Sukamto (1982).

The field check was carried out in the Celebes Canyon where the rocks exposed are volcanic turbidite deposits. The sampling and analysis were conducted on andesitic lava intercalation (Figure 3) since the rock was thought to be a common marker in the trilogy of Southeast Sundaland (Late Cretaceous volcanic and related sediments).

Field Work in Amandit River, Loksado, Meratus Mountains

The field work in the Meratus Mountains was carried out in November 2019 on the Haruyan Formation (Late Cretaceous) in the Loksado area on the Amandit River (Figures 1, 2). The rocks exposed were volcanic deposits and igneous rocks; where sampling was carried out on ignimbritic tuff and microdiorite (Figure 3).

In the Meratus Mountains, the Late Cretaceous volcanic rocks are well exposed in the western and southern part of the mountains. Old literatures called the volcanics as the Alino Formation (Koolhoven, 1935). The Haruyan Formation was introduced by Heryanto and Sanyoto (1994). There are several names of stratigraphic subdivisions for Late Cretaceous volcanic and related volcanic-clastic deposits in the Meratus Mountains (lava of Pitanak Formation, and volcanic breccia and volcanic sandstones of Paau Formation). Heryanto (2010) discussed this matter in detail. For simplicity, Hartono (2012) suggested the name of Haruyan Volcanics for all the Late Cretaceous volcanic and related deposits in the Meratus Mountains.

Hartono (2012) evaluated the nature and origin of the Haruyan Volcanics of the Meratus Mountains. The Haruyan Volcanics consist of alternating andesitic to basaltic composition of lavas and volcaniclastic rocks (volcanic breccias, tuffs, conglomeratic volcanic sandstone). Comagmatic dykes and stocks of diorite, andesite, and dacite are found locally. The volcanic breccia is dominant rock followed by tuff and lava. Volcanic clastic sediments are mainly composed of andesitic and few basaltic fragments. Several sedimentary structures, found in the volcanic breccia and tuff, and basaltic pillow structures, indicate a submarine depositional environment The submarine magmatic activities during Late Cretaceous time may also be supported by the interfingering relationship between the Haruyan Volcanics and turbiditic submarine fan deposits of Pitap Group. The Haruyan Volcanics are Late Cretaceous in age based on K-Ar dating. Based on geochemical data showing calc-alkaline affinity, the Haruyan volcanics originated from magma formed within a subduction zone tectonic setting.

Satyana (2014) reconstructed the Late Cretaceous Haruyan volcanic to be related to subduction of Ceno-Tethys oceanic plate beneath Southeast Sundaland. The volcanic arc was in similar position with Jurassic-Early Cretaceous subduction zone and mid-Cretaceous suture of the Meratus Mountains.

Petrography of Late Cretaceous Volcanics of Haruyan Meratus, Balangbaru South Sulawesi, and Lasipu Sumba

Petrographic analysis was performed on all samples collected from the Haruyan Volcanics of the Amandit River, Loksado, Meratus Mountains; Balangbaru Volcanics of the Celebes Canyon, South Sulawesi, and Lasipu Volcanics of Lapopu area South Sumba (Figure 3). All rock samples are igneous rock group consisting of pyroclastic, intrusive, and extrusive rocks. Petrographic analyses include observations through megascopic, stereo-binocular microscopic and polarizing microscopic.

Ignimbritic tuff of Haruyan Volcanics, Meratus Mountains show a silicified alteration (Figure 4). Texture is pyroclastic, massive structure to flow banding (flow). Fragment is dominated by quartz (20%) and some of the feldspar (15%) with the groundmass has been largely replaced by microgranular quartz (50%) and some chlorite (8%) and epidote (2%) filling in between the flow structures. The rock is slightly oxidized, hematite and limonite replaced mafic and opaque minerals (5%). Microdiorite of the Haruyan Volcanics is intrusive igneous rock, phaneritic texture, fine-very fine crystals < 1 mm – 2 mm. The composition is dominated by plagioclase andesine (45%) and hornblende amphibole (45%), and contains a small amount of minerals opaque (magnetite, 7%). The rock has not been altered, although there are minor chlorite (2%) and illite clay minerals (1%). This rock can also be called hornblende microdiorite in the presence of dominant mafic mineral in the form of hornblende

The Late Cretaceous Balangbaru Volcanics of South Sulawesi are represented by andesitic lava (Figure 5) with an aphanitic texture, a small number of phenocrysts are amphibole (15%), plagioclase (5%) minor quartz (1%) pyroxene (2%), magnetite accessory minerals (2%) and altered minerals in the form of carbonates (<5%) and clay minerals. The rock is slightly altered. The ground mass forms a flow structure – trachytic (70%).

Late Cretaceous Lasipu Volcanics of Sumba is represented by porphyry andesite rock (Figure 6). Porphyritic textured igneous rock with aphanitic bedrock, phenocrysts are dominated by plagioclase (20%) and slightly amphibole (4%) and pyroxene (3%), wherein most of the phenocrysts are altered with moderate intensity to chlorite (6%) and epidote (3%). The bedrock is dominated by plagioclase microlites which are partially altered to clay minerals (60%) and a little carbonate (tr). Quartz (4%) is present in trace amounts as phenocrysts and ground mass.

All rocks underwent hydrothermal alteration. The mineralogical composition of the rock is relatively the same, intermediate in nature. Based on petrographic analyses, it indicates that the rocks from Meratus Mountains, Celebes Canyon, and Sumba Island originated from similar magma sources (cogenetic) showing the areas were adjacent to each other and in same magmatic setting but different in depth from intrusive to extrusive.

Petrochemistry and Petrotectonic Setting of the Late Cretaceous Volcanics/ Volcaniclastics

Petrochemical analysis of major oxide, trace, and rare earth elements is available for Haruyan volcanic, Meratus Mountains and Lasipu volcanic, Sumba (Tables 1, 2). Rocks are dominated by intermediate (andesite) compositions with arc volcanism petrogenesis, subduction-related, calc-alkaline series and high K calc-alkaline series compositions, based on trace elements they are derived from an arc orogenic tectonic setting.

The petrochemistry of the Haruyan Volcanics, Meratus Mountains, was evaluated by Hartono (2012), whose many findings are described below. Based on major elements, most of the rocks include basaltic andesite, andesite, basaltic trachyandesite, and trachyandesite (Figure 7). The SiO_2 content ranges from 50 to 64 wt.%. The rocks are also characterized by high Al_2O_3 (16 to 19 wt.%) and low TiO_2 (< 1wt%) concentrations consistent with rocks originated from subduction related magmas (Table 1). Based on plotting of K_2O and SiO_2, the Haruyan Volcanics are calc-alkaline and high-K calc alkaline series with minor tholeiitic and shoshonitic series (Figure 7). The two series of tholeiitic and calc-alkaline are also clearly shown when the data are plotted into SiO_2 vs FeO/MgO. As it is generally known that the calk-alkaline signature is the only magma formed in a subduction environment, and has never been originated in other tectonic settings. The trace element characteristics of the Haruyan Volcanics, like in many other arc magmas, the Haruyan Volcanics are high in large ion lithophile elements (LILE: Ba, Rb, K, Sr) concentration compared to MORB (mid-oceanic ridge basalt) (Figure 8). In contrast, the content of high field strength element (HFSE: Nb, Ti) are low. It is consistent with the major element signatures. The depletion in Nb content relative to K and La (Figure 8) is characteristic of rocks generated from magma in an orogenic tectonic setting.

The petrochemistry of Late-Cretaceous Sumba Volcanics was evaluated by Abdullah et al. (2000) in the Masu and Lasipu Formations (Table 2). The erupted magmas display the characteristics of a predominantly calc-alkaline (CA) and a minor potassic calc-alkaline (KCA) series (Figure 7); they are characterized by variable K_2O contents, relatively high Al_2O_3 and low TiO_2 contents, suggesting a typical island arc environment. Such affinity is consistent with their moderately to fairly enriched incompatible element patterns showing negative anomalies in Nb, Zr, and to a lesser extent in Ti, typical of subduction-related magmas. The whole rock major trace element compositions of Late Cretaceous Sumba Volcanics in Southeast Sumba show typically calc-alkaline to potassic calc-alkaline and their incompatible element patterns clearly show the negative Nb, Zr and Ti anomalies (Figure 8) typical of arc volcanic. All of the Late Cretaceous Volcanics of South Sumba plot are within the calc-alkaline field in the K_2O-

SiO_2 diagram, and their multi-element patterns exhibit negative Nb and Zr anomalies and enrichment in REE.

Geochemical studies of Balangbaru Formation were conducted by Hasan (1991) on the sandstone. The sandstone shows relatively high Al_2O_3 (12%) and Fe_2O_3 content (6%). This is related to a high lithic content. In general, from the base to top of the succession, they show an increase of SiO_2, MnO, and K_2O, but decrease in TiO_2, Fe_2O_3, $A1_2O_3$, MgO and Na_2O which correspond to the increase in the quartzose content and decrease in the unstable lithic grains. High Al_2O_3 and low TiO_2 concentrations indicate a provenance of subduction-related arc.

Based on petrochemistry, the Late Cretaceous Haruyan Volcanics, Sumba Volcanics, and Balangbaru sandstone show similar signatures of calc-alkaline, magmatic arc subduction-related features, indicating they were in a similar petrotectonic setting or that they were adjacent to each other in the Late Cretaceous. There are no petrochemistry data of Balangbaru Volcanics in addition to the sandstone, but the geochemical analysis of the sandstone indicates a provenance of a magmatic arc. This is confirmed by sedimentologic study of the Balangbaru Formation explained below.

Sedimentology of Late Cretaceous Balangbaru Formation, South Sulawesi

Analyses of the Late Cretaceous volcaniclastic turbidite of the Balangbaru Formation were done by Hasan, (1991). The formation is composed of siliciclastic deposits characterized by a turbidite structure containing volcanic materials, lava, and tuff (Sukamto, 1982). Hasan (1991) evaluated the source of sediments of the Balangbaru Formation using paleocurrent indicators and fan facies associations; petrographic composition of sandstone, silty-shale and conglomerate; geochemistry (explained above) and heavy minerals.

Sandstones of the middle part of the Balangbaru Formation (Panggalungan Member) show quartzose-contents fall in part into the field of recycled orogen provenance, some plot near the field of magmatic arc provenance, whilst sandstones from the Bua Member (upper part of the Balangbaru Formation) plot in both the fields of a magmatic arc and recycled orogen provenances, although some fall between these fields (Figure 9). The upper part of the succession shows a systematic increase in detrital quartz and a slight increase in feldspar content, but a decrease in the lithic rock fragments. That is, there is a decrease in the lithic rock fragments of subduction derivation, such as chert, metamorphic and serpentinite clasts; but an increase in lithic volcanic derivation which suggests more influence from a magmatic arc provenance.

From heavy mineral analysis, it can be seen that the lower part of the Balangbaru formation (Allup Member) is characterised by distinctive heavy mineral assemblages of garnet, spinel, glaucophane and chloritoid grains. Meanwhile, zircon, apatite and tourmaline increase in proportion towards the top of the succession; and there is notable sharp decrease in garnet and spinel frequency from the lower to upper part of the formation. Glaucophane and chloritoid grains are completely absent in the Bua Member. These mineral assemblages strongly suggest that the basal sediments of the Balangbaru Formation are more influenced by a basement complex source, and the upper sediments more influenced by a magmatic arc provenance. The paleocurrents of the flysch succession of the Balangbaru Formation were predominantly from north to south, and northwest to southeast, with subsidiary flows from east to west (Figure 9). Thus, most of the clastic detritus was probably derived from two general source areas in the northwest to north of the basin.

Based on sedimentological analyses (Figure 9), the middle and upper parts of the Balangbaru sediments were derived from magmatic arc provenances and recycled orogen provenances. Paleocurrent measurements of the sedimentary structures show dominant east and east-southeast directions, indicating the origin associated with the Late Cretaceous volcanic arc of the Meratus Mountains.

Pb-Nd Isotopic Signatures of Balangbaru, South Sulawesi and Lasipu, Sumba

Based on Pb-Nd isotopic characteristics of sediments and the volcanics, Vroon et al. (1996) evaluated provenances of terranes/ continental fragments in Eastern Indonesia (Figure 10). The evidence is based on a comparison of Pb-Nd isotopic signatures between meta-sedimentary or volcanic rocks from the microcontinents and possible provenance areas. North Australia has very high $^{206}Pb/^{204}Pb$ (up to 19.57) and low $^{143}Nd/^{144}Nd$ (0.51190-0.51200). Western New Guinea has low $^{206}Pb/^{204}Pb$ (18.6-19.0) and relatively high $^{143}Nd/^{144}Nd$ (0.51218-0.51225). The Bird's Head area has $^{206}Pb/^{204}Pb$ of 18.60-18.75. Southern New Guinea has $^{206}Pb/^{204}Pb$ of 18.75-19.0. Sundaland has less radiogenic Pb isotopes.

Marine sedimentary rocks of the Late Cretaceous Lasipu Formation in Sumba were analysed for the Pb-Nd isotopes. They display limited variations in $^{143}Nd/^{144}Nd$ (0.51244-0.51248) and Pb isotopes ($^{206}Pb/^{204}Pb$ = 18.74-18.77). Vroon et al. (1996) interpreted that these isotopic signatures do not correspond to the Australian or New Guinean continental domains, and thus favour a northern rather than a southern origin. Because of stratigraphic indications for a paleoposition of Sumba near SW Sulawesi, Late Cretaceous flysch sedimentary rocks from the Balangbaru Formation of SW Sulawesi were analysed for comparison. They yielded $^{143}Nd/^{144}Nd$ of 0.51246-0.51255 and Pb isotopes ($^{206}Pb/^{204}Pb$) of 18.67-18.74, which implies a close isotopic similarity with the Lasipu Formation (Figure 10). Based on this, it is considered that Sumba originated from SE Sundaland.

Geochronology and Biostratigraphy of Haruyan Volcanics, Lasipu Volcanics, Balangbaru Formation

Table 3 shows absolute dating analysis using K-Ar radiometry for Haruyan Volcanics, Meratus Mountains (Hartono and Permanadewi, 1998; Hartono, 2012) and Lasipu volcanic, Sumba (Abdullah, 2000). The biostratigraphy of the Balangbaru Formation (Sukamto, 1982) is also shown on Table 3.

The Haruyan Volcanics are Late Cretaceous in age based on radiometric dating, K-Ar results on basalts, andesites, diorites, and granitic rock related intrusives (Hartono and Permanadewi, 1998) showing the range of 82.9-66.3 Ma, equivalent to Campanian – Maastrichtian of the Late Cretaceous. The Late Cretaceous time for the age is also supported by the interfingering relationship between this volcanic and the Late Cretaceous Pitap Formation (Heryanto and Sanyoto, 1994. The Haruyan Volcanics are younger than Early Cretaceous Belawan Granite intrusions and mid-Cretaceous Batununggal *Orbitolina*-bearing limestones, and unconformably overlain by the Eocene Tanjung Formation.

Magmatic rock samples representing granitoid intrusions, lava flows and subvolcanic dykes of mafic to intermediate composition from East and South Sumba were selected for 40K-40Ar dating (Abdullah et al., 2000). Two periods of Late Cretaceous magmatic activity were recognized on the basis of most of these data, at around 86 - 77 Ma (Santonian - Campanian) in East Sumba and 71 - 56 Ma (Maastrichtian - Thanetian) in South Sumba. Two K-Ar ages were obtained from the granitoid intrusion of East Sumba, respectively at 83.7 ±1.8 Ma and 85.4 ±1.6 Ma, whereas five volcanic rocks (basalt, basaltic andesite, andesite) gave ages from 85.9 ± 2.0 to 77.2 ± 1.8 Ma. The K-Ar whole-rock ages of the granitoid samples from Tanadaro, South Sumba range from 64.3 ±1.2 Ma, to 56.6 ± 1.2 Ma. Those of the volcanic unit are scattered between 70.3 ±1.5 Ma and 59.2 ±1.2 Ma.

The age of the Balangbaru Formation is based on the fossil content of *Globotruncana* found in silty shale from east of Bantimala and from greywacke (from the road between Padaelo-Tanettariaja) showing Late Cretaceous age (P.F. Burollet, 1979 -written communication to Sukamto, 1982).

Based on the geochronology of Haruyan-Meratus and Sumba Volcanics, and biostratigraphy of the Balangbaru Formation the time of common marker or commonality of the trilogy of Meratus, South Sulawesi and Sumba terranes was in the time range of 84 - 72 Ma (Campanian) in the Late Cretaceous (Table 3). This time range was when the terranes were located adjacent to each other and underwent similar geologic processes of the Late Cretaceous volcanism -as the common marker of the terranes.

Volcanism in the area was still taking place until Early Tertiary. This suggests that subduction-related magmatism occurred along the southeastern margin of Sundaland at this time (Soeria-Atmadja et al., 1998). The volcanism occurred in the present Makassar Straits to South Sulawesi. Two wells penetrated the volcanic basement in the Makassar Straits, Rangkong-1 and Kaluku-1, the volcanic dated as 57 Ma at Rangkong-1 well, and 67-65 Ma at Kaluku-1 well equivalent to Late Cretaceous-latest Palaeocene (Maastrichtian-Thanetian stage) (Satyana, 2015). The K-Ar absolute dating on post-collision radiolarian chert of Bantimala, South Sulawesi recording the intercalation of rhyolitic tuff layers along the Pateteyang River may be partly contemporaneous with the Haruyan volcanic - Late Cretaceous (Wakita, 2000). In South Sulawesi, during Palaeocene to Eocene calc-alkaline volcanism activity still took place (Yuwono et al., 1988; Soeria-Atmadja et al., 1998).

Amalgamation and Dispersion of Meratus, South Sulawesi, Sumba

Eastern part of Kalimantan and western part of Sulawesi formed a single area in the Late Mesozoic (Katili 1978; Hamilton 1979). Tectonic reconstructions illustrating South Kalimantan, South Sulawesi, and Sumba as amalgamated terranes of Southeast Sundaland in mid-Cretaceous time – Eocene was shown by a number of authors (Abdullah et al., 2000; Satyana, 2003; Hall et al., 2009; Satyana and Purwaningsih, 2011; Satyana, 2014). Paleotectonic map of Southeast Sundaland at early Eocene time is shown on Figure 11.

South Sulawesi and Sumba docked with South Kalimantan as part of Southwest Borneo terrane in mid-Cretaceous time, closing the Meso-Tethys Ocean at the Meratus suture (Satyana, 2014). South Sulawesi and Sumba was part of West Sulawesi and/or Paternoster-Kangean terranes which collided with South Kalimantan at approximately 100 Ma. Hall et al. (2009) called this terrane as Argoland. This amalgamation existed until early Eocene time (Figure 11). It cannot be defined further as to where were the positions of South Sulawesi and Sumba in this terrane relative to the Meratus Suture. In the Late Cretaceous time, the sites of Meratus, Sumba, and South Sulawesi became the sites of and/or close to volcanic arc/ volcanism activity related to the Late Cretaceous subduction of Ceno-Tethys oceanic plate to the southeast of the terrane where Sumba and South Sulawesi were positioned.

The Late Cretaceous Haruyan Volcanics of the Meratus Mountains, the Late Cretaceous Sumba Volcanics, and the andesitic lava intercalation of the Balangbaru Formation sampled at Celebes Canyon, South Sulawesi were all part of or related to the Late Cretaceous volcanic arc. The volcanics, as discussed previously, show similar signatures based on petrography, petrochemistry, isotopic geology, and were contemporaneous (Campanian, Late Cretaceous). This shows that the volcanics were common marker, showing the Trilogy was previously united before their current separation. Soeria-Atmadja et al. (1998) and Abdullah et al. (2000) based on the presence of three periods of magmatic activity recognized in Sumba at ca 86-77 Ma (Santonian-Campanian), 71-56 Ma (Maastrichtian-Thanetian), and 42-31 Ma (Lutetian-Rupelian) reconstructed that Sumba Island was part of the terrane of Southeast Sundaland from Late Cretaceous to early Oligocene. The last magmatic period from middle-Eocene to early Oligocene is considered to develop while Sumba was drifting by the opening of the Makassar Straits.

The dispersion of the three terranes discussed in the study was experienced only by South Sulawesi and Sumba (Figure 12). Meratus, South Kalimantan has been relatively fixed during these geologic periods, and only rotated in the Neogene. The dispersion of South Sulawesi from South Kalimantan by the opening of the Makassar Straits based on new data of basement of the Makassar Straits was discussed by Satyana et al. (2012) and Satyana (2015). The dispersion of Sumba from Southeast Sundaland was discussed by Soeria-Atmadja et al. (1998), Abdullah et al. (2000), Satyana (2003), Satyana and Purwaningsih (2011).

Dispersion of South Sulawesi and Sumba was initiated by the opening of the Makassar Straits in early Eocene (Figure 12). The opening of the Makassar Straits could most likely be the resultof two mechanisms:1) tectonic escape following collision of India to Eurasia at 50 Ma and 2) back arc rifting due subduction rollback related to slower rate of subduction beneath Southeast Sundaland. Following the collision of India to Eurasia in 50 Ma, Southeast Asia became the area of post-collision tectonic escape (Tapponnier et al., 1982). Almost the whole Southeast Asia escaped southeastwardly away from the collision. Major strike-slip faults and opening of marginal basins occurred as responses to the escape tectonics. Gunawan and Damayanti (2010) detailed the mechanism of how the Makassar Straits opened due to trans-tension movement by three regional strike-slip faults across the straits.

Subduction roll back due to a slower rate of subduction, related to collision of India into Eurasia, possibly initiated the rifting in back-arc positions including the Makassar Straits. Regionally for Sundaland, Pubellier and Morley (2013) showed this starting from the early Paleogene and following fractures initiated during the India Eurasia collision, subsequent rifting began along large faults (mostly N-S and NNW-SSE strike-slip), which crosscut the whole region. Some rifted structures were marked by extremely stretched crust (North Makassar) or even reached the ocean floor spreading stage (Flores). Rifting of North and South Makassar Straits ceased by the end of early Miocene (Situmorang, 1982), as it failed to develop further into sea-floor spreading. The cause was collisions of microcontinents to the east of Sulawesi in Neogene time, firstly by collision of Buton-Tukang Besi microcontinent in early-late Miocene and secondly by collision of Banggai-Sula microcontinent in Mio-Pliocene time (Satyana and Purwaningsih, 2011). South Sulawesi has been positioned in its present position since Oligo-Miocene time.

Following the separation from South Kalimantan by the opening of the Makassar Straits through rifted structures, Sumba further dispersed from South Sulawesi or Southeast Sundaland by transcurrent-transformal displacement prior to the development of the Mio-Pliocene volcanic arcs in the Lesser Sunda region (Simandjuntak, 1993; Satyana, 2003) (Figure 12). The later dispersion of Sumba by major strike-slip faults related to escape tectonics. The escape tectonics refers to the lateral motion of fault bounded geological blocks to a free oceanic edge (Satyana, 2006). Strike-slip and extensional/ rifting structures accommodate the lateral motion. In Kalimantan, major shear related to the India collision is the Lupar-Adang/Paternoster Fault (Satyana, 1996). The trace of this major fault may also continue or attach to the major faults in South Sulawesi such as Walanae Fault, Salayar Fault until the Sumba Fracture. The detachment of Sumba from the Walanae depression in South Sulawesi seems to have taken place in the middle Miocene by reactivated sinistral strike-slip fault of the Walanae Fault-Salayar Fault-Sumba Fracture prior to the development of the volcanic arcs in Lesser Sunda.

The beginning of Sumba dispersion has various ranges from the Late Cretaceous (Wensink, 1994, 1997) to Middle Miocene (Simandjuntak, 1993). Wensink (1994) and Wensink and van Bergen (1995) argued that based on the recent paleomagnetic evidence, there are indications that Sumba started to drift in the Late Cretaceous and had already arrived at or near its present position in the Early Miocene. Most of the authors suggested the Paleogene as the period of Sumba dispersion (Figure 12). Detailed K-Ar chronology of Sumba magmatism shows it was beginning during Late Cretaceous and it was vanishing in Late Eocene-Early Oligocene. Regionally as well as chronologically, these result in constraints that Sumba dispersed to its present position during the Oligocene and Miocene.

Implications for Petroleum Prospectivities

Dispersion of South Sulawesi and Sumba from South Kalimantan or Southeast Sundaland through the opening of the Makassar Straits and Flores Sea had formed rifted structures in forms of grabens and horst (Figures 13-15) with some structures related to major strike-slip faults. These rifted structures in western Indonesia have been proven as places for deposition of some elements of petroleum system (source, reservoirs, seals), and places for developments of stratigraphic and structural traps. The generation of hydrocarbons mostly occurred in the Pliocene time by overburden of Neogene sediments overlying the rifted structures. These circumstances provide petroleum system opportunities to the areas where South Sulawesi and Sumba were dispersed. The North Makassar Straits, the South Makassar Strait, the Gulf of Bone, and the Flores Sea are the areas with sediments within, on, or overlies rifted structures. Said deposits lend themselves toward potential for petroleum system opportunities.

Rifted structures within the Makassar Straits (Figure 13), Gulf of Bone, Flores Sea, and offshore Sumba (Figure 15) are clearly shown on seismic sections. The half graben, graben, and horst structures resulted from rifting are clear. Sediments were deposited within graben, on horst, and overlying the rifted structures. Potential source rocks are syn-rift Early Tertiary lacustrine, woody terrigenous to marine lagoonal source rocks in buried half grabens, all Eocene to early Oligocene in age. Potential reservoirs are syn-rift fluvial and paralic sands, late syn-rift paralic to nearshore marine sand and early sag phase, carbonate reefs and sand reservoirs, all Eocene to early Miocene in age. Potential seals are interbedded claystone in syn-rift and early sag phase deposits and interbedded hemipelagic claystone in basinal deposits. Overburden rocks to mature source rocks are all rocks deposited overlying the rifted structures. Play types that developed at the rifted structures are: tilted fault blocks related to rifted basin and drape channel sands overlying the basement high, reefal buildups over the horst, faulted anticlines, traps in synrift sections, stratigraphic subcrop plays, turbidite fans, slope channel fill, stratigraphic pinchout, and fractured basement highs. Hydrocarbon kitchens may exist in the synrift, generated petroleum migrated to available traps within the synrift section or to the horst block.

These rifted structures have been proven generating, migrating and trapping petroleum as shown by oils discovered by Kaluku-1 well (ConocoPhillips, 2011) in Eocene sandstones draped at horst block of rifted structures in the Makassar Straits (Figure 13), and oils tested by L 46-1 well (Amoco, 1985, tested 936 BOPD) at Eocene sandstones draped at horst block of rifted structure at the offshore area the north of Lombok-Sumbawa Islands (Figure 14). Offshore hydrocarbon seeps identified by satellite at South Makassar, Gulf of Bone, and offshore Sumba (Figure 15) and their strong correlation with geological features may show that hydrocarbon systems are active in the areas. Further exploration of these rifted structures where South Sulawesi and Sumba had dispersed during the Paleogene are interesting to investigate in the future since the Paleogene objectives in these rifted structures have not been explored sufficiently in the past.

CONCLUSIONS

The three areas, called here the Trilogy of Southeast Sundaland terranes includede: Meratus Mountains, South Sulawesi, and Sumba Island. Each are tectonically reconstructed to be connected to Southeast Sundaland in the Mid-Cretaceous time. The actual amalgamation of the terranes took place in mid-Cretaceous time. During the Late Cretaceous until the early Eocene, the areas became the sites of volcanism and related volcanic-clastic deposition. Starting in middle Eocene and during the Oligocene, South Sulawesi and Sumba dispersed from South Kalimantan or Meratus Mountains. Sumba further dispersed to its present position and arrived there in early-middle Miocene. The dispersion occurred through the opening the Makassar Straits and Flores Sea by rifting and regional strike-slip faulting.

This study proved that the terranes were once united on Southeast Sundaland using a common marker developing on the three terranes namely the Late Cretaceous volcanics. Field work were conducted on the three terranes, sampling the Late Cretaceous volcanic or related volcanic-clastic rocks, and analysed them. Based on petrographic, petrochemical, isotopic, and biostratigraphic-geochronologic data, it is proven that the three terranes were once united or close to each other in Late Cretaceous time.

Rifted structures, formed during separation of South Sulawesi and Sumba from South Kalimantan, provide sites for deposition of Paleogene sources rocks, reservoirs, and seals, as well as the formation of structural and stratigraphic traps. Some oil has been discovered relative to these structures. Thus, further exploration of these rifted structures and their potential petroleum systems is quite encouraging since these objectives have not been explored sufficiently in the past.

ACKNOWLEDGMENTS

We thank Geotrek Indonesia, a non-profit community for Indonesia's geo-history for participating in the field work and financed a part of the analyses. We thank Dr. Rachmat Heryanto (retired scientist from Geological Agency) for sharing his research works in the Meratus Mountains, and Dr. Chalid Idham Abdullah (lecturer at Institute of Technology Bandung) for sharing his research works in Sumba Island. We thank Wynn Gajkowski for reading the manuscript and suggesting editorial improvement. Technical Program Committee IPA is thanked for accepting this paper to publish in IPA Convention, guidance for publication and presentation, and additional time to complete the paper.

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TABLE 1. Major, trace, and rare earth element analyses of the Haruyan volcanics, Meratus Mountains (Hartono, 2012).

	95UH10A	95UH10F	95UH10G	95UH11	95UH12B	95UH13	95UH22A	96UH4A	96UH4B	96UH7A	96UH7C	96UH7D	96UH9	96UH15A	96UH15B	96UH15C	96UH15D	96UH15F	96UH2
Major Elements																			
SiO_2	55.89	58.34	56.98	53.5	60.82	60.77	59.89	47.61	46.99	56.54	54	50.24	53.51	53.24	58.9	55.38	52.11	54.11	61.92
TiO_2	0.66	1.43	1.16	0.83	1.15	1.16	1.12	0.86	0.82	0.98	0.66	0.7	0.6	0.89	0.72	0.87	0.72	0.82	0.61
Al_2O_3	19.48	15.17	16.37	17.87	15.97	15.77	16.04	16.62	17.9	15.63	19.39	17.84	17.44	17.67	16.79	17.15	18.13	16.22	18.3
Fe_2O_3	5.15	8.06	8.04	9.17	6.18	6.23	6.54	10.95	10.63	8.73	5.49	9.51	6.83	8.73	6.12	8.32	8.26	10.07	4
MnO	0.07	0.14	0.12	0.16	0.1	0.1	0.11	0.2	0.18	0.15	0.14	0.19	0.15	0.18	0.14	0.13	0.13	0.18	0.13
MgO	3.48	2.86	3.53	4.52	2.4	2.51	2.74	6.79	6.89	3.36	2.24	3.54	4.13	2.76	1.85	2.52	3.54	3.16	0.99
CaO	8.26	6.51	6.02	5.11	4.26	4.79	4.64	8.04	9.83	4.81	4.61	8.48	3.83	6.68	6.33	6.69	6.62	6.4	4.56
Na_2O	3.51	2.67	3.72	5.07	4	3.31	4.16	4.49	3.09	4.07	5.27	4.27	3.36	4.22	3.5	4.06	5.32	4.7	4.58
K_2O	1.59	2.34	2.43	0.81	3.2	3.12	2.84	0.33	1.06	3.03	3.69	1.68	6.42	1.79	2.35	2.05	1.5	1.25	3.34
P_2O_5	0.16	0.39	0.3	0.15	0.38	0.39	0.38	0.12	0.06	0.47	0.47	0.23	0.37	0.44	0.37	0.42	0.25	0.33	0.34
Loss	1.21	1.89	1.67	2.63	1.5	1.78	1.99	4.19	3.12	2.03	3.99	2.78	3.06	2.88	2.29	2.56	2.96	2.6	0.96
Total	99.46	99.8	100.34	99.82	99.96	99.93	100.45	100.2	100.57	99.8	99.95	99.46	99.52	98.89	99.63	100.55	99.18	98.2	101.81
Mg#	61.14825	45.24988	50.55951	53.4467	47.49367	48.41101	49.38836	59.08847	60.15442	47.26992	48.72678	46.43842	58.47892	42.4086	41.31729	41.36514	49.95536	42.22665	36.56713
Trace Elements																			
Ba	406	638	470	247	551	647	512	64.4	223.8	392.9	576.6	120.8	1313.1	475.1	427.4	339.1	245.5	379.8	152.7
Rb	40	86	84	18	113	107	99	5.05	15.55	39.7	51.65	35.45	74.15	12.45	18.6	21.05	18.5	54.3	16.5
Th	5.7	16.4	10.6	1.3	13.2	11.4	11.7	1.2	0.3	3.15	2.95	0.9	1.65	4.15	3.7	2.95	2.3	2.4	1.5
K																			
Nb	3.9	7.4	4.5	2.6	6.9	7.2	6.5	1.2	<1	3.1	3.6	1.1	2.7	3	3	2.9	1.6	2.9	1.9
La	13	30	23	5	24	24	23	3.2	2.1	25.4	18.6	8.6	17.1	20.6	19.4	17.6	11.6	13.1	9.4
Ce	34	72	52	18	61	56	53	10.1	8.4	51.5	44.5	23.5	41.3	47	48.3	38.5	27.7	33.2	24.5
Sr	371	353	320	449	233	377	304	327	527.2	602.9	1264	786.9	674.2	1269	613.4	844.3	685.4	740.8	300.3
Nd	18	33	26	11	31	28	25	7.2	5.6	34	26	15.7	24.5	31.5	31.1	24.1	20.3	18.6	17.1
P																			
Zr	111	298	220	68	262	250	235	44.5	30.1	165.1	119.9	68.8	93.2	167.6	159.8	139.6	88.8	115.9	80.6
Ti																			
Y	25	42	33	19	38	35	36	18.5	15.7	36.8	16.5	16.7	17.5	24.9	25.6	21.5	16.9	17.7	21.3
Ni	22	29	29	20	19	20	22	29.5	22.3	12.9	15.1	10.8	6	9.7	9.2	3.7	20.9	2.9	8.2
Cr	109	30	36	39	32	41	42	32.4	23.4	5.5	17.4	13.6	7.2	10.2	12.1	5	22	3.8	6.1
V	96	261	221	271	122	136	148	336.2	326.3	331.4	219.6	299	217.8	262.6	252.6	172.5	283.9	122.4	249.1
Sc	19	21	23	31	17	17	19	37.9	35.8	20.5	16.5	24.8	21.4	20.9	20.8	16.5	19.2	13.6	21.2
Pb	17	45	29	6	26	26	26	18	0.6	7.8	8.3	3.6	1.3	8.55	9.95	9.35	6	5.05	0.05
U	<1.5	5.1	3.5	<1.5	3.1	2.7	2.5	0.15	0.15	0.85	1.55	0.5	0.75	1.65	1.4	0.9	0.55	1.3	-0.05
Rare Earth Elements																			
La															18.73				
Ce															44.03				
Pr															6.64				
Nd															30.9				
Sm															7.43				
Eu															1.82				
Gd															5.67				
Dy															4.47				
Er															2.5				
Yb															2.29				

TABLE 2. Major and trace element analyses of Sumba magmatic rocks (Abdullah *et al*., 2000).

	Santonian–Campanian magmatism							Maastrichtian–Paleocene magmatism				
	Masu Mt							South Coast				
%	CIA-728	CIA-735	CIA-353	CIA-348	CIA-733	CIA-351	CIA-347	CIA-317	CIA-339	CIA-487	CIA-491	CIA-481
SiO_2	48.8	54	55.3	56.4	56.5	59	64.5	52.6	53	53.5	53.8	53.4
TiO_2	0.98	0.77	0.84	0.85	0.84	0.71	0.47	1.05	0.84	0.94	0.82	0.91
Al_2O_3	18.25	17.96	19	16.75	17.25	16.75	16.52	16.95	17.1	18.5	17.25	20.25
Fe_2O_3	10.95	7.65	8.4	8.8	8.5	6.9	4.58	8.8	8.65	8.4	8.56	8.4
MnO	0.19	0.16	0.1	0.21	0.17	0.15	0.1	0.15	0.16	0.13	0.16	0.13
MgO	5.7	3.67	2.61	2.69	3.29	2.9	1.75	3.54	4.46	3.33	4.2	3.32
CaO	9.05	6.4	7.63	7.4	7.3	6.05	4.42	9.16	7.3	5.4	6.35	3.3
Na_2O	2.91	3.68	3.27	3.4	2.88	3.13	3.6	2.54	3.81	3.69	3.32	3.95
K_2O	0.76	1.54	1.15	1.68	1.75	2.52	3.65	0.83	2	2.55	2.08	3.2
P_2O_5	0.21	0.18	0.26	0.34	0.2	0.23	0.11	0.24	0.18	0.23	0.17	0.23
LOI	1.67	3.15	0.93	0.73	1.48	1.45	0.58	3.48	2.97	2.6	2.81	1.16
Total	99.47	99.16	99.49	99.25	100.16	99.79	100.28	99.7	100.47	99.27	99.52	98.25
ppm												
Cr	27	27	2	1	15	6	8	32	70	19	48	18
Nl	31	14	3	3	9	6	6	29	20	5	12	9
Co	35	21	14	18	22	17	11	32	26	22	25	22
Sc	29	21	23	23	21	20.5	12	30	28	23	27	24
V	326	227	190	215	226	170	106	310	250	233	240	222
Rb	10	35.5	33	36	26.5	51	102	20				
Ba	184	510	365	390	355	510	560	160	292	382	450	890
Sr	562	570	653	610	485	490	381	340	490	705	560	760
Nb	2.3	2.6	2.9	2.9	3.4	2.3	3.95	1.4	2.3	3.1	2.2	2.9
La	10.5	12.5	14.3	17.9	14.8	15.35	17.9	9.75	10.1	13.1	9.4	12.5
Ce	24.5	26			32				25	31	22	31
Nd	16	15	19	24	18.4	21	20	15	15	19.3	14	19
Zr	69	88	26	16	106	60	18	100	89	137	59	125
Eu	1.22	1.02	1.2	1.3	1.13	1.35	1	1.1	1.12	1.12	1.05	1.15
Y	20	16.8	25	29.5	20.5	22	20	27	22	27	22	25
Dy	3.4	2.75	4	4.9	3.55	3.6	3.2	4.4	3.85	4.4	3.6	4.5
Er	1.9	1.5	2.3	3.2	2.05	1.9	2.2	2.5	2.2	2.5	2	2.6
Yb	1.83	1.6	1.95	2.7	1.97	1.85	1.8	2.4	2.07	2.48	1.92	2.40

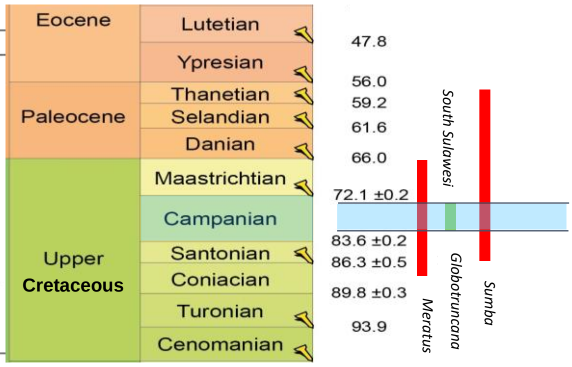
	Maastrichtian–Paleocene magmatism							Late Eocene–Early Oligocene (Lutetian–Rupelian) magmatism				
	Tanadaro Mt							Lamboya and Jawilla Mts				
%	CIA-71	CIA-204	CIA-73	CIA-202	CIA-115	CIA-132	CIA-133	CIA-62	CIA-717	CIA-44	CIA-493	CIA-21
SiO_2	49.35	55.4	56.1	57	58.1	59.4	67	51.5	55	60.8	64.5	67.2
TiO_2	0.74	0.7	0.63	0.75	0.84	0.62	0.56	0.78	0.94	0.76	0.67	0.9
Al_2O_3	21.15	17	20.2	17.21	17.46	16.7	14.8	19.15	17.4	15.44	16.1	126
Fe_2O_3	8.76	8.22	6.55	7.38	6.9	7.03	4.62	8.12	9.45	7.3	4.52	3.57
MnO	0.15	0.16	0.1	0.13	0.13	0.12	0.08	0.16	0.18	0.13	0.09	0.08
MgO	4.55	4.34	2.07	3.65	3.53	3.26	2.13	5.6	3.37	3.09	1.63	0.38
CaO	9.59	7.43	7.95	7.17	7.22	6.36	4.3	8.1	7.7	6.12	3.45	3.29
Na_2O	3.03	3.62	3.88	3.46	3.54	3.49	3.48	3.6	3.53	3.4	4.6	5.74
K_2O	0.72	1.63	0.83	1.2	1.04	1.63	2.33	0.55	0.59	1.64	1.87	1.4
P_2O_5	0	0.08	0.06	0.07	0.06	0.04	0	0.2	0.16	0.02	0.18	0.22
LOI	2.29	1.59	1.88	1.59	1.49	1.4	0.68	2.88	1.55	1.55	1.77	0.79
Total	100.33	100.17	100.25	99.61	100.31	100.05	99.98	100.64	99.86	100.25	99.38	99.57
ppm												
Cr	32	48	10	48	47	39	34	157	11	24	11	12
Nl	26	18	9	25	26	22	18	85	5.5	14	1	6
Co	31	26	19	24	22	19	16	30	20	21	11	7
Sc	29	29	15	23	21	21	14	23	31	23	17	20
V	196	157	110	143	131	142	95	174	269	140	55	56
Rb	19	41	18	37	32	45	85	6	8	39	17.7	28
Ba	191	228	131	229	188	300	350	125	81	134	1010	187
Sr	646	430	525	408	409	404	293	410	302	210	231	282
Nb	2	5	2.5	4	5	4	4	1.8	1.8	5	2.8	9
La	5	18	7.5	11	11	14	15	10.2	5.8	9.5	18	15
Ce									15.5		42	
Nd	9	16	12	14	13	15	15	13.5	10.5	15	28.5	24
Zr	39	14	27	8	9	12	8	83	71	26	148	219
Eu	0.5	1	0.9	1	1	0.9	0.7	1.2	1	1	1.95	1.8
Y	17	30	20	23	22	27	28	21	22.5	33	55	54
Dy	2.2	4.08	2.8	3	2.9	3.4	3.6	3.1	3.55	4.7	8.6	8.1
Er	1.7	2.2	1.7	1.6	2.1	2.4	2.3	2.1	2.35	2.6	5.3	2.7
Yb	1.45	2.13	1.52	1.86	1.73	2.25	2.2	1.9	2.29	2.74	5	4.86

TABLE 3. Top Left: K-Ar dating of Haruyan volcanics, Meratus Mountains. Bottom Left: K-Ar dating of Sumba magmatic rocks. Top Right: Geochronologic relation of Meratus and Sumba volcanics as well as *Globotruncana* fossil as Late Cretaceous - Campanian (84-72 Ma). Bottom Right: Explanation of *Globotruncana* fossil content of Balangbaru Formation, South Sulawesi.

K-Ar results of the Cretaceous Haruyan volcanics from the Meratus Range

Sample numbers	Rock names	Mineral analized	Age (Ma)
95SP12C	Andesite	Plagioclase	69.628 ± 2.03
95IS11	Andesite	Pyroxene	82.929 ± 2.21
95IS04	Andesite	Hornblende	66.931 ±1.14
95UH4B	Basalt	Pyroxene	79.093 ± 3.82
96UH7D	Basalt	Pyroxene	66.268 ± 11.63
96UH15C	Basalt	Plagioclase	79.628 ± 4.30
96UH21A	Andesite	Plagioclase	81.553 ± 0.94
96GR27	Granite	Hornblende	15.904 ± 3.88
94SP07A	Diorite	Hornblende	71.251 ± 0.46
94SP07B	Tonalite	Hornblende	70.962 ± 0.49
94SE60B	Diorite	Hornblende	87.184 ± 1.81
96MD16	Tonalite	Hornblende	71.363 ± 5.22

Hartono & Permanadewi (1998)



ICS (2019)

age of Globotruncana sp. based on Gradstein et al. (2005)

Sumba K-Ar Dating

Sample No.		Location	Type	Age (Ma) ±error	$^{40}Ar_R$ (e^{-7} cm^3/g)	$^{40}Ar_R$ (%)	K_2O (wt %)	LOI (wt %)	Analysis No.
			Santonian–Campanian episode						
Mt Masu									
CIA-347	WR	Cape Malanggu (Pameti Hawu)	Granodiorite	85.4 ± 1.6	101.60	84.9	3.68	0.58	2794
CIA-348	WR	Cape Malanggu (Pameti Hawu)	Microdiorite	83.7 ± 1.8	48.59	70.8	1.76	0.73	2813
CIA-351	WR	Cape Malanggu	Andesite	85.9 ± 2.0	71.44	72.0	2.52	1.45	4715
CIA-353	WR	Cape Malanggu	Bas. andesite[b]	78.6 ± 1.7	32.39	84.2	1.25	0.93	2814
CIA-728	WR	Tanarara (Km 5)	Basalt	85.4 ± 2.0	21.71	73.8	0.79	1.67	3933
CIA-733	WR	Gunung Kapunduk (Nggongi valley)	Bas. andesite[b]	80.9 ± 1.9[a]	49.11	81.1	1.84	1.48	3922
				84.4 ± 1.9	51.24	87.8			3921
CIA-735	WR	Road from Tatunggu to Tanarara (Km 2)	Bas. andesite[b]	76.9 ± 1.8[a]	40.25	74.8	1.59	3.15	4362
				77.6 ± 1.8	40.63	72.1			3947
			Maastrichtian–Paleocene episode						
Wanokaka area									
CIA-317	WR	Western side of Wanokaka beach	Basalt	71.1 ± 1.3[a]	20.35	89.2	0.87	3.48	2792
				69.5 ± 1.5	19.87	90.3			2793
Sendikari and Tengairi Gulfs									
CIA-339	WR	Eastern part of the Sendikari Gulf (Cape Teki)	Microgabbro	70.1 ± 1.4[a]	49.11	79.9	2.13	2.95	2857
				68.7 ± 1.4	48.11	79.7			2856
CIA-491	WR	Eastern part of the Sendikari Gulf (Cape Teki)	Bas. andesite[b]	65.2 ± 1.3	46.27	77.8	2.16	2.81	2880
CIA-481	WR	Bottom of the Tengairi Gulf	Bas. andesite[b]	68.0 ± 1.3	73.94	82.2	3.31	1.16	2879
CIA-487	WR	Bottom of the Tengairi Gulf	Bas. andesite[b]	65.3 ± 1.8	55.52	75.8	2.59	2.60	2878
Mt Tanadaro									
CIA-133	WR	Mt Tanadaro (Western part)	Granodiorite	64.3 ± 1.2	55.78	85.7	2.74	0.68	2848
	Bio			66.6 ± 1.3	173.40	79.0	7.93		2830
	Fds			63.6 ± 1.5	44.03	66.9	2.11		2833
CIA-132	WR	Mt Tanadaro (Western part)	Diorite	64.3 ± 1.2[a]	33.74	82.8	1.60	1.40	2790
				61.8 ± 1.2	32.45	82.7			2791
	Chl			62.1 ± 1.2	69.51	79.0	3.41		2851
	Fds			62.9 ± 1.5	51.04	67.3	1.54		2850
CIA-115	WR	Pamalar river (South-western edge of Mt Tanadaro)	Diorite	61.8 ± 1.2	35.09	84.9	1.73	1.49	2846
	Bio			63.4 ± 1.2	128.40	88.1	6.17		2826
	Fds			57.7 ± 1.6	17.96	57.7	0.95		2823
CIA-204	WR	Pamalar river (South western edge of Mt Tanadaro)	Diorite	57.6 ± 1.3	33.00	69.4	1.75	1.59	2753
	Chl			61.0 ± 1.2	71.97	81.6	3.60		2852
	Fds			61.4 ± 1.4	32.23	67.5	1.60		2853
CIA-202	WR	Pamalar river (South western edge of Mt Tanadaro)	Diorite	56.6 ± 1.2	28.01	75.3	1.51	1.59	2754
CIA-71	WR	Nyengu river	Basalt	66.5 ± 1.6	15.73	70.0	0.72	2.29	4722
CIA-73	WR	Nyengu river	Bas. andesite[b]	59.2 ± 1.2[a]	16.12	78.8	0.83	1.88	2633
				59.2 ± 1.2	16.11	80.1			2632
			Lutetian–Rupelian episode						
Mt Lamboya									
CIA-62	WR	Eastern part of Rua beach (Cape Watumete)	Basalt	43.5 ± 3.2[a]	8.09	26.4	0.57	2.88	2952
				41.2 ± 2.8	7.66	28.1			2923

Abdullah et al. (2000)

Kb BALANGBARU FORMATION: flysch type sedimentary rocks; sandstones interbedded with siltstone, claystone and shale; intercalated with conglomerate, conglomeratic sandstone, tuff and lava; the sandstones composed of greywacke and arkose, partly tuffaceous and calcareous; generally show a turbidite structure; in places conglomerate with components of basalt, andesite, diorite, shale, silicified tuff, schist, quartz, cemented with compact sandstone occurred; generally the rocks are dense and part of the shale is silicified. Microscopically the sandstone and siltstone show fragments of igneous, metasediment, and radiolarian chert. The northwestern part of the area contains more sandstone, and the southeastern part contains more claystone and shale.

Recently, TOTAL-CFP identified *Globotruncana* from silty shale from east of Bantimala and from greywacke (from the road between Padaelo-Tanettariaja) showing Late Cretaceous age (P.F. Burollet, written communication, 1979).

Sukamto (1982)

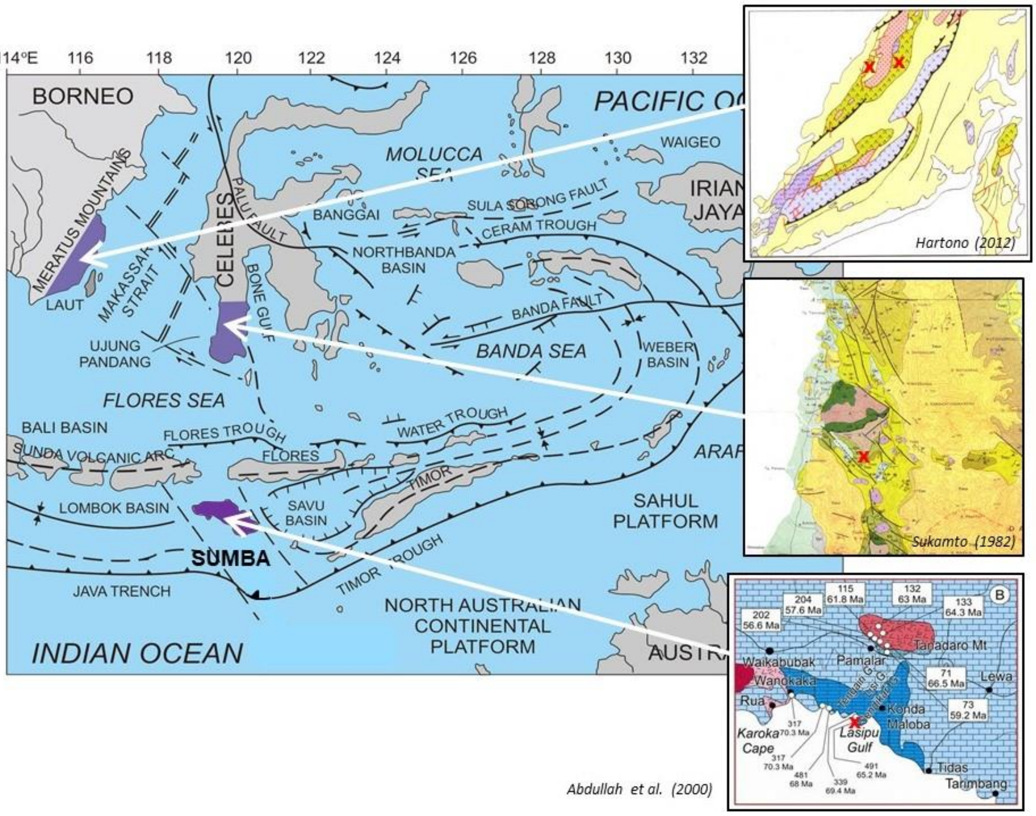


FIGURE 1 – Trilogy of Southeast Sundaland terranes, including Meratus Mountains, South Sulawesi, and Sumba. It is considered they were once united or close to each other then drifted. Insets are simplified geologic maps of the three areas, red crosses on the maps are locations of samplings for the rocks thought to be related.

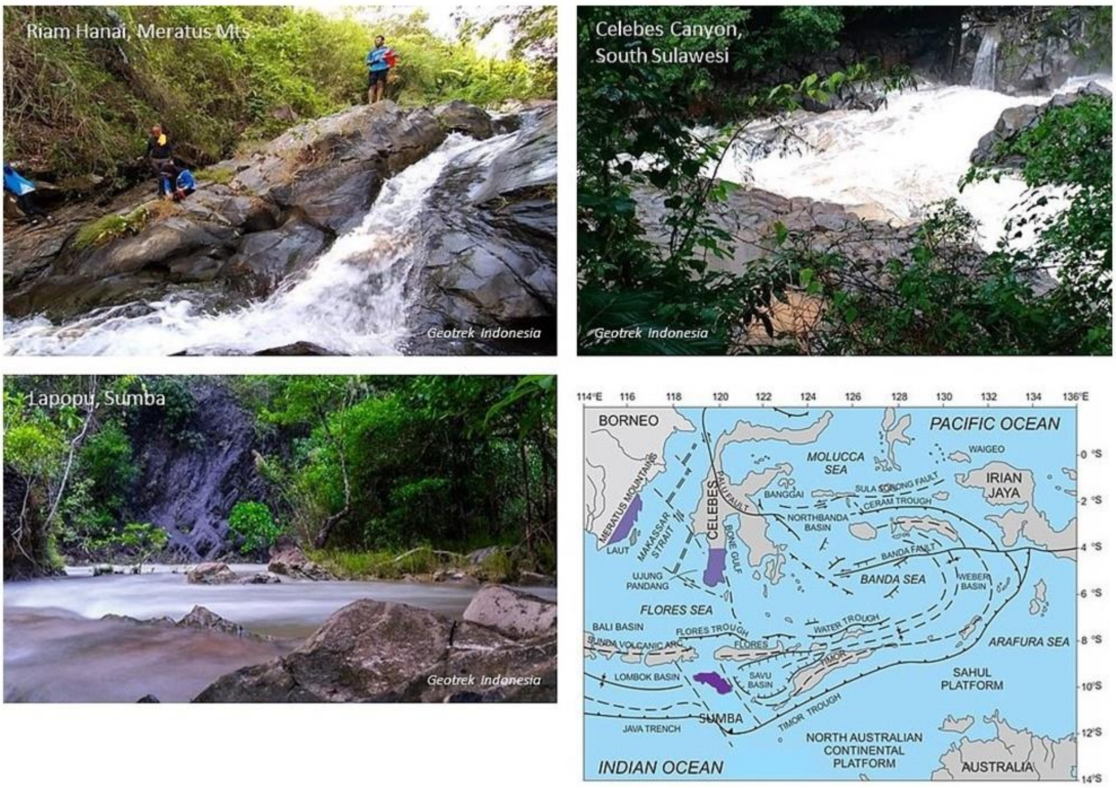


FIGURE 2 –Rock outcrops of Haruyan volcanics at Riam Hanai, Meratus Mountains; Balangbaru at Celebes Canyon, South Sulawesi; and Lasipu at Lapopu, Sumba. The rocks are geologically thought to be related in petrogenesis in the Late Cretaceous.

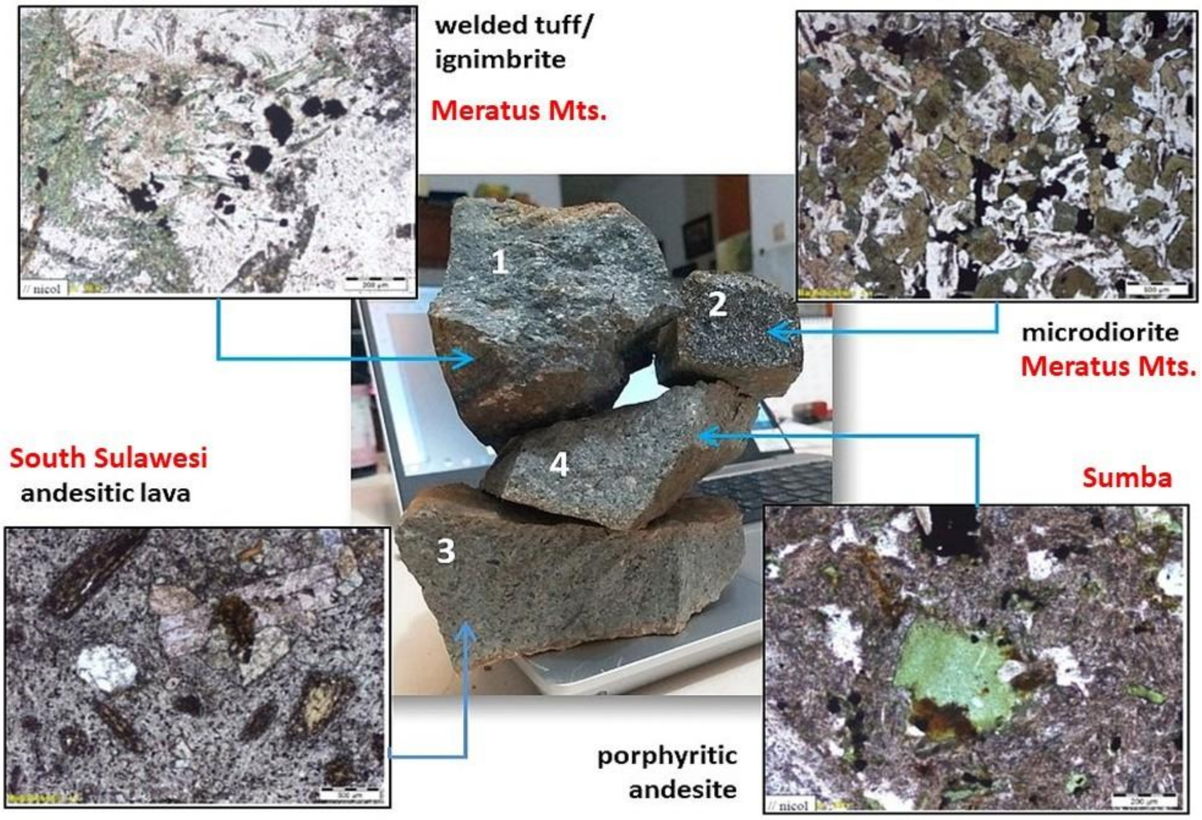


FIGURE 3 – Four rock samples and their petrographic pictures from selected areas of the Meratus Mountains, South Sulawesi, and Sumba geologically thought to be related. Based on their petrographic analyses, the rocks are co-genetic with similar mineralogical composition (intermediate).

Meratus

Ignimbritic tuff of Haruyan Volcanics, Meratus Mountains show a silicified alteration. Texture is pyroclastic, massive structure to flow banding (flow). Fragment is dominated by quartz (20%) and some of the feldspar (15%) with the groundmass has been largely replaced by microgranular quartz (50%) and some chlorite (8%) and epidote (2%) filling in between the flow structures. The rock is slightly oxidized, hematite and limonite replace mafic and opaque minerals (5%).

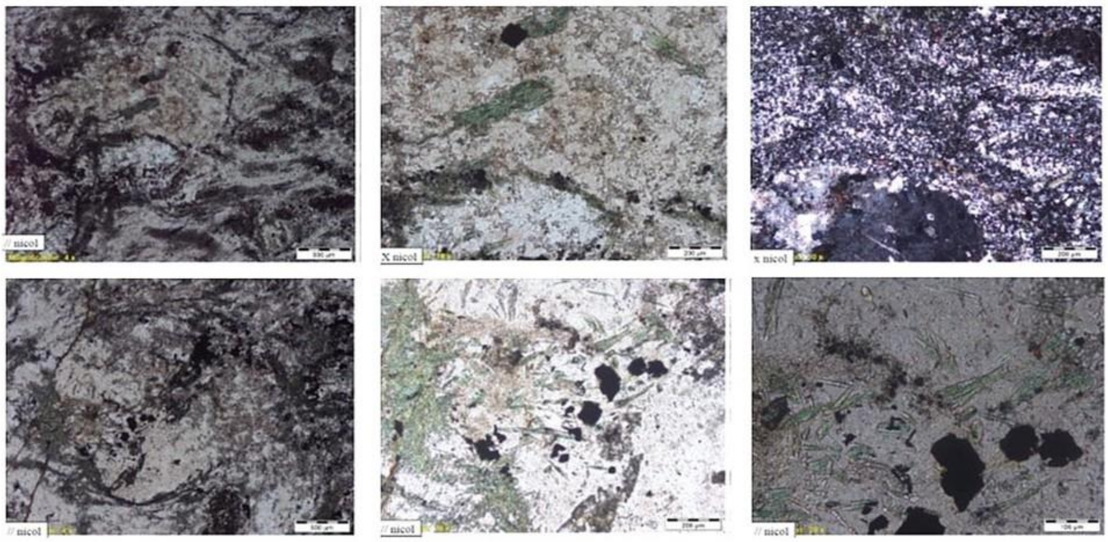


FIGURE 4 – Petrographic analysis showing mineralogical composition and texture of the ignimbritic tuff of the Haruyan Volcanics, Meratus Mountains.

South Sulawesi

Balangbaru andesitic lava of South Sulawesi is characterized by aphanitic texture, small amount of phenocrysts are amphibole (15%), plagioclase (5%) and minor quartz (1%) and pyroxene (2%), and magnetite accessory minerals (2%) and altered minerals in the form of carbonates (<5%) and clay minerals. The rock is slightly altered. The ground mass forms a flow structure – trachitic (70%).

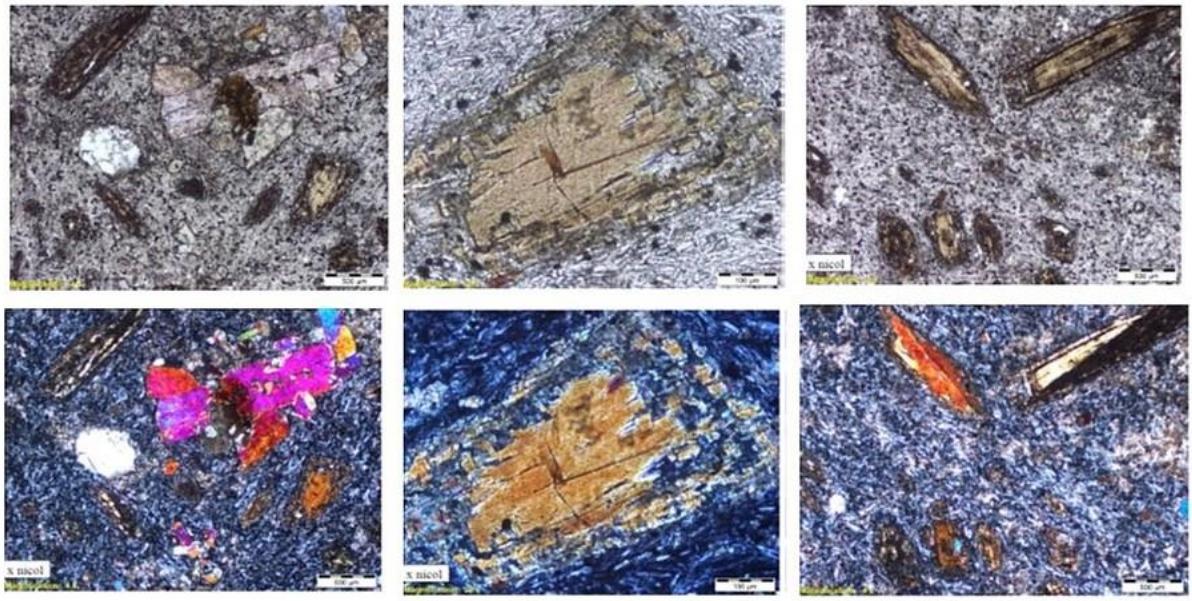


FIGURE 5 – Petrographic analysis showing mineralogical composition and texture of the Balangbaru andesitic lava of South Sulawesi.

Sumba

Lasipu porphyry andesite of Sumba is characterized by porphyritic textured igneous rock with aphanitic bedrock, phenocrysts are dominated by plagioclase (20%) and slightly amphibole (4%) and pyroxene (3%), wherein most of the phenocrysts are altered with moderate intensity to chlorite (6%) and epidote (3%). The bedrock is dominated by plagioclase microlites which are partially altered to clay minerals (60%) and a little carbonate (tr). Quartz (4%) is present in trace amounts as phenocrysts and ground mass.

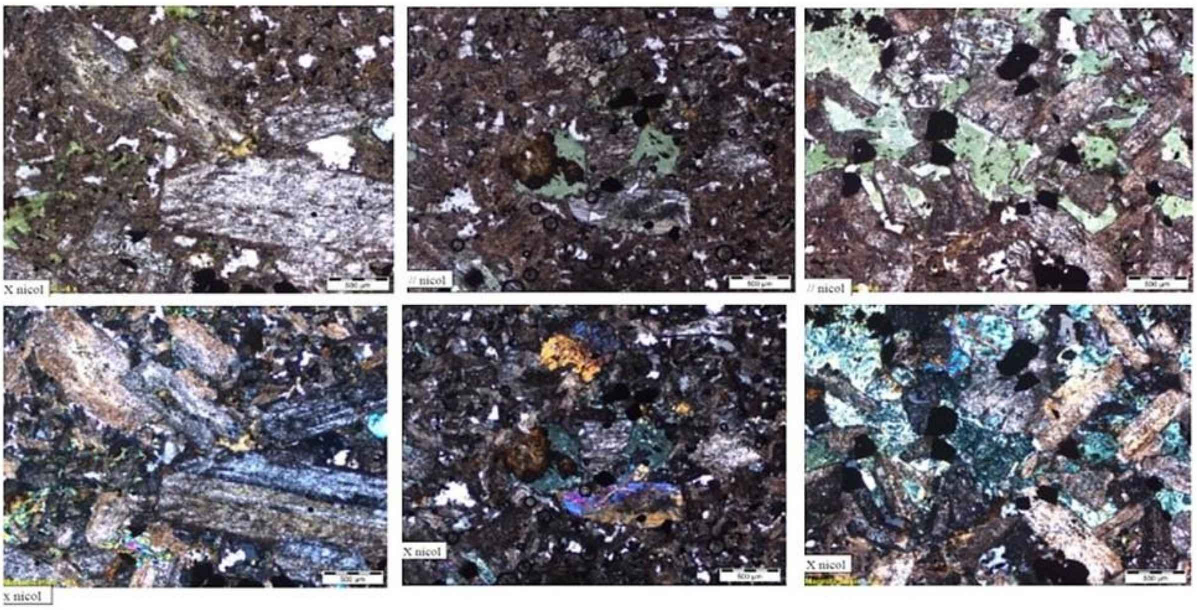


FIGURE 6 – Petrographic analysis showing mineralogical composition and texture of the Lasipu porphyry andesite of Sumba.

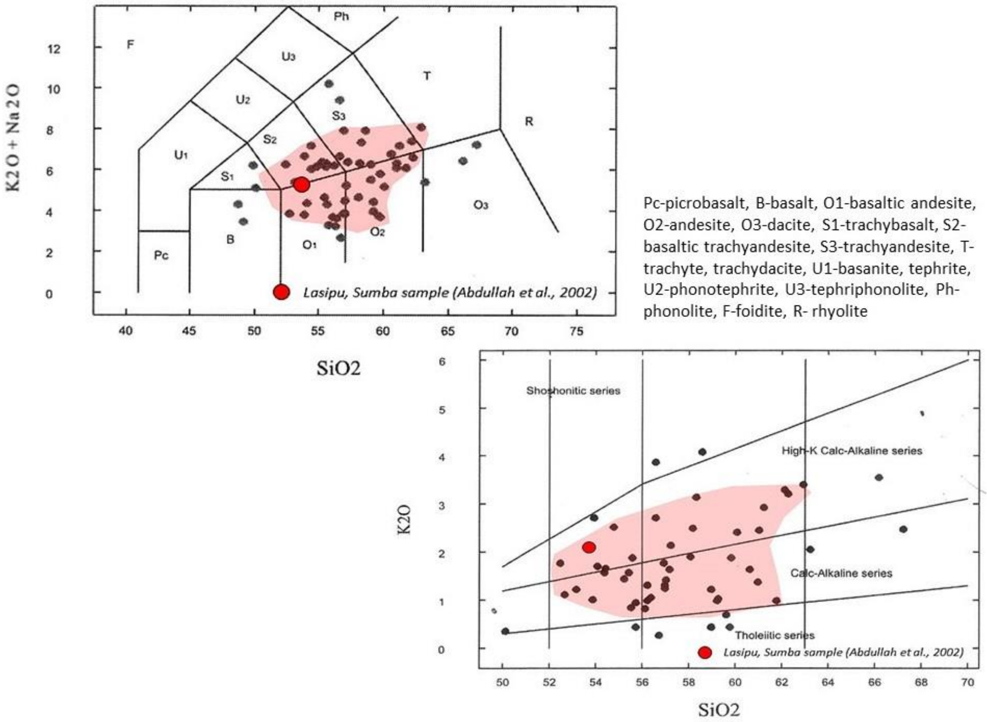


FIGURE 7 – Top: Nomenclature of the Haruyan and Sumba volcanics based on TAS (total alkali silica) diagram (Le Bas et al., 1986). Most of the rocks are basaltic andesite, andesite, basaltic trachyandesite, and trachyandesite. Bottom: SiO_2 vs. K_2O diagram (Peccerillo and Taylor, 1976) for the Haruyan Meratus and Sumba volcanics. Tectonic setting of the rocks is subduction-related calk-alkaline and high K calk-alkaline series.

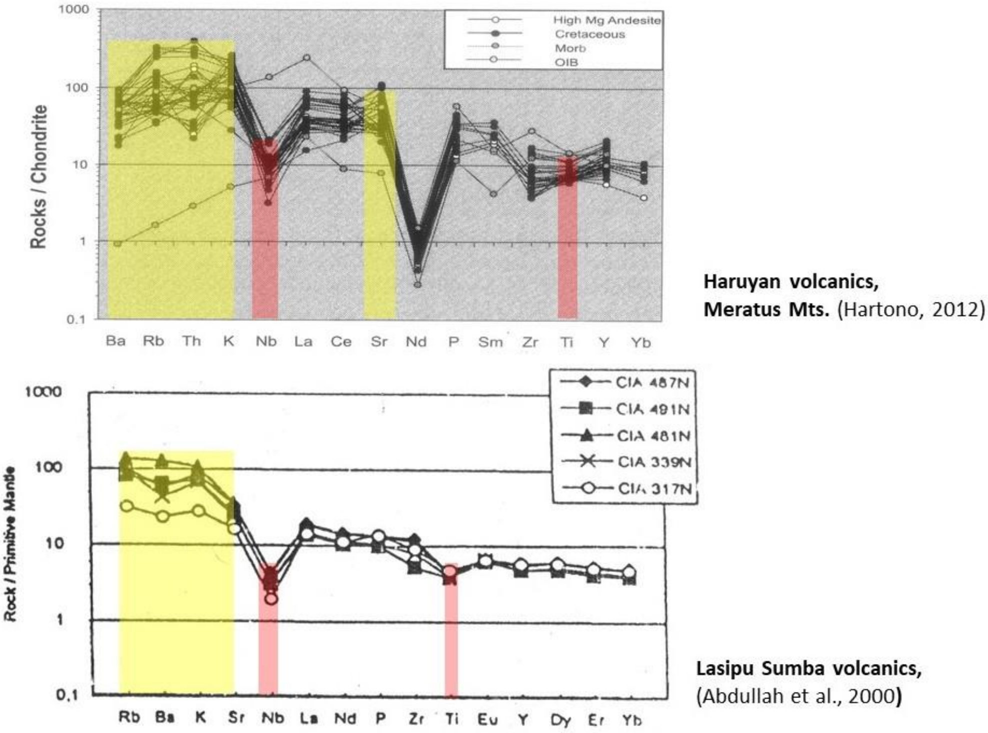


FIGURE 8 – Spider diagrams of trace elements for Haruyan volcanics, Meratus Mountains (top) and South Sumba volcanics (bottom), showing high in large ion lithophile elements (LILE: Ba, Rb, K, Sr) concentration and low content of high field strength element (HFSE: Nb, Ti). High LILE and low HFSE signify arc generation. The depletion in Nb content relative to K and La is characteristic of rocks generated from magma in an orogenic tectonic setting, negative Nb, Zr and Ti anomalies typical of arc volcanic.

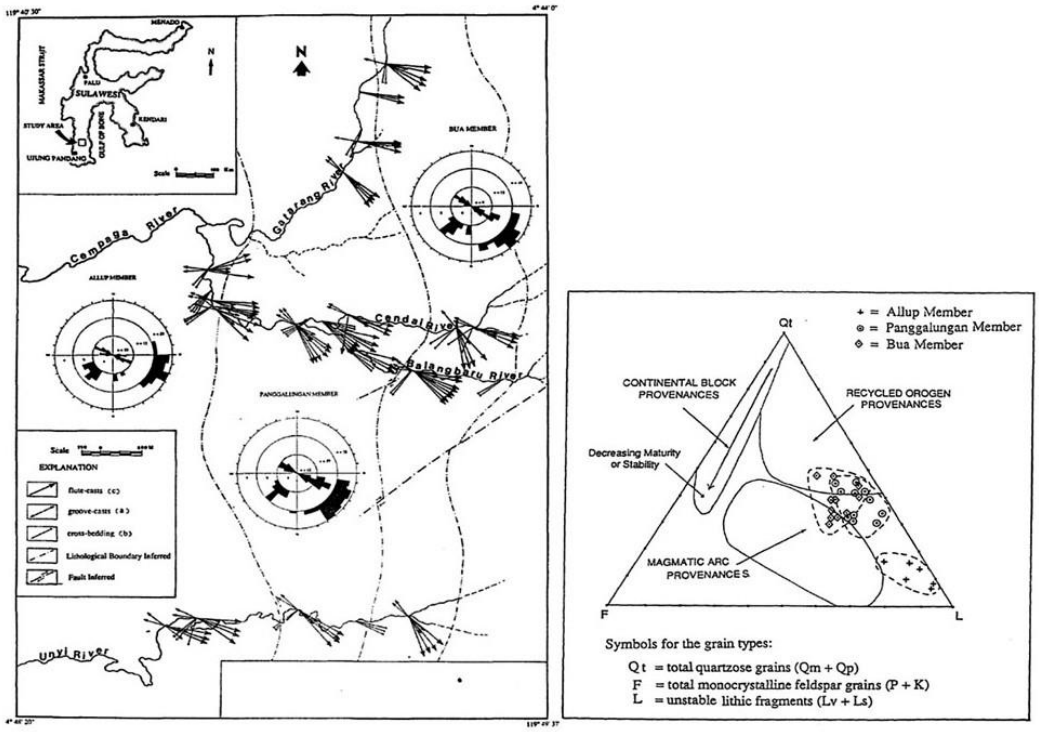


FIGURE 9 – Left: Paleocurrent measurements in the Balangbaru Region, South Sulawesi, showing dominant east and east-southeast directions (Hasan, 1991), indicating west and northwest origin, it could be the Late Cretaceous volcanics of the Meratus Mountains. Bottom: Triangular QFL plot showing mean framework modes for sandstones of the Balangbaru Formation (Hasan, 1991), showing dominant magmatic arc and recycled orogen provenances.

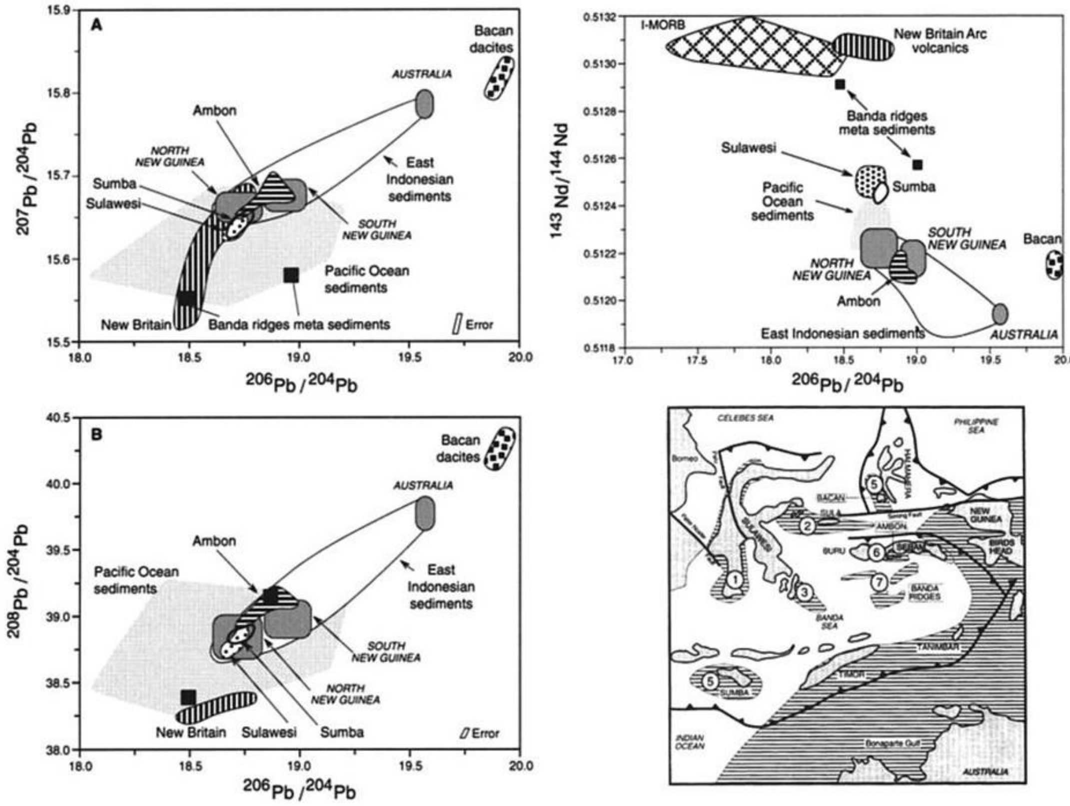


FIGURE 10 – Pb-Nd isotopic characteristics of sediments and volcanics (Vroon *et al*., 1996). Note the similar signatures/plot of Pb-Nd isotopic characteristics of Sumba (Lasipu Formation) and South Sulawesi (Balangbaru Formation), indicating a close relationship between the two areas.

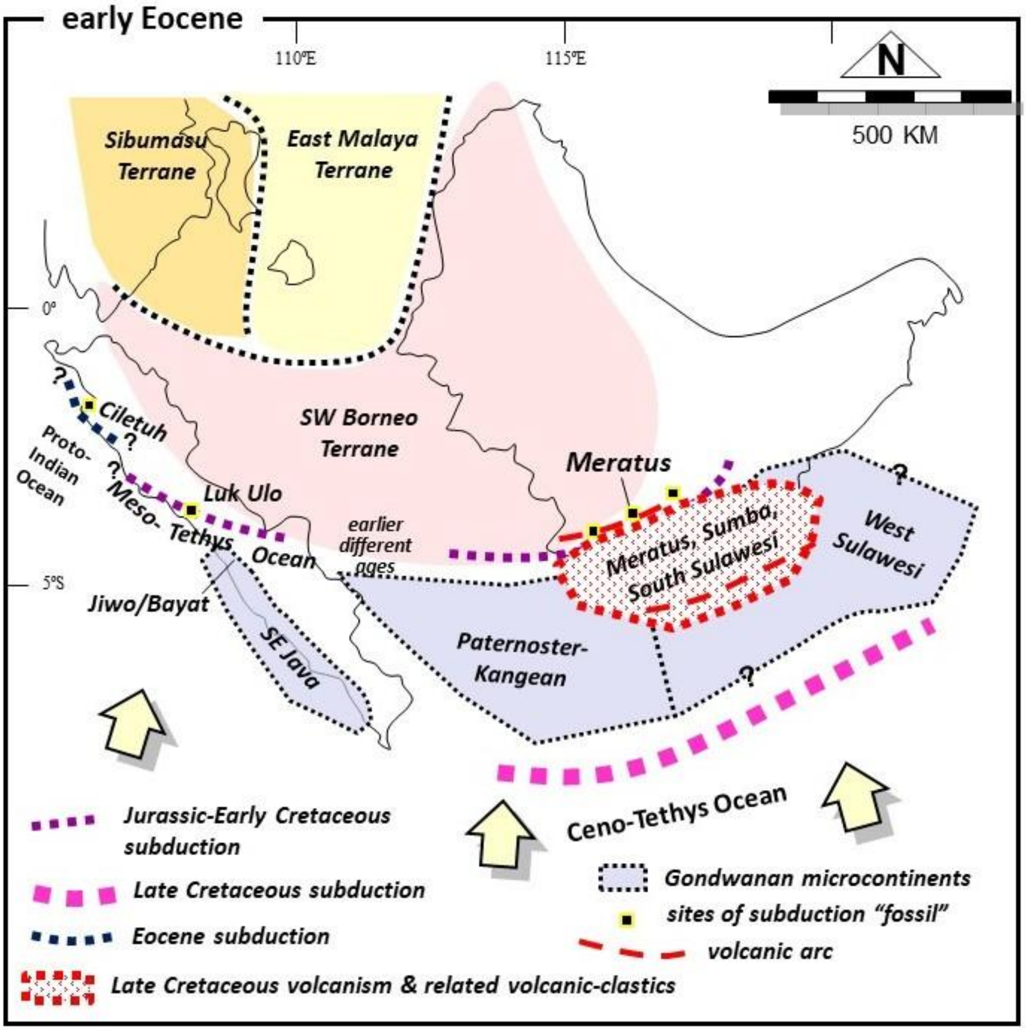


FIGURE 11 – Schematic paleotectonic map of Southeast Sundaland in early Eocene. Meratus, South Sulawesi, and Sumba were positioned at similar area where Late Cretaceous volcanism and related sedimentation (volcanic-clastic) took place. Presently, these volcanics at the three areas show similar geochemical signatures and ages, indicating that they were once united.

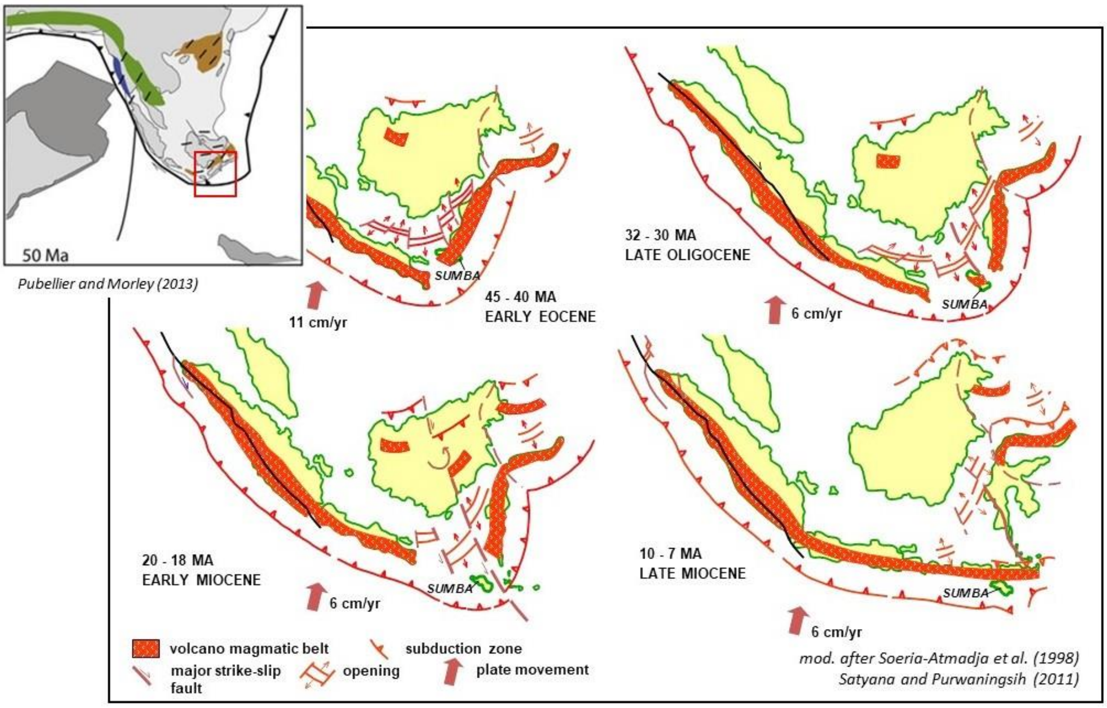


FIGURE 12 - Schematic reconstruction showing the detachment of Southeast Sundaland through rifting of the area opening the Makassar Straits, drifting South Sulawesi and Sumba from Southeast Kalimantan/ Meratus Mountains, and further drifting of Sumba from South Sulawesi through opening of the easternmost part of the East Java Sea/ westernmost part of the Flores Sea through rifting and major strike slip faulting. South Sulawesi has occupied its present position since the Oligo-Miocene time, and Sumba in the early-middle Miocene. Inset is a schematic paleotectonic map at 50 Ma showing initial detachment of Southeast Sundaland, brown area represents extension, green for compression.

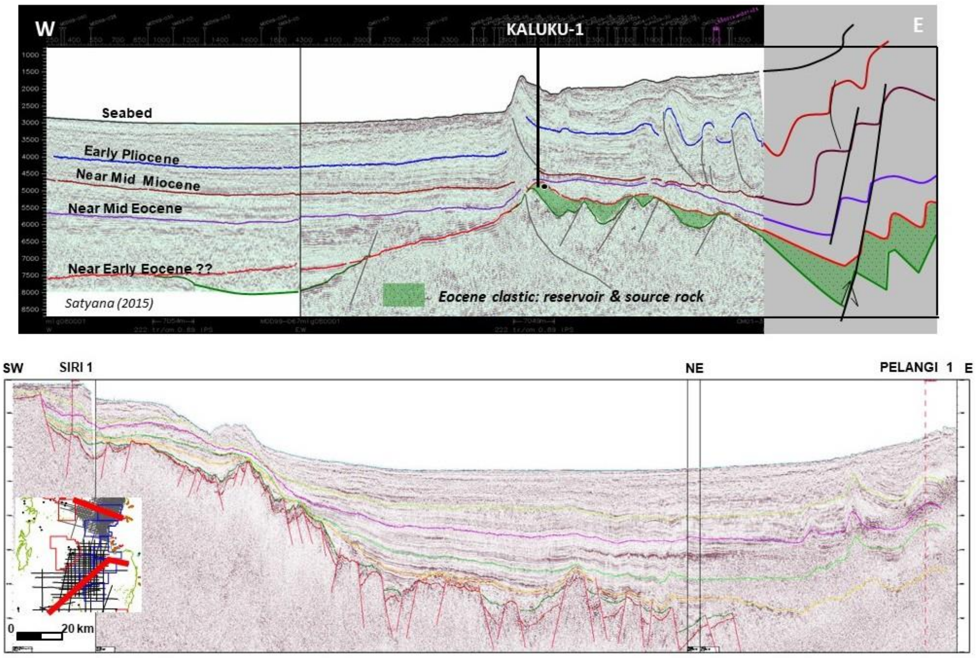


FIGURE 13 – Detachment of South Sulawesi and Sumba from Southeast Kalimantan opened the Makassar Straits through rifting, both at northern (top) and southern (bottom) parts. Rifted structures in forms of horsts and grabens were resulted from. These configurations provided some of the petroleum system elements developed. Kaluku-1 well (ConocoPhillips, 2011) discovered oils on Eocene sandstones draping at the horst block, sourced by Eocene shallow lacustrine shales deposited at the adjacent graben (Satyana, 2015).

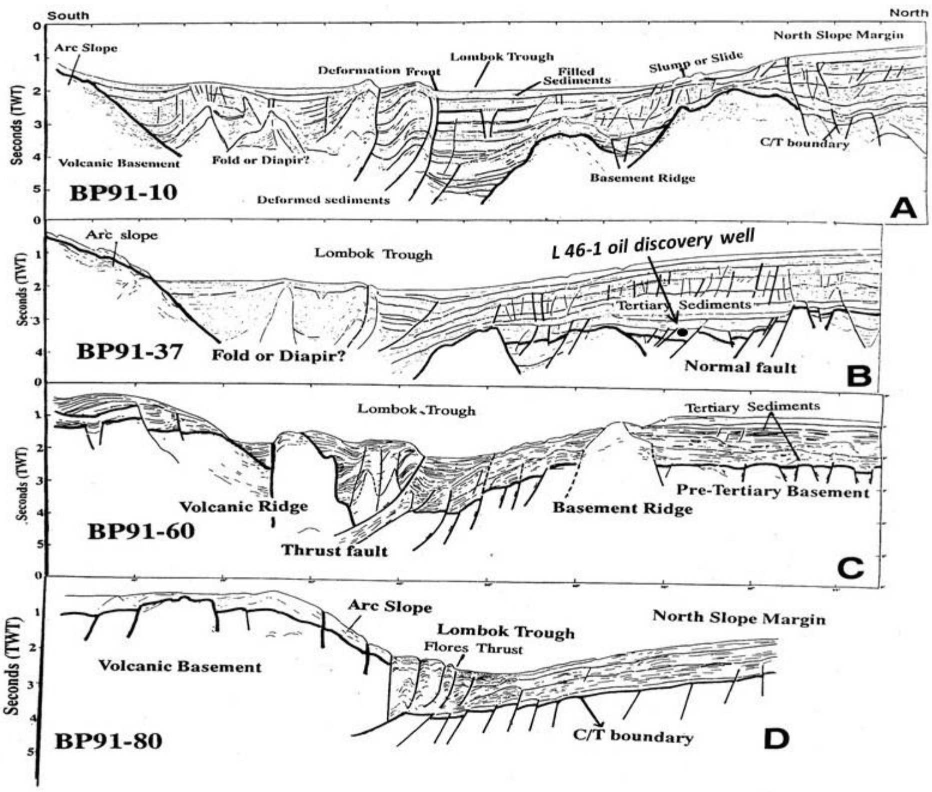


FIGURE 14 – Line drawing interpretation across the Lombok Trough, showing well-defined rifted structures (Prasetyo, 1992) which developed when South Sulawesi and Sumba detached from Southeast Kalimantan and Sumba further drifted from South Sulawesi. The grabens and horsts of the rifted structures provided some elements of petroleum system. L 46-1well (Amoco, 1985) tested 936 BOPD at Eocene sandstones draping at the horst block, sourced by Eocene shallow lacustrine shales deposited at the adjacent graben.

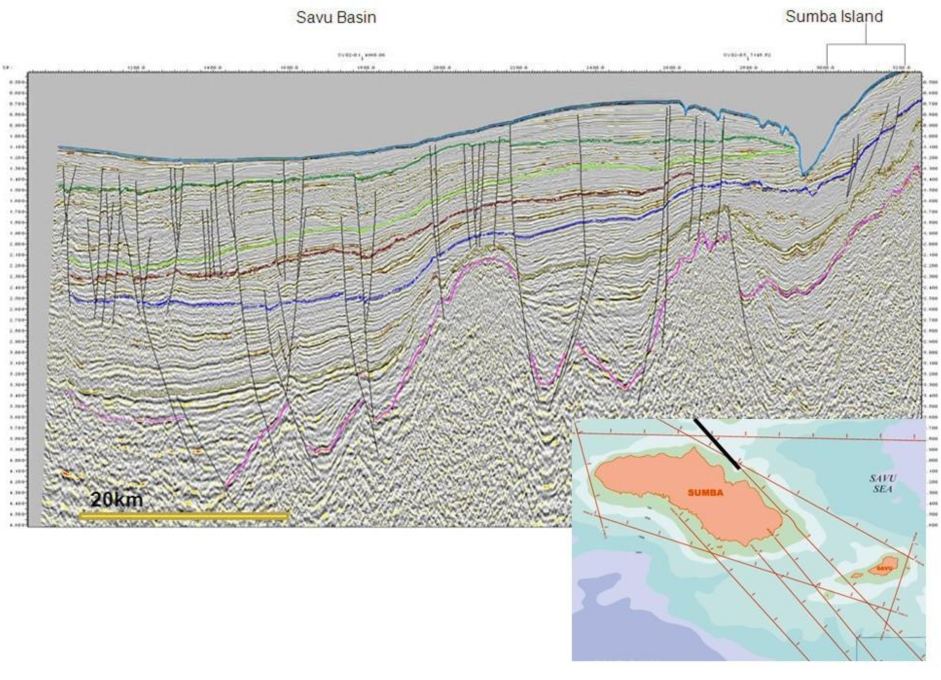


FIGURE 15 – Seismic section at offshore area north of Sumba Island (Toothill and Lamb, 2009), showing rifted structures with well-defined horst and grabens at which some elements of petroleum systems developed. There are some hydrocarbon seeps identified by satellite occur at offshore area north of Sumba, indicating generation of petroleum has taking place here.