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FINDING REMNANTS OF THE TETHYS OCEANS IN INDONESIA : SUTURES OF THE TERRANES AMALGAMATION AND PETROLEUM IMPLICATIONS

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ABSTRACT

Indonesia was built by a number of terranes rifting and drifting from Gondwana during Early Devonian to Paleogene. Separation of the terranes from Gondwana was accommodated by opening of a series of successively Tethyan oceans called the Paleo-Tethys, Meso-Tethys and Ceno-Tethys. The amalgamation of the terranes had closed these Tethys oceans to become sutures. Finding remnants of the Tethys oceans is therefore recognizing their sutures.

The study found five belts of sutures preserving the Paleo-Tethys, Meso-Tethys and Ceno-Tethys oceans in Indonesia. The sutures are made up of oceanic affinities. The Paleo-Tethys sutures are : (1) Karimun-Bangka suture in east offshore Sumatra marking the amalgamation between East Malaya and Sibumasu (Malacca part) terranes and (2) Natuna-Belitung suture marking the amalgamation between Southwest Borneo and East Malaya terranes. The Meso-Tethys sutures are : (1) Takengon-Bandarlampung suture in western Sumatra marking the amalgamation between Sibumasu (Mergui part) and Woyla terranes and (2) Meratus-Bawean suture marking the amalgamation between Southwest Borneo (Schwaner part) and Paternoster-Kangean terranes. The Ceno-Tethys suture is East Sulawesi Ophiolite Belt marking the suture of amalgamation between the Banggai microcontinent and western Sulawesi terrane.

Several sedimentary basins in Indonesia had developed in association with reactivation of these Tethys sutures. Ombilin pull-apart basin developed associated with reactivation of Meso-Tethys Takengon-Bandarlampung suture in West Sumatra area. Producing Barito and Banggai basins developed related to uplifts of the Meratus and East Sulawesi sutures, respectively. The suture has also been known affecting thermal history of sedimentary basins such as the Mutus Assemblage, a splay of Paleo-Tethys suture in Central Sumatra Basin.

Recognizing sutures of Tethyan oceans in Indonesia is important for understandings of tectonic concept of ‘from Gondwana dispersion to Asia accretion’ and its associated sedimentary basin formation.

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INTRODUCTION

The concept, definition and recognition of the Tethys Ocean both temporally and spatially have varied considerably. The Tethys has been variously regarded as a single elongate seaway laying across southern Eurasia (Figure 1), a single ocean or geosyncline from which the Alpine-Himalayan mountain belts had grown, or a wide single oceanic embayment in Pangaea. More recently, based on plate tectonic reconstructions, the Tethys has been regarded as a series of ocean basins which opened and closed in the eastern embayment of Pangaea during Paleozoic to Cenozoic times. Three successive Tethyan ocean basins are therefore established : the Paleo-Tethys, Meso-Tethys, and Ceno-Tethys (Figure 1).

The opening and closing of Tethys oceans basins were due to rifting and collision of Gondwanan terranes or microplates. For the purposes of this paper, microplates are defined as discrete fragments of the major plates; that is, regionally homogeneous terrains separated by megafaults (Nelson, 1983) which extend to the base of the lithosphere. They had: (1) separate histories until brought together by suturing, (2) similar histories until separated by rifting or transforms, (3) briefly dissimilar histories whilst separated by short-lived rifts. The boundary faults, in the first and third type of setting are frequently occupied by ophiolites. However, their presence is not mandatory as crustal extension during short-lived rifting episodes may have been insufficient for ophiolite emplacement. Also, ophiolites may have been destroyed either during suturing or in subsequent strike-slip episodes (Pulunggono and Cameron, 1984).

Indonesia, which globally has been occupying the site where the eastern embayment of Pangaea

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existed, and has been constructed by collision of terranes (continental lithospheric blocks) rifting and drifting away from Gondwana, is an important place to study remnants of the Tethyan oceans. Presently, the remnants of the Tethys oceans are preserved as sutures of the terrane collisions. Before the collision, these terranes were separated by a series of Tethyan oceans.

The paper will evaluate several sutures in Indonesia and based on published tectonic reconstructions, the sutures will be examined to know which Tethyan oceans they represent. Recognizing the sutures as the remnants of the Tethyan ocean basins in Indonesia and largely East - and Southeast Asia will assist tectonic reconstruction from Gondwana dispersion to Asian accretion.

Several sedimentary basins developed in areas of terranes collision. How geologic setting of terrane collision or closing of Tethyan oceans affect the formation of sedimentary basins and their hydrocarbon potential will be addressed in the paper.

METHODS

Terrane analyses (Howell et al., 1985) and tectonic reconstruction formed the backbone of this study. In the light of terrane concepts, plate motion can raft fragments of crust tremendous distances. Eventually, any fragment not consumed by subduction is added (accreted) to a larger continental mass. Some of the fragments are island arcs formed by subduction of oceanic crust beneath oceanic crust. Other fragments form when they are sliced off the margin of a large continent by a transform fault. Other combination of volcanism, rifting, faulting and subduction can also form fragments of crust that are too buoyant to be subducted. Each fragment, called a terrane, is a geologic entity characterized by a distinctive stratigraphic sequence ad structural history.

Western Indonesia was built by many terranes of Gondwana rafted by the opening of Tethyan seas and collided forming large Sundaland. Recognizing terranes of Sundaland is recognizing their sutures because sutures define terranes. The paper identified ophiolite belts or another oceanic affinities at the sites of terranes collision (sutures). Published tectonic reconstructions for Indonesia from Metcalfe (1996, 1998), Hall (1996, 2002), Hall et al. (2009), Barber (2000), Barber et al. (2005) were reinterpreted to find terranes and their adjacent remnants of Tethyan oceans (sutures). Sedimentary basins and their hydrocarbon potential developed in areas of terranes collision were evaluated using published data and studies.

RESULTS

Development of Concepts of Tethys Oceans

Figure 1 illustrates the development of several concepts on Tethys Ocean/s.

The concept of 'Tethys' was started paleobiogeographically, by Neumayr in 1885 who conceived the existence of a 'seaway' (Centrales Mittelmeer) laying across southern Eurasia. This 'seaway' was subsequently given a tectonic connotation by Suess (1893) and named the Tethys (after the sister and wife of Okeanos –the god of the ocean in ancient Greek mythology). This early concept of Tethys was of a single ocean or 'geosyncline' from which the Alpine-Himalayan mountain belts had grown and was originally defined as solely Mesozoic (Triassic-Jurassic) concept. Suess (1901) however, later considered the Tethys to span the Permian and Mesozoic and possibly extend from the Upper Carboniferous to Recent in eastern Asia.

During the first half of the twentieth century there developed two different concepts of Tethys based on the fixist and mobilist tectonic philosophies. Most mobilists of the time regarded Tethys as a 'geosyncline' that lay between the supercontinents of Laurasia and Gondwana that had existed from at least the late Paleozoic and obliterated in the Cenozoic by collision of Gondwana-derived fragments with Laurasia. The interpreted shape of Tethys evolved from a single elongate trough to an easterly widening triangular shaped ocean. Alternatively, the Tethys was viewed by the fixists as a composite geonsyncline that had existed from the late Proterozoic and evolved through episodic orogenic cycles of Assyntian (end of Precambrian), Caledonian (Silurian-Devonian), Hercynian (Carboniferous-Permian), and Alpine (Tertiary). This temporarily and spatially Tethys was called by Stille (1958) as Paleotethys (for Caledonian), Mesotethys (Variscan/ Carboniferous-Permian) and Neotethys (Alpine).

With the advent of plate tectonics, the Tethys was depicted as a single wide triangular ocean extending into the supercontinent Pangaea from the east (Bullard et al., 1965). Recognition of sutures of different ages in southern Eurasia which clearly represents parallel but temporarily different ocean basins led Sengör (1979) to propose that the Permo-Triassic Paleo-Tethys closed in the Mid-Mesozoic by collision between Laurasia and Cimmerian continent (an elongated continental fragment that had rifted away from Gondwana during the Triassic). The revived concept of a Paleo-Tethys and Neo-Tethys were viewed as successive ocean basins separated by the northward migrating Cimmerian continent or continental blocks. Sengör (1984) defined the Paleo-Tethys as the original triangular oceanic embayment of the Permo-Triassic Pangaea that came into existence as a byproduct of the Pangaean assembly. Neo-Tethys was defined by Sengör (1984) as the ocean, or the complex of oceans, that opened to the south of Paleo-Tethys, as a consequence of the counterclockwise rotation of the Cimmerian continent between it and Gondwana.

Further work on the timings of the rifting and separation, drifting, and collisions of continental blocks, and on the ages and age-durations of suture zones that represent former oceans between continental terranes, led to a tectonically delineated three Tethys ocean basin concept (designated Tethys I, Tethys II, and Tethys III by Audley-Charles, 1988; and as the Paleo-Tethys, Meso-Tethys, and Ceno-Tethys by Metcalfe, 1996, 1998).

Sutures as Sites of Tethys Closure

Suture was originally defined as a zone along which oceanic lithosphere has been totally subducted (Gansser, 1964). Suture as site of closure of Tethys ocean due to collision of continents -once separated by the Tethys- was demonstrated by Sengör (1979) who considered that the Permo-Triassic Paleo-Tethys closed in the Mid-Mesozoic by collision/ amalgamation between Laurasia and Cimmerian continent leaving the suture belt now located at the southern rim of Eurasia.

Suture zones that represent former oceans between continental terranes therefore, can be used as keys to tectonically delineate and reconstruct Tethys ocean basins (Metcalfe, 1996). The ages of the successive Tethys ocean basins can be constrained by a variety of data obtained from suture zones that include the remnants of the ocean basins (as part of accretionary complexes, ophiolites, island arcs, etc.) and also from the continental lithospheric blocks that were separated by these ocean basins (Metcalfe, 1998).

Sutures and suture zones, however, are rarely simple, well-defined, easily recognizable lineaments. Reconstructing the intervening Tethyan oceans is difficult since they have disappeared by subduction. Continental collision/ amalgamation, the terminal form of suturing, is normally preceded by a long history of suturing on various scales and results in the generation of great array of intercontinental high-strain zones that may resemble sutures sensu stricto, but many of which do not mark the sites of the obliteration of oceanic lithosphere and some of which may not penetrate the lithosphere. Continental collision may be regarded as only a terminal, though spectacular, form of suturing that is preceded by an array of sutures dating from the initiation of subduction in the oceanic tract, whose demise occurs during the terminal suturing (Dewey, 1987).

Gondwana Dispersion and Asia accretion : Opening and Closing of Tethys Oceans

It had become clear by the early 1990s that the evolution of Asia was one of dispersal of continental slivers/ fragments from Gondwana, their northward drifting, and collision/ amalgamation to form present-day Asia, including Indonesia. This process was called by Metcalfe (1998) as “Gondwana dispersion and Asia accretion”. This process of Gondwana dispersion and Asia accretion involved the rifting and separation of three continental fragments from the margin of Gondwana, opening the Tethys ocean between the continental fragments and Gondwana, northward translation of the continental fragments, and their amalgamation through collision to form Asia.

The northward drift of these continental fragments was effected by the opening and closure of successive Tethys ocean basins named by Metcalfe (1996) as the Paleo-Tethys, Meso-Tethys, and Ceno-Tethys that essentially represent the temporal and spatial concept of the traditional Tethys. These three ocean basins are now represented in East and Southeast Asia by various suture zones that bound allocthonous continental lithosphere fragments of the region.

DISCUSSIONS

Regional Tectonics

The evolution of East and Southeast Asian terranes, in the framework of the evolution of Gondwana, Laurasia, Pangaea and Tethys, has important scientific implications for both regional and global earth sciences. Indonesia, which has been globally occupying the site where the eastern embayment of

Pangaea existed, and has been constructed by terranes which rifted from the northern Gondwana, is important place on Earth to find remnants of a series of the Tethyan oceans presently preserved as sutures of collisions. Sundaland in Western Indonesia is a heterogeneous region assembled by closure of Tethyan oceans and addition of Gondwana fragments.

The continental terranes are bounded by sutures (representing former oceans), by narrow mobile belts or major fault zones. Comparative studies of the stratigraphy, paleontology and paleomagnetism of the various pre-Cretaceous continental terranes of East and Southeast Asia suggest that they were all derived directly or indirectly from Gondwana (Metcalfe, 1996). The evolution of Gondwana and Tethys during the Paleozoic and Mesozoic involved the rifting of continental slivers/fragments (terranes) from northern Gondwana, and the northward drift and amalgamation/collision/accretion of these terranes to form proto East and Southeast Asia. Three continental slivers were rifted from the northern margin of Gondwana in the Early-Late Devonian (North China, South China, Indochina/East Malaya/Qamdo-Simao, Qaidam and Tarim terranes); Early-Middle Permian (the Cimmerian continent including the Sibumasu/Siam-Burma-Malaya-Sumatra and Qiangtang terranes); and Late Triassic-Late Jurassic (Lhasa, West Burma, Woyla terranes). The northward drift of these terranes was accompanied by the opening and closing of three successive oceans, the Paleo-Tethys, Meso-Tethys and Ceno-Tethys.

Assembly of Asian terranes began with amalgamation of South China and Indochina/East Malaya along the Song Ma/Song Da zone during the Late Devonian/Early Carboniferous to form ‘Cathaysialand’. Paleomagnetic, climatic and biogeographic data indicate that Cathaysialand and North China were located within the Paleo-Tethys at low northern/equatorial latitudes during the Late Carboniferous and Permian. The Tarim, Kunlun, Qaidam, and Ala Shan terranes accreted to Kazakhstan/Siberia in the Permian.

A major episode of rifting occurred on the northern margin of Gondwana in the Late Carboniferous-Early Permian and the Cimmerian continent separated in the early Permian resulting in the opening of the Meso-Tethys. Suturing of Sibumasu and Qiangtang to Cathaysialand occurred in the Late Permian-Triassic, closing a major branch of the Paleo-Tethys. South and North China amalgamated and then accreted to Laurasia by Late Triassic-Early Jurassic times.

The Lhasa, West Burma and Woyla (western Sumatra) terranes rifted from Northwest Australian Gondwana in the Late Triassic to Late Jurassic and drifted northwards during the Jurassic and Early Cretaceous as the Ceno-Tethys opened and the Meso-Tethys was destroyed by subduction beneath Eurasia. Accretion of these terranes to proto-Southeast Asia occurred in the Cretaceous. The SW Borneo (Schwaner core in southern Kalimantan and the Java Sea) and Semitau (western Kalimantan) were derived from the South China/Indochina margin by the opening of a marginal basin in the Cretaceous which was subsequently destroyed by southward subduction during the rifting of the Reed Bank-Dangerous Grounds terrane from South China when the South China opened in the Paleogene.

Remnant of Paleo-Tethys Ocean: Karimun-Bangka Suture

The Paleo-Tethys ocean basin was formed by sea-floor spreading between the separating elongated continental slivers (comprising Tarim, Qaidam, Qamdo-Simao, North China, South China, East Malaya) and Gondwana (Figure 2). This ocean basin, as it widened, and as Gondwana and Laurasia collided in the west to become Pangaea, broadly corresponds to the original concept of Tethys and of the Paleo-Tethys in particular (Sengör, 1984). The ocean basins that existed to the north of Gondwanaland prior to the opening of Paleo-Tethys can not be assigned to a Tethys concept and the term ‘Proto-Tethys’ is not appropriate. These ocean basins must be referred to by some other non-Tethyan terminology such as Panthalassa or Paleo-Pacific (Metcalfe, 1999). The opening of the Paleo-Tethys ocean was Early-Late Devonian and the closure of the main Paleo-Tethys ocean due to amalgamation of younger Gondwanan terranes occurred in the Middle-Upper Triassic. Thus, the Paleo-Tethys ocean existed from Early Devonian to Late Triassic.

Pulunggono and Cameron (1984) was the first who described in detail the microplates configuration of Sumatra (Figure 3). They concluded that the pre-Tertiary framework of Sumatra consists of a mosaic of continental and oceanic microplates accreted in the late Triassic when the Mergui, Malacca and East Malaya microplates were joined together to form Sundaland. Further accretion involving the west coast Woyla terrains followed in the late Mesozoic. In Metcalfe (1996)’s map of Southeast Asian terranes, Mergui and Malacca microplates of Pulunggono and Cameron (1984) are included into Sibumasu which is younger than East Malaya terrane.

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The microplates were apart to each other separated by branches of Tethys ocean. Assembly of these microplates would need the closures of the Tethys branch oceans. Primary assembly was essentially completed by the end of the Triassic. Two of the main sutures across Sumatra and separate the Mergui, Malacca and East Malaya Microplates. Much of the evidence for the suture separating the Malacca and East Malaya microplates exists in West Malaysia. Here the tin-bearing Main Range Granites are considered to have formed as crustal melts as the host Mergui Mircoplate was overridden along the Raub-Bentong Line by the East Malaya Microplate. The present pattern and trend of microplate boundaries in Sumatra differs considerably from that existed at the end of the Mesozoic. Collision of India into Eurasia during the early Paleogene affected much the suture belt by which it was rotated clockwisely (Satyana, 2006b, Satyana et al., 2007).

The remnants of the main Paleo-Tethys Ocean are principally represented in East and Southeast Asia by the Lancangjiang, Changning-Menglian, Jinshajiang, Nan-Uttaradit, and Raub-Bentong suture zones. These suture zones include accretionary complexes in which fault bounded packages of ocean floor sequences including pillow basalts, ribbon-bedded chert, pelagic limestones, shallow-marine (sea mount) limestones, siliceous mudstones and turbidite flysch sediments are contained. The Raub-Bentong suture forms the remnant of Paleo-Tethys destroyed by the collision between the Sibumasu (Siam-Burma-Malaya-Sumatra) and Indochina/ East Malaya terranes.

In Sumatra and its eastern offshore area, the continuation of Raub-Bentong suture zone has been defined. Its extension into Sumatra from Peninsular Malaysia was suggested by Hamilton (1979), Pulunggono and Cameron (1984), Tjia (1989), and Huthchison (1993). The suture is exposed as a circa 13 km wide zone in Peninsular Malaysia and comprises mélange, oceanic sediments (including ribbon-bedded cherts, limestones, volcanics and volcaniclastic rocks. The precise age of suturing is still poorly constrained but a latest Permian-earliest Triassic is favored (Metcalfe, 1996).

The southern extension of the Raub-Bentong suture in Sumatra area has various interpretations. It continues its north-south trending across southern Sumatra Island and called as Bentong-Bengkalis suture (Tjia, 1989), alternatively it swings to southwest across Central Sumatra (Hamilton, 1979), or it swings to southeast in offshore east Sumatra between Bangka and Belitung (Pulunggono and Cameron, 1984; Hutchison, 1989). The suture likely separates Bangka and Belitung, because relative to Peninsular Malaysia, Bangka has similarities with the Main Range S-type granite and Belitung has similarities with the East Coast volcano-plutonic arc. Which one is right is difficult to examine because the Paleo-Tethys suture in Sumatra geologically is not as clear as that in Peninsular Malaysia. The widespread Permian and Triassic granites of the Tin Belt are the products of associated subduction and post-collisional magmatism terminating the Paleo-Tethys ocean (Hutchison, 1989).

Pulunggono and Cameron (1984) believed that the continuation of Raub-Bentong suture passes between Kundur and Karimun Islands, Riau offshore area, through the centre of Singkep Island and thence across the northeast corner of Bangka before it is lost in the Java Sea. True ophiolites have not been recorded, but the suggested trace is accompanied by the same change of geology as is seen in West Malaysia. The Kundur-Karimun boundary is marked by the Merak Complex which consists of metagabbros, diallagites (a kind of pyroxenite) and microfolded hornblende schists. A belt of identical hornblende schists crosses central Singkep lsland. In northeast Bangka discontinuous serpentinites are present. The line of suture in this study is called as the “Karimun-Bangka suture” (Figure 3). The end of the suture may also relate to a depression called the Bangka Depression (Ben-Avraham and Emery, 1973).

Remnant of Paleo-Tethys Ocean: Natuna-Belitung Suture

Recent paper by Hall et al. (2009) proposed the possibility of the presence of suture of Paleo-Tethys from Natuna to Belitung area (Figure 4). The closure of the Paleo-Tethys ocean in this area was resulted from the docking of SW Borneo to East Malaya terranes. Metcalfe (1988, 1990, 1996) interpreted that SW Borneo drifted from Cathaysialand due to opening of the South China Sea. Hall et al. (2009) argued that SW Borneo was a terrane drifting form northern Gondwanaland and collided East Malaya.

The evidence for the origin of SW Borneo is very limited. Metcalfe (1988, 1990, 1996) based his suggestions of an Asian origin on palaeontological evidence from rocks found in Sarawak and NW Kalimantan. There are rocks with Cathaysian faunas and floras, but all are found within the Kuching zone (Hutchison, 2005) or NW Kalimantan Domain (Williams et al., 1988) in, or closely associated

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with, melanges and deformed ophiolites. Hall et al. (2009) suggested that these rocks are not part of the SW Borneo terrane but are fragments of ophiolitic and Asian continental material accreted to it during the Cretaceous. The SW Borneo terrane has its northern limit at about the position of the Boyan zone and further south there is very little to indicate its origin. Williams et al. (1988) implied that SW Borneo was part of Sundaland in the Cretaceous and intruded by subduction-related granites formed in a continuation of an east Asian magmatic arc. The Schwaner Mountains are dominated by Cretaceous igneous rocks which intrude a poorly dated metamorphic basement suggested to be Permo-Triassic (e.g. Williams et al., 1988; Hutchison, 2005). There are Devonian limestones from the Telen River in the Kutai basin (Rutten, 1940) with a fauna resembling that of Devonian limestones from the Canning Basin (Hall et al., 2009). There are also alluvial diamonds and those from SE Kalimantan resemble diamonds from NW Australia (Taylor et al., 1990).

Based on above data, Hall et al. (2009) interpreted SW Borneo to be a continental block rifted from the West Australian margin, and added to Sundaland in the Early Cretaceous (Figure 4). The suture is suggested to run south from the Natuna area along the structural lineament named the Billiton Depression (Ben-Avraham 1973; Ben-Avraham & Emery 1973) and originally interpreted by Ben-Avraham & Uyeda (1973) as a transform fault associated with Cretaceous opening of the South China Sea. In this study, the suture is called as the “Natuna-Belitung suture” (Figure 5).

If Hall et al. (2009)’s consideration is right then the Tethys Ocean destroyed by the collision of SW Borneo to East Malaya is the Paleo-Tethys Ocean. In this case, SW Borneo is an eastern counterpart to the Sibumasu terrane which closed the Paleo-Tethys Ocean to the west of East Malaya resulting in Raub-Bentong suture. Hall et al. (2009) suggested that the age of collision was 110 Ma (mid-Cretaceous) based on radiolaria in rocks associated with basic igneous rocks that represent accreted oceanic crust and sedimentary cover, the age of high pressure–low temperature (HP–LT) metamorphic rocks in accretionary complexes, ages of subduction-related magmatism, ages of post-collisional rocks, and the widespread paucity of magmatism in Sumatra, Java and Borneo.

Remnant of Meso-Tethys Ocean: Takengon-Bandarlampung

The Meso-Tethys is interpreted to have opened in the Middle Permian as the Cimmerian continental sliver (now it covers Sibumasu : Siam/Thailand-Burma/Myanmar-Malaya-Sumatra and Qiangtang/ southern Tibet area) separated from the northern Gondwanaland (Metcalfe, 1999) (Figure 6). Rapid spreading of the Meso-Tethys and northward drift of the Cimmerian continent is indicated by paleomagnetic data showing rapid northward drift of the Sibumasu terrane during the Permo-Triassic. The age of closure of the Meso-Tethys to become Meso-Tethys suture is deduced from the Banggong, Shan Boundary, and Woyla (western Sumatra) sutures of East and Southeast Asia. The belt of the sutures has been rotated clockwisely following the collision of India into Asia (Satyana 2006b, Satyana et al., 2007). The Banggong suture in Tibet is blanketed by Cretaceous and Paleogene rocks and structural data indicates continental collision and hence closure of the Meso-Tethys around the Jurassic-Cretaceous boundary. Cretaceous thrusts in the back-arc belt and a Late Cretaceous age for collisional tin bearing granites along the San Boundary suture indicate Early Cretaceous suturing and ocean closure age. A mid-late Cretaceous age is indicated for the Woyla suture in western Sumatra (Pulunggono and Cameron, 1984; Barber, 2000; Barber and Crow, 2005). These together suggest that the age of the Meso-Tethys ranged from late Early Permian to Late Cretaceous (Metcalfe, 1999).

Sibumasu terrane (including Mergui and Malacca microplates of Pulunggono and Cameron, 1984) was the main Mesozoic terrane in Sumatra which amalgamated Paleozoic terranes of Indochina and Malaya closing the Paleo-Tethys ocean. Behind the Sibumasu terrane was the Meso-Tethys ocean formed by the rifting of the Sibumasu from the northern part of Gondwana. The Meso-Tethys ocean was closed to become suture when Woyla terranes now become the basement of western Sumatra accreted the Sibumasu in mid-Late Cretaceous.

The continental Mergui Microplate occupies the central core of Sumatra from Aceh to southern Jambi and is characterised by a complex history which included older and younger Paleozoic granite plutonism, late Permian arc volcanism and the widespread deposition of Permo-Carboniferous "pebbly mudstones". The Malacca microplate is poorly known, but appears to be dominated by low grade metasediments cut in the east by granites that represent the continuation of the Triassic Main Range Granites of the Malay Paninsula. A northwest-southeast to north-south trending Triassic suture complex, traceable at subcrop from Riau to the Palembang district and named the Mutus

Assemblage (Pulunggono and Cameron, 1984), separates the Mergui and Malacca microplates.

The Mutus Assemblage is not a remnant of main Meso-Tethys ocean. Pulunggono and Cameron (1984) detailed the nature of the Mutus Assemblage. The origin of the Mutus Assemblage is problematic, mainly because there is insufficient information on the petrography and chemistry of the volcanics. Mutus was identified only from the occurrence of mauve shales, cherts, volcanic rocks, gabbros and serpentinites in oil company boreholes (Eubank and Makki, 1981). The magnitude of the break across the Kerumutan Line (northern part of Mutus) at first suggests the Mergui and Malacca Microplates had separated histories prior to suturing. However, this would require the abundance of tuffs to be explained by the development of a westward inclined Benioff zone during suturing. Since an eastward inclined Benioff zone existed in western Sumatra at this time, this model seems improbable. A preferable alternative is that the Mutus Assemblage is the product of back-arc rifting and volcanism. The disparity in geology across the Kerumutan Line in this case would require strike-slip faulting, either during closure or in the younger Mesozoic. The Mutus Assemblage boundaries in the northern portion of the South Sumatra are schematic. The limited evidence points to a series of rifts and grabens in this region. The width of the Mutus Assemblage appears to be severally reduced to the northeast of the Tigapuluh Mountain boundary faults. It is not known whether this is a primary feature or the result of later strike-slip disruption. The Mutus Assemblage was regarded as rupture lines formed during the accretion of the Woyla Terrains to Sundaland in Late Cretaceous.

The closure of the main Meso-Tethys ocean in present Sumatra occurred when Woyla terranes (Sikuleh, Natal, Woyla microplates) amalgamated the Sibumasu terrane, destroying the existence of the Meso-Tethys ocean presently become the Meso-Tethys suture (Figure 7).

The concept of the Woyla terranes, was developed from the interpretation of the mapping results of northern Sumatra conducted jointly by Indonesian and British geological surveys from 1975 to 1980 (Cameron, 1980). Geological mapping of southern Sumatra by joint Indonesian-American geological surveys from 1970s-1995 completed the geological mapping for whole Sumatra. Rock units correlated with the Woyla Group are described from Natal in North Sumatra, at Indarung near Padang in West Sumatra, in the Gumai and Garba Mountains of South Sumatra, and further south near Bandarlampung along the Sunda Strait (Barber, 2000).

Cameron (1980) and Pulunggono and Cameron (1984) proposed that the Sikuleh and Natal of Woyla are continental fragments could represent blocks rifted from Sundaland by marginal basin opening or accreted to it. Metcalfe (1996) suggested these were continental fragments with a Northwest Australian origin. However, Wajzer et al. (1991), Barber (2000) and Barber and Crow (2005) argued that there is no convincing evidence for any microcontinental blocks accreted to the margin of Sundaland in the Cretaceous. They interpreted the Sikuleh and Natal fragments as part of the Woyla Terrane or Nappe which is an intraoceanic arc that was thrust onto the Sumatran Sundaland margin in the mid Cretaceous (Figure 7).

The Jurassic-Cretaceous Woyla Group of northern Sumatra includes fragments of volcanic arcs and an imbricated oceanic assemblage. Rocks of the arc assemblage are considered to be underlain by a continental basement because of the occurrence of the intrusive granite. From this relationship, a model has been proposed in which a continental sliver was separated by the oceanic assemblage from the margin of Sundaland in the Late Jurassic to Early Cretaceous. The separated continental fragments have been designated the Sikuleh and Natal microcontinents. In mid-Cretaceous time, these microcontinents back against the Sundaland margin, destructing the oceanic assemblage once located in the middle (Meso-Tethys Ocean).

Age-dating of the volcanic assemblage and intrusive granites in the Natal area (Wajzer et al., 1991) however, showed that the volcanics were of Late Eocene age, and therefore unrelated to the Triassic-Early Cretaceous Woyla Group, which forms the remainder of the section, and therefore also quite unrelated to the Woyla component of Late Jurassic-Early Cretaceous Bentaro volcanics of Aceh. Thick-bedded radiolarian chert and paleontological studies in the oceanic Woyla Group rocks of the Natal and Padang areas showed that they formed part of a more extensive and long-lived ocean basin which lasted from at least Triassic until mid-Cretaceous. Wajzer et al. (1991) and Barber (2000) proposed that the volcanic assemblage of Woyla terranes developed as intra-oceanic arcs built up on the oceanic crust of Meso-Tethys before colliding with Sumatra.

Wajzer et al. (1991) reinterpreted the continental nature of Natal based on Batang Natal river section, Natal area, West Sumatra. They pointed to the absence of any significant amount of quartz in the volcaniclastic sediments or any continental clastic material in the massive limestones of the Maurosoma Formation, and suggested that these deposits were oceanic, rather than of continental margin origin. They concluded from the extensive deposits of bedded radiolarian chert and associated manganiferous argillites, that the oceanic deposits represented accreted fragments of the floor of a major ocean basin, rather than the floor of a restricted marginal sea.

The suture of Meso-Tethys is now located to the east of Woyla terrane constituting the oceanic (ophiolitic) assemblages of the Woyla Group. This includes serpentinized harzburgite, metagabbro, mafic to intermediate volcanics, often basaltic and showing pillow structures, volcanic breccias, volcaniclastic sandstones, red and purple manganiferous slates, red radiolarian cherts. These rock types also occur as blocks in breccio-conglomerates or mélanges (Cameron, 1980). Presently, all these units lie close to the Sumatran Fault. The oceanic assemblage of the Woyla Group, especially in Aceh area, shows an intimate mixture of ocean floor materials from different structural levels, from mantle to abyssal sediments, variously internally deformed, separated by faults, often identified as thrusts and arranged in a random order. These are the characteristic features of an accretionary complex, where ocean floor materials are imbricated against the hanging wall of a subduction zone. This process had destroyed the Meso-Tethys ocean. The suture belt of Meso-Tethys in northern Sumatra is now represented by Takengon, Kra, and Geumpang Lines. The suture has been re-activated by Sumatran Fault. The present distribution and emplacement of the fragments of Woyla terranes (Sikuleh, Natal, and others) was controlled by strike-slip movement.

Suture of Meso-Tethys is also found at outcrops of western and southern Sumatra with similar lithologies to those of the Woyla Group or which were formed within the same Jurassic-Cretaceous age range. These include Mesozoic Indarung Formation occurring near Padang, West Sumatra; Gumai and Garba Mountains, South Sumatra, and Bandarlampung area, Lampung (Barber, 2000). In this study, the suture belt is called the “Takengon-Bandarlampung suture”.

Pillow lavas and cherts of the Indarung Formation have been equated with the oceanic assemblage of the Woyla Group. The volcanic breccias tuffs and volcaniclastic sandstones were interpreted by McCarthy et al. (2001) as the products of seamount volcanism, and the massive limestone with its Late Jurassic-Early Cretaceous fossil fauna is interpreted as part of a fringing reef formed around the seamount. During suturing, subduction of the seamount with its carbonate cap collided with already accreted ocean floor materials, and the whole assemblage was imbricated to form the present complex.

The Pre-Tertiary rocks of Gumai Mountains consist of Saling, Lingsing and Sepingtiang formations which are Jurassic-Early Cretaceous in ages comprising mainly of andesitic-basaltic lavas, breccias, tuffs, calcilutite and chert serpentinized ultrabasic pyroxenites. Chemical analyses and discriminant plots show lavas as tholeiites of oceanic affinity (Gafoer et al., 1992). The Saling and Lingsing formations are overlain discordantly by the Sepingtiang Limestone Formation containing fossils of Late Jurassic-mid Cretaceous ages. The presences of andesites together with association of the volcanics with the massive Sepintiang limestone suggest that the Saling Formation also includes of a volcanic arc (seamount) with the massive limestone as fringing reef encircling the mount, precisely like those at Indarung area.

In Garba Mountains, the Garba Formation consists of basaltic and andesitic lavas, associated with sheared serpentinite and lenses and intercalations of radiolarian chert showing volcanic seamount with oceanic affinity. The Garba Formation has been compared to the Woyla Group of Natal (Gafoer et al., 1994). Limestone block within the melange may represent fragments of fringing reefs or the collapsed carbonate capping of seamounts.

In Bandarlampung area, outcrops of unmetamorphosed rocks, identified as the Menanga Formation, consist of tuffaceous and calcareous claystones, sandstones and shales with intercalated radiolarian-bearing cherts, manganese nodules and coral limestones and rare porphyritic basalt. The occurrence of Orbitolina sp. (Zwierzycki, 1932; confirmed by Andi Mangga et al., 1994) within this formation marks the age of mid-Cretaceous. The contact of this unit with another unit (Late Cretaceous granitic pluton) is friction breccia (Zwierzycki, 1932) or thrusts (Andi Mangga et al., 1994). The Menanga Formation is interpreted by Amin et al. (1994) as a deep water marine sequence with interbedded basalt lavas and andesitic clastic fragments, derived from a volcanic arc, and deposited in a trench or forearc environment. These

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sediments were deformed during accretion to the margin of Sumatra. The age of suturing or accretion based on K/Ar radiometric dating of amphibolitic schist in the Menanga Formation is 125-108 Ma (mid-Cretaceous) (Andi Mangga et al., 1994).

Remnant of Meso-Tethys Ocean: Meratus-Bawean Suture

There was another important episode of rifting around northern Australia in the Jurassic (Hamilton, 1979; Pigram & Panggabean, 1984; Audley-Charles et al., 1988; Metcalfe, 1988; Powell et al., 1988).

Several major blocks have been interpreted to have rifted from northwest Australia before India-Australia separation began and oceanic crust formed soon after breakup is still preserved close to western Australia.

Luyendyk (1974) suggested that Borneo and Sulawesi had rifted away from Australia but this suggestion seems to have been mainly forgotten or overlooked. A major rifted fragment was later named Mt Victoria Land (Veevers, 1988) or Argoland (Powell et al., 1988). Ricou (1994) suggested that Argoland corresponds to the Paternoster 'plateau' –presently located to the east of Kalimantan and southern part of the Makassar Strait which he interpreted to have collided with Kalimantan in the Paleocene.

There have been many suggestions that there was a collision between a Gondwana continental fragment and the Sundaland margin in the mid Cretaceous (e.g. Sikumbang, 1990; Hasan, 1991; Wakita et al., 1996; Parkinson et al., 1998; Satyana, 2003) with a suture located in the Meratus region (Figures 8, 9). Geochemical evidence (Elburg et al., 2003) and zircon dating (van Leeuwen et al., 2007) indicate continental crust may lie beneath much of west Sulawesi and it has an Australian origin.

Continental crust is also suggested to underlie parts of the southern Makassar Straits and East Java Sea between Kalimantan and Java based on basement rocks encountered in exploration wells (Manur & Barraclough, 1994; Satyana, 2003). Hall et al. (2009) considered all these areas as a single fragment, Paternoster-East Java Sea–West Sulawesi (or called as Paternoster-Kangean – Satyana, 2003), recognizing that it may be a number of smaller fragments, interpreted to have rifted from the West Australian margin, and added to Sundaland at a suture running from the Meratus Mountains and its southwestern extension (Parkinson et al., 1998; Satyana, 2003; Satyana and Armandita, 2008).

The Meratus Mountains are remnants of the Meso-Tethys ocean. They have long been believed as the Late Cretaceous subduction zone extending from the contemporaneous subduction zone across Java exposed in Ciletuh and Luk Ulo areas. The mountains are made up of assemblage of oceanic fragment (ophiolite), metamorphics, submarine volcanics and deep-sea sediments marking the suture of collision. Satyana (2003) and Satyana and Armandita (2008) reconstructed the mountains as resulted from subduction and collision of micro-continents (Schwaner – part of SW Borneo and Paternoster) in the mid-Late Cretaceous time (Figures 8, 9).

Situmorang (1989) and Metcalfe (1996) reconstructed the origin of the Schwaner and Paternoster micro-continents from the Gondwanaland, rifted and drifted to their present positions during the Mesozoic by the opening of the Ceno-Tethys ocean. These micro-continents collided and sutured forming the Meratus Orogen. Therefore, the Meratus ophiolites may represent the obducted Meso-Tethys oceanic crust initially located between the Schwaner and Paternoster micro-continents. An ultra-basic wedge once part of the Meso-Tethys oceanic crust was obducted and north-directed overthrusted onto the margin of the Sundaland where it presently found in the Meratus Range. The suture may continue southwestward from the Meratus Mountains into Bawean area to accommodate the whole collision front with Paternoster-Kangean area (Manur and Barraclough, 1994; Satyana, 2003) therefore, in this study the suture is called as the "Meratus-Bawean suture".

Hall et al. (2009) suggested that the closing of the Meso-Tethys ocean by the East Java–West Sulawesi block (Paternoster-Kangean terrane) occurred at about 90 Ma (early Late Cretaceous) or contemporaneous with the amalgamation of Woyla arc to the Sumatran Sundaland margin.

Remnant of Ceno-Tethys Ocean: East Sulawesi Suture

The Ceno-Tethys ocean opened progressively between Late Triassic and Late Jurassic times (Metcalfe, 1999) when continental fragments now located in Borneo and Sulawesi, separated from Gondwana. Remnants of the Ceno-Tethys that record this separation are preserved in the ocean floor off Northwest Australia. The Ceno-Tethys that existed to the north of Australia was destroyed by subduction beneath the Philippine sea plate as Australia drifted northward and that part of the Ceno-Tethys had closed by about 20 Ma.

East Sulawesi ophiolite belt (ESOB) occurred in the middle between West Sulawesi arc and metamorphic belt to the west and microcontinent of Banggai to the east. The East Sulawesi Ophiolite represents the remnant of Ceno-Tethys forming behind West Sulawesi terrane. It comprises, from base to top, residual mantle peridotite (spinel lherzolite, intercalated with harzburgite and dunite), mafic-ultramafic cumulate through layered to isotropic gabbro, to sheeted dolerites, and basaltic volcanic rocks (lavas) of normal mid-oceanic-ridge basalt (MORB) composition (Monnier et al., 1995). Major and trace element geochemistry of basalt and dolerite suggests origins of MOR, oceanic plateau (major), and supra-subduction zone (minor). Based on the chemical similarity between the ESO lavas and those from the Eocene Celebes Sea back-arc basin crust together with their identical age, Monnier et al., (1995) suggested that the ESO was initially generated in a back-arc tectonic environment representing a fragment of the Eurasian Plate obducted onto the East Sulawesi basement of Australian origin. Kadarusman et al. (2004) based on published paleolatitude data of lava sequence in the Balantak area reconstructed using plate trajectory analyses, indicated that the site of generation of the ESO was somewhere at area located 2000 kms south from the present position

Hall (1996, 2002) reconstructed the detachment of the Banggai microcontinent from the northern Australia or the Bird's Head of Papua, opening a part of the Indian Ocean at the Banda Sea area, its transfer to the west, and its collision to West Sulawesi closing the Ceno-Tethys ocean (Figure 10). At 20 Ma (Early Miocene), the microcontinent was dismembered from the Bird's Head by the Sorong Fault splay. At 15 Ma, a strand of the Sorong Fault propagated westward, at 11 Ma Buton-Tukang Besi collided with Sulawesi. Collision of Buton-Tukang Besi with Sulawesi locked the strand of the Sorong Fault and requiring a development of a new fault strand which caused the detachment of Banggai-Sula microcontinent. Banggai-Sula drifted northward and collided with East Sulawesi ophiolites. Overthrusting of the ophiolites onto the western edge Banggai-Sula microcontinent occurred in the latest Miocene indicating that collision of the Sula platform with East Sulawesi must have occurred at 5 Ma (end of Miocene) (Satyana et al., 2006a).

The collision caused the leading edge of the Banggai microcontinent was thrust beneath the ophiolites, obducted the ophiolites onto the microcontinental blocks. The collision has uplifted the tightly folded, faulted and imbricated ophiolites and their pelagic covers to heights more than 3000 meters. Also, as a result of the collision, the metamorphic belt of Central Sulawesi was thrust westward over West Sulawesi and uplifted to form mountain ranges of nearly 3000 meters (Satyana et al., 2007) (Figure 10).

Petroleum Implications

Several sedimentary basins in Indonesia had developed in association with reactivation of these Tethys sutures. Ombilin pull-apart basin developed associated with reactivation of Meso-Tethys Takengon-Bandarlampung suture in West Sumatra area. Producing Barito and Banggai basins developed related to uplifts of the Meratus and East Sulawesi sutures, respectively. The suture has also been known affecting thermal history of sedimentary basins such as the Mutus Assemblage, a splay of Paleo-Tethys suture in Central Sumatra Basin.

Koning (1985) considered that the Ombilin Basin is a graben-like, pull-apart structure resulting from Early Tertiary tensional tectonics related to strike-slip movement along the Great Sumatran Fault Zone. The Great Sumatra Fault Zone probably has had a long and complex geologic history. The fault zone is situated on suture zone of Woyla and Mergui terranes collision, a part of Meso-Tethys Takengon-Bandarlampung suture. When India collided Eurasia at 50 Ma, this suture hed been reactivated as Sumatran strike-slip fault zone and its pull-apart movement had formed the Ombilin Basin. A major tectonic feature bisecting a large portion of the Ombilin Basin is the Tanjung Ampalo Fault. The Fault is believed to be a second order dextral wrench fault formed in response to first order dextral strike-slip stress associated with the Great Sumatra Fault Zone. Ombilin Basin is a very deep pull-apart basin containing up to 15,000 ft (4600 m) of Tertiary sediments. The total amount of sedimentary section deposited within this Basin may have exceeded 30,000 ft (9200 m). Outcrop and subsurface data indicate that hydrocarbon source rocks, reservoir rocks, seals and ample structuring are present in the Ombilin Basin. Oil seeps and gas-condensates of well Sinamar-1 (Caltex, 1983) show the prospectivity of Ombilin Basin.

Examination of production records for the Central Sumatra Basin and South Sumatra Basin reveals 95 % of their cumulative output, that is 65 % of Indonesia's total production, is from fields either located directly over the Mutus Assemblage or in

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areas considered to have been affected by related Triassic tectonism (Pulunggono and Cameron, 1984). Mutus Assemblage is a splay of Pale-Tethys suture. It was a major zone of basement weakness during the development of the back-arc Central and South Sumatra Basins. This region experienced Miocene alkaline magmatism and. Due to a combination of high heat flow and the early growth of structures, the Mutus Assemblage is the site o f 95% of the Central and South Sumatra Basin's oil production (Figure 11).

Subduction, accretion, and collision during Late Jurassic to Late Cretaceous and later exhumation of the Meratus Meso-Tethys suture during the Tertiary had resulted in Tertiary pro-foreland basins of the Pasir - Asem-Asem Basin and retro-foreland basin of the Barito Basin (Satyana et al., 2008). Foredeep and fold-thrust belts developed in the basins close to the orogenic core. The Meratus Mountains have been uplifted more to the west and northwest due to the exhumation of subducted part of the Paternoster continental crust beneath the Meratus ophiolites. The retro-foreland Barito Basin and its foredeep have been subsided significantly due to this uplift. The Barito foredeep has subsided deeper than those of Asem-Asem and Pasir Basins. Generated hydrocarbons from the graben area in the Barito foredeep migrated northwestward and charged the structures of fold-thrust belts.

The collision of Banggai-Sula micro-continent closing East Sulawesi Ceno-Tethys was responsible for formation of pro-foreland basin of Banggai Basin, its foredeep and fold-thrust belt, suture/axial belt/ of East Sulawesi Ophiolites, internal metamorphic zone of Central Sulawesi, and retro-foreland basin of basins in western Sulawesi (such as Lariang Basin) (Satyana, 2006a; Satyana et al., 2008). Closing and uplift of East Sulawesi Ceno-Tethys suture significantly affect : (1) basin formation due to isostatic subsidence and underthrusting of the micro-continent, and post-collision extension, (2) sedimentation of post-collision/molassic deposits sourced from the suture, (3) subsidence of the basins due to deposition of molasses and/or thrust sheet of post-collision sequences, (4) generation of hydrocarbons in Miocene and Mesozoic sources due to maturity by isostatic subsidence and/or burial by multiple thrust sheets, and (5) trap formation related to collisional thrusting and post-collision wrench fault.

CONCLUSIONS

Figure 12 summarizes terranes and sutures of Indonesia marking the closing of the Tethys Oceans from Paleo-Tethys, Meso-Tethys to Ceno-Tethys.

1. The concept of "from Gondwana dispersion to Asia accretion" has been established. Asia was built up during the Phanerozoic by the amalgamation of allochthonous terranes derived from northern part of Gondwana. A series of elongated terranes separated successively from northern Gondwana by the development of ocean basins behind them. These oceans are referred to as Paleo-Tethys, Meso-Tethys and Ceno-Tethys. Amalgamation of terranes closed Tethys ocean in front of them to become a suture. Finding remnants of successive Tethyan oceans is recognizing their sutures.

2. Indonesia was built by a number of terranes hence preserving the remnants of successive Tethys oceans. Two belts of oceanic affinities recognized as the remnants of Paleo-Tethys ocean are: (1) Karimun-Bangka suture in east offshore Sumatra marking the amalgamation between East Malaya and Sibumasu (Malacca part) terranes and (2) Natuna-Belitung suture marking the amalgamation between Southwest Borneo and East Malaya terranes. Two belts of oceanic affinities recognized as the remnants of Meso-Tethys ocean are : (1) Takengon-Bandarlampung suture in western Sumatra marking the amalgamation between Sibumasu (Mergui part) and Woyla terranes and (2) Meratus-Bawean suture marking the amalgamation between Southwest Borneo (Schwaner part) and Paternoster-Kangean terranes. Remnant of the Ceno-Tethys ocean is preserved as an oceanic affinity of East Sulawesi Ophiolite Belt marking the suture of amalgamation between the Banggai microcontinent and western Sulawesi terrane.

3. Several sedimentary basins in Indonesia had developed in association with reactivation of these Tethys sutures. Ombilin pull-apart basin developed associated with reactivation of Meso-Tethys Takengon-Bandarlampung suture in West Sumatra area. Mutus Assemblage is a splay of Pale-Tethys suture accommodating the site o f 95% of the Central and South Sumatra Basin's oil production due to a combination of high heat flow and the early growth of structures. Producing Barito and Banggai basins developed related to uplifts of the Meso-Tethys Meratus suture and Ceno-Tethys East Sulawesi sutures, respectively.

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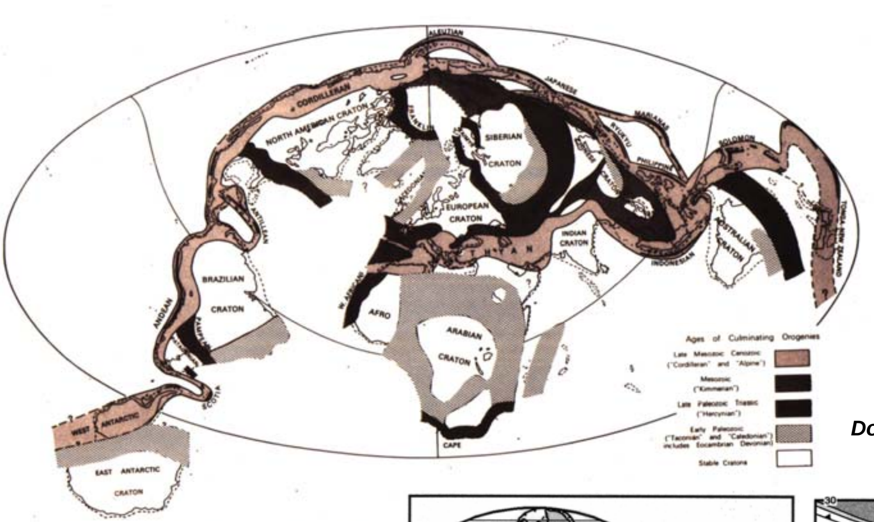
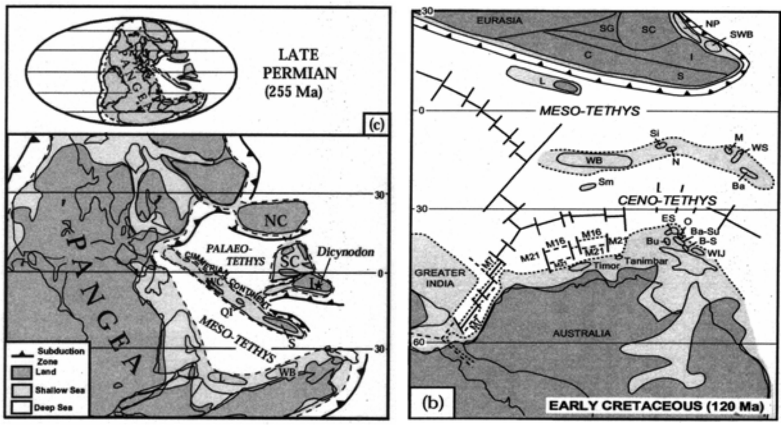


Dott and Batten (1971)



Metcalfe (1996)

Figure 1 - Development of concepts on Tethys Ocean. Old concepts (above) defined Tethys as a single ocean or 'geosyncline' from which the Alpine-Himalayan mountain belts had grown and was originally defined as solely Mesozoic (Triassic-Jurassic) concept. New concept (below) sees Tethys as a series of ocean basins which opened and closed in the eastern embayment of Pangaea during Paleozoic to Cenozoic times. Three successive Tethyan ocean basins are therefore established : the Paleo-Tethys, Meso-Tethys, and Ceno-Tethys.

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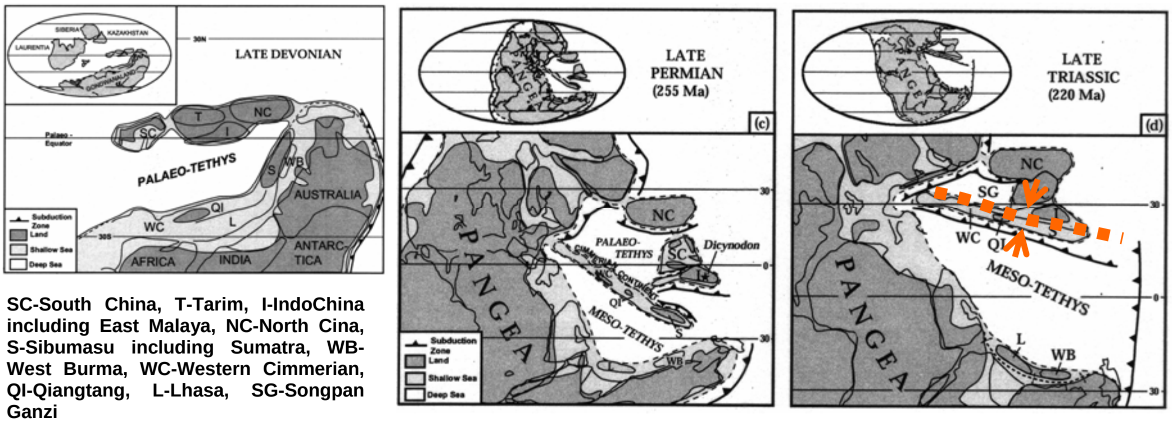

SC-South China, T-Tarim, I-IndoChina including East Malaya, NC-North Cina, S-Sibumasu including Sumatra, WB-West Burma, WC-Western Cimmerian, QI-Qiangtang, L-Lhasa, SG-Songpan Ganzi

▪▪▪▪▪▪ ***Paleo-Tethys suture***

map from Metcalfe (1996)

- **The Paleo-Tethys ocean basin was formed by sea-floor spreading between the separating elongated continental slivers (comprising Tarim, North China, South China, IndoChina-East Malaya) and Gondwana.**
- **The opening of the Paleo-Tethys ocean was Early-Late Devonian and the closure of the main Paleo-Tethys ocean due to amalgamation of younger Gondwanan terranes (West Cimmerian, Qiangtang, Sibumasu including Sumatra occurred in the Middle-Upper Triassic. Thus, the Paleo-Tethys ocean existed from Early Devonian to Late Triassic.**

Figure 2 - The origin of Paleo-Tethys Ocean and its closure.

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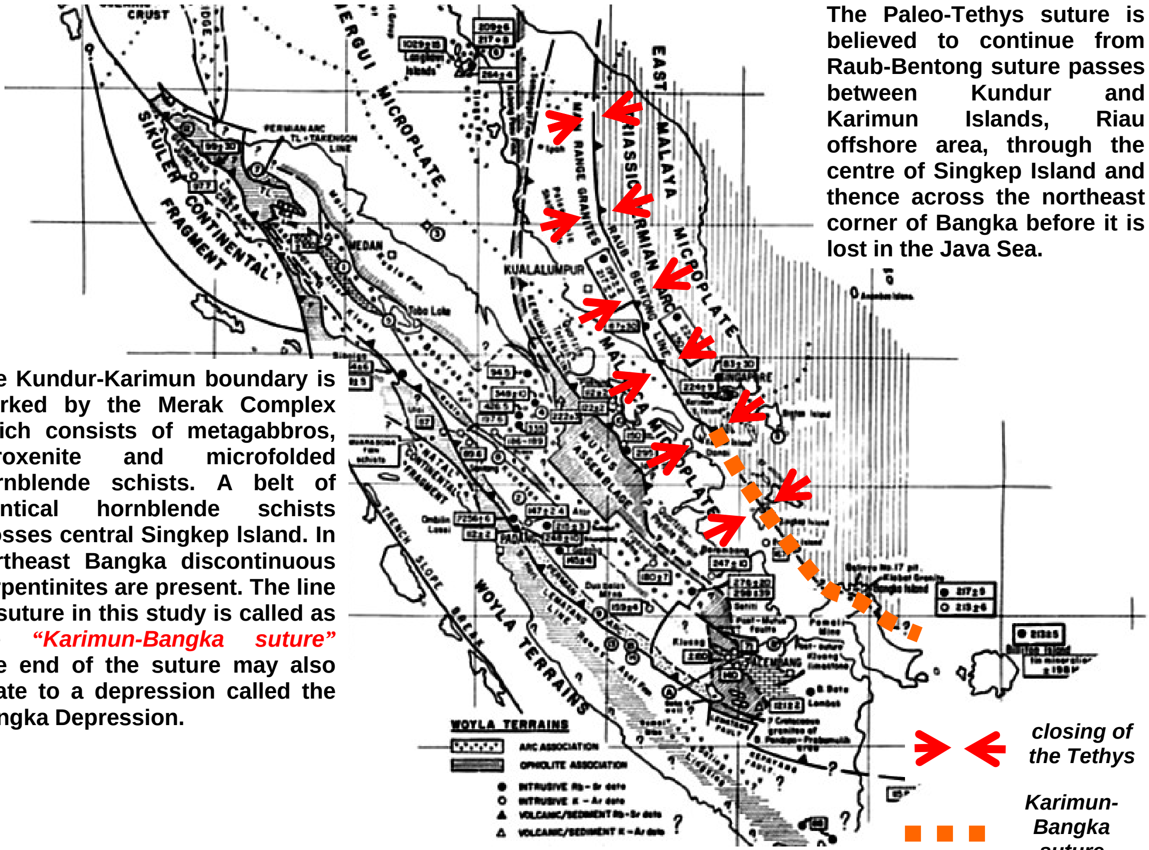

The Paleo-Tethys suture is believed to continue from Raub-Bentong suture passes between Kundur and Karimun Islands, Riau offshore area, through the centre of Singkep Island and thence across the northeast corner of Bangka before it is lost in the Java Sea.

The Kundur-Karimun boundary is marked by the Merak Complex which consists of metagabbros, pyroxenite and microfolded hornblende schists. A belt of identical hornblende schists crosses central Singkep Island. In northeast Bangka discontinuous serpentinites are present. The line of suture in this study is called as the *"Karimun-Bangka suture"*. The end of the suture may also relate to a depression called the Bangka Depression.

map from Pulungono and Cameron (1984)

Figure 3 - Raub-Bentong-Karimun-Bangka Suture, marking the closure of the Paleo-Tethys Ocean by collision between East Malaya and Mergui (eastern Sibumasu) terranes/ microplates.

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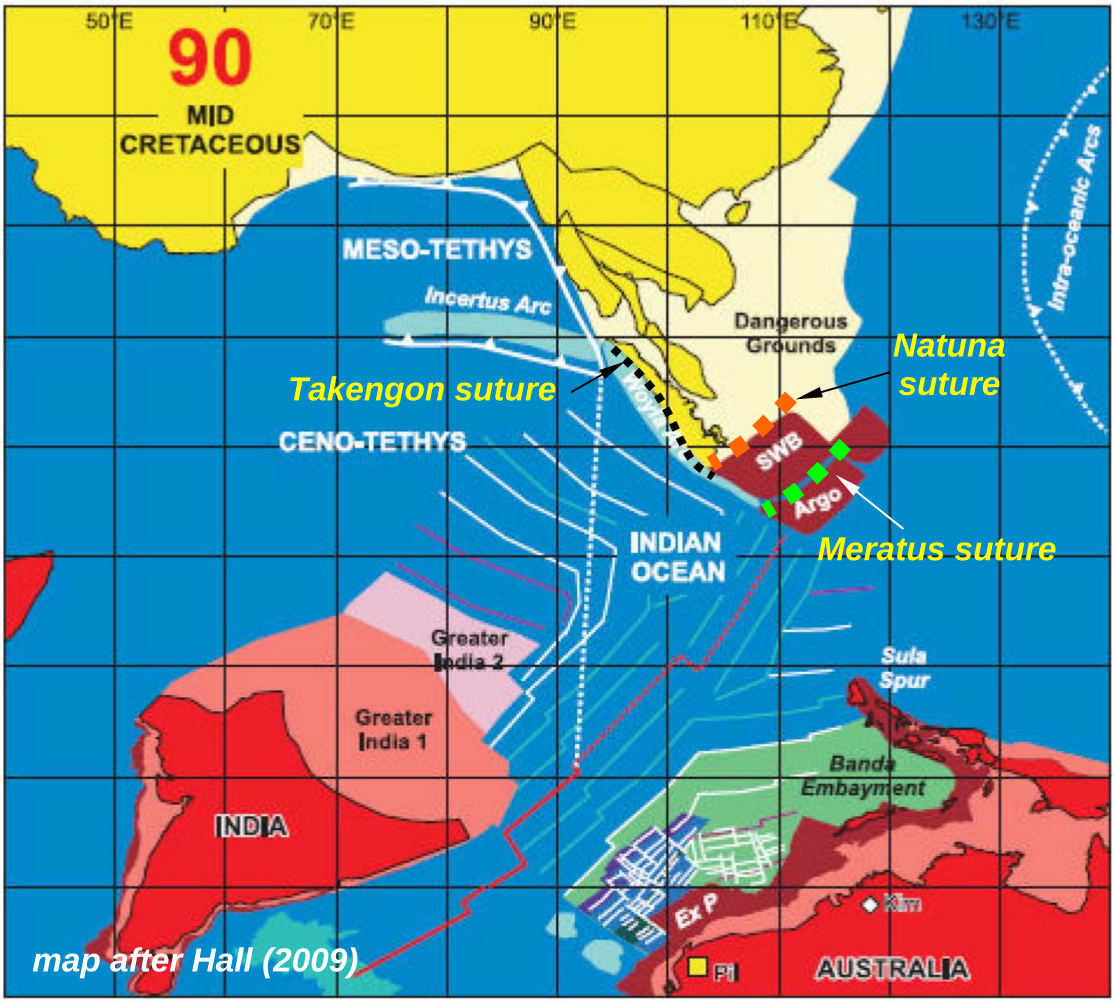

Figure 4 - Accretion of SWB (Southwest Borneo) and Woyla terranes to East Malaya and Sumatra terranes, closing the Paleo-Tethys and Meso-Tethys, respectively. Argo is another terrane known as the Paternoster terrane, closing the Meso-Tethys to the east of SWB.

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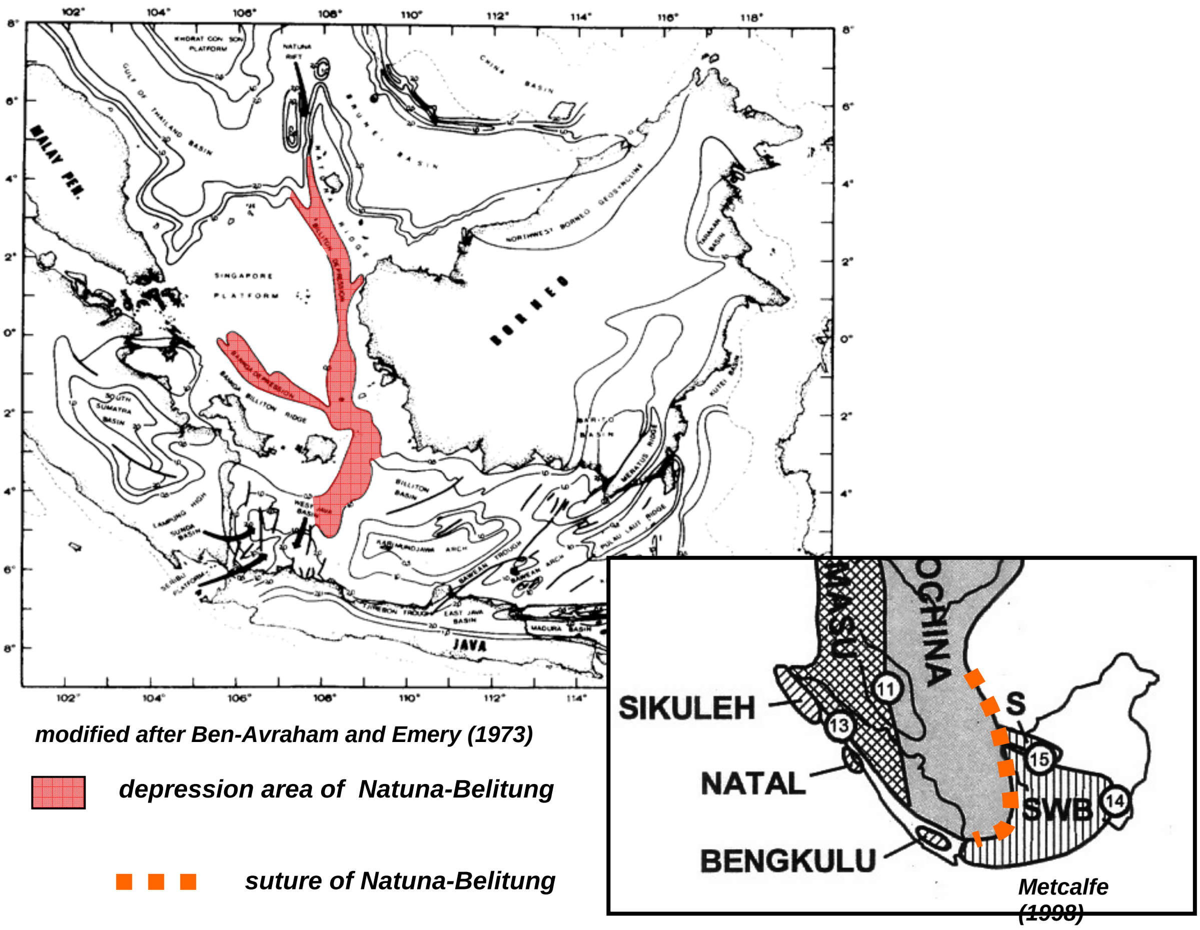
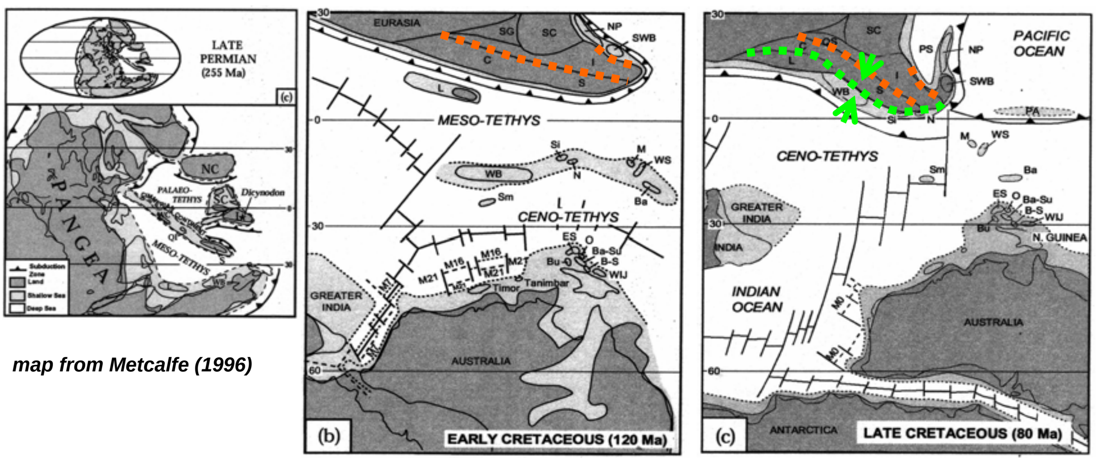


Figure 5 - Natuna-Belitung Suture, a suture of Paleo-Tethys Ocean marking the collision between East Malaya/Indo-China and SWB (Southwest Borneo) terranes.



map from Metcalfe (1996)

Paleo-Tethys suture

Meso-Tethys suture

NP-North Palawan, Sm-Simao, SWB-Southwest Borneo, Si-Sikuleh, N-Natal, M-Mangkalihat, WS-West Sulawesi, Ba-Banda allochthon, PA-Philippine Arc, ES-East Sulawesi, Bu-Buton, Ba-Su-Banggai-Sula, O-Obi, WIJ-West Irian Jaya

- **The Meso-Tethys opened in the Middle Permian as the Cimmerian continental sliver separated from the northern Gondwanaland. Continental collision closed of the Meso-Tethys around the Jurassic-Cretaceous boundary.**

Figure 6 - The origin of Meso-Tethys Ocean and its closure.

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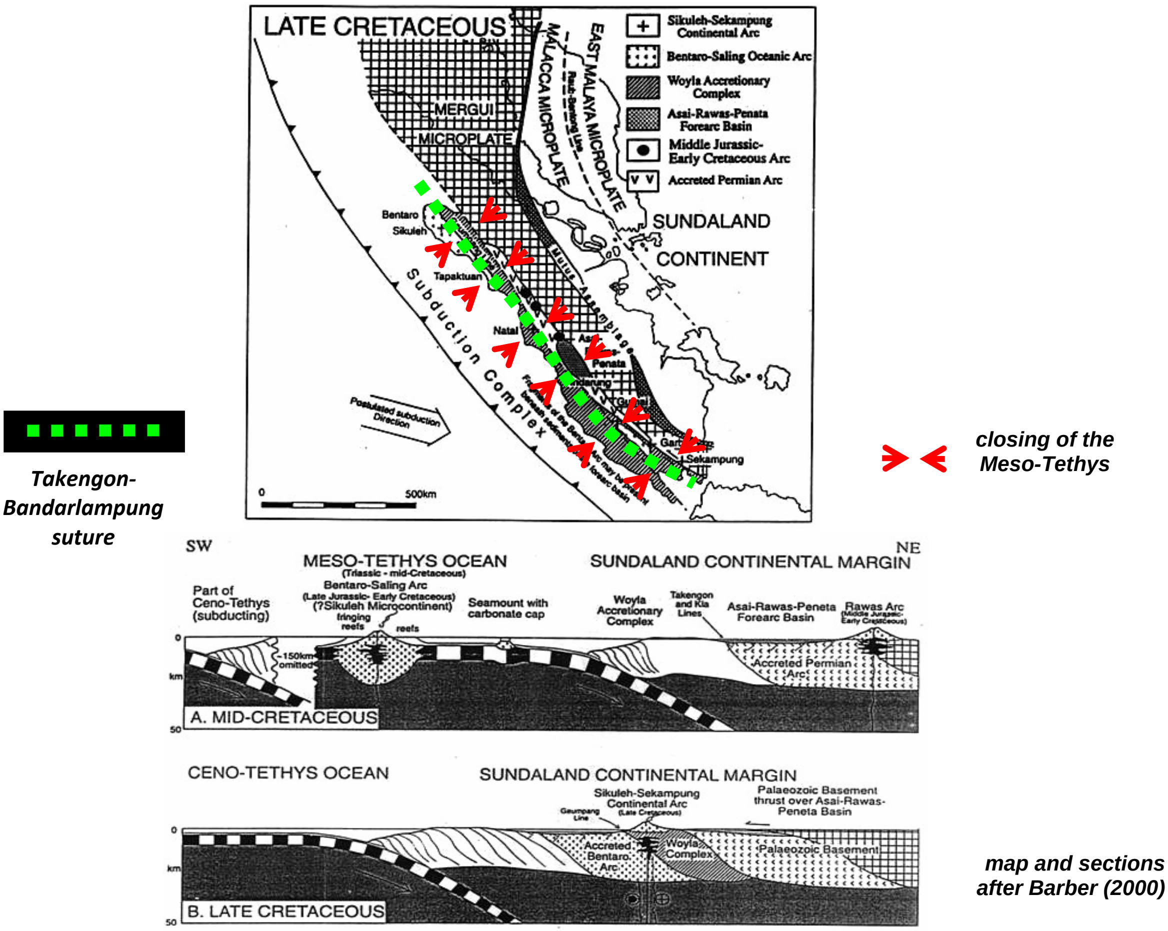

Figure 7 - Amalgamation of Woyla Arc (Bentaro-Sikuleh oceanic arc) along the border of Mergui closed the Meso-Tethys ocean once located to the west of Mergui microplate, resulting in Takengon-Bandarlampung Suture.

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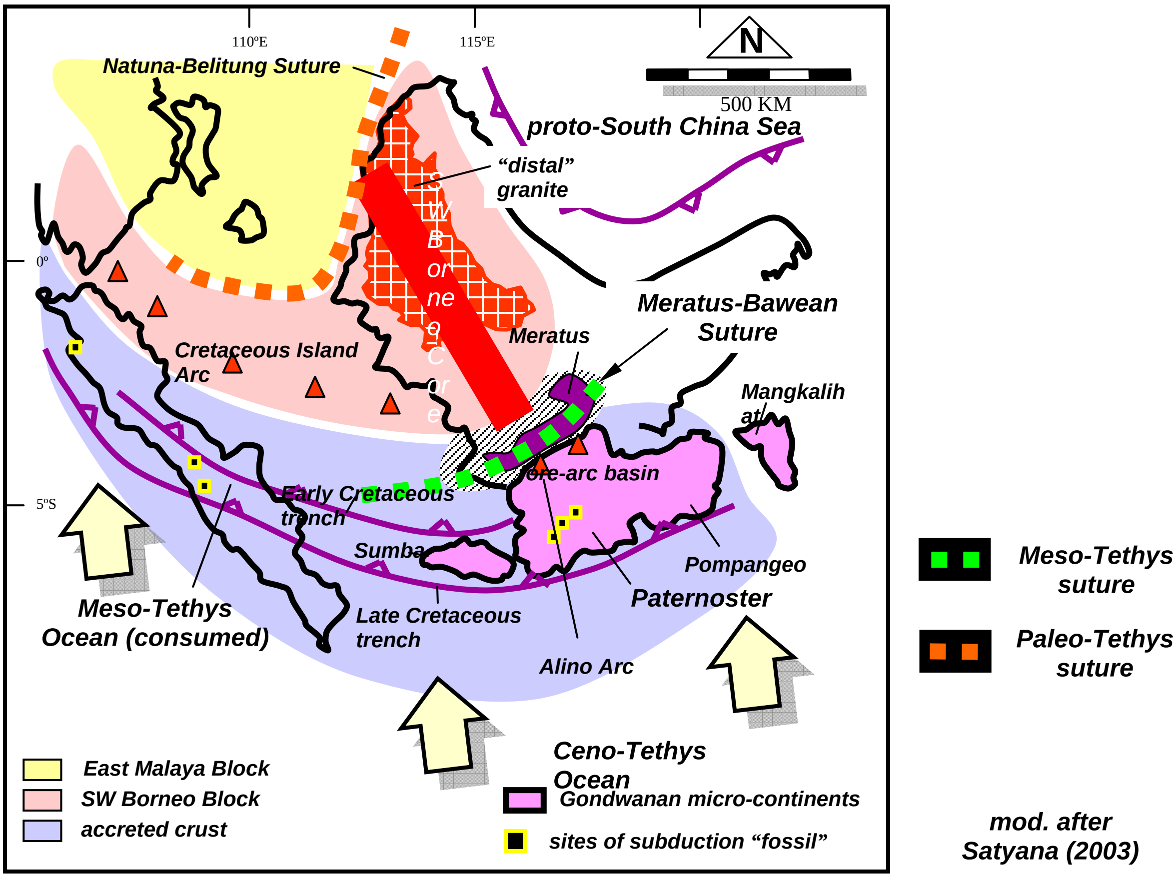

Figure 8 - Amalgamation of Paternoster to SW Borneo terranes, consuming Meso-Tethys Ocean, resulting in Meratus suture.

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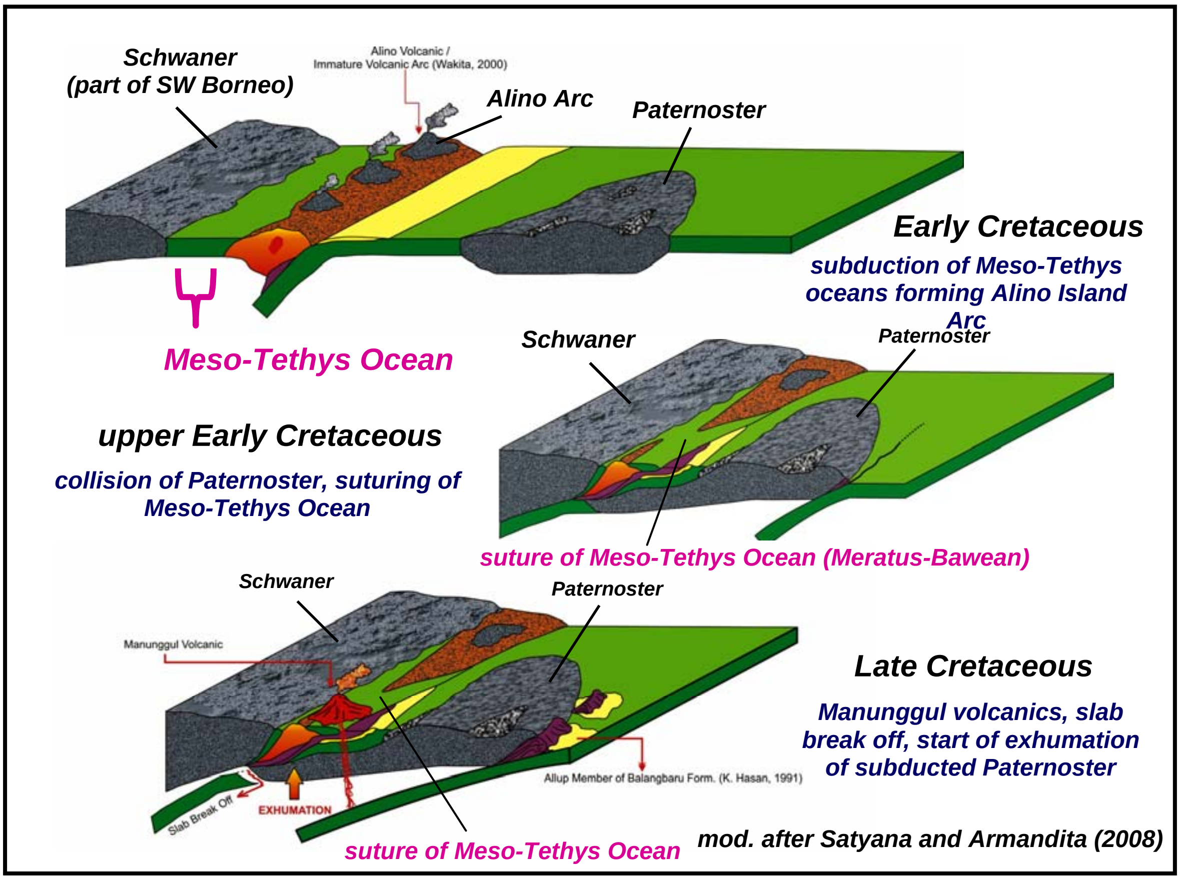

Figure 9 - Schematic 3-D diagram showing the closure of Meso-Tethys Ocean by collision of Paternoster terrane onto Schwaner (part of SW Borneo terrane) resulting in Meratus-Bawean suture. Part of Paternoster microcontinent was subducted below the suture because it was dragged by Meso-Tethys slab. When the slab broke-off from the Paternoster terrane, the subducted continent exhumed and uplifted the Meratus Mountains (suture).

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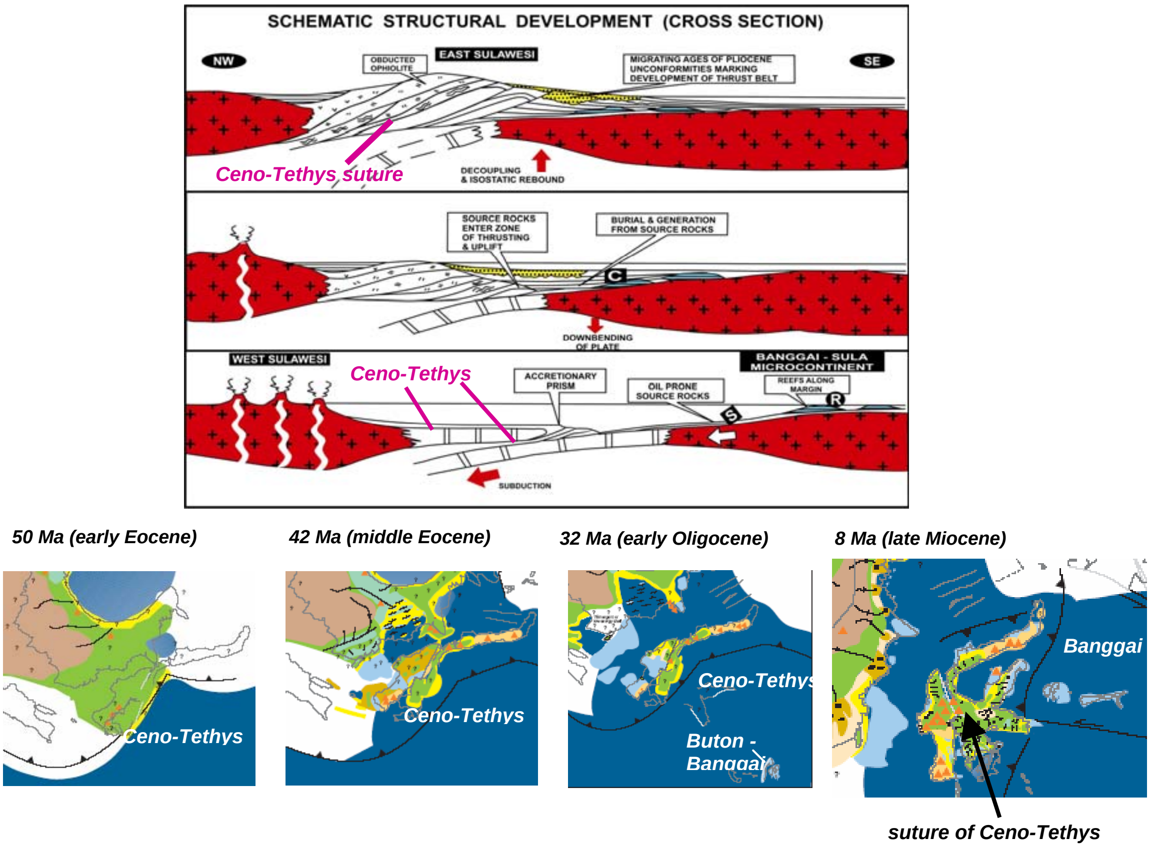

Figure 10 - Closing of Ceno-Tethys Ocean by collision of Banggai terrane to East Sulawesi, resulting in East Sulawesi Suture.

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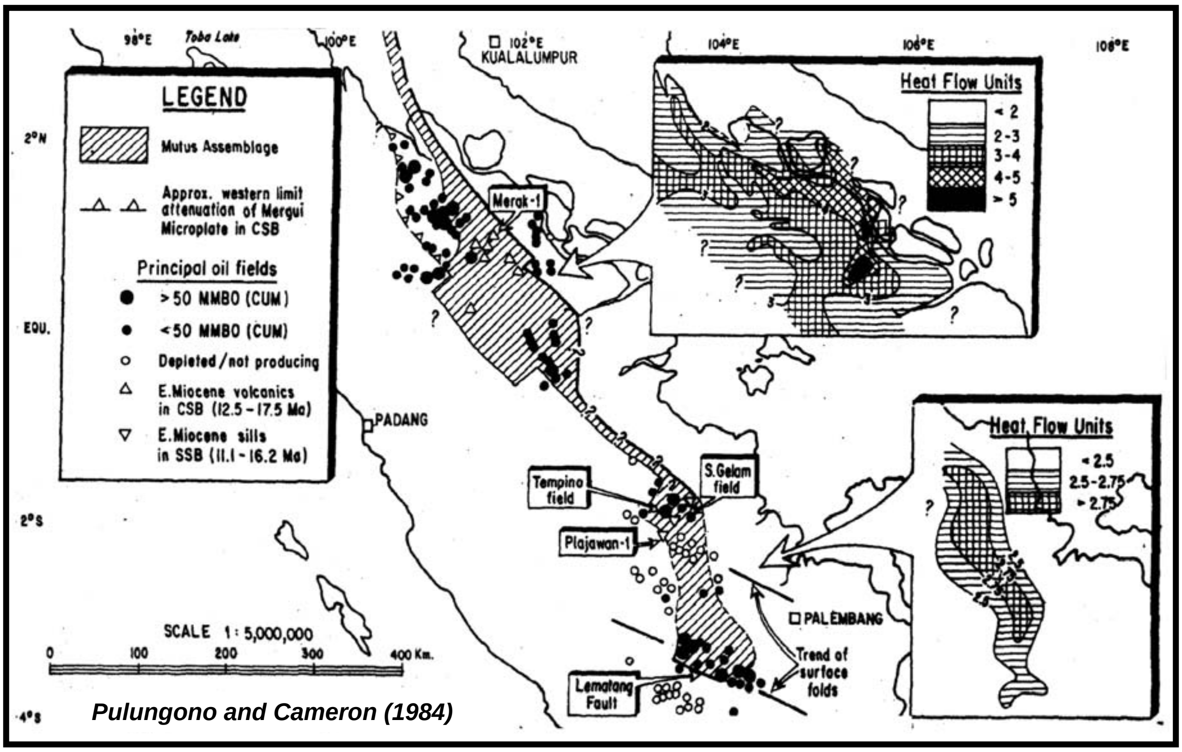

Figure 11 - How suture of Tethys affected petroleum system is shown by petroleum implications of Mutus Assemblage. Mutus Assemblage is a splay of Pale-Tethys suture. It was a major zone of basement weakness during the development of the back-arc Central and South Sumatra Basins. This region experienced Miocene alkaline magmatism and. Due to a combination of high heat flow and the early growth of structures, the Mutus Assemblage is the site o f 95% of the Central and South Sumatra Basin’s oil production.

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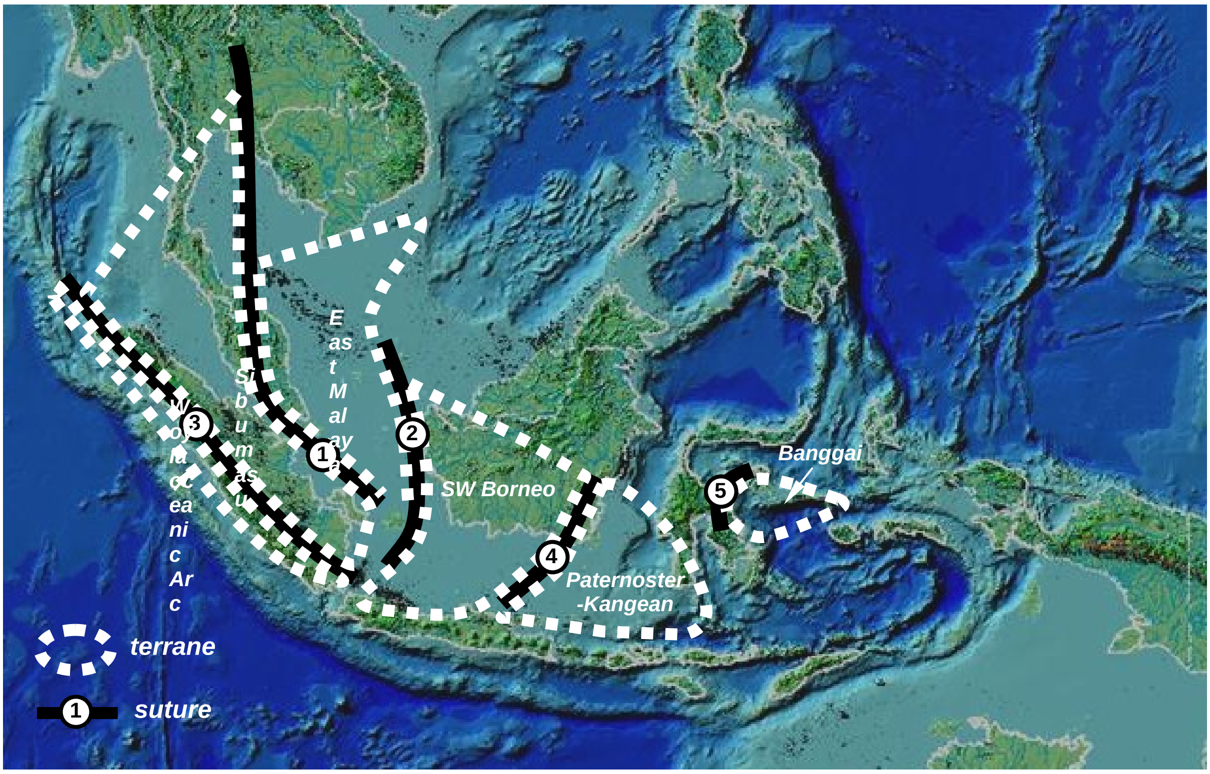

- *Nan-Uttaradit, Raub-Bentong, Karimun-Bangka Paleo-Tethys suture (Middle-Late Triassic)*
- *Natuna-Belitung Paleo-Tethys suture (Early-Mid. Cretaceous)*
- *Takengon-Bandarlampung Meso-Tethys suture (mid-Late Cretaceous)*
- *Meratus-Bawean Meso-Tethys suture (mid-early Late Cretaceous)*
- *East Sulawesi Ceno-Tethys suture (late Miocene)*

Figure 12 - Summary of terranes and sutures of Indonesia marking the closing of successive Paleo-, Meso- and Ceno-Tethys Oceans from Middle Triassic to late Miocene time.