Tectonic Models of the Lesser Sunda Islands

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Introduction

The Lesser Sunda Islands or 'Nusa Tenggara' as they are known in Indonesia, are a group of islands located to the immediate east of Java and to the north of Western Australia. Major islands in the group include Bali, Lombok, Sumbawa, Flores, Sumba and Timor. Most of the islands, except for Sumba and Timor, contain active volcanoes and are volcanic in origin. The volcanic islands are aligned in a W to E direction, forming the magmatic arc that constitutes the East Sunda-Banda Arc (Figure 1). Sumba and Timor are located to the south of the volcanic chain and they form the southern part of Banda Arc.

The East Sunda Arc includes Bali, Lombok and Sumbawa (Figure 1). Flores, which is the next island located to the east of Sumbawa, is the beginning of the Banda Arc. The Banda Arc itself is subdivided into the volcanic inner Banda Arc that includes Flores, Alor, Wetar, and other smaller volcanic islands to the northeast of Wetar; and the non-volcanic outer Banda Arc that includes islands such as Sumba, Timor, Babar, Tanimbar and Kai. The boundary between the East Sunda and Banda Arcs coincides with a change in present-day relationship of Australia-Eurasia plates, from an oceanic subduction type to continental collision type. In the inner Banda Arc, no active volcanic activities currently exist in the Alor, Lirang and Wetar islands.

This article summarizes the tectonic models of the Lesser Sunda Islands, particularly of the area between Java and the Timor islands. The summary is based on various publications of several key researchers, who have used their own findings and also those of other authors to propose their interpretation. The objective of this article is to review current understanding and interpretation of crust composition, tectonic models and arc volcanism of the region.

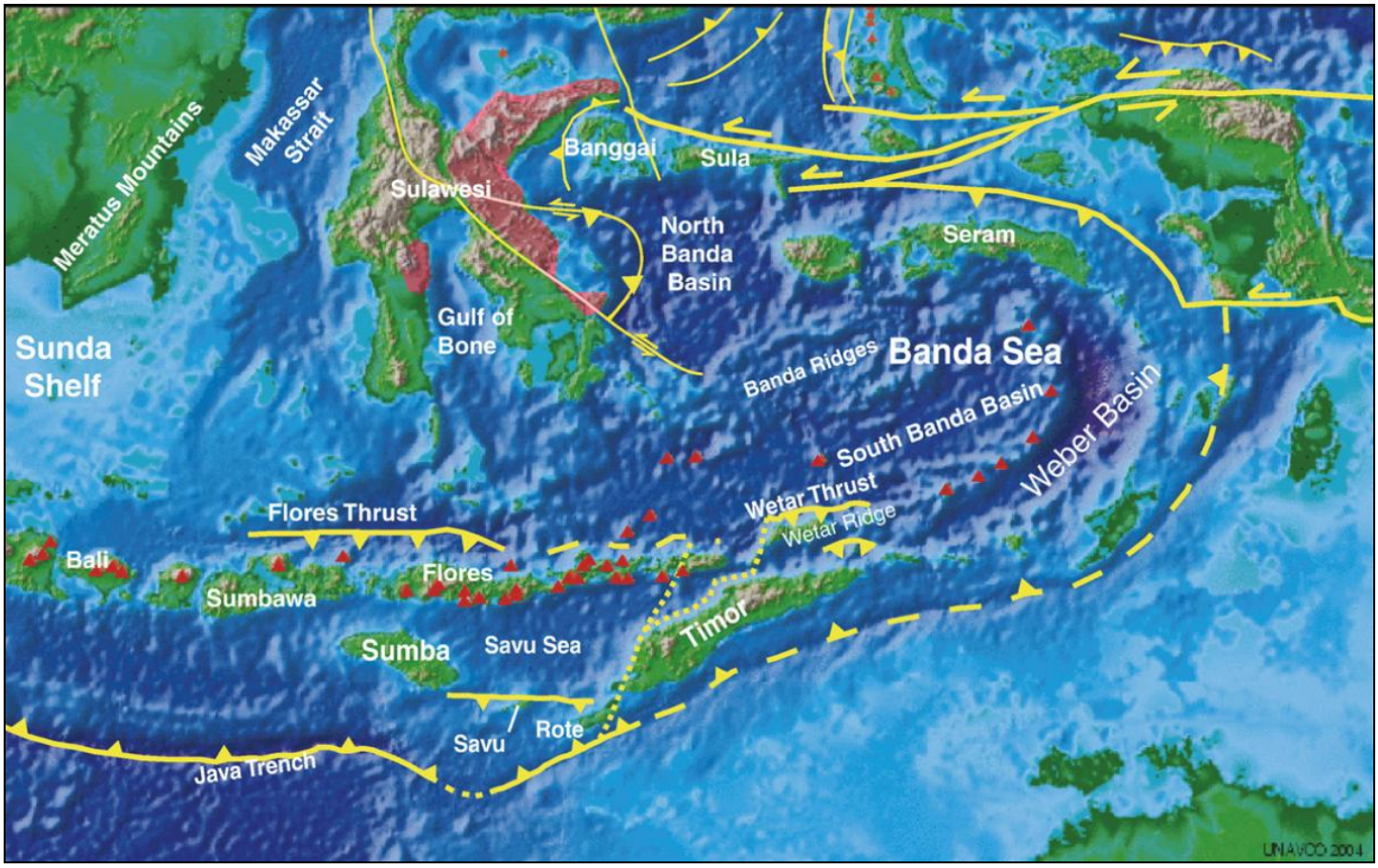


Figure 1. *Tectonic elements of eastern Indonesia with focus on East Sunda-Banda Arc (from Harris, 2006). Red triangles mean active volcanoes*

Key Publications

The geological evolution of the Lesser Sunda Islands is usually discussed as part of the larger and more complex Banda Arc system. Key papers on the tectonics of the region include Hamilton (1979), Audley-Charles et al. (1988), Charlton (2000) and Hall (2002; 2012). Hamilton (1979) described the topography, structural elements, crustal composition and seismicity of the entire arc system. He also interpreted subducting lithosphere around the Banda arc as a continuous and gravitation-controlled downgoing slab. Hamilton (1979) is one of the earliest publications on the tectonics of the Indonesian region, which provided a valuable foundation for later researchers to work on.

Audley-Charles et al. (1988) provided an early tectonic reconstruction model of eastern Gondwanaland and they also recognized various continental blocks that rifted away from Australia in the Late Jurassic, including those currently exposed in the Indonesian region and forming the outer Banda Arc.

The Banda Arc subduction-collision system began to develop in mid Miocene [*ca.* 18 Ma according to Charlton (2000) or 15-12 Ma according to Hall (2002) or 12 Ma (Abbott and Chamalaun, 1981; Scotney et al., 2005)], initially during the northward subduction of the Indo-Australia Plate. The subsequent arc-continent collision between the passive margin of northern Australia and the Banda arc occurred from *ca.* 8 Ma onward (Charlton, 2000), however other researchers proposed a younger collision, probably in the Pliocene (e.g. Audley-Charles, 2011; Hall, 2012). The most modern and comprehensive tectonic reconstruction of the entire Indonesian region is provided by Hall (2002; 2012).

Tectonic Setting

It is well-documented that the geology of the Indonesian region is influenced dominantly by interactions between three major tectonic plates that include Indo-Australia, Eurasia and Pacific Plates. The Indo-Australian plate currently subducts beneath Indonesia and creates a continuous deep sea trench along the offshore western Sumatra and south of Java. The trench ceases just south of the Sumba island and from this location eastward, the Australian continental margin is colliding against the outer Banda Arc system (Figure 1). The Pacific plate pushes westward, causing strike slip deformations at the northern part of the Papua island and also bending the horse-shoe-shaped, eastern part of the Banda arc. The Lesser Sunda Islands, being located at the western limb of the arc, are products of the subduction, collision and volcanism that are all linked to the plate movements.

The underlying crust of the Lesser Sunda Islands consists of continental, oceanic and transition crust. The East Sunda-Banda volcanic inner Arc is generally believed to be underlain by oceanic crust (e.g. Hamilton, 1979; Whitford and Jezek, 1982; Snyder et al., 1996; Garwin, 2000; Fiorentini and Garwin, 2010) and the non-volcanic outer Banda Arc by continental crust. Hall & Sevastjanova (2012) suggested that Australian continental fragments also exist in the volcanic inner Banda Arc, for example in central Flores, Sumbawa and Bali (Figure 2). However, this has not yet been substantiated by rock data on these islands and deep seismic and other marine geophysical data generally suggest oceanic crust beneath the Lesser Sunda and Banda Arc East of Bali (e.g. Snyder et al., 1996; Planert et al., 2010). This interpretation of the presence of continental blocks was based on the presence of Jurassic shallow marine siliciclastic rocks in the Bantimala Complex (Sulawesi), which is believed as a remnant of a continental fragment that were added to SE Asia in mid to Late Cretaceous *(note: evidence for Jurassic ages on Sumba and SW Sulawesi may be questionable; see Van Gorsel, this issue)*; and evidences of crustal contamination in the magma source of east Sunda-Banda Arc as traced from Helium isotopes (e.g. Gasparon et al. & Hilton et al.; in Hall and Sevastjanova, 2012) - *(although most authors that studied volcanic chemistry and isotopes explained this contamination from sediment cover of the subducting plate)*. Hall (2012) even suggested that the Banda Arc is a young arc built largely on continental crust.

Bali is underlain by crust of transitional type in term of density or thickness, between continental and oceanic, which may be product of mélange (e.g. Hamilton, 1979). In the Hall model, the western part of Bali is probably underlain by continental crust that may belong to Argoland (Figure 2), but the eastern part is probably part of a suture zone that continues to the Central Metamorphic Belt of Sulawesi. Sumba reportedly is underlain by continental crust, which most authors think is a continental fragment that accreted to SE Asia (SE Sundaland) by Late Cretaceous (e.g. Hamilton, 1979; Von der Borch et al., 1983; Simandjuntak, 1993; Wensink, 1997; and Satyana and Purwaningsih, 2011) and so is the Savu Basin to the WNW of the Timor island (e.g. Hall, 2012). However, Charlton (2000) suggested that Sumba island is entirely composed of non-Australian crustal elements *(see also Van Gorsel paper; this volume)*. Timor was initially believed to be underlain by Tertiary subduction mélange and imbricated complexes (Hamilton, 1979), where deep and shallow water sediments, metamorphic rocks, continental crystalline rocks, ophiolites and others, with age ranges from Permian to Quaternary are all mixed together. However, recent publications suggest the presence of continental crust beneath Timor (the Lolotoi-Mutis Complex) [e.g. Charlton, 2002; Hall and Sevastjanova, 2012].

A south-dipping megathrust has developed in the Flores basin, creating an E-W-trending trench just to the north of the Sumbawa and Flores islands. The trench is not accompanied by a south dipping Benioff zone and is most likely an incipient arc reversal (Hamilton, 1979). A similar young megathrust has also been observed to the north of Wetar. These young megathrusts developed in order to accommodate the collisional stress between Australian northern margin and the outer Banda Arc. The thrusts are now considered as the new boundary between SE Asia and Australian plate (Hall, 2002).

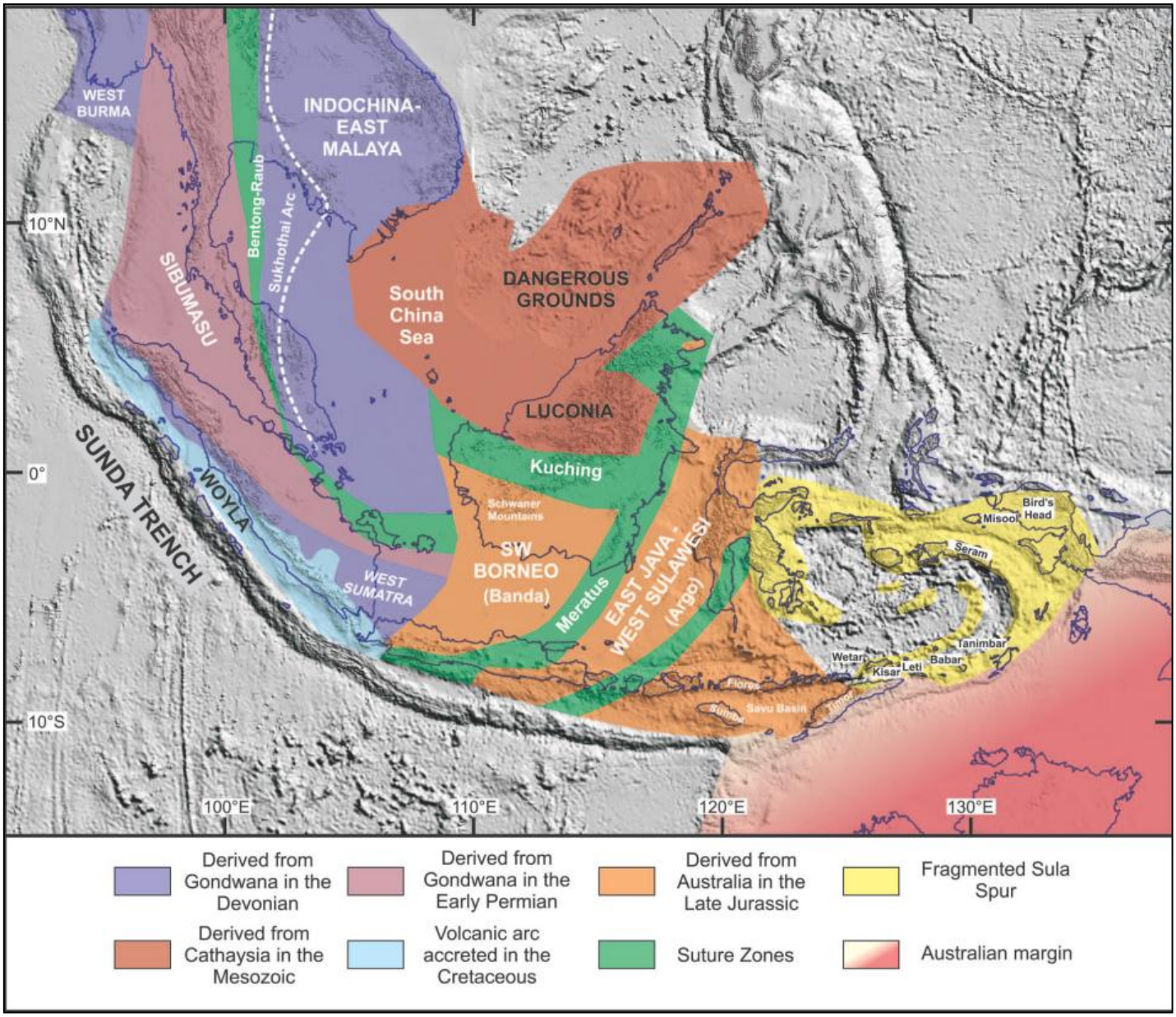


Figure 2. *Principal crustal blocks in SE Asia. Green colour means ophiolithic/arc suture, orange colour means continental crust (from Hall & Sevastjanova, 2012)*

Tectonic Models

The following section discusses the most recent tectonic models for the Lesser Sunda Islands based on the more regional work of Charlton (2000) and SE Asia Research Group of Royal Holloway University of London (e.g. Hall, 2012). For alternative recent plate reconstruction models see Pubellier et al. (2005) and Harris (2006; 2011). Charlton (2000) offered a fairly simple pre-collisional plate configuration in his reconstruction of the eastern Indonesia region from 35 Ma to the present-day. He believed that the complexity of the region developed only recently and can be achieved through some simple changes in regional dynamics, which included collision, post-collisional indentation and post-collisional disaggregation by left-lateral shear. His tectonic reconstruction has been based on a detailed paleogeographic evolutionary study of the northern Australian continental margin. Due to his focus on mainly the arc-continent collision zone and the eastern side of the Banda arc, Charlton (2000) did not discuss the Lesser Sunda Islands in great details, except for the Sumba and Timor islands.

At 35 Ma, Sumba was already part of the Sundaland (Figure 3) and was located close to its present-day position. Bali, Lombok, Sumbawa and Flores were also shown on the reconstruction map, but with 50% lateral shortening to compensate for arc expansion interpreted by Charlton (2000) in a later reconstruction. It is still unclear which volcanogenic formation of this age (Oligocene) in any of the islands support subaerial exposures of the Lesser Sunda Islands at the time.

The Australian plate at *ca.* 35 Ma also included a region called Greater Sula Spur, which was separated from the Lesser Sunda Islands by a northward-dipping subduction. This subduction zone, which was oriented in west-east direction, was a plate boundary separating Sundaland and the Philippine Sea plate to the north and Australian plate to the south. The SW & North arms of the Sulawesi

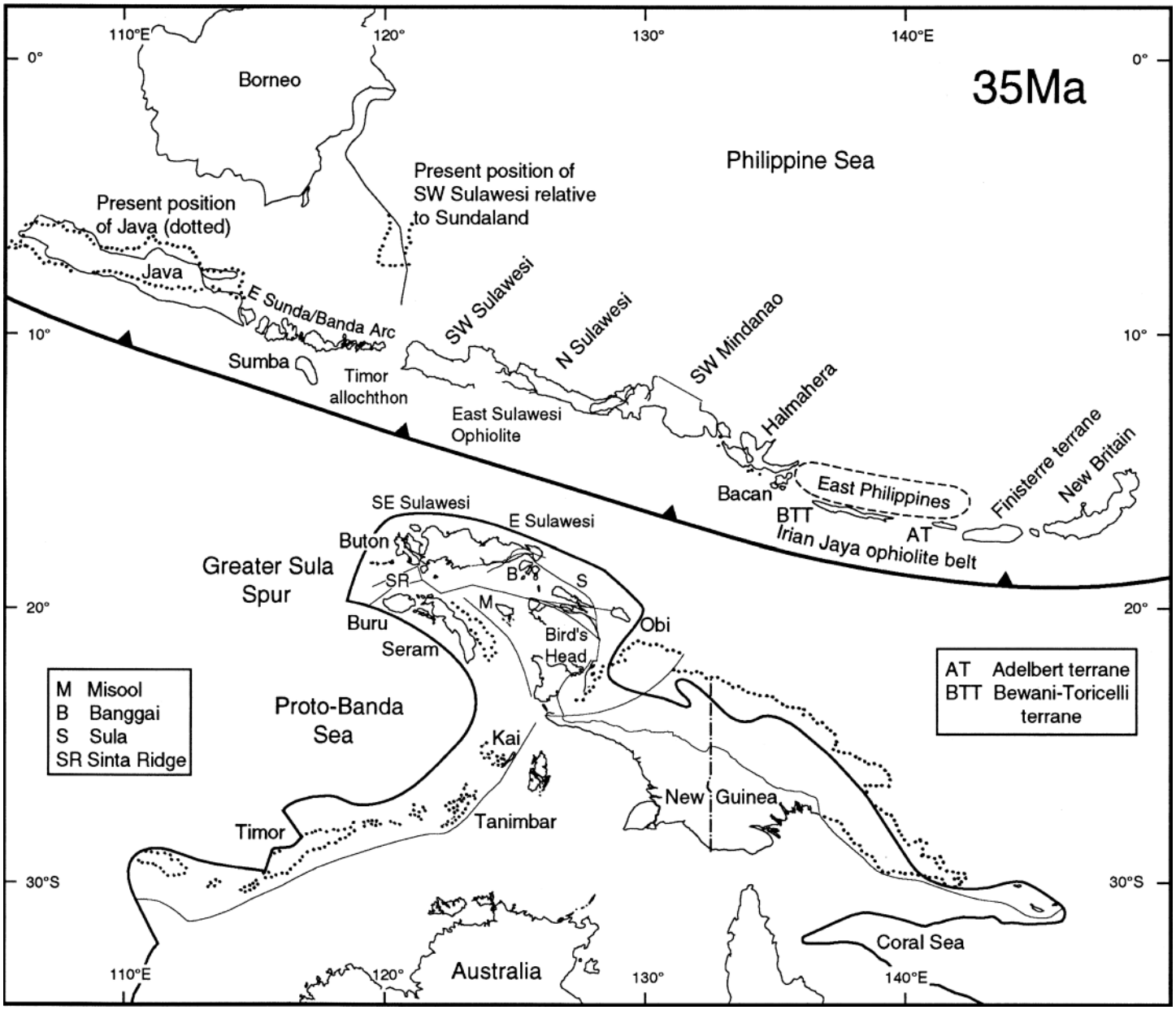


Figure 3. *Tectonic reconstruction of eastern Indonesia at ca. 35 Ma, as proposed by Charlton (2000)*

island , Halmahera and the East Philippines were all located near the southern edge of the Philippine Sea plate. The Greater Sula Spur was separated from the proto-southern Banda arc and Timor by an oceanic embayment called Proto-Banda Sea (Figure 4).

The Proto-Banda Sea was almost entirely closed by 10 Ma, bringing the Lesser Sunda Islands much closer to the northern margin of Australian continent. By *ca.* 8 Ma, the arc-continent collision between the northern margin of Australia and Banda arc took place in both Timor and Seram (e.g. Linthout et al., in Charlton, 2000), effectively closing the Proto-Banda Sea, as illustrated on the reconstruction at 5 Ma (Figure 4). Hall (2012) presented a different tectonic model for the Lesser Sunda Islands region, particularly on: (1) The nature and shape of the boundary between the Australian and Eurasian (Sundaland)-Philippine Sea plates. (2) Bali being submerged until *ca.* 15 Ma. (3) The emergence of Lombok and Sumbawa by *ca.* 10 Ma and Flores by *ca.* 7 Ma. (4) The Early Pliocene (*ca.* 4 Ma) arc-continent collision at Sumba and Timor. (5) Sumba being composed of an Australian continental fragment.

Sumba, Flores, East Java and West Sulawesi were added to the Sundaland margin in early Late Cretaceous when a continental fragment called "Argo" arrived from Australia (e.g. Hall and Sevastjanova, 2012). The 90 Ma collision of Argo and the Woyla Arc terminated subduction along the Sundaland margin therefore this reconstruction does not support the concept of a long-lived arc that stretched from Sumatra into the Pacific (Hall, 2012). There was s short period of subduction *ca.* 63 to 50 Ma beneath the south east corner of Sundaland due to NW-directed plate convergence, however major subduction at the Sumatra-Java and Sulawesi North Arm Arcs restarted from Middle Eocene once the Australian plate commenced to move northward. At *ca.* 35 Ma, the two arcs were not connected and subduction ceased at the SE corner of Sundaland where Sumba and West Sulawesi were located (Figure 5). Furthermore, Hall (2012) pointed out that no Paleogene igneous activity has been identified in the Wester

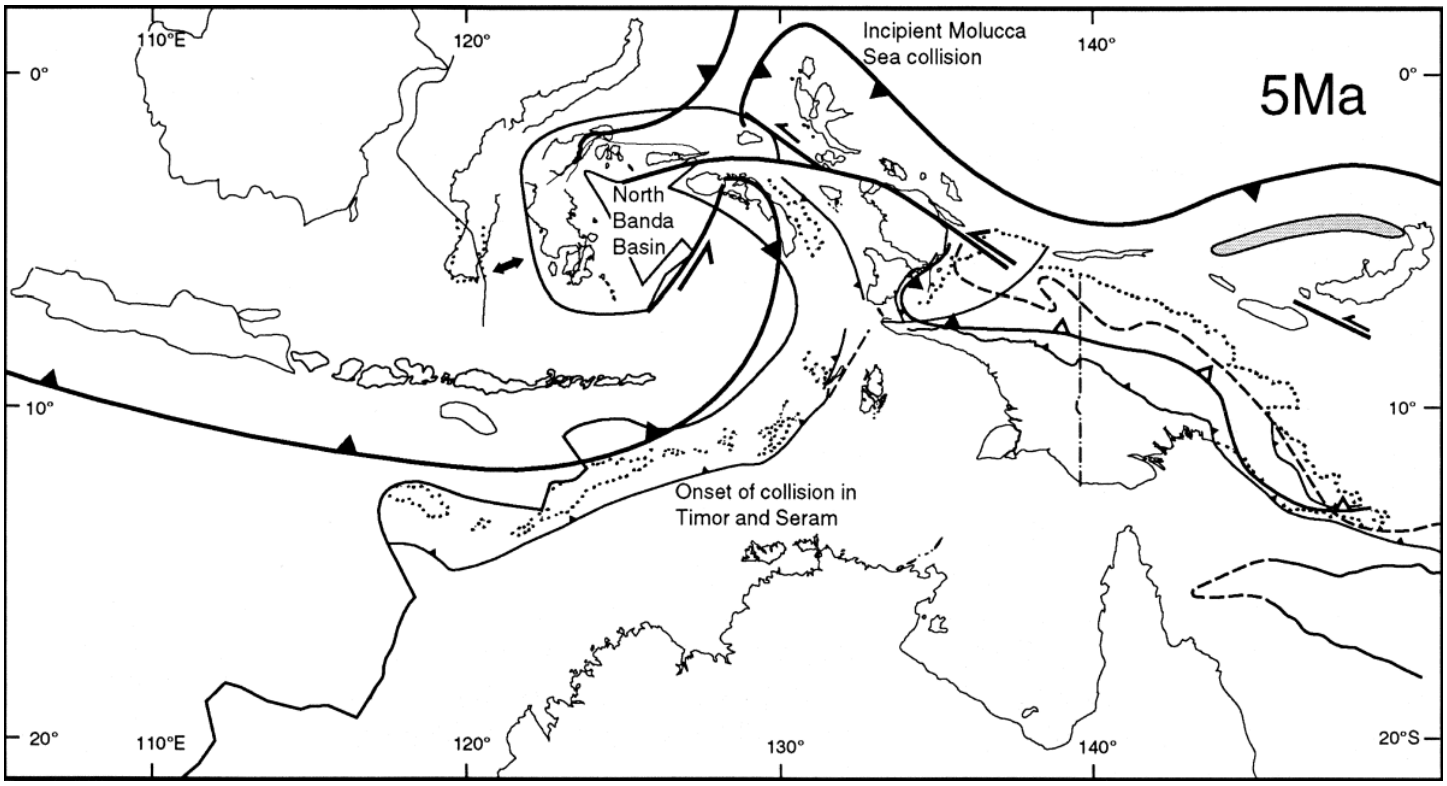


Figure 4. *Tectonic reconstruction at ca. 5 Ma as proposed by Charlton (2000)*

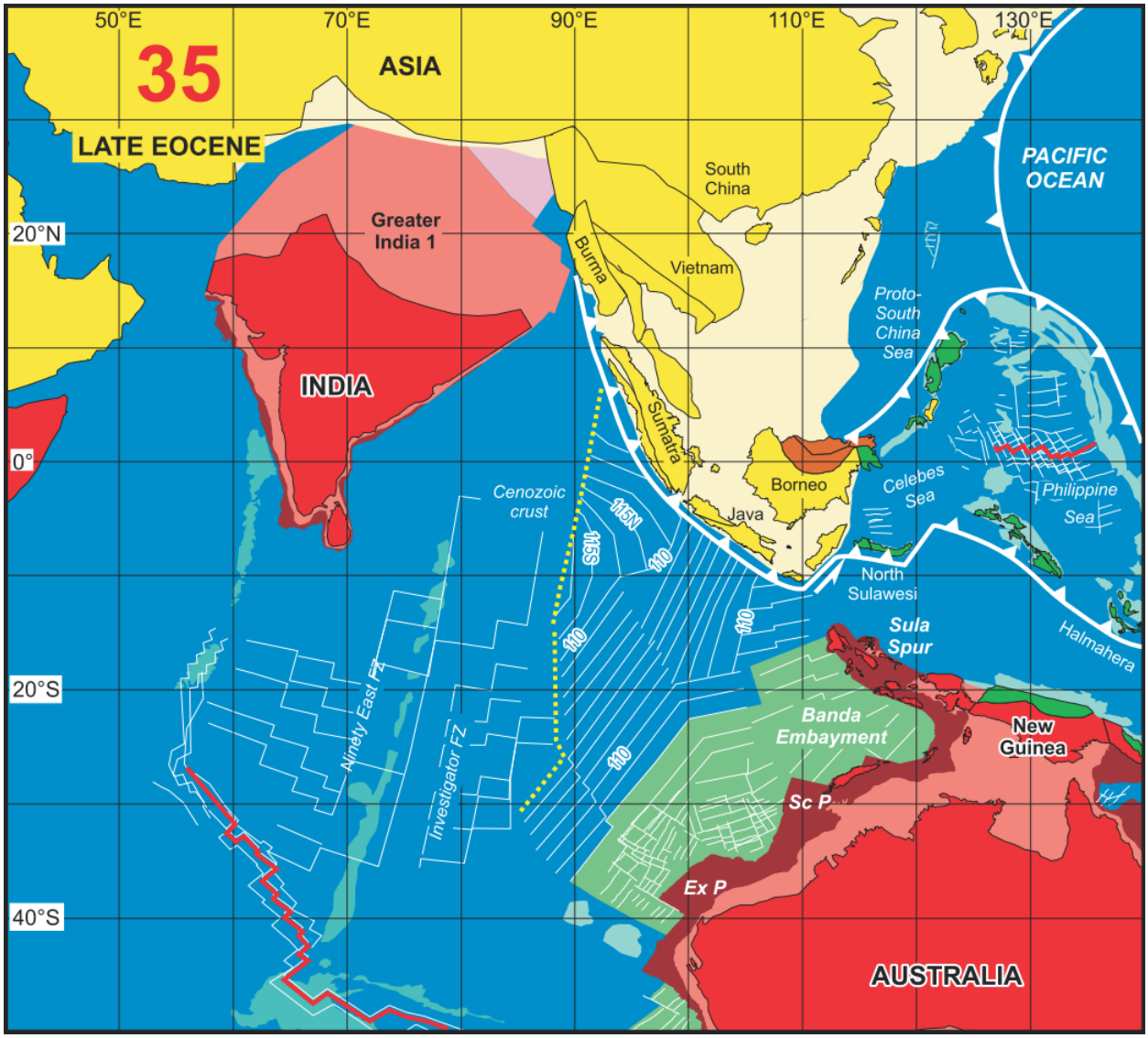


Figure 5. *Reconstruction of Indonesia region at ca. 35 Ma proposed by Hall (2012)*

Sulawesi and there was no subduction-related arc activity to the east of Java even in the Miocene.

Bali emerged to the surface by *ca.* 15 Ma (Figure 6) and was then followed by Lombok and Sumbawa by *ca.* 10 Ma (Figure 7). A trend of progressively younger age of the islands toward the east has been observed from Bali to Lombok, Sumbawa and then Flores and Wetar, respectively. Flores and Wetar emerged by *ca.* 7 Ma (Figure 6), as indicated from the oldest volcanics identified in the Lirang and Wetar Islands, which were dated as 7 - 3 Ma by Abbott and Chamalaun (1981). Hall (2012) suggested that the collision between northern Australia continental margin with Banda Arc occurred at *ca.* 4 Ma. This is based on the cessation of volcanisms in Wetar and Alor by 3 Ma as dated by Abbott and Chamalaun (1981). The reconstruction for the Lesser Sunda Islands region after Timor collision is shown on Figure 6.

Several deep ocean basins including Lombok, Bali-Flores and Savu Basins are present in the vicinity of the Lesser Sunda Islands. The Lombok Basin is a fore-arc basin while Bali-Flores is a back-arc basin. The Savu Basin is an inter-arc basin that developed due to rifting along the axis of eastern Sunda-Banda volcanic arc in the Middle-Late Miocene. Rapid subsidence in the basin commenced *ca.* 16 Ma, contemporaneous with the main volcanic arc to the north of the basin becoming inactive (Fortuin et al., in Charlton, 2000).

Arc Volcanism

Arc volcanism occurred in the Lesser Sunda Islands for much of the Tertiary, except in Late Oligocene (Charlton, 2000). Tertiary volcanic deposits identified from the region include Paleocene Masu Volcanics (Sumba), Eocene Metan Volcanics (Timor), Early Miocene Jawila Volcanics (Sumba), Middle Miocene (*ca.* 12 Ma) Wetar Volcanics (e.g. Abbott and Chamalaun; in Charlton, 2000) and Late Miocene Manamas Volcanics (Timor; e.g. Bellon, in Charlton, 2000). The volcanics in the inner Banda Arc are mostly of calc-alkalic magma and they are intercalated with volcanogenic sediments and carbonates (Hamilton, 1979).

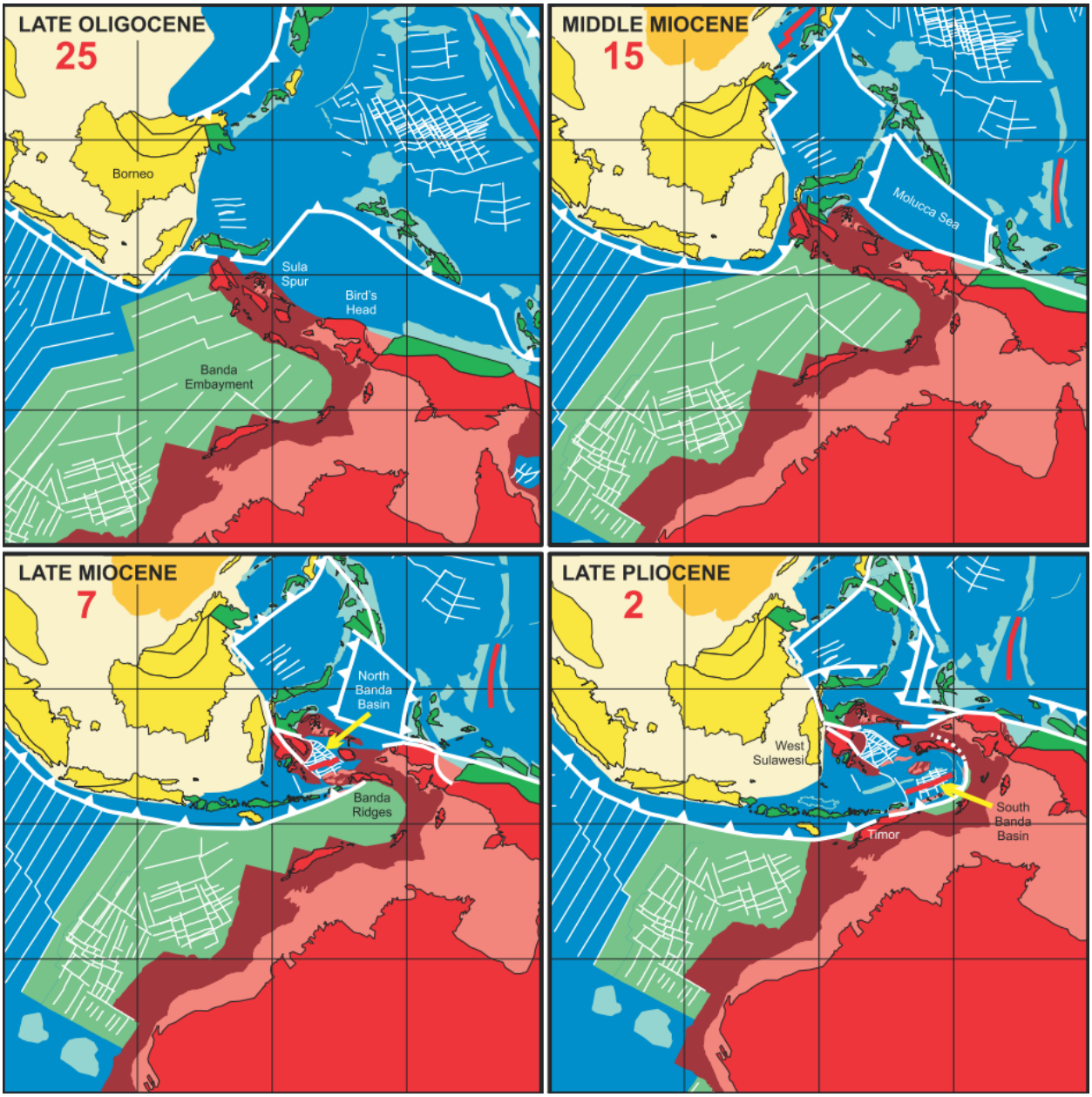


Figure 6. *Detailed reconstruction of Banda region at 25 Ma, 15 Ma, 7 Ma and 2 Ma (Hall, 2012)*

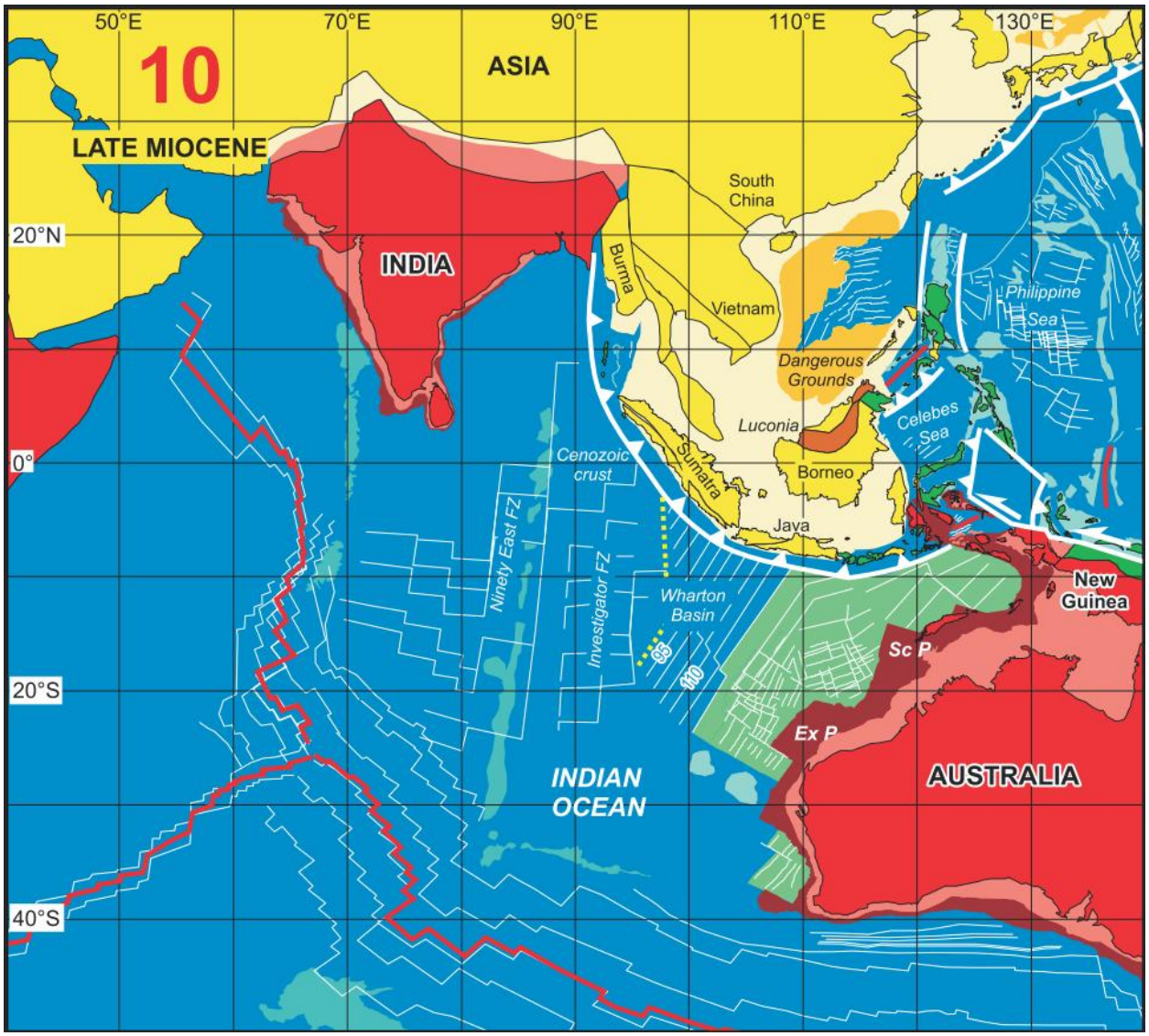


Figure 7. *Reconstruction at ca. 10 Ma (Hall, 2012)*

Young volcanism from Late Miocene to Pliocene-Pleistocene is common, although volcanic activity has ceased in Alor, Lirang, Wetar, Romang, and in central and eastern Timor due to the collision between northern Australia continental margin and the Banda Arc. The young volcanoes overprinted older arc crust, probably of Eocene to Early Miocene (Hamilton, 1979). Materials from Australian continental crust are also found in the igneous rocks along the East Sunda-Banda Arc. Elburg et al. (2004) interpreted that an increase in $^{206}Pb/^{204}Pb$ ratios toward the zone of collision with the Australian continent indicates input of subducted upper-crustal materials. In central part of the collision zone (Alor to Wetar), the $^{206}Pb/^{204}Pb$ ratios are lower than most radiogenic values in the nearby areas, which reflects input from subducted lower crust, while outside the collision area the Pb isotope signatures are believed to reflect a mixture between subducted MORB-type crust and sediments (Elburg et al. 2004).

Concluding Remarks

A lot of progress has been made in understanding the tectonic evolution of the Lesser Sunda Islands through various researches, nevertheless debates and disagreements on some issues related to the tectonic models still exist to date. The debates include: (1) Nature of the crust underlying the eastern Sunda-Banda Arc (particularly beneath Lombok, Sumbawa and Flores) - is it dominantly oceanic or continental crust? Existing rock data to date do not seem to support the continental crust ideas therefore they remain to be proven. (2) Nature of plate convergence along the boundary of Australian-Eurasian plates during the Oligocene to Early Miocene: unconnected subduction zone or a single subduction zone across Indonesia? (3) Existence of Oligo-Miocene magmatism in eastern Sunda Arc. The tectonics of the Lesser Sunda Islands region is a very interesting topic to investigate and further work in the future should be able to resolve some of the issues.

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