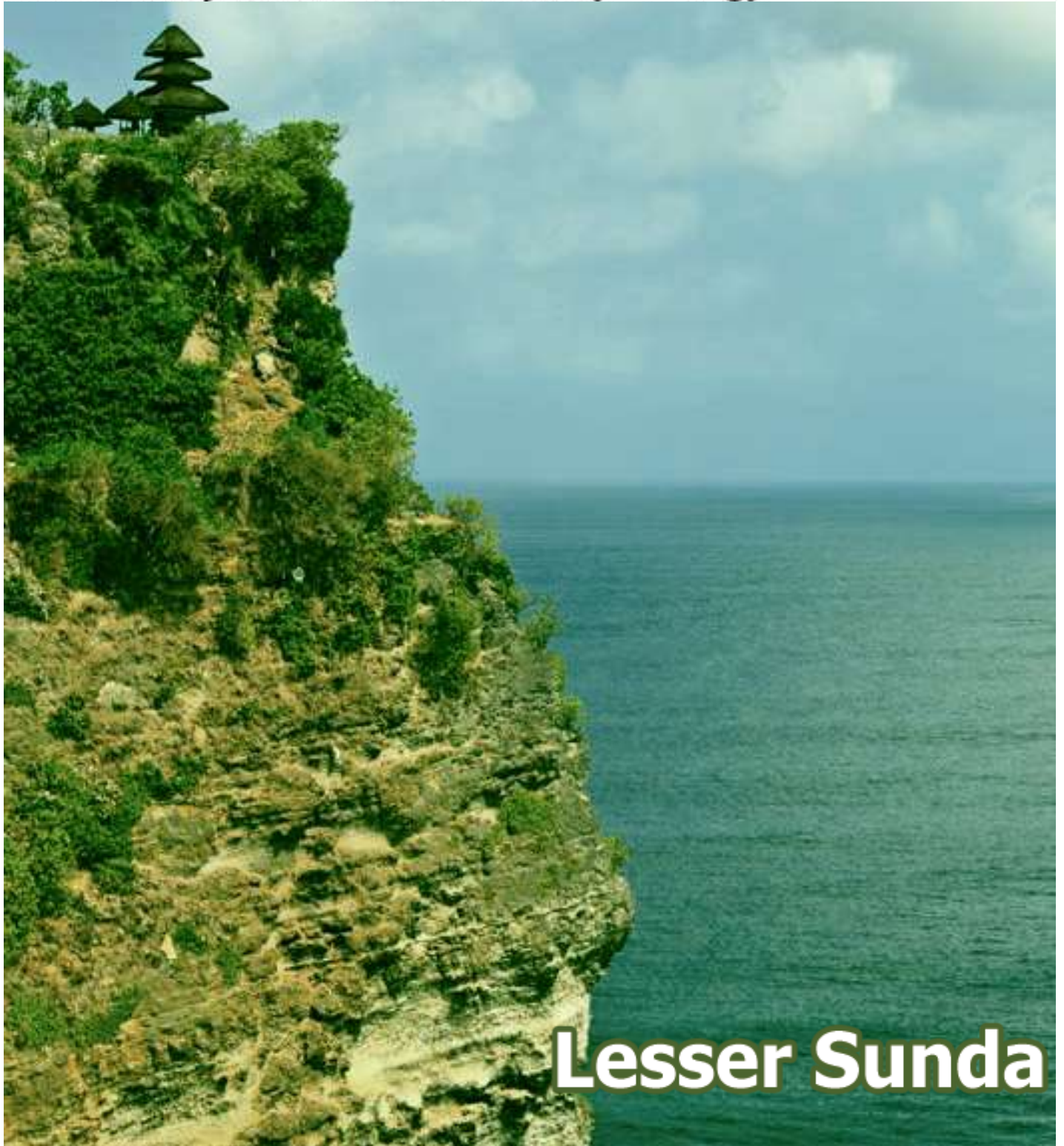


Berita Sedimentologi

Number 25
11/2012

Indonesian Journal of Sedimentary Geology

ISBN 0853-9413



Lesser Sunda



Published by

The Indonesian Sedimentologists Forum (FOSI)
The Sedimentology Commission - The Indonesian Association of Geologists (IAGI)



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Cover Photograph:

Pura Luhur Uluwatu on top of the cliff

Taken from website :

<http://goseasia.about.com/od/bali/tp/Must-See-Temples-In-Bali-Indonesia.htm>

Berita Sedimentologi

A sedimentological Journal of the Indonesia Sedimentologists Forum (FOSI),
a commission of the Indonesian Association of Geologist (IAGI)

From the Editor

Welcome to Berita Sedimentologi number 25!

We are very pleased to present you our final edition of Berita Sedimentologi in 2012, Berita Sedimentologi No 25. This edition will focus on the Lesser Sunda Islands, with some articles on Bali, Lombok and Sumba islands in particular. Some of the mentioned islands are well-established tourist destinations in Indonesia because they possess beautiful natural sceneries and cultural richness. They are also an interesting region geologically, so next time when you book your vacation in one of the islands, perhaps it won't be a bad idea to bring along your sedimentology, stratigraphy or even vulcanology skills while you're enjoying the nature.

The contents of BS No. 25 include two articles written by Awang Satyana, one on Wallace Line (Bali-Lombok gap) and the other one on Sumba island

(co-authored by M. Purwaningsih). There is also a short communication on Sumba written by J.T. van Gorsel on the age of Ammonite found in the island. Other articles include a review on tectonic models of the Lesser Sunda Islands, two short notes on the sedimentology of some tourist attraction locations in Bali and Lombok and an article about volcano tourism potential or Mt. Rinjani in Lombok Island. Volcanoclastic sediments are the main deposits in these islands.

As we're about to change year from 2012 to 2013, there will be some changes as well in the editorial team of Berita Sedimentologi in 2013. Agus Suhirmanto, our main lay out editor, is leaving the team due to family and work commitments. Agus has done outstanding job while serving FOSI and we cannot thank him enough for his contributions. Agus will be replaced by Rahmat Utomo, an exploration

geologist in Mubadala Petroleum (Thailand) Ltd. We also have a new international reviewer, Dr. Peter Barber (Isis Petroleum, Australia), whose skill in clastic sequence stratigraphy would be very useful to support Berita Sedimentologi team. Dr. Barber will start his role from this edition onward.

We hope that you will enjoy reading this volume and Happy New Year 2013. See you again next year!

Best Regards,



Minarwan
Deputy Chief Editor

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About FOSI

The forum was founded in 1995 as the Indonesian Sedimentologists Forum (FOSI). This organization is a communication and discussion forum for geologists, especially for those deal with sedimentology and sedimentary geology in Indonesia.

The forum was accepted as the sedimentological commission of the Indonesian Association of Geologists (IAGI) in 1996. About 300 members were registered in 1999, including industrial and academic fellows, as well as students.

FOSI has close international relations with the Society of Sedimentary Geology (SEPM) and the International Association of Sedimentologists (IAS). Fellowship is open to those holding a recognized degree in geology or a cognate subject and non-graduates who have at least two years relevant experience.

FOSI has organized 2 international conferences in 1999 and 2001, attended by more than 150 international participants.

Most of FOSI administrative work will be handled by the editorial team. IAGI office in Jakarta will help if necessary.

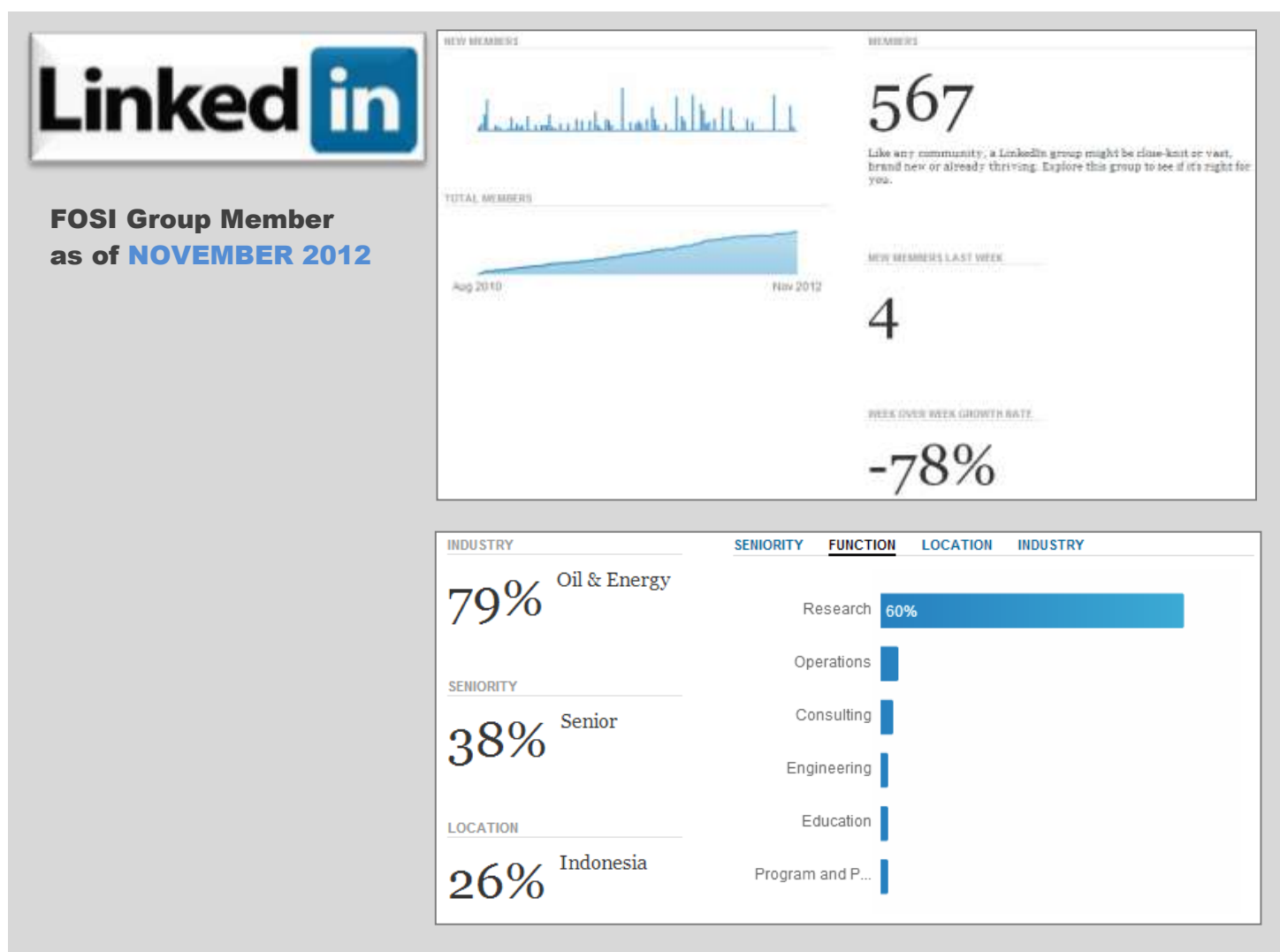


The official website of FOSI is:

<http://www.iagi.or.id/fosi/>

FOSI Membership

Any person who has a background in geoscience and/or is engaged in the practising or teaching of geoscience or its related business may apply for general membership. As the organization has just been restarted, we use **LinkedIn** (www.linkedin.com) as the main data base platform. We realize that it is not the ideal solution, and we may look for other alternative in the near future. Having said that, for the current situation, LinkedIn is fit for purpose. International members and students are welcome to join the organization.



Bali–Lombok Gap: A Distinct Geo-Biologic Border of the Wallace Line

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Introduction

"Bali and Lombok Islands located to the east of Java are very interesting for several reasons. Only on these two islands Hinduism exists in Indonesia. Both islands represent different ends of two zoological realms in the East. The islands are similar in shapes and physical characteristics, but they are different in their floras and faunas." (Wallace, 1863)

The "Wallace Line", a line that divides faunal distribution, came into being in 1863 and was named after Alfred Russell Wallace, the great English naturalist travelling the 'Malay archipelago' or the Indonesian islands from 1854-1862. The Wallace Line separates the Oriental (Asian) fauna to the west from the Australasian fauna to the east (Fig. 1). The original Wallace Line ran between Bali and Lombok, extending northward between Borneo/Kalimantan and Sulawesi, and between the Philippines and Indonesia. The Asian animal community

includes such mammals as rhinoceroses, orang-utans, tapirs, tigers, and elephants. Animals related to Australian fauna include birds such as cockatoos, birds of paradise, marsupials and cuscuses.

Bio-Geological Aspects of Wallace Line

Wallace did not believe that accidental dispersal events in ecological time explained mammalian and avian distributions within the archipelago. Instead, he linked geological connection to biological diversity. "Facts such as these can only be explained by a bold acceptance of vast changes in the surface of the earth", Wallace stated in a paper with the title "On the Zoological Geography of the Malay Archipelago" presented to the Linnaean Society on 3 November 1859.



Figure 1. The Wallace Line runs between Bali and Lombok. It geologically marks the border of the Sunda Shelf to the east. Bali is the easternmost island sitting on the Sunda Shelf. (modified Wikipedia, 2012)

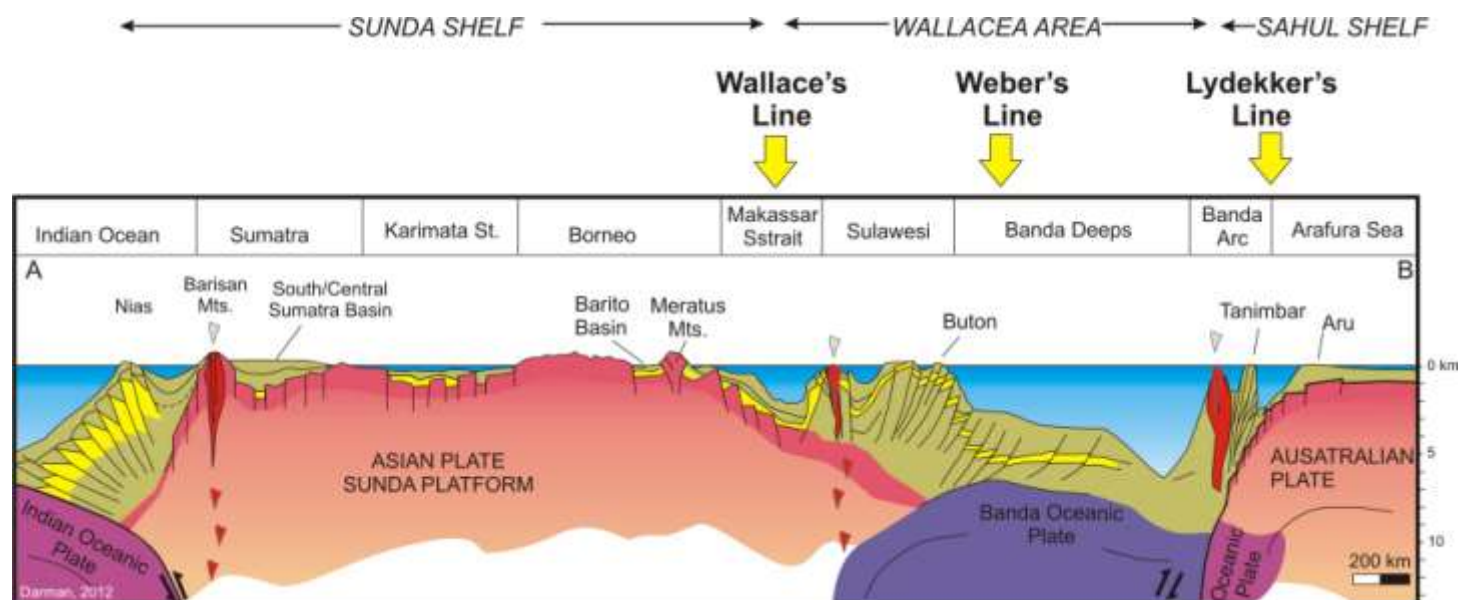


Figure 2. A schematic cross section across Indonesia showing the relationship of Sunda Shelf, Wallacea Area and Sahul Shelf. See Figure 1 for location. Wallace's line is located between Sunda Shelf and Wallace Area, close to the border between two tectonic plates (source Darman, 2012 in prep.)

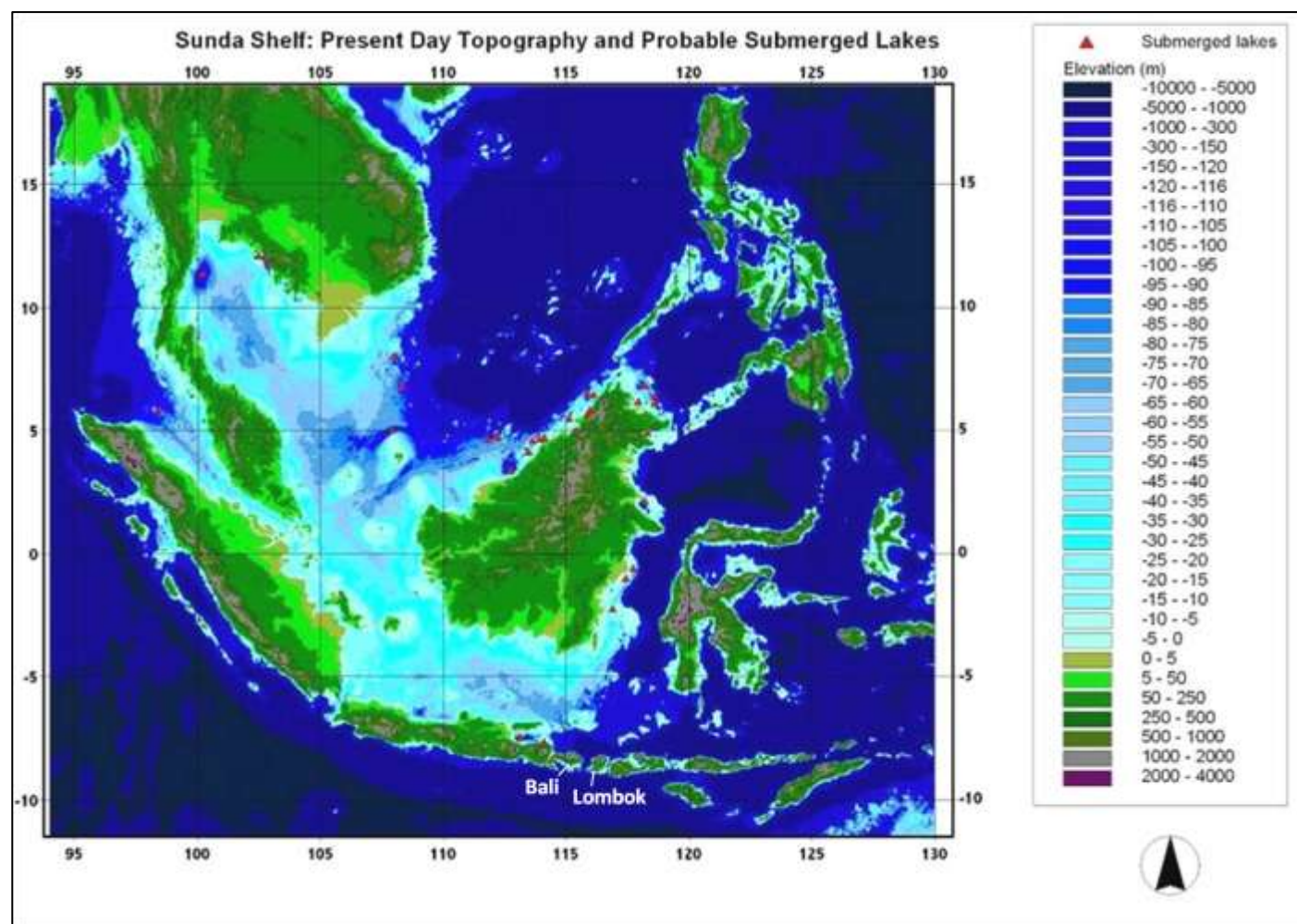


Figure 3. Bali and Lombok sit on different substrates. Bali sits on shallow shelf of the easternmost part of Sunda Shelf. By contrast, Lombok sits on the deep Flores Sea. This difference creates a geological gap between Bali and Lombok affecting faunal distribution in both

Therefore, although the Wallace Line was primarily a biologic line, already since the beginning Wallace thought that the line could also have a geologic meaning. This

short note discusses geologic control of the Wallace Line between Bali and Lombok.

Currently it is known that the position of the line is geologically-dependent, as a result of plate tectonic movements. Geologically, the physiographic configuration of Indonesia consists of three parts: the Sunda Shelf on the west, the Arafura/Sahul Shelf on the east, and the Wallacea area in between (Figures 1 and 2). The islands of Sumatra, Kalimantan, Java and Bali lie on the Sunda Shelf and are therefore the part of Asian Block/Sundaland. Papua lies on the Arafura/Sahul Shelf and is part of the Australian Block. The area between these two shallow seas is known as Wallacea, encompassing Sulawesi, Maluku and smaller islands called the Lesser Sunda islands, starting with Lombok on its westernmost part (Figure 1).

Since Bali is part of the Asian Block and Lombok is part of the Wallacea region, the area separating Bali and Lombok is a geological gap, occupied the deep Lombok Strait. It connects the eastern part of the Java-Flores Seas to the Indian Ocean. The strait is 20 to 40 km wide, 60 km long, and 250 m deep. The Lombok Strait is one of the main passages for the Indonesian major through flow current that exchanges water between the Indian Ocean and the Pacific Ocean.

Conclusions

Understanding the biogeography of the region depends on understanding the relationship of ancient sea levels to the continental shelves (Figure 3). Wallace's Line is geographically critical when the continental shelf contours are examined; it can be seen as a deep-water channel that marks the southeaster edge of the Sunda Shelf linking Borneo, Bali, Java, and Sumatra underwater to the mainland of southeastern Asia. Likewise Australia is connected via the shallow sea over the Sahul Shelf to New Guinea.

During ice age glacial advances, when the ocean levels were up to 120 metres (390 ft.) lower, both Asia and Australia were united with what are now islands on their respective continental shelves as continuous land masses,

Bali is a continental island that sits on the continental shelf called Sunda Shelf, currently separated from the mainland by a sea strait. By contrast Lombok is an oceanic island; it rises from the ocean floor in isolation and is not part of the continental shelf. Both Bali and Lombok are parts of Sunda inner volcanic arc, formed after the mid-Miocene (< 15 Ma). Both islands appeared above sea level during the late Miocene-Pliocene.

Biologists believe it was the depth of the Lombok Strait that isolated animals on either side. When the sea levels dropped during the Pleistocene ice age, the islands of Bali, Java and Sumatra were all connected to one another and to the mainland of Asia. They shared the Asian fauna. The Lombok Strait's deep water kept Lombok and the Lesser Sunda islands in isolation from the Asian mainland. These islands were colonized by Australasian fauna.

Ornithologist G.A. Lincoln studied birds in Java, Bali, Lombok and Sumbawa, on either side of the Wallace Line in the 1970s (van Oosterzee, 1997). He found that on Java and Bali the birds were nearly all Oriental and dominated by the Oriental Bulbul. On crossing the Wallace Line from Bali to Lombok the birds were predominately Australian.

but the deep water between those two large continental shelf areas was, for over 50 million years, a barrier that kept the flora and fauna of Australia separated from those of Asia. Wallacea area consists of islands that were never recently connected by dry land.

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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.

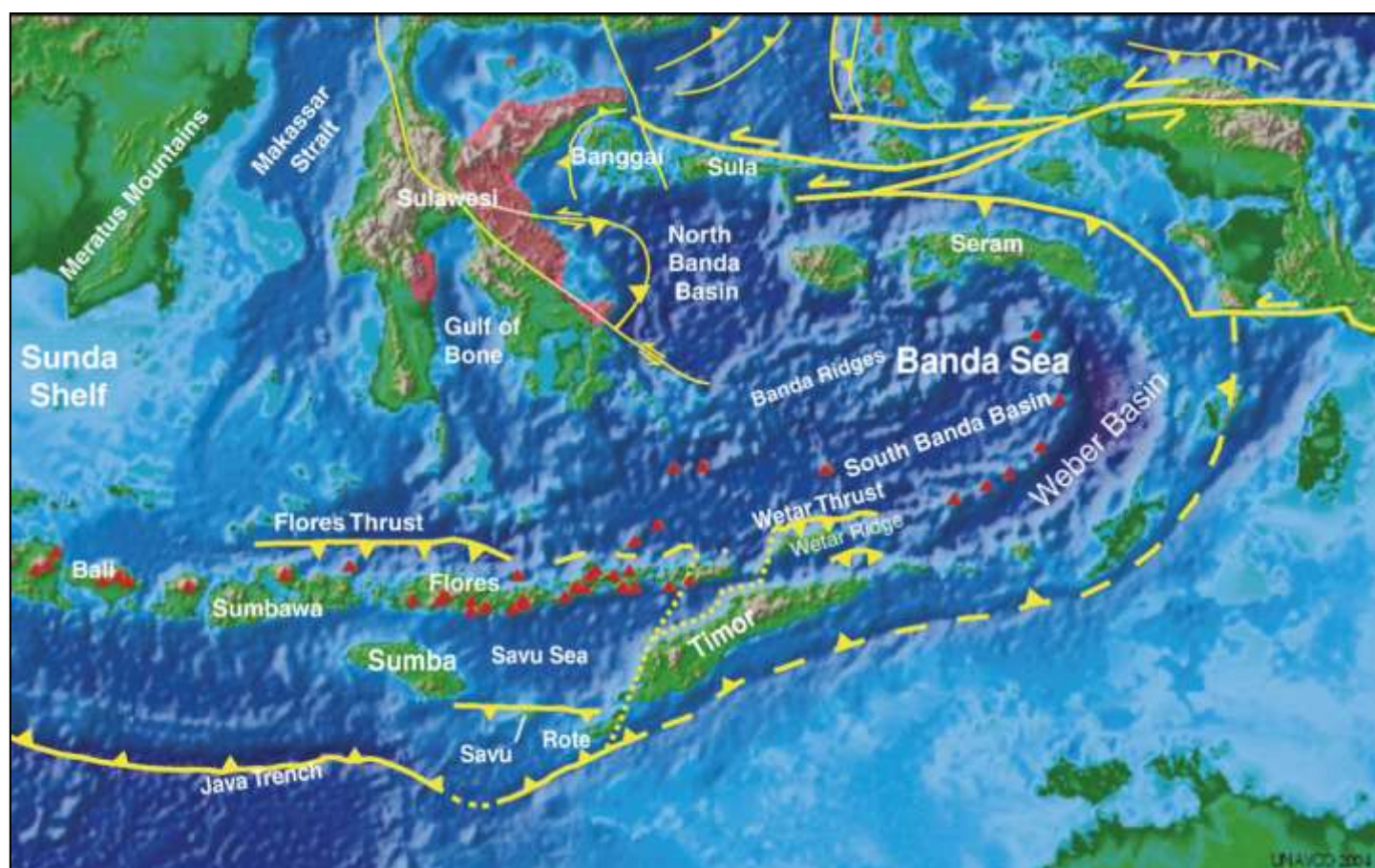


Figure 1. Tectonic elements of eastern Indonesia with focus on East Sunda-Banda Arc (from Harris, 2006). Red triangles mean active volcanoes

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).

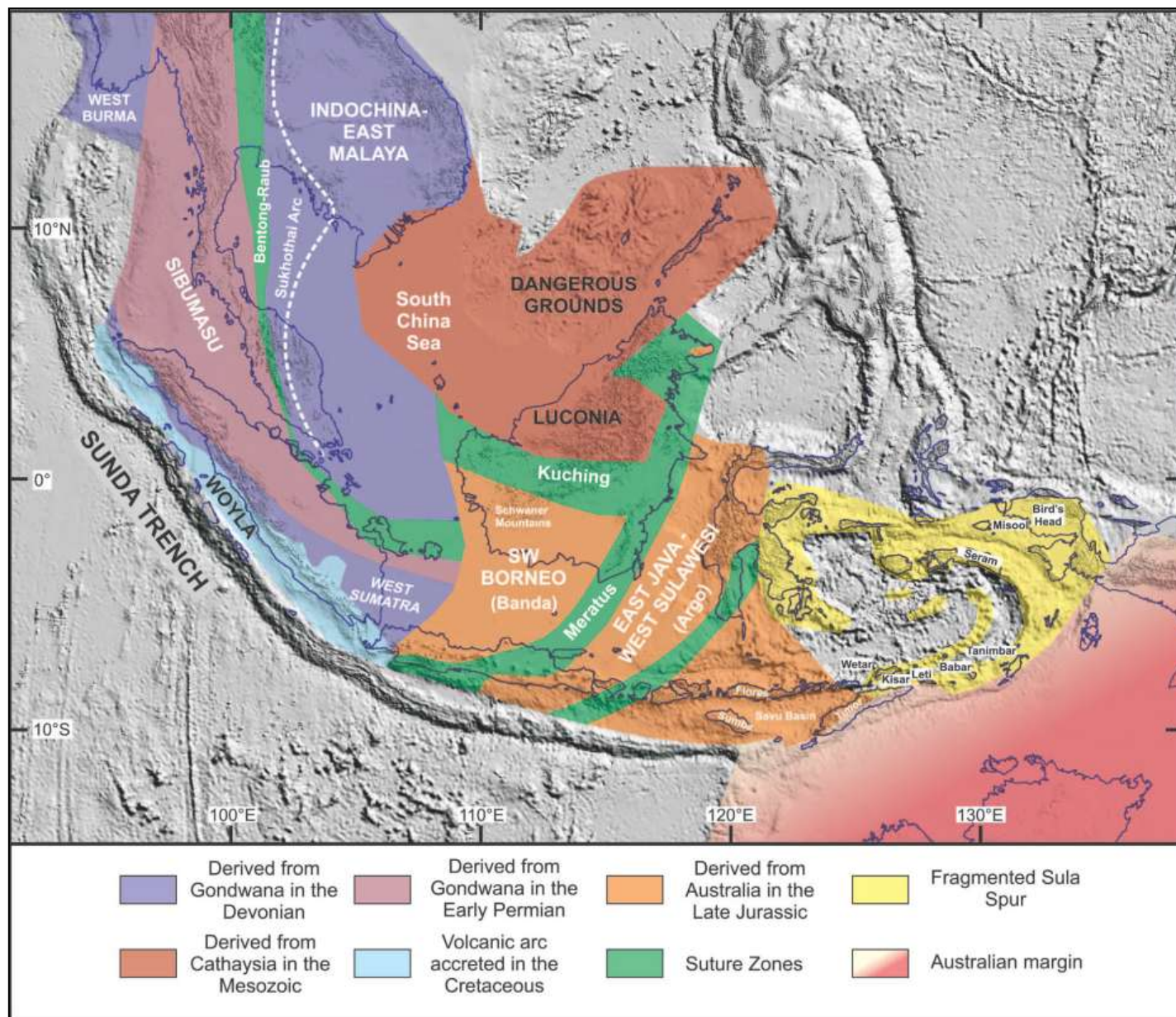


Figure 2. Principal crustal blocks in SE Asia. Green colour means ophiolitic/arc suture, orange colour means continental crust (from Hall & Sevastjanova, 2012)

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

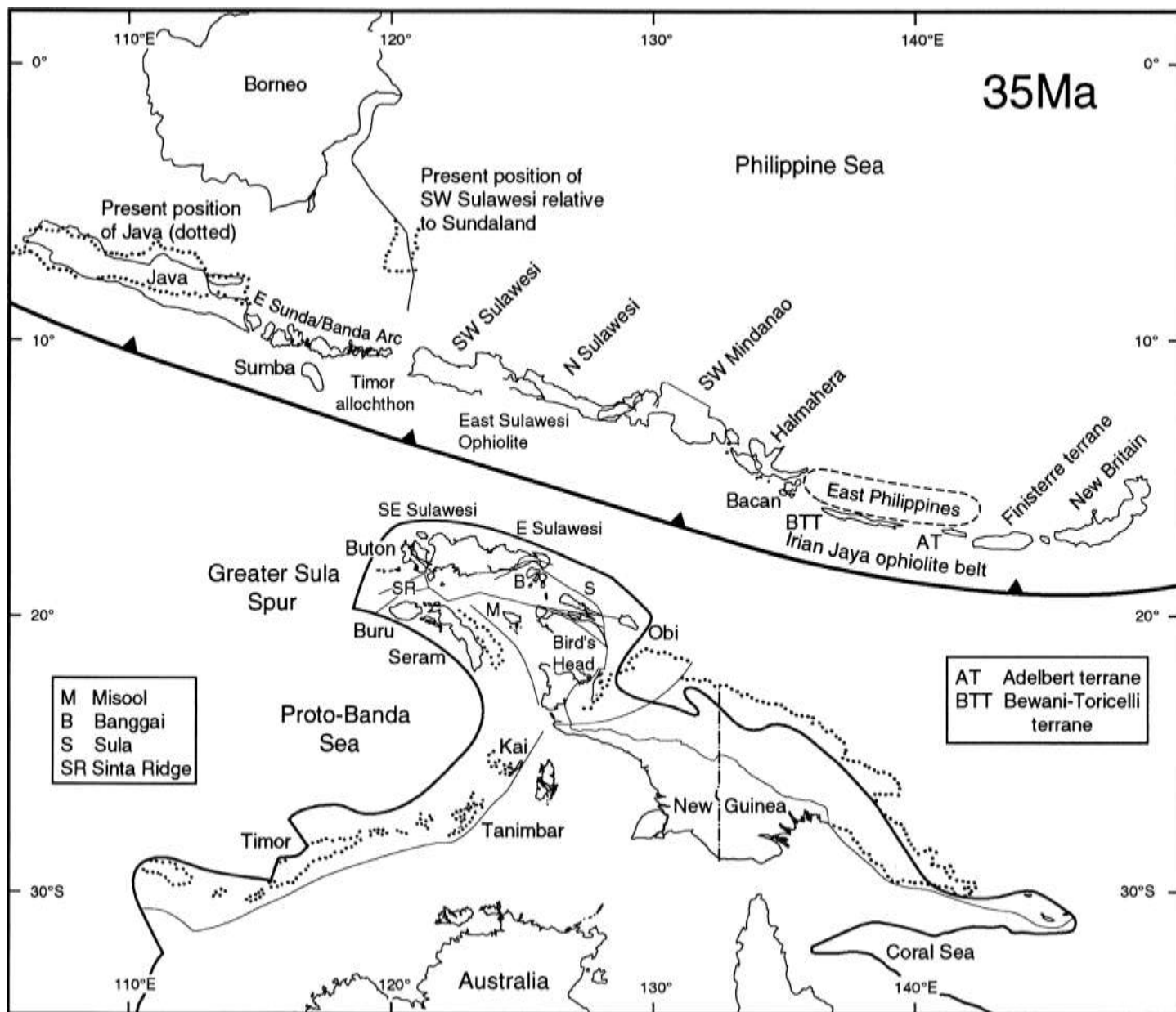


Figure 3. Tectonic reconstruction of eastern Indonesia at ca. 35 Ma, as proposed by Charlton (2000)

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 a 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

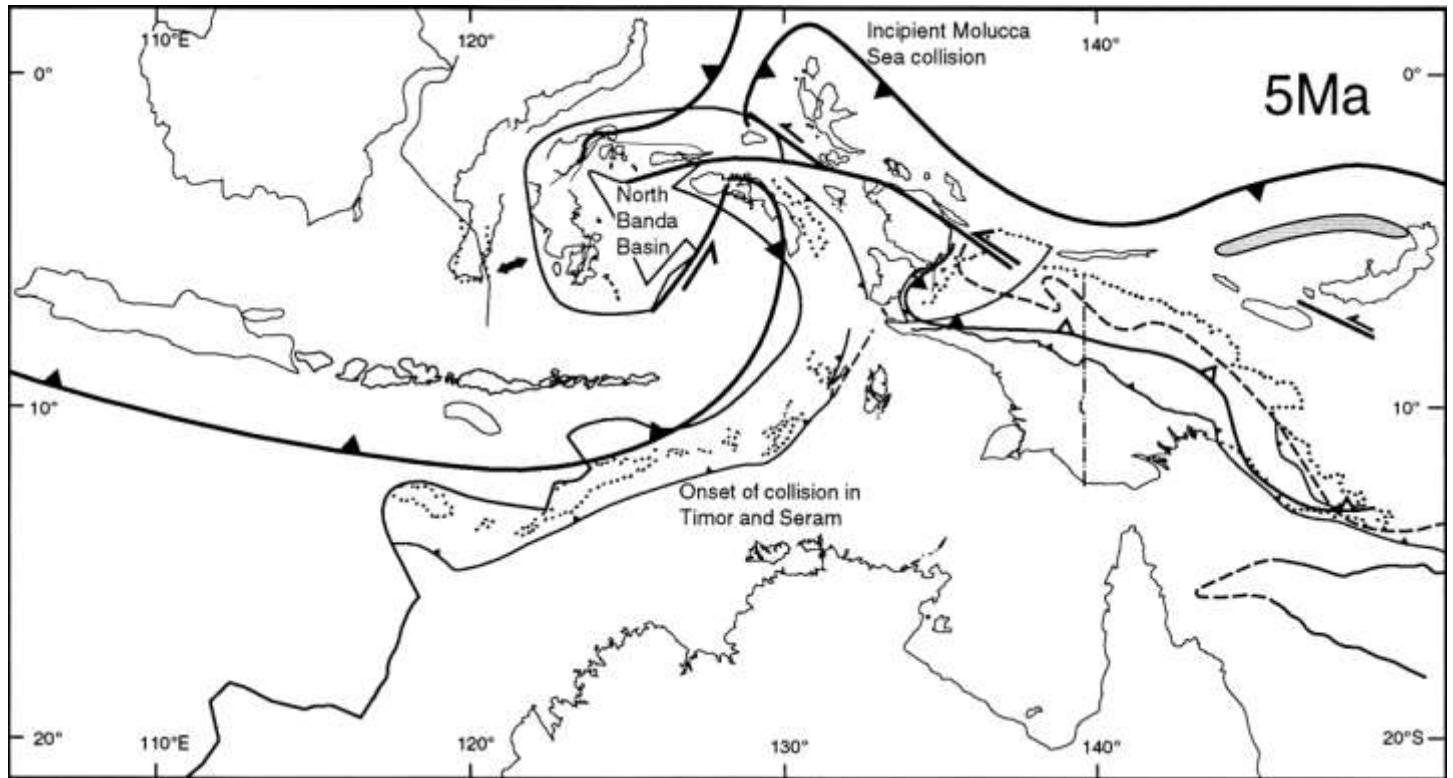


Figure 4. Tectonic reconstruction at ca. 5 Ma as proposed by Charlton (2000)

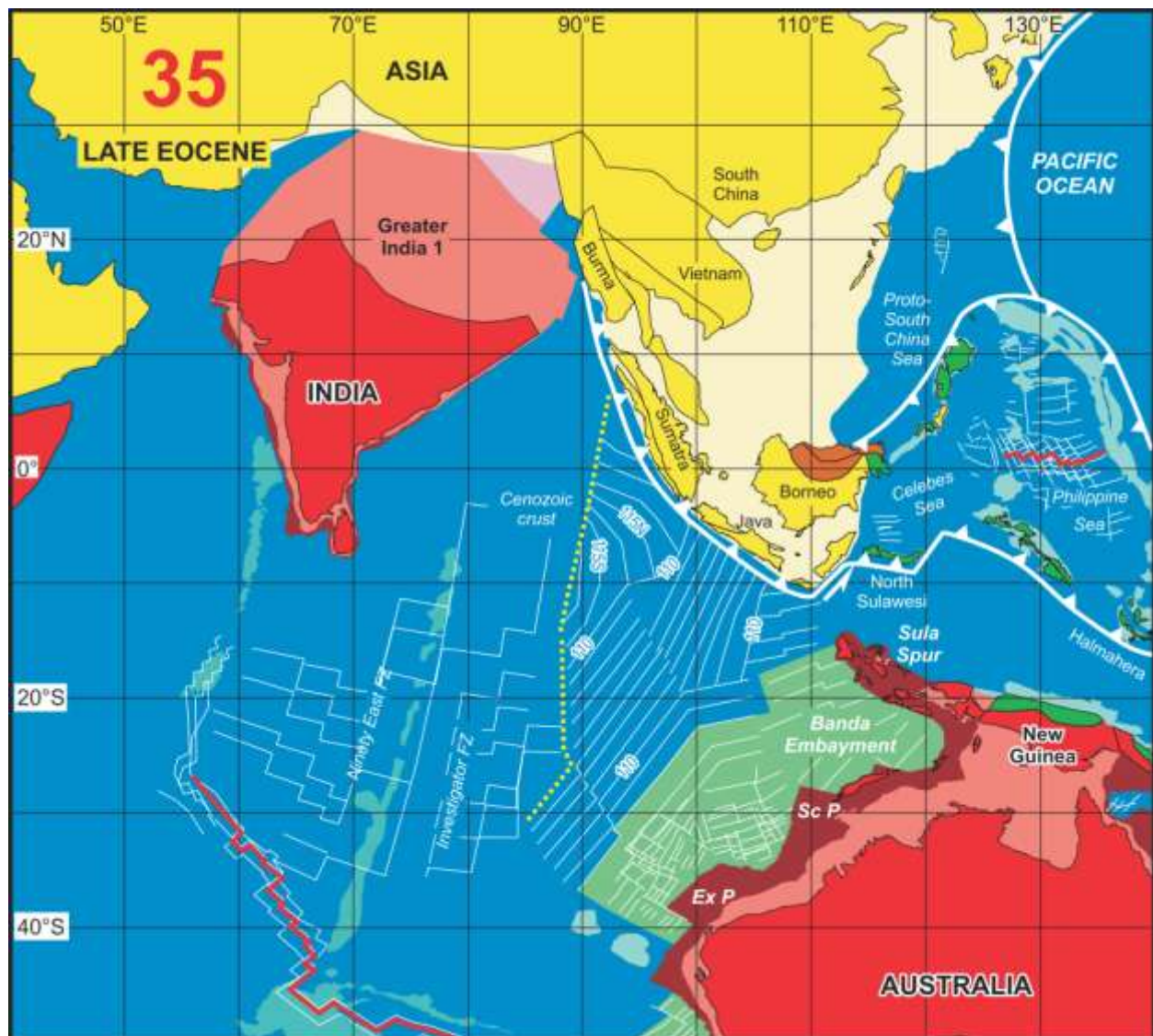


Figure 5. Reconstruction of Indonesia region at ca. 35 Ma proposed by Hall (2012)

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).

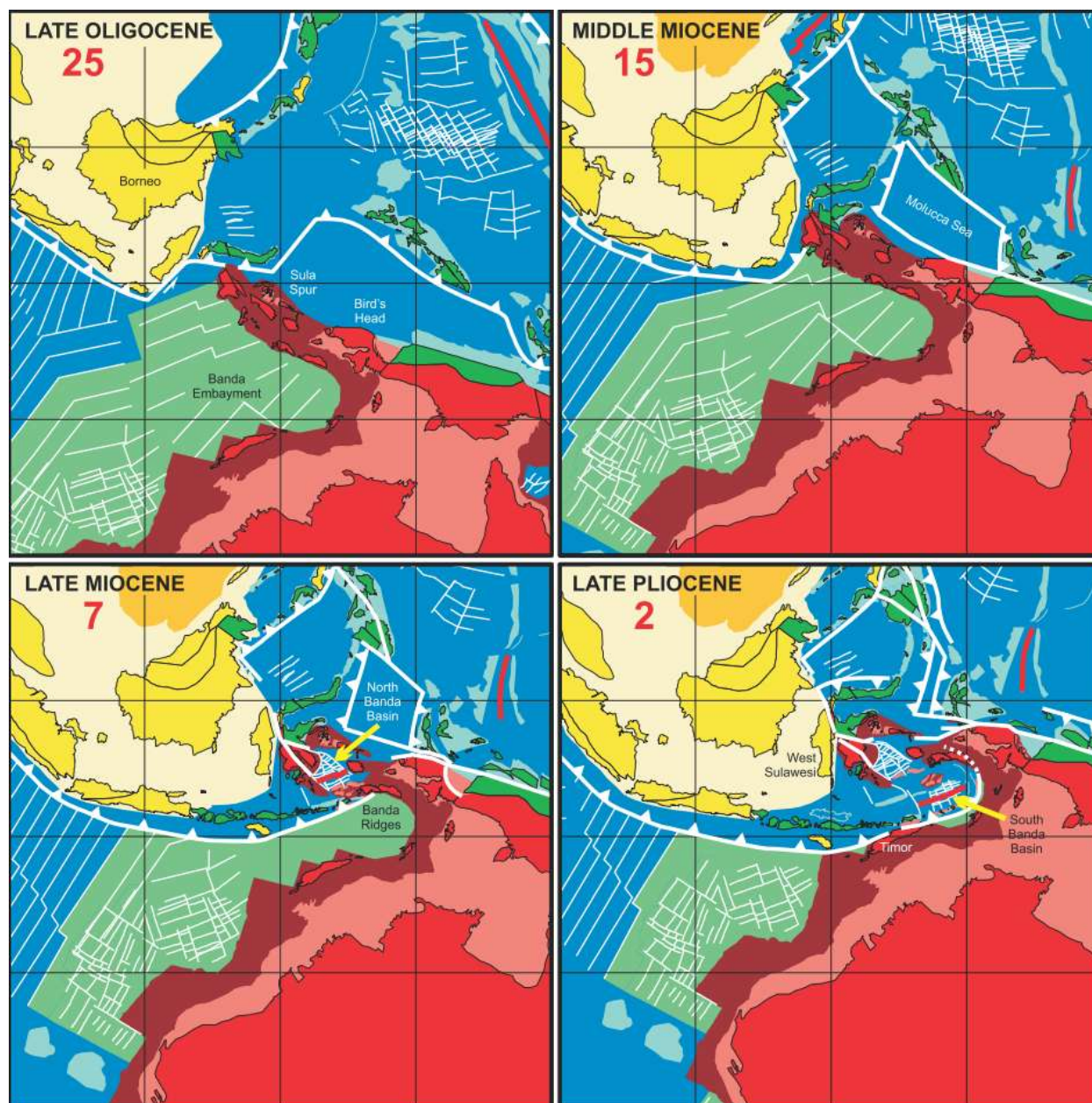


Figure 6. Detailed reconstruction of Banda region at 25 Ma, 15 Ma, 7 Ma and 2 Ma (Hall, 2012)

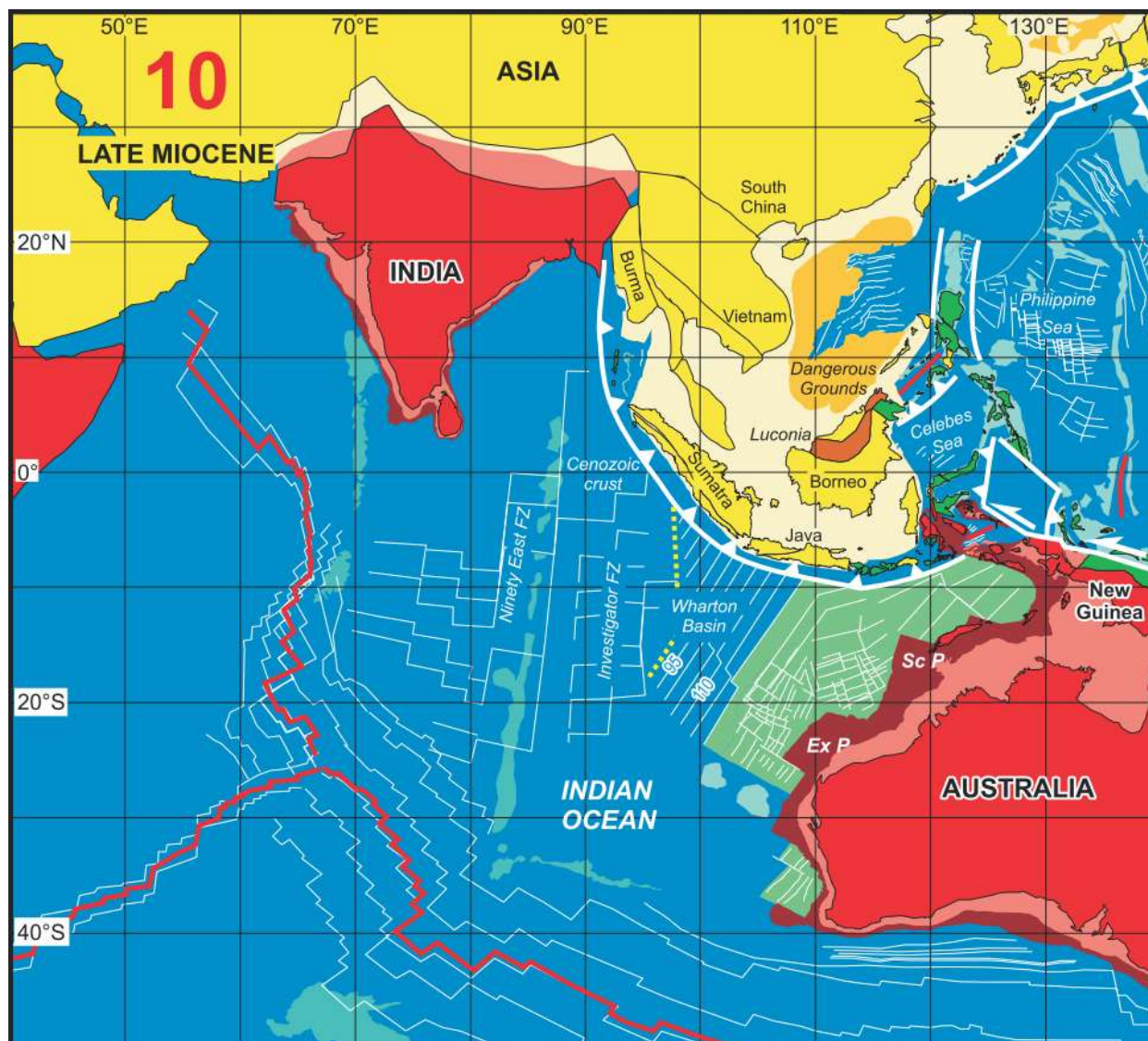


Figure 7. Reconstruction at ca. 10 Ma (Hall, 2012)

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 $^{206}\text{Pb}/^{204}\text{Pb}$ 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 $^{206}\text{Pb}/^{204}\text{Pb}$ 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.

Acknowledgements

I would like to thank J.T. van Gorsel (www.vangorselslist.com) and Nugroho Setiawan (Kyushu University, Japan) for reviewing this article. Comments and discussions from J.T. van Gorsel in particular have greatly improved this article.

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Seismic Expression of Tectonic Features in the Lesser Sunda Islands, Indonesia

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Introduction

The Sunda Arc is a chain of islands in the southern part of Indonesia, cored by active volcanoes. The western part of the Sunda arc is dominated by the large of Sumatra and Java, and is commonly called 'the Greater Sunda Islands'. The tectonic terrain within this part is dominated by the oceanic subduction below the southeastern extension of the Asian continental plate, which is collectively known as the Sunda Shield, Sunda Plate or Sundaland. Towards the east the islands are much smaller and are called 'the Lesser Sunda Islands' (Fig. 1). The transition from oceanic subduction to continent-island arc collision developed in this area, while further west the Banda Arc marks full continent to island arc collision between Australia and the Asian plate. The Australian lithosphere, which is interpreted as Precambrian continental crust (Hamilton, 1979) is moving northward at a rate that currently varies from 6.7 to 7 cm/year

The Sunda Arc has long been considered as a classical accretionary margin system where the Indo-Australian oceanic plate is underthrust beneath the Asian

Continent, active since the Late Oligocene (Hamilton, 1979). At the eastern end of the Sunda Arc the convergent system changes from oceanic subduction to continent-island arc collision of the Scott Plateau, part of the Australian continent, colliding with the Banda island arc and Sumba Island in between (Figure 1).

The Lesser Sunda Islands are also called the inner-arc islands. The formation of these islands is related to the subduction along the Java Trench in the Java Sea. The island of Bali marks the west end of the Lesser Sunda Islands and Alor Island at the east end (Fig. 2). To the south of the inner-arc islands, an accretionary wedge formed the outer-arc ridge. The ridge is subaerially exposed in the east as Savu and Timor Island. The northwest of the Lesser Sunda Islands are underlain by a Late Cretaceous Accretionary Crust, which changes to an oceanic crust in the northeast (Doust & Lijmbach, 1997; Fig. 1). The Sumba Island has a unique orientation and the origin of the island is still debated (Rutherford et al., 2001, Longley et al 2002, Hall et al 2012).

The aim of this article is to provide a broad overview about the structures of the tectonic units based on some selected seismic lines. These lines also give a better geological understanding, including recent processes that developed in the area.

Seismic data

A number of surveys have been deployed in the past 30 years to acquire seismic data in this area. Selected seismic data used for this article were acquired in the following expeditions:

- R. V. Vema cruise 28 and R. V. Robert Conrad cruise 11 (in Hamilton, 1979)
- Rama 12 expedition (Prasetyo, 1992; Scripps Institute of Oceanography, <http://www.ig.utexas.edu/sdc/>)
- R. V. Baruna Jaya late 90's (Krabbenhoef, A., 2010) for bathymetric data acquisition.

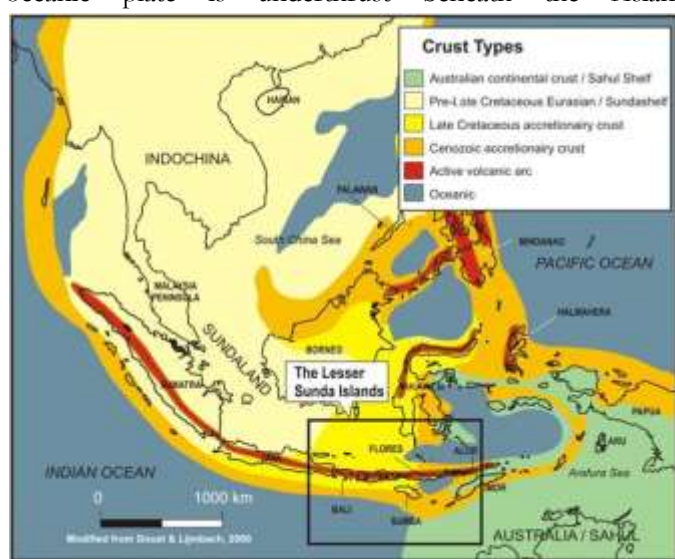


Figure 1 Map of Southeast Asia showing the different crustal type in the region and the location map of the Lesser Sunda Islands (after Doust & Lijmbach 1997).

- R. V. Sonne, cruise SO190 (Lüschen et al, 2011)
- CGG Veritas Spec. Survey (Rigg & Hall, 2012)
- ION-GXT JavaSPAN 2008 (Granath et al, 2011)

The earlier surveys, such as R. V. Vema and R. V. Robert Conrad in Hamilton (1979) provided limited data as they were mainly restricted to information on bathymetry and shallow depth of image. The later images, acquired by CGG Veritas are considered as a modern industry standard for seismic, providing seismic images down to 8 seconds Two-Way-Time. Recent long cable with improved technology by ION helped to acquire seismic more than 10 km deep. These ION deeper sections help geoscientists

to acquire a better understanding about the basement structure and moho mantle to lithosphere transitions.

Tectonic features

The Lesser Sunda Islands area consists of several tectonic units (Fig. 2). Several regional seismic sections were acquired over these features with the more recent lines giving improved geological understanding about crustal composition and the tectonic processes.

1. Outer-arc Ridge

The outer-arc ridge, or also called the fore-arc ridge is an accretionary wedge formed by the subduction of the

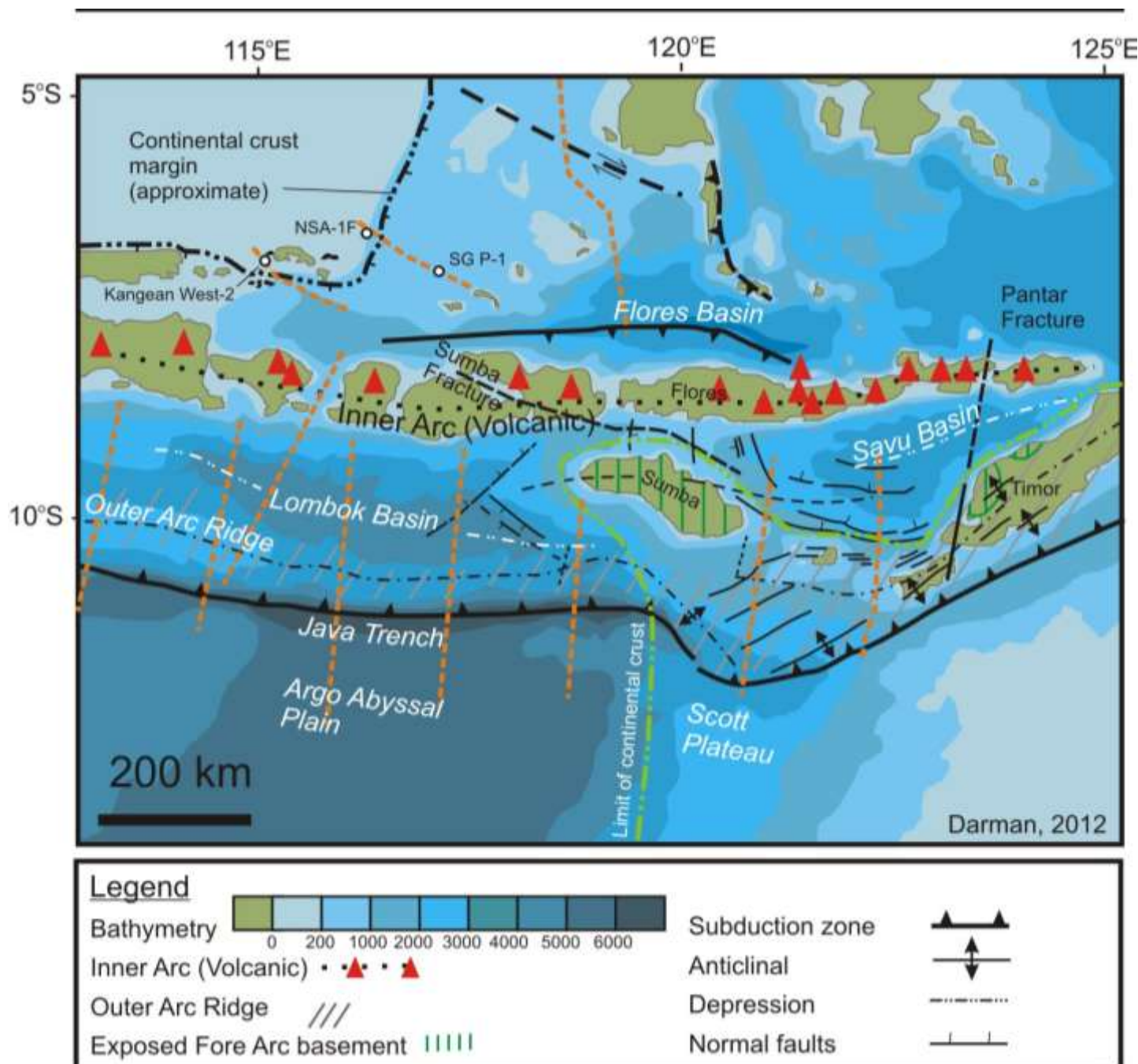


Figure 2 Tectonic map of the Lesser Sunda Islands, showing the main tectonic units, main faults, bathymetry and location of seismic sections discussed in this paper.

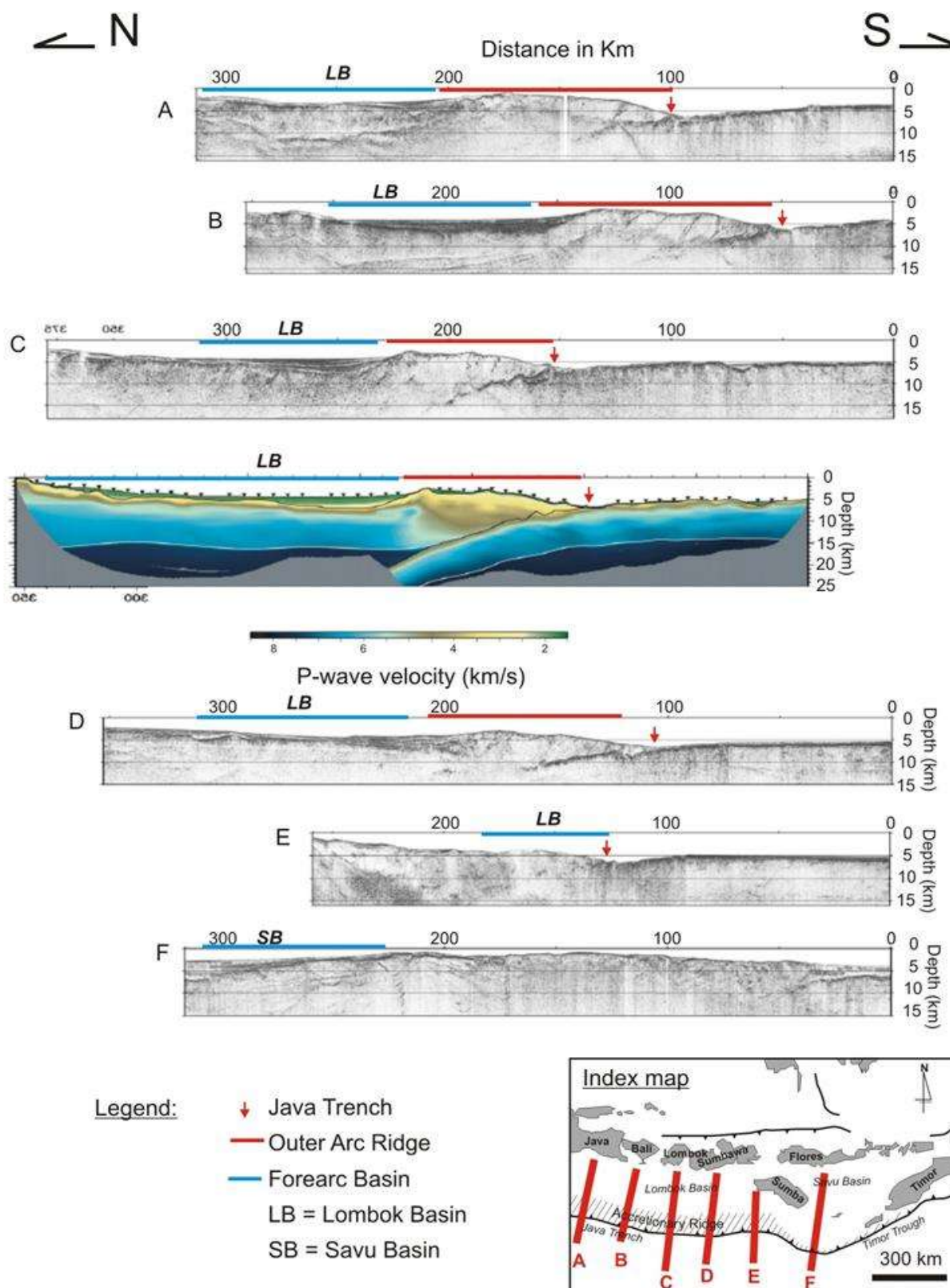


Figure 3 Six 15 km deep seismic sections acquired by BGR from west to east traversing oceanic crust, deep sea trench, accretionary prism, outer arc high and fore-arc basin, derived from Kirchhoff prestack depth migration (PreSDM) with a frequency range of 4-60 Hz. Profile BGR06-313 shows exemplarily a velocity-depth model according to refraction/wide-angle seismic tomography on coincident profile P31 (modified after Lüschen et al, 2011).

Indian plate. In the west of the Lesser Sunda Island region, the Outer Arc Ridge formed about 3000 m below sea level, parallel to the Inner Arc. To the east, the outer-arc ridge is exposed sub aerally as the outer-arc islands of Roti and Timor. (Fig. 2) which are believed to have formed when the northern leading edge of the Australian continental plate was refused entry to the subduction zone due to all oceanic crust having been consumed. (Audley-

Charles 2012). These islands are mainly composed of raised shallow and deep marine sediments. Mud diapirs and mud volcanoes are common in the outer-arc islands (Hamilton, 1979; Zaim, 2012). The outer arc is bounded by the Java Trench which marked the subduction point in the south. The northern margin of the Outer Arc Ridge is partly covered by the fore-arc basin sediment fill.

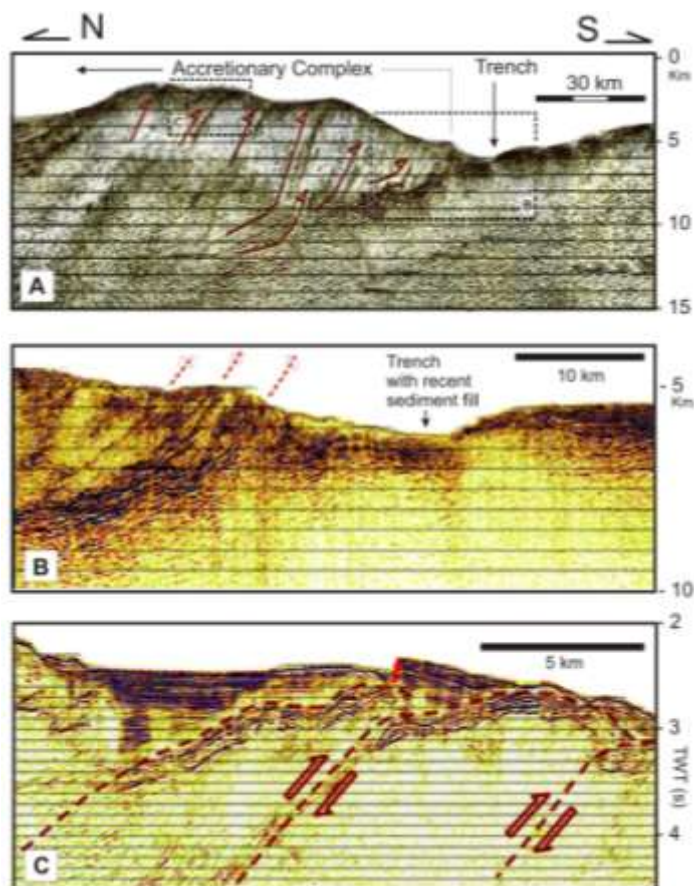


Figure 4 Detail sections of BGR06-303. A) Outer-arc ridge with thrust faults which formed the accretionary complex. B) Detail section of A) showing the trench sediment fill and the thrust faults in the north of the section. C) Detail section of A) showing the sediment fills of the Piggy-Back Basin, with relatively undisturbed flat surface on the north. The active fault has disturbed the continuation of the

sediments in the south of the section.

Figure 3 shows regional seismic sections acquired by the Sonne cruise in the region (Lüschen et al, 2011). Section - A, B, C and D in this figure show similar patterns of the outer-arc ridge. The subduction zone in the north of the trench and below the accretionary complex is well imaged. Lüschen (2011), also provide detail seismic images of Section B in Figure 4, showing the structures of the outer-arc ridge. The outer-arc ridge is a structurally complex unit with a series of thrust faults (Fig. 4A and further detail in Fig 4B). Some of these faults generated topographical relief on top of the outer-arc ridge and formed 'piggy-back basins', about 4 km wide and 0.5 second 'TWT' deep, which are filled with recent sediments from surrounding structural highs. On seismic these sediments appear as brighter and relatively flat reflectors throughout the section to the surface (Fig. 4C).

Sections E and F in Figure 3, located in the east of the area, show different patterns compared to the sections A to D in the west. The outer-arc ridge in Figure 3E has a gentle relief and the thrust faults are not as clear as the sections in the west. Figure 3F also shows a gentle and wider relief. The difference between the Sections A to D in the west and Sections E to F two in the east reflects the transition from oceanic subduction to continent to continent-island arc collision in the east and west respectively (Kopp, 2011).

Lüschen et al, 2011, also mapped piggy-back basin development in the centre of the Outer Arc Ridge which

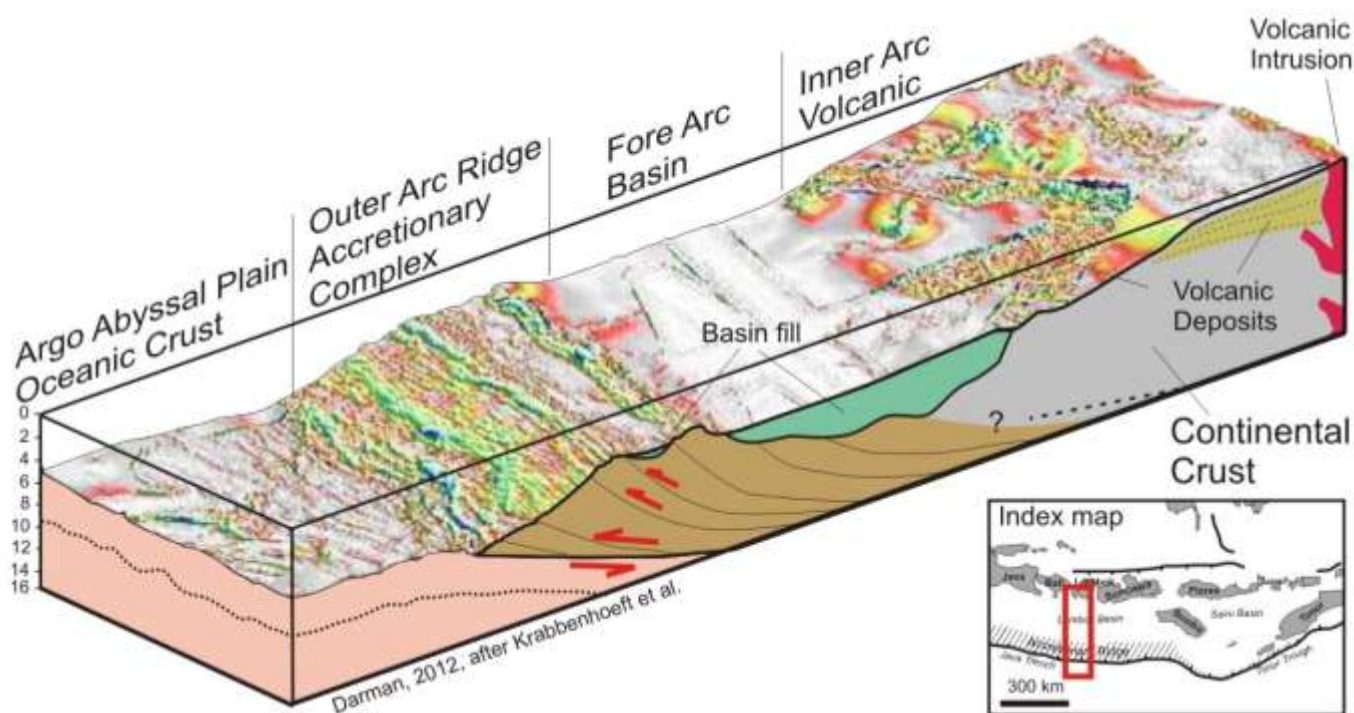


Figure 5 Block diagram of the southern part of Lombok Island. The surface is a gradients map of bathymetric data. Gradients are draped on perspective view of bathymetric relief. Trench, outer wedge, slope break and inner wedge are indicated. The section is modeled based on sea bottom profile (after Krabbenhoef et al, 2010).

was created by the thrust fault system. These basins are generally small and filled with recent sediments. Similar to the trench deposit, these basins are characterized by semi

parallel reflectors with flat surfaces (Fig. 3C).

2. Fore-arc Basin.

Depressions in the seabed between the inner volcanic arc

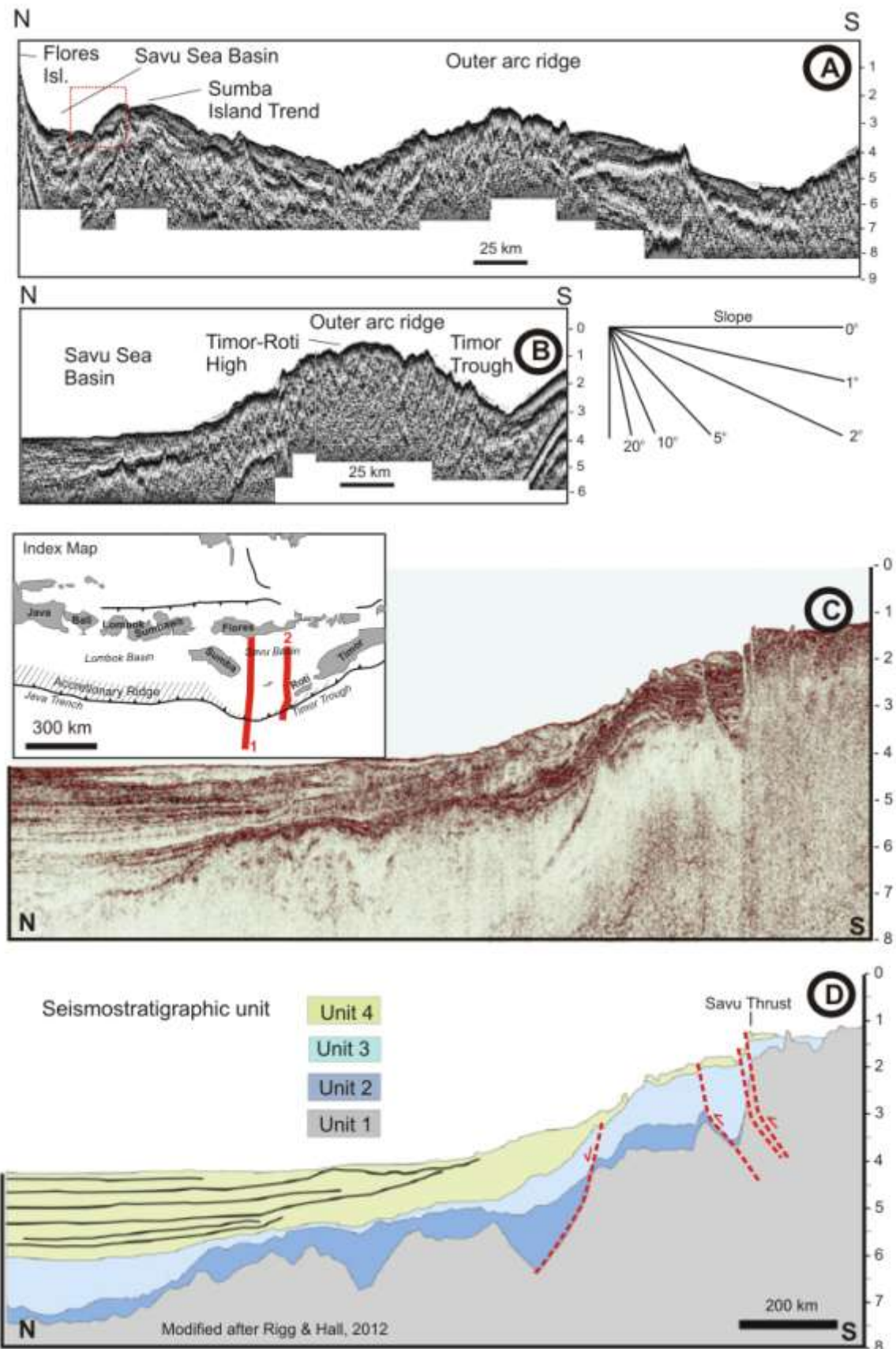


Figure 6 North-south seismic sections across the Savu Basin. A) Rama expedition seismic, shows the relationship of the outer-arc ridge, Sumba Island high, Savu basin and Flores Island in the north. B) Another Rama expedition seismic in the centre of Savu Basin. C) A CCG Veritas seismic lines parallel to section 6B with higher resolution image with the seismo-stratigraphic unit interpretation in D).

and the outer-arc are known as fore-arc basins. The fore-arc basin in the west is called the Lombok Basin (Fig. 2). Further east, the Savu Basin is a continuation of fore-arc basin located in the eastern Lesser Sunda Islands, separated from the Lombok Basin by Sumba Island.

The Lombok Basin is an elongated basin in the south of Bali, Lombok and Flores Island. The basin is about 600 km long and 200 km wide. Water depths in this basin are

direction. The basin is narrowing to the east. To volcanic island arc bounded the north part of the basin (Fig. 1).

Figure 6A and 6B shows 2 regional seismic sections across the Savu Basin, acquired during Rama expedition in early 1980's. The section on the west (Fig. 6A) shows the narrow part of the basin, with the southern flank of the volcanic arc (Flores Island) in the north and the east continuation of the Sumba Island high in the south. A

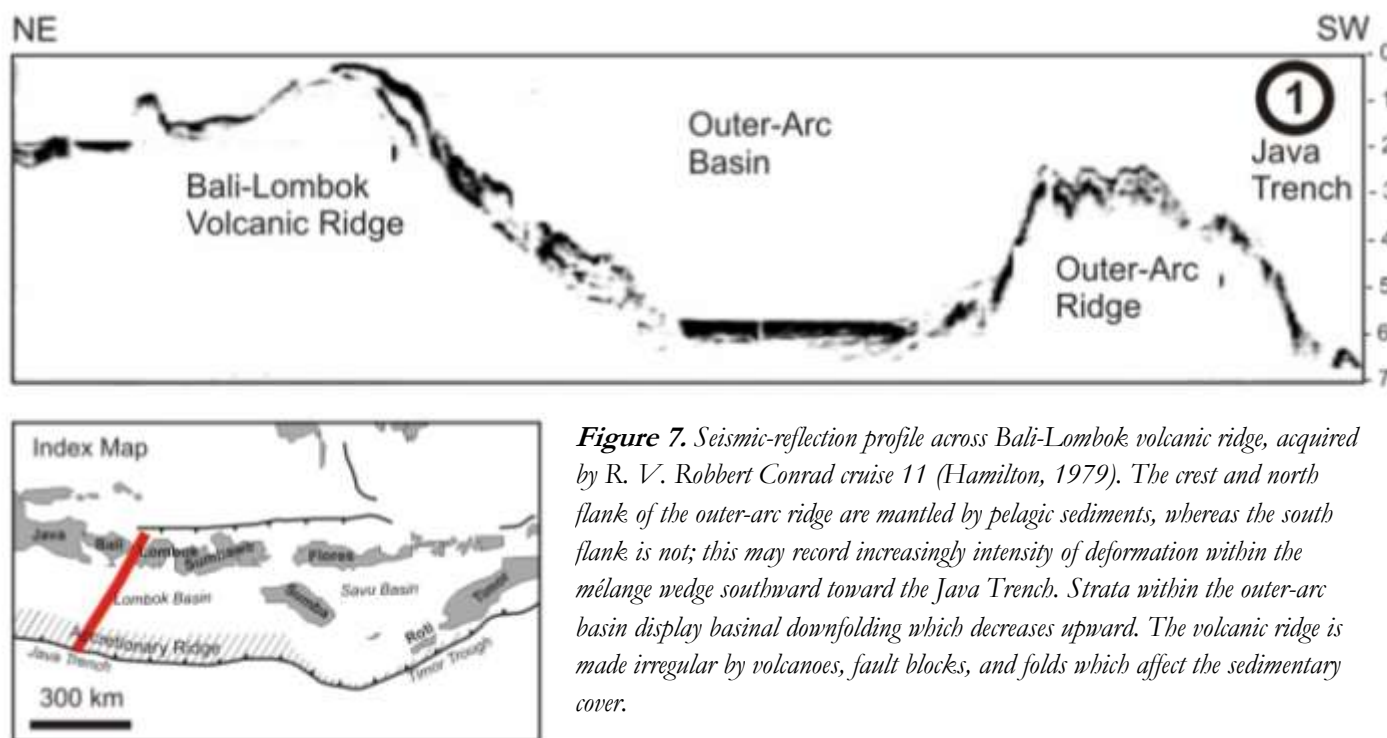


Figure 7. Seismic-reflection profile across Bali-Lombok volcanic ridge, acquired by R. V. Robbert Conrad cruise 11 (Hamilton, 1979). The crest and north flank of the outer-arc ridge are mantled by pelagic sediments, whereas the south flank is not; this may record increasingly intensity of deformation within the mélange wedge southward toward the Java Trench. Strata within the outer-arc basin display basinal downfolding which decreases upward. The volcanic ridge is made irregular by volcanoes, fault blocks, and folds which affect the sedimentary cover.

about 4000 to 5000 m (Fig. 2) as indicated on seismic profiles (Sections A to D (Figure 3) which indicate undeformed gentle surfaces with relatively undisturbed beds. The seismic reflectors are brighter compare to the outer arc ridge. The reflector packages are getting thinner at the basin margin. Lüschen et al (2011) provided the P-wave velocity values of section C in Figure 3, which differentiate between the Lombok Basin and the outer ridge.

Figure 5 shows the relationship between the fore-arc basin with the outer-arc ridge in the south and the inner arc in the north. The inner arc supplied a significant amount of volcanic material to the fore-arc basin. These sediments cover the contact between the accretionary complex and the volcanic system.

The Savu fore-arc basin developed in the east of the Lesser Sunda islands, where there is a change from oceanic subduction to arc-continent collision (Rigg and Hall, 2012). In parts the water depth of Savu Basin is deeper than 2000 m. The Savu Basin is bounded to the west by the island of Sumba and by a submarine ridge (the Sumba Ridge) that crosses the fore-arc obliquely in an NW-SE

detail section of the southern margin of the basin is shown in Fig. 6C with seismo-stratigraphic interpretation (Fig 6D) by Rigg and Hall (2012). At the south end of this section Unit 1 is uplifted and thrust northwards towards the basin while Units 2, 3 and 4 are largely missing and interpreted to have been redeposited in the basin as Unit 4. Figure 6D shows a significant southward thinning of Unit 3 and 4. Steep dipping of the base of Unit2 is probably controlled by faults. Unit 3 is generally a brighter reflective package which wedges out to the north (Fig. 6C). A rather transparent seismic package developed in the north part of the unit. The top of Unit 4 is relatively undisturbed in the distal part. Please explain what this means in terms of tectonic history?

3. Inner Arc – Volcanic

The Inner volcanic arc islands are some of the simplest geological structures within this complex region, and are certainly simpler than the outer-arc islands. The islands arc is basically a chain of young oceanic volcanic islands, often ringed by reef limestones or by pyroclastics and detritus eroded from the volcanic cones. In general, the age of the

volcanic cones become progressively younger from west to east, following the evolution of the Banda Arc eastward from the Sumba Fracture (Monk et al, 1997).

Figure 7 shows a seismic section acquired between Bali and Lombok island by Robert Conrad cruise 11 (Hamilton, 1979). The volcanic ridge is made irregular by volcanoes, fault blocks, and folds which affect the sedimentary cover. The southern flank of the volcanic ridge is rich of volcanic deposits. A smaller sea bottom high in the north is probably formed by volcanic intrusion.

4. Continental shelf edge

There are 2 continental margins in the vicinity of the Lesser Sunda Islands. The Australian Continental Shelf is located in the southeast of the Lesser-Sunda Islands with the Asian continental margin is located to the northwest.

The edge of the Australian continent is interpreted to be in the north side of Sumba and Timor Island (Fig. 1, after Harris et al, 2009). Unfortunately the seismic images acquire in these area are either too shallow or impaired quality to see of the edge of the Australian Continental Shelf.

The Sunda Shelf which marks the northern buttress of the collision zone is located in the northwest of the study area which has been surveyed by a deep seismic section

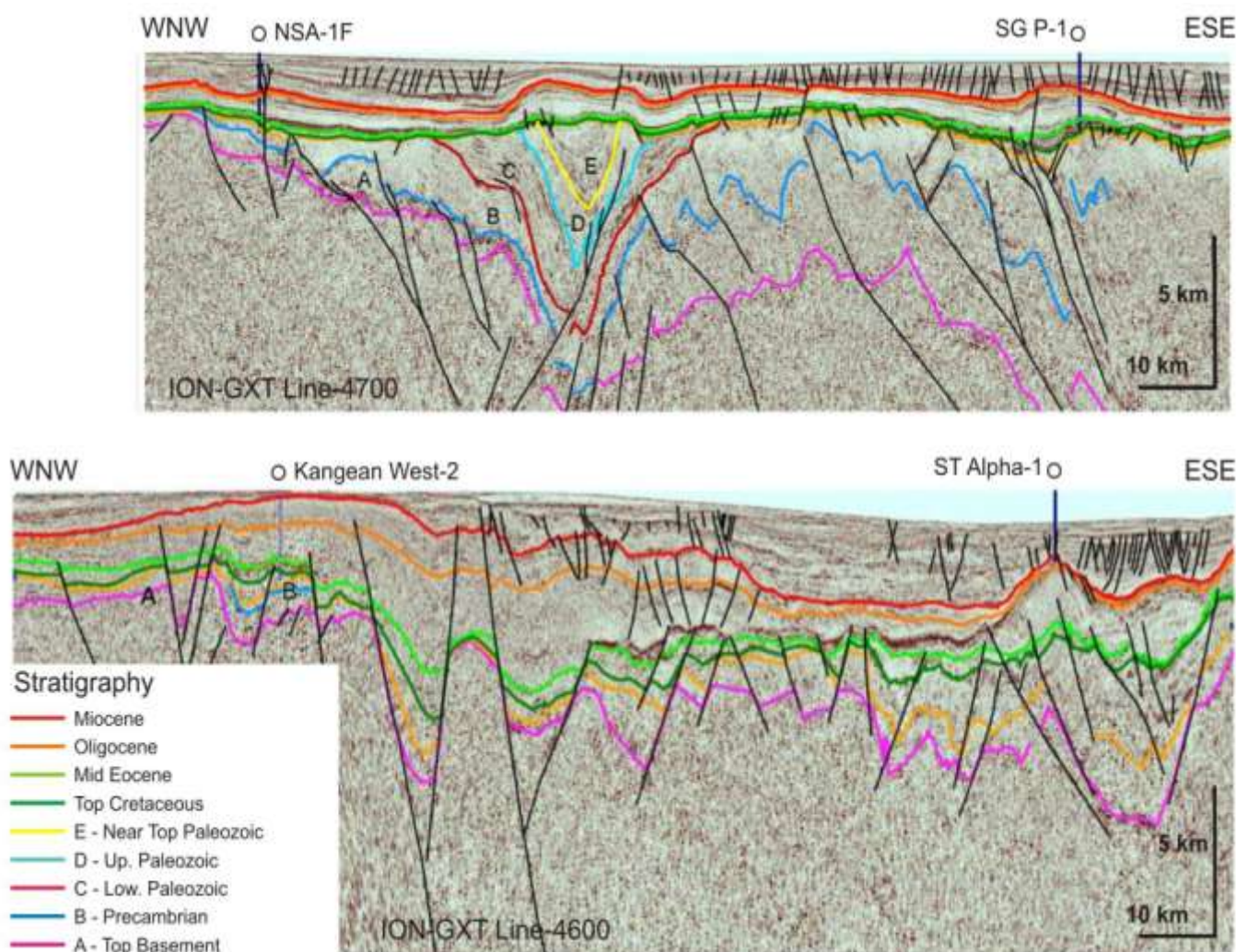


Figure 8. Two WNW-ESE seismic lines in the north of the Lesser Sunda Islands showing the potential margin of the Sunda Shelf or Eurasian Continental crust margin. These seismic sections were acquired by ION (Granath et al, 2011). A) Seismic line between NSA-1F and SG P-1 well with significant drop of basement (Horizon A) about 35 km ESE of NSA-1F. An isolated basement high raised about 30 km WNW of SG P-1 well. B) Seismic line between Kangean West-2 and ST Alpha-1. A significant horse-graben system developed in the east of Kangean West-2 which brought the basement (Horizon A) deeper towards the ESE.

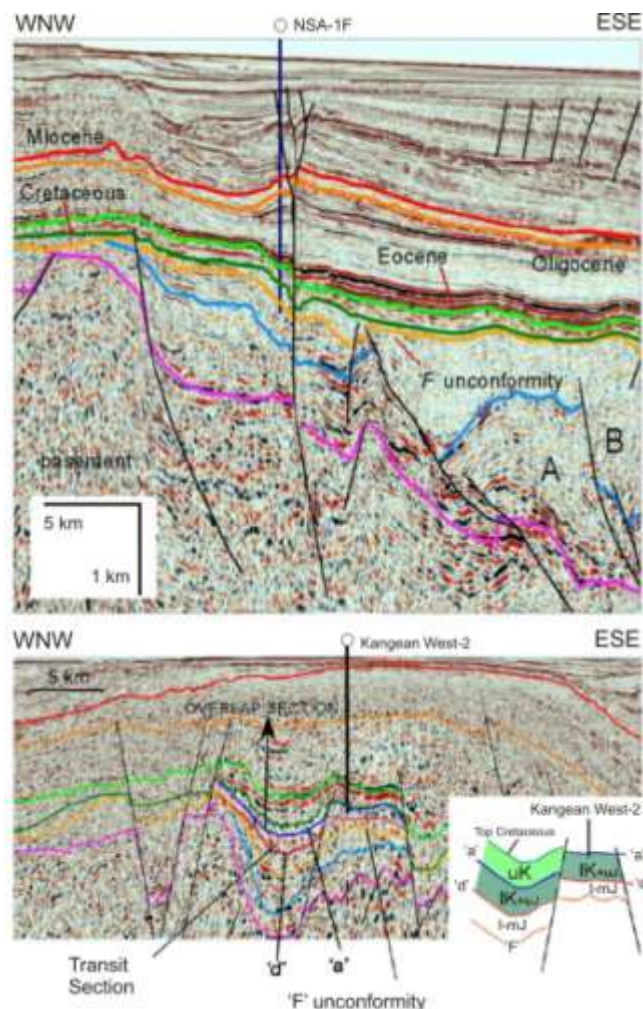


Figure 9. Detail sections of the profiles shown in Figure 7. A) A section located near to NSA-1F and B) A detail section located near to Kangean West-2 well.

acquired by ION (Fig. 8B) and allowed definition of top basement on this area Granath et al (2011). To the WNW, shallow basement beneath the NSA-1F (Fig. 9A) and Kangean West-2 (Fig. 9B) wells respectively are interpreted as being part of the Sunda Shelf while deeper basement in the ESE has been interpreted as Late Cretaceous accretionary crust (Doust & Lymbach, 1997). Hamilton, 1979, identified the latter area as Tertiary oceanic and arc crust.

5. Flores Basin

A west-east trend normal fault, which is dipping to the south, developed in the north of the Lesser Sunda Islands forming the Flores Basin. The Flores Basin is poorly understood as it is deep and covered only by sparse data. The map in Figure 1 shows that the water depth in this basin reaches about more than 4000 meters. A seismic section acquired by R. V. Robert Conrad (Fig. 10, Hamilton, 1979) shows a deep trench developed by the fault. Recent sediment accumulation is well imaged in this section at about 6.5 seconds.

Prasetyo (1992) published a number of seismic lines which cover Flores Basin and discussed the Flores Thrust Zone in great detail. The thrust zone is a prominent E-W oriented structural feature extending from east to the west of the Flores Basin. The fault zone separated south dipping sedimentary sequences, including Paleocene rift and related sediments, from complex deformed material to the south (Prasetyo, 1992)

6. Sumba Island

The position of the Sumba Island is unique. It is not part of the Sunda arc, which formed a lineation of volcanic islands in the north of Sumba. From the position it may be more related to Timor but it has different orientation (Fig. 1 and 2). The origin of the island is still a debate amongst worker on this area (Hall et al 2012, Longley et al 2002); however it is recognised as an exposed forearc fore-arc basement which is located between the Inner and Outer Arc. Several workers have considered Sumba Island as a micro continent within a region of arc-continent collision (Audley-Charles, 1975; Hamilton, 1979), and more recently as accreted terrane (Nur and Ben-Avram, 1982; Howell et al., 1983). De Werff et al (1994) and Harris et al (2009) conclude that the Sumba Island is a continuation of Timor which is an arc-continent collision zone.

Two major tectonic discontinuities; the Pantar and Sumba Fracture separate the Banda Arc from the Sunda Arc in the Lesser Sunda area. The Pantar Fracture extends approximately north-south between the island of Pantar and Alor, and the Sumba Fracture separates Sumba and Flores islands from Sumbawa (Nishimura and Suparka, 1986). Unfortunately the discontinuity of the arc, or the transition from Sunda to Banda arc is not clearly seen on seismic section. Nishimura and Suparka (1986) use 'fracture' to describe the separation, which indicates a small offset and therefore may not be imaged well on seismic sections, especially by older sections

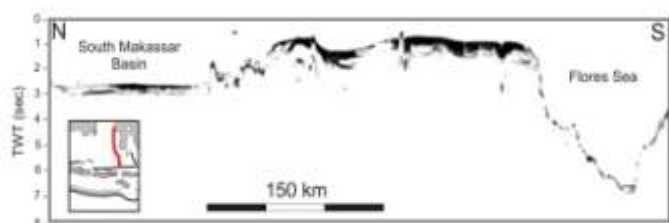


Figure 10. A N-S seismic section from Lamong Doherty Geological Observatory, acquired by R. V. Robert Conrad cruise 11 (Hamilton, 1979). This section shows little sediment on the narrow floor of the Flores Sea or Flores Basin, in contrast to the thick strata on the platform between that sea and the South Makassar Basin which probably consist of carbonate units.

Neo-Tectonic activity

The Sunda Arc is an active convergence zone producing hazards such as volcanic eruptions, earthquakes, and tsunamis which has been active since Eocene (Hall & Smyth, 2008). The overriding plate is continental including Sumatra and western Java (Kopp et al, 2001) and the basement below the forearc basin offshore Bali and Lombok is probably a rifted crust of a continental character in transition to oceanic character at Sumbawa and further east (Banda Sea, Van der Weff, 1996).

The Indo-Australian plate currently moves at 6.7 cm/annum in a direction N110E beneath western Java and is thus almost normal to the Java trench (Tregoning et al. 1994). Convergence speed slightly increases from western Java towards the east at a very subtle rate such that it reaches 7 cm/annum south of Bali (Simons et al, 2007)

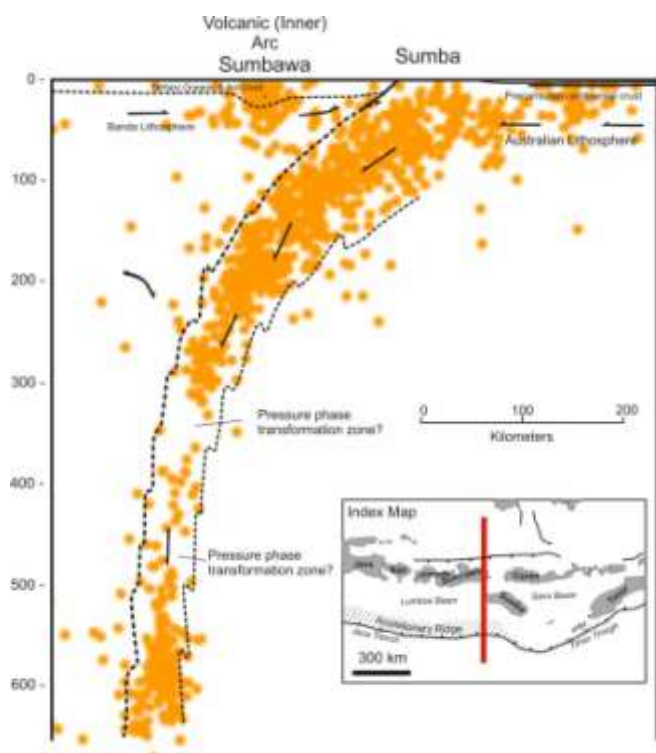


Figure 11. This plot shows the earthquake localizations on a South-North cross section for the lat $-14^{\circ}/-4^{\circ}$ long $114^{\circ}/124^{\circ}$ quadrant corresponding to the Lesser Sunda Islands region. The localizations are extracted from the USGS database and corresponds to magnitude greater than 4.5 in the 1973-2004 time period (shallow earthquakes with undetermined depth have been omitted).

Data source: USGS-NEIC; displayed in <http://bigideasroots.wordpress.com/6-1/>

The locations of the earthquake epicenters in the centre part of the Lesser Sunda Island reflect the subduction of the Australian Lithosphere under the Asian continent (Fig. 11). This subduction angle is also getting steeper northwards.

Closing Remarks

The Lesser Sunda Islands are a very active tectonic region, formed by the subduction of the Indian oceanic plate in the west and Australian continent-island arc collision in the east as marked by the island of Timor. This has given rise to a number of fore-arc and intra-arc troughs such as the Flores and Savu Basins. While the overall plate tectonic setting is becoming better known, the enigma of the origins of Sumba Island continue to require the attention of ongoing research

Acknowledgement

The author would like to thank Tom Reijers and Peter Barber for their comments on this paper.

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New Look at the Origin of the Sumba Terrane: Multidisciplinary Approaches

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Regional Setting & Geology

Sumba Island belongs to the Lesser Sunda Islands Group. Geologically, the island is located in a forearc setting in front of the Quaternary Sunda-Banda volcanic arcs, which comprise the islands of Bali-Lombok-Sumbawa-Flores-Alor and Wetar. Sumba Island is presently non-volcanic and is tectonically important since it is located at the border of subduction and collision zones. To the west of Sumba, oceanic crust of the Indian Ocean is being subducted beneath the Sunda Arc. To the east of Sumba, there is collision zone where Australian continental crust underthrusts Timor Island (Figure 1).

Based on tectonic studies, Sumba has been considered as a micro-continent or continental fragment/ sliver (Hamilton, 1979) which detached itself from its provenance and was transported to its present position as an exotic terrane. Gravity data show that Sumba has a gravity anomaly of +160 to +200 mgal and is underlain by

continental crust with a thickness of 24 km (Chamalaun et al., 1981).

The pre-Tertiary basement of Sumba reveals faulting with rifted blocks (Wensink, 1994). Overlying this are Late Cretaceous-Paleocene marine turbidites of the Lasipu Formation. This period is accompanied by two major calc-alkaline magmatic episodes, the Santonian-Campanian episode (86-77 Ma) and the Maastrichtian-Thantetian one (71-56 Ma) (Abdullah, 1994). Overlying these are volcaniclastic and neritic sediments accompanied by volcanic rocks belonging to the Lutetian-Rupelian Paumbapa Formation (42-31 Ma). The Neogene rocks are composed of widespread transgressive and turbiditic chalky sediments of the Kananggar/Sumba Formation, which contain reworked volcanic materials. Synsedimentary tectonism with normal faulting and large-scale slumping occurred during the Neogene. The Quaternary rocks are coral reefs, uplifted to form terraces (Figures 2 and 3).

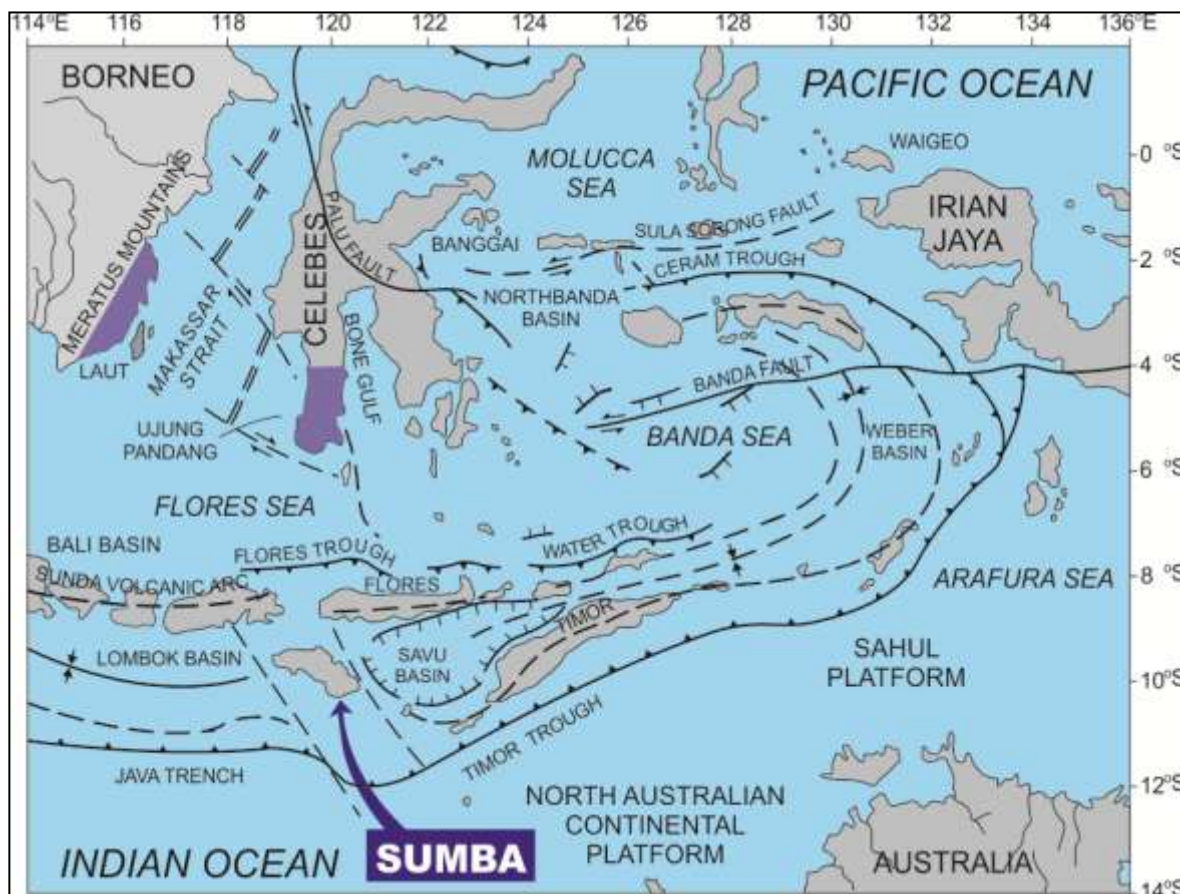


Figure 1. Sumba Island in the regional tectonic setting of Eastern Indonesia. The island is located at the forearc setting of Sunda-Banda volcanic arc and at the border between the Java trench (subduction zone of Indian Ocean) and Timor trough (collision zone of Australian Continent). (after Hamilton, 1979; Burrollet and Salle, 1981; Abdullah et al., 2000)

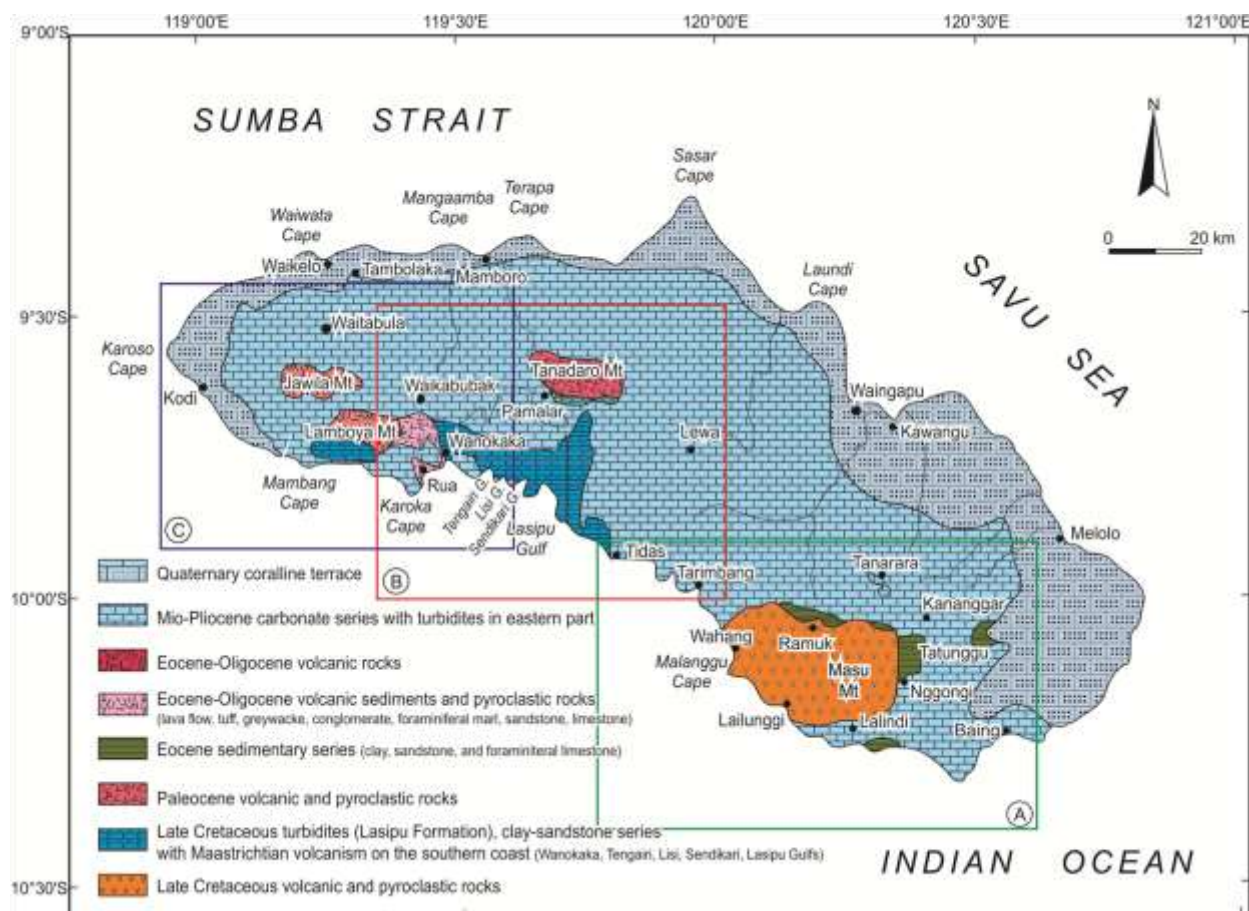


Figure 2. Geological sketch map of Sumba. Boxes A, B, C are profiled in Figure 3. (Abdullah et al., 2000)

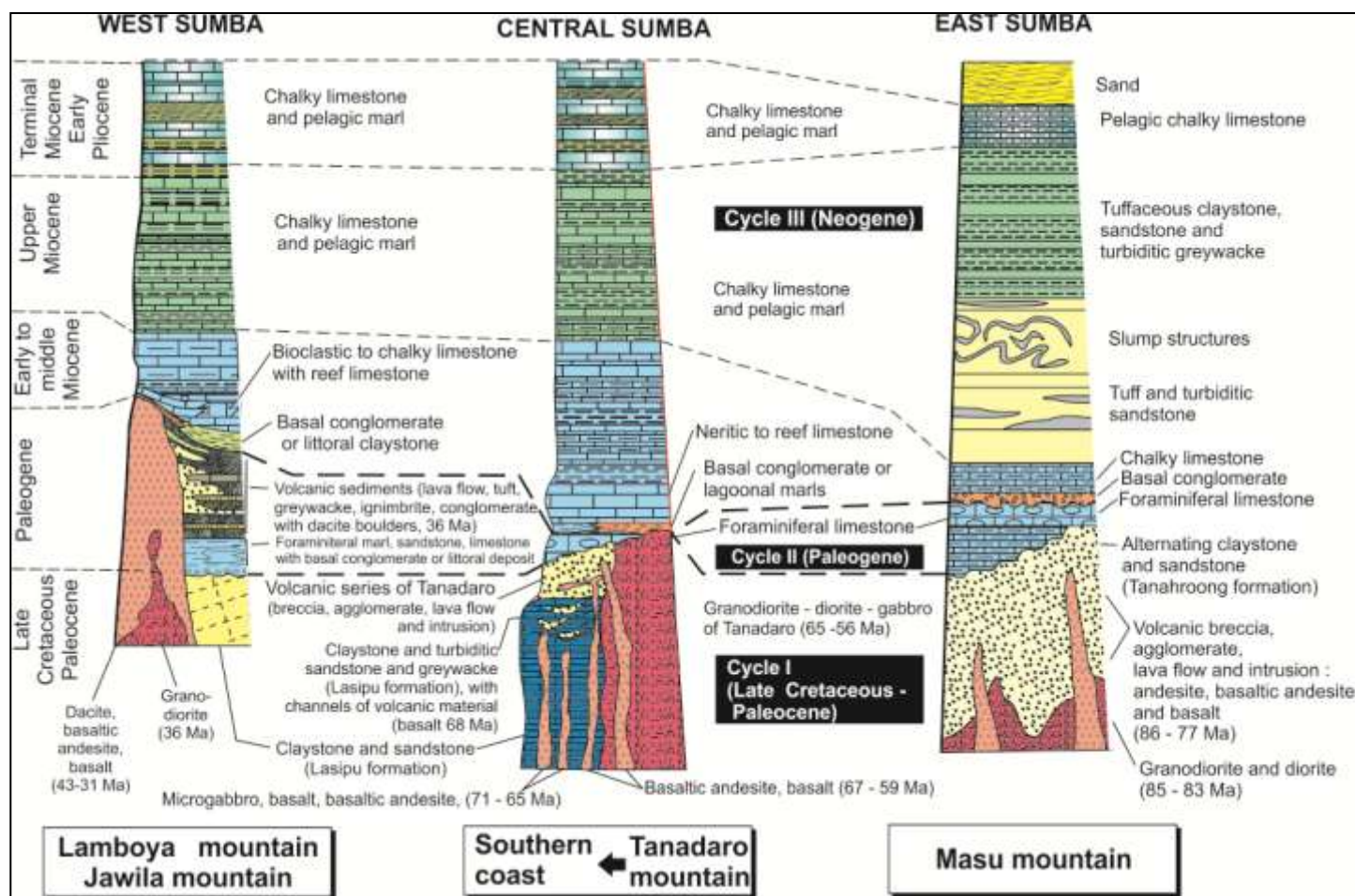


Figure 3. Stratigraphic columns/profiles of Sumba from west to east. Areas of profiles are shown at Figure 2. (Abdullah et al., 2000)

Debate on the Origins of the Sumba Terrane

The origin of Sumba has been a matter of debate. Four provenances have been considered, and these competing proposals from previous authors have been summarized by Satyana and Purwaningsih (2011a, 2011b); and references therein). (1) Sumba was originally a part of the Australian Continent which was detached when the Wharton basin was formed, drifted northwards and was subsequently trapped behind the eastern Java Trench (Audley-Charles, 1975; Norvick, 1979; Otofui et al., 1981; Pigram and Panggabean, 1984; Hartono and Tjokrosapoetro, 1984; Nishimura and Suparka, 1986; Budiharto, 2002 – *complete references see Satyana and Purwaningsih, 2011a, 2011b*). (2) Sumba was once part of Sundaland and drifted southwards during the opening of the marginal seas in the eastern margin of the Sundaland (most authors are in favour of this proposal, such as: Hamilton, 1979; Buroillet and Salle, 1981; von der Borch et al., 1983; Rangin et al., 1990; Wensink, 1994; Abdullah, 1994; van der Werff et al., 1994; Wensink and van Bergen, 1995; Vroon et al., 1996; Fortuin et al., 1997; Soeria-Atmadja et al., 1998; Abdullah et al., 2000; Rutherford et al., 2001; Satyana, 2003; Abdullah, 2010; Rigg and Hall, 2010). (3) Sumba was either a micro-continent or part of a larger continent within the Tethys, which was later fragmented (Chamalaun and Sunata, 1982). (4) Sumba was part of Timor and escaped to its present position after the collision of Timor with Australian continent through the opening of the Savu Basin (Audley-Charles, 1985; Djumhana and Rumlan, 1992).

Each of the authors has employed a different method/approach and this has complicated the debate. Multidisciplinary approaches using various methods are expected to result in better constraints and an integrated evaluation since each method will be complementary to other methods. We compiled various methods used by previous authors and present a new synthesis on the origin of Sumba terrane (Satyana and Purwaningsih, 2011a, 2011b).

SE Sundaland as the Origin of Sumba Terrane: Constraints

Based on various methods including stratigraphic succession (Buroillet and Salle, 1981; Simandjuntak, 1993; Abdullah, 1994); geochronology-geochemistry of magmatic rocks (Abdullah, 1994; Abdullah, 2010), paleomagnetism (Wensink, 1994; Wensink and van Bergen, 1995), isotope geology (Vroon et al., 1996) and Eocene large foraminifera (Lunt, 2003); we consider that Sumba Island originated as part of the eastern/southeastern margin of the Sundaland (Satyana and Purwaningsih, 2011a, 2011b).

Constraints from Stratigraphic Succession

Based on the Sumba stratigraphic succession, magmatic rocks, and structural episodes; Buroillet and Salle (1981) concluded that in contrast to Timor, whose framework belongs to the Australian foreland, Sumba represents a borderland of the Sunda shelf. The first tectonic phase of Sumba at the end of the Cretaceous, which was associated with Lower Paleocene (dated 59–66 Ma) calc-alkali trachyte with hypersthene and calcalkali syenite, may be compared to one of the main tectonic phases known in East Kalimantan and Sulawesi, contributing to cratonisation at the beginning of Paleocene. The existence of andesitic and calc-alkali trachyandesitic lavas at the beginning of the Upper Eocene, which were persistent through the Paleogene, are reflected in the extensive submarine arc of the Sunda islands.

Based on regional stratigraphic correlation (Figure 4), Simandjuntak (1993) argued that the Cretaceous-Paleogene geology of Sumba Island is quite similar to the South Arm of Sulawesi and in some aspects to the southeastern part of Kalimantan (both of which were located in SE Sundaland): The lithological association of flysch slope sediments containing *Globotruncana* sp of Late Cretaceous age (Praikajelu Formation) and associated basaltic, andesitic and rhyolitic volcanics of the Massu Formation in Sumba Island is similar to sequences in the South Arm and Central Sulawesi (Latimojong Formation and Langi Volcanics) and in Southeast Kalimantan (Pitap Formation). Late Cretaceous-Paleogene intrusives of syenite, diorite, granodiorite and granite occurring in the South Arm of Sulawesi and SE Kalimantan seem similar to the Early Paleocene intrusions in Sumba Island. The Paleogene carbonate platform and greywackes of Sumba are correlative to SE Kalimantan and the South Arm of Sulawesi (Berau and Tonasa carbonates, respectively).

Constraints from Geochronology and Geochemistry of Magmatic Rocks

Abdullah (1994), Soeria-Atmadja et al. (1998), and Abdullah et al. (2000) carried out a detailed study of the stratigraphic succession and magmatic/volcanic rocks of Sumba and of their expected provenance in SE Sundaland. Numerous magmatic rock samples were studied petrographically (Abdullah et al., 2000). Three periods of magmatic activity were recognized by Abdullah (1994) on the basis of most of these data: 86–77 Ma (Santonian-Campanian), 71–56 Ma (Maastrichtian-Thantetian) and 42–31 Ma (Lutetian-Rupelian), respectively. Erupted magmas display the characteristics of a predominantly calc-alkaline (CA) and a minor potassic calc-alkaline (KCA) series; they are characterized by variable K₂O contents, relatively high Al₂O₃ and low TiO₂ 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. No evidence of Neogene magmatic activity has been recorded anywhere on Sumba. Similarities between Sumba and the Southwestern Sulawesi magmatic belt with respect

to both the Late Cretaceous-Paleocene magmatism and the stratigraphy, support the idea that Sumba was part of an 'Andean' magmatic arc near the Western Sulawesi magmatic belt (Abdullah, 1994; Soeria-Atmadja et al., 1998).

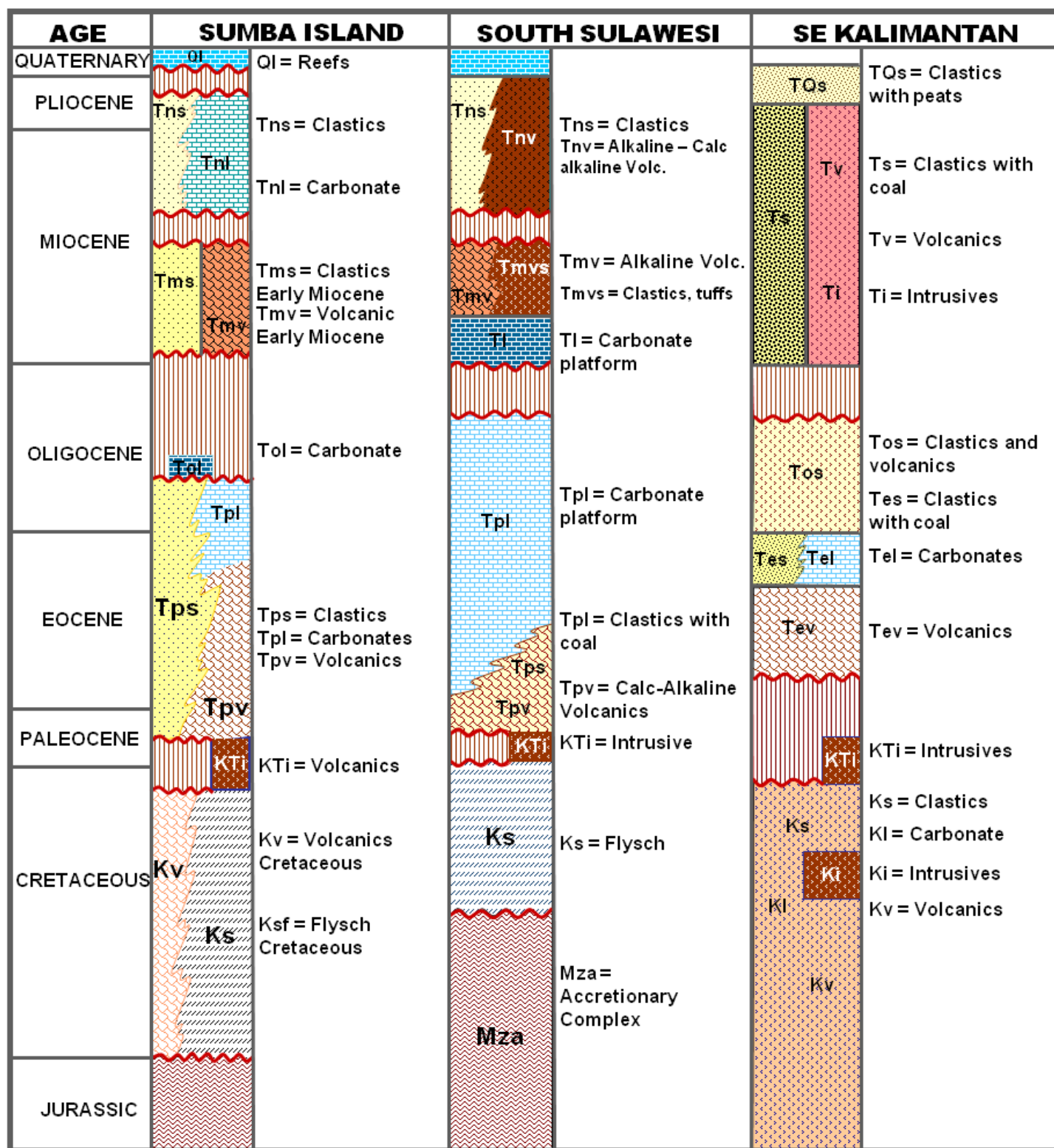


Figure 4. Stratigraphic correlation between Sumba, South Sulawesi and SE Kalimantan. Based on the stratigraphic succession, it is obvious that Sumba is similar to South Sulawesi, suggesting that Sumba shared same place with South Sulawesi before dispersion. (Simandjuntak, 1993)

Constraints from Paleomagnetism

A comprehensive paleomagnetic study of Sumba Island was provided by Wensink (1994). Paleomagnetic analyses of suitable rocks can be a valuable tool for the unravelling of tectonic problems and can be helpful in elucidating the provenance of terranes. Wensink (1994) collected two hundred samples from three formations: mudstones of the Late Cretaceous Lasipu Formation, volcanics of the Paleocene Massu Formation and basalts of the early Miocene Jawila Formation (Figure 5). The sediments of the Lasipu Formation revealed a paleolatitude of 18.3° ; the volcanics of the Massu Formation gave a paleolatitude of 7.4° ; the volcanics of the Jawila Formation presented a paleolatitude of 9.9° . These paleomagnetic data have been interpreted in terms of an original position of the Sumba fragment in the northern hemisphere in Late Cretaceous time. Between the Late Cretaceous and Paleocene, Sumba performed a counterclockwise (CCW) rotation of 50° and a drift of 11° to the south; between the Paleocene and early Miocene the fragment moved a CCW rotation of 85° and a drift of 17° to the south. Since the early Miocene, Sumba has occupied its present position. During its drifting, Sumba underwent several cycles of counterclockwise rotation until it reached its present position. In total, the Sumba drifted from its provenance at 18.3° N to its present position at 9.9° S, moving southward as far as 28.2° cross latitudinal. Based on a later paleomagnetic study, Wensink (1997) interpreted that Eastern Sundaland with Borneo, west and south Sulawesi, and Sumba formed one continental unit in the Late Mesozoic, most likely attached to the Southeast Asian mainland.

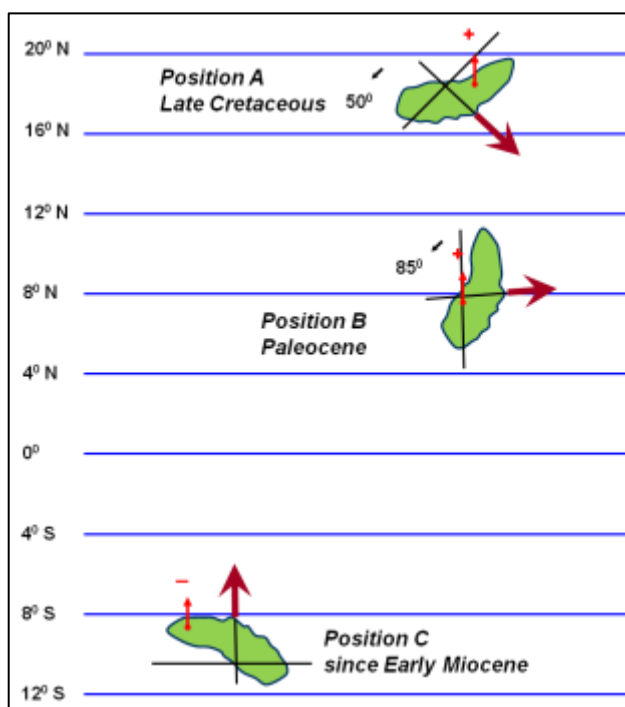


Figure 5. Paleolatitudinal positions for the island of Sumba derived from paleomagnetic data of three different formations. The sediments of the Lasipu Formation revealed a paleolatitude of 18.3° N; the volcanics of the Massu Formation gave a paleolatitude of 7.4° N; the volcanics of the Jawila Formation presented a paleolatitude of 9.9° S. Since the early Miocene, Sumba has occupied its present position. (Wensink, 1994)

Constraints from Isotope Geology

Based on Pb-Nd isotopic characteristics of sediments and volcanics, Vroon et al. (1996) evaluated the provenance of continental fragments in Eastern Indonesia (Figure 6). The evidence is based on a comparison of Pb-Nd isotopic signatures between meta-sedimentary or volcanic rocks from the micro-continents and possible provenance areas. Pb-Nd isotopic variations in expected provenances have been studied. North Australia has very high $^{206}\text{Pb}/^{204}\text{Pb}$ (up to 19.57) and low $^{143}\text{Nd}/^{144}\text{Nd}$ (0.51190-0.51200). Marine sedimentary rocks of the Late Cretaceous Lasipu Formation in Sumba were analysed for their Pb-Nd isotopes. They display limited variations in $^{143}\text{Nd}/^{144}\text{Nd}$ (0.51244-0.51248) and Pb isotopes ($^{206}\text{Pb}/^{204}\text{Pb} = 18.74$ -18.77). Vroon et al. (1996) concluded 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. Late Cretaceous flysch sedimentary rocks from the Balangbaru Formation of SW Sulawesi (Hasan, 1991) were analysed for comparison. They yielded $^{143}\text{Nd}/^{144}\text{Nd}$ of 0.51246-0.51255 and Pb isotopes ($^{206}\text{Pb}/^{204}\text{Pb}$) of 18.67-18.74, which implies a close isotopic similarity with the Lasipu Formation.

Constraints from Eocene Larger Foraminifera

Provenance of Sumba Island can also be investigated using certain Eocene larger foraminifera (Figure 7). Indo-Pacific Eocene carbonate sediments can be divided into two groups based on the presence of certain larger foraminifera (Lunt, 2003). One of these faunal groups is associated with the Sundaland Craton, the geological core of western Indonesia, and is also found on low latitude Pacific islands as well as low latitude western Tethyan regions. The second fauna is found on the Australian Plate, and the micro-plate terrains derived from it since the Eocene. This correlation leads to the hypothesis that the Middle and Late Eocene Sundaland fauna, identified by the three, probably related genera: *Assilina*, *Pellatispira*, and *Biplanispira* [hereafter abbreviated to "APB"] indicate a low latitude, shallow marine fauna, able to cross oceanic migration barriers but restricted from migrating far outside the tropics. In contrast, the fauna identified by the genus *Lacazinella*, which has about the same stratigraphic range as the APB lineage, is thought to be a higher latitude fauna centred on the Australian continent.

The origin of Sumba as a fragment of Sundaland based on geological criteria is consistent with the faunal data. Caudri (1934, described in Lunt, 2003) reported and illustrated *Assilina orientalis* Douvillé and several species of *Pellatispira* from southern Sumba in the mid Eocene through Oligocene shallow marine Tanah Roong series. The presence of two typical Eocene low-latitude Sundaland fauna of three APB *Assilina*, *Pellatispira*, and *Biplanispira* and no Eocene high-latitude Australian fauna of the *Lacazinella* association supports the theory that the provenance of Sumba Island was Sundaland.

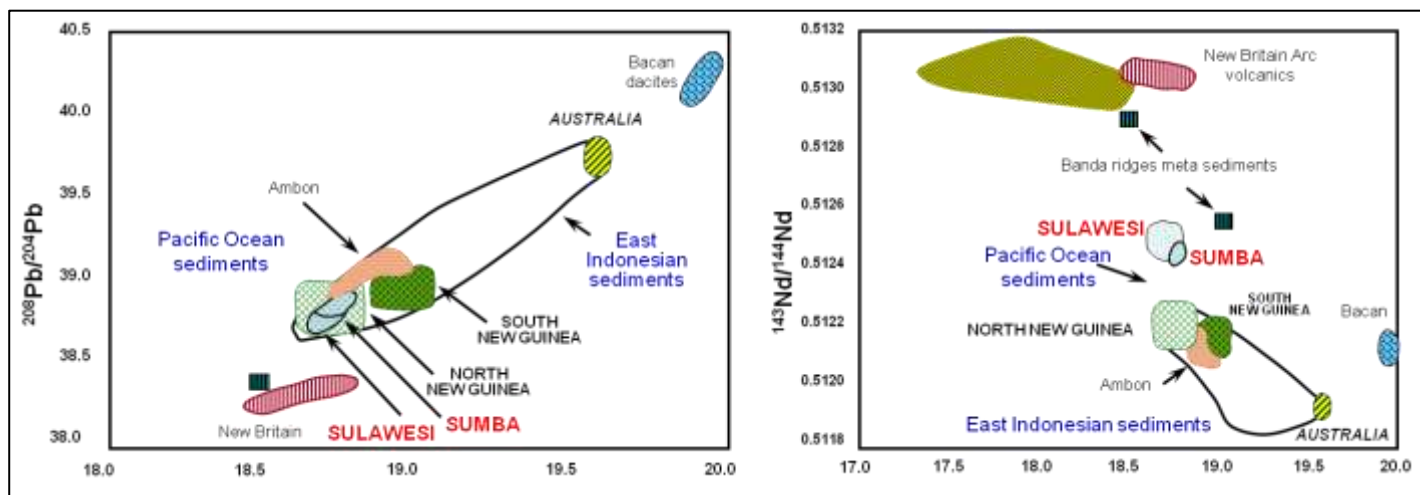


Figure 6. Comparison of Pb-Nd isotopic signatures between meta-sedimentary and/or volcanic rocks from the micro-continents and their possible provenance areas. Note that Sumba and Sulawesi isotopic signatures always fall in the same fields and are separate from Australia, suggesting that Sulawesi was the area of Sumba provenance. (Vroon et al., 1996)

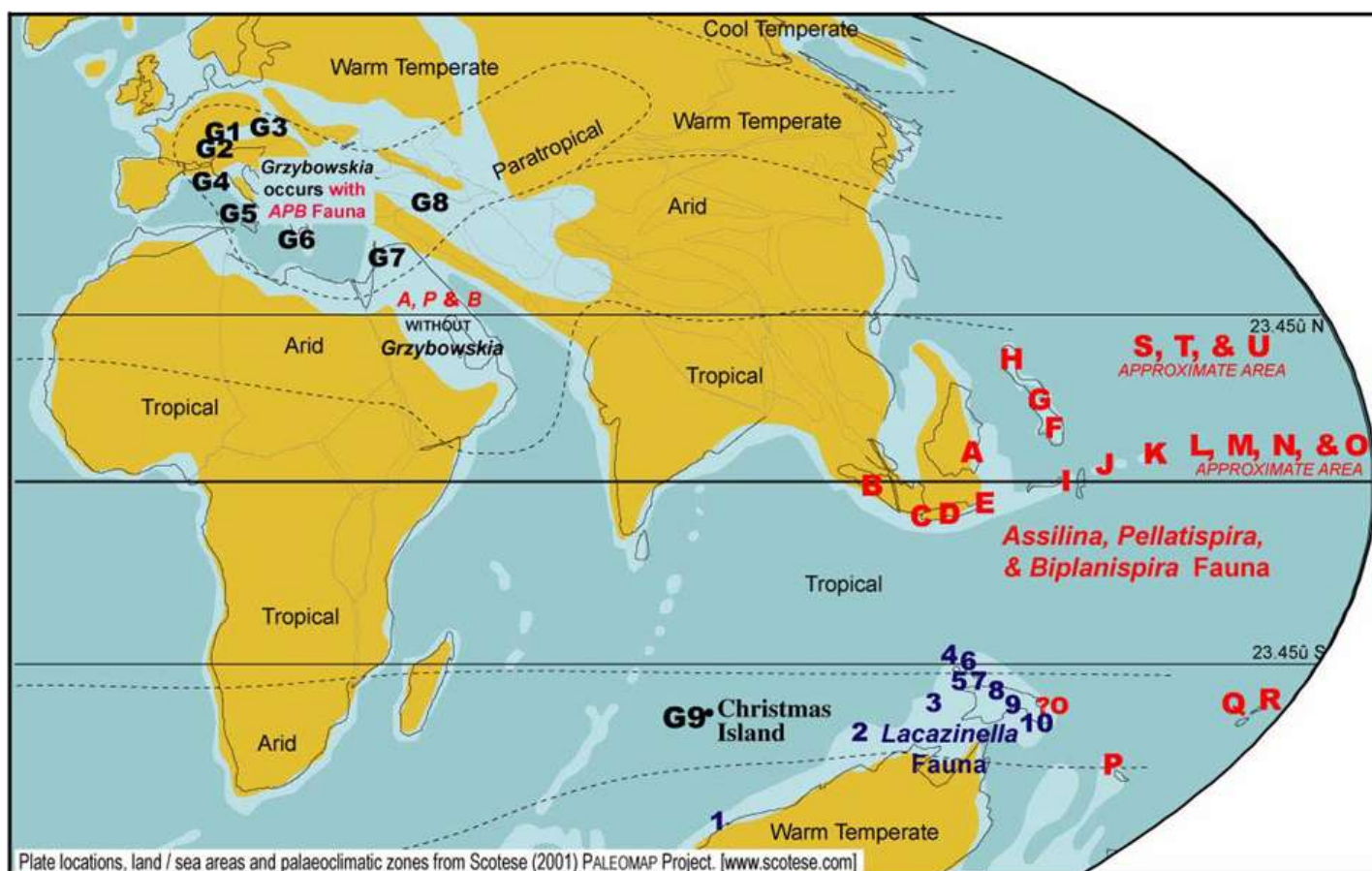


Figure 7. The “APB” faunal group is associated with the Sundaland craton. The *Lacazinella* fauna is found on the Australian Plate. Note Sumba (I) is included into the Sundaland APB group. (Lunt, 2003)

Objections to Other Provenances

The main objection to an Australian provenance for Sumba is that the pre-Tertiary and the Palaeogene stratigraphy of Sumba differ from that of the NW Australian shelf. No Palaeozoic and Mesozoic sediments are present, and no volcanic, volcanoclastic and magmatic rocks have been discovered in NW Australia in the Late Cretaceous and Palaeogene, as discovered in Sumba. Wensink (1994) emphasised the difficulty of correlation by noting that the granodiorite intrusions and related rocks

have an age of approximately 64 Ma, as well as that the volcanics of the Massu Formation are Paleocene in age. The rifting along Australia's coasts took place in the Jurassic and the early Cretaceous so the igneous rocks of Sumba are too young for correlation with the Australian rifting.

The outline of the geology of Sumba shows that both stratigraphy and tectonics of the island are rather simple. In contrast, the geology of Timor is very complicated, both in terms of stratigraphy and of tectonics (Wensink, 1994). The main objection to a Timor provenance for

Sumba is similar to that of relating Sumba to NW Australia provenance. The pre-Tertiary and Palaeogene stratigraphy of Sumba is different to that of NW Australian shelf and no Palaeozoic or Mesozoic sediments are present in Sumba.

The Tethys micro-continent origin model proposes that Sumba was either an isolated micro-continent or part of a larger continent within the Tethys that later fragmented (Chamalaun and Sunata, 1982). However, the geology of Sumba shows that the island has relationship with other continental units and was not isolated from other continents. The composition and structure of both the Lasipu and the Sumba sediments are indicative for such relationship, meaning that Sumba did not originate as isolated micro-continent.

Mechanism of Detachment and Emplacement

Simandjuntak (1993) suggested that displacement of the Sumba terrane could be kinematically linked to one of the following tectonic movements. (1) Sumba detached from SE Kalimantan and rifted away southwards by transcurrent-transformal displacement prior to the development of the Late Neogene volcanic arcs in the Lesser Sunda region. (2) The Sumba terrane detached from the rifting zone subsequent to the extensional faulting leading to the break up and formation of the Makassar Strait during the separation of South Sulawesi from SE Kalimantan, and prior to the development of the Late Neogene volcanic arcs in the Lesser Sunda region. (3) Since Mid-Miocene successions of turbidites in Sumba are quite different to the volcanic, carbonates, and molasse sediments in South Sulawesi, the detachment of Sumba

from near Bone Bay, or from the Walanae depression in the South Arm of Sulawesi, may have taken place in the middle Miocene by reactivated sinistral wrenching of the Palu-Koro Fault or the Walanae Fault, prior to the development of the volcanic arcs in the Lesser Sunda. Simandjuntak (1993) proposed that the northern part of Bone Bay is more likely to be the original site of the Sumba terrane, as indicated by the geological similarity and a relatively good fit of the topography of Sumba with the northern part of the Bone Bay region.

Satyana (2003) proposed that movement of the Sumba terrane from its provenance along major strike-slip faults can be related to escape tectonics. Escape tectonism in western Indonesia followed collision of India to Eurasia in the Palaeogene (Satyana, 2006). In Kalimantan, major shears related to the India collision include the Lupar-Adang/Paternoster Fault (Satyana et al., 1999). This is a major structural element traversing the island of Kalimantan from the Natuna Sea through Kalimantan to the Strait of Makassar and is as long as 1350 km. The trace of this fault may continue through the major faults of South Sulawesi such as the Walanae and Palu-Koro faults perhaps persisting into the Sumba Fracture.

In the Late Cretaceous-earliest Palaeogene, Sumba and other terranes amalgamated to form SE/Eastern Sundaland (Figure 8). It is considered that following the Eocene collision of India to Eurasia, major strike-slip movement along the Adang-Paternoster-Walanae-Sumba Fracture allowed terranes, one of which was Sumba, to escape southeastward/southward to the free oceanic edge which at that time was the ocean between the Sundaland and Australia (Figure 9).

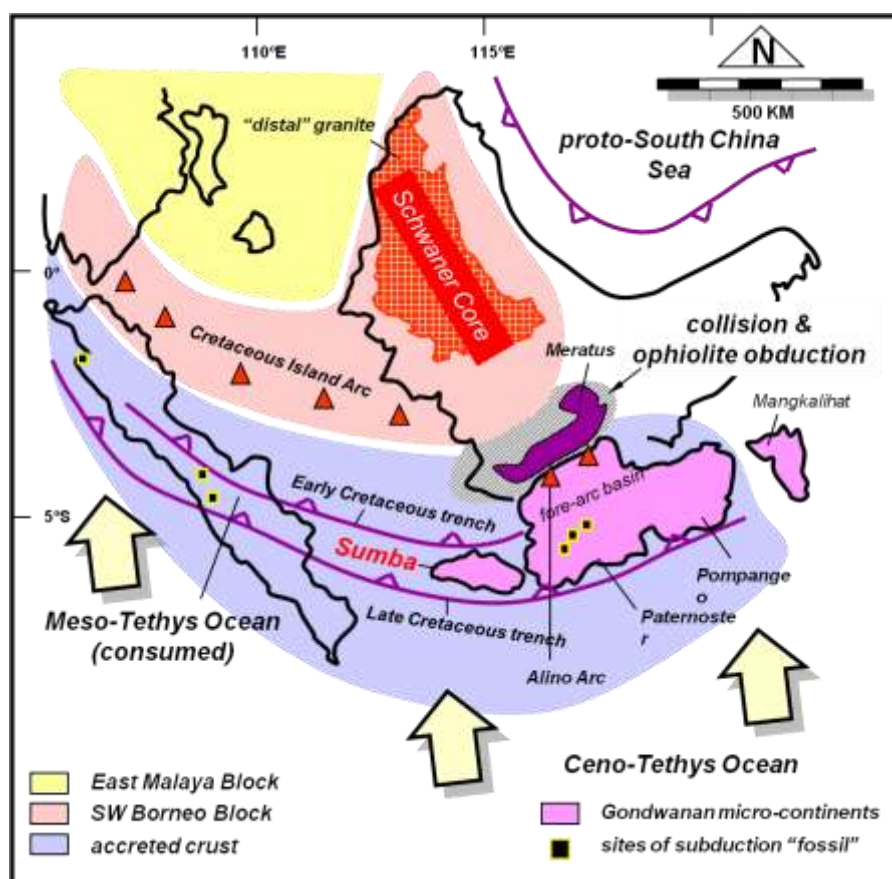


Figure 8. Palaeotectonic reconstruction of SE/Eastern Sundaland and its accreted crust during the Late Cretaceous. Sumba was a microcontinent accreted to this area. (Satyana, 2003)

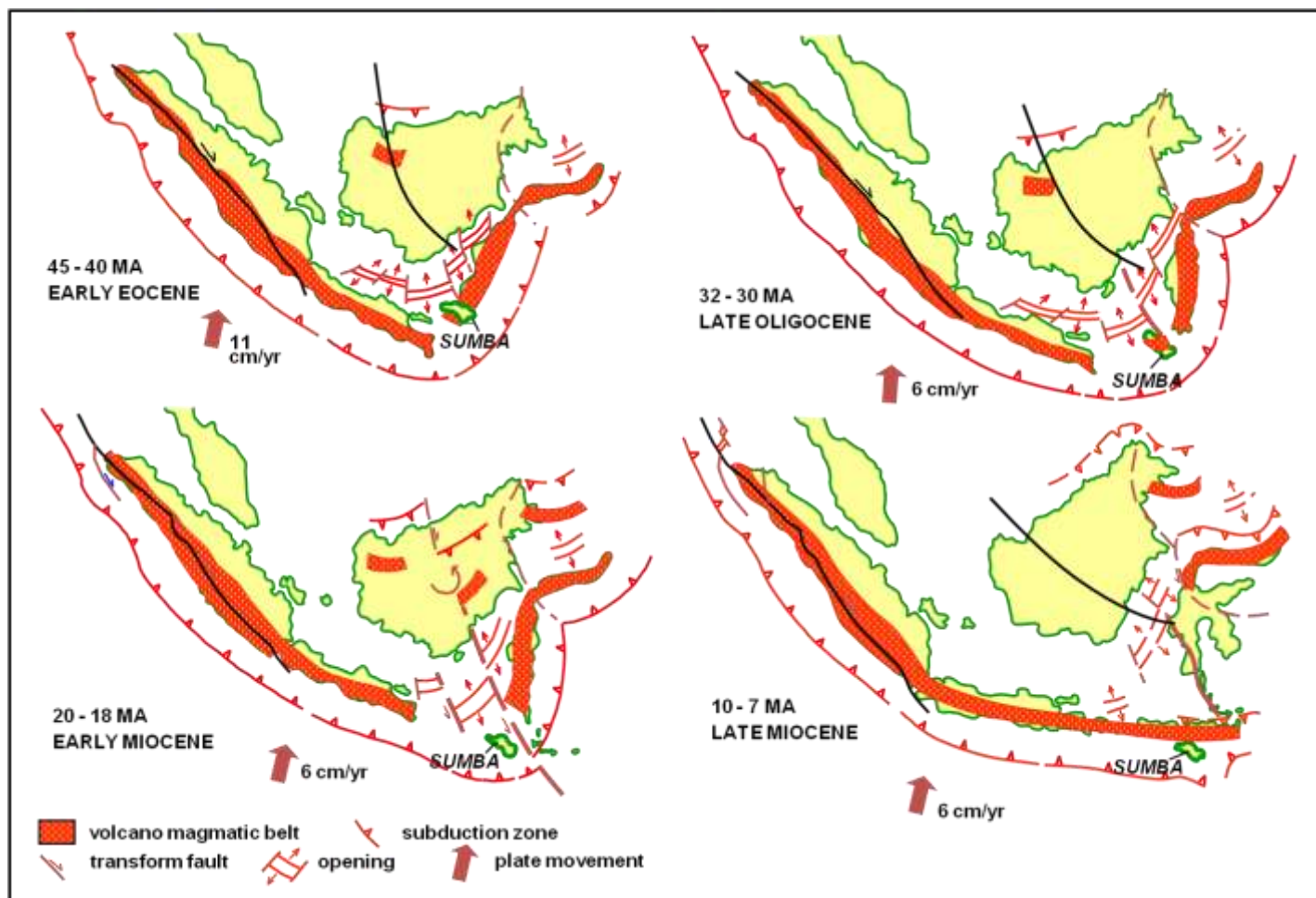


Figure 9. Palaeotectonic reconstruction of the detachment and emplacement of Sumba from South Sulawesi to its present position by major strike-slip faulting across Kalimantan, Makassar Straits, South Sulawesi and Sumba (Faults of Lupa-Adang-Paternoster-Walanae-Sumba Fracture). (modified after Soeria-Atmadja et al., 1998)

Conclusions

Sumba has a basement of Upper Cretaceous turbidites overlain unconformably by gently dipping Palaeogene shallow water sediments and volcanic rocks and resembles the stratigraphy of the adjacent Sundaland margin in SW Sulawesi.

The Cretaceous-Palaeogene geology of the Sumba Platform is correlative with the South Arm of Sulawesi and SE Kalimantan. Similarities in the sedimentary facies and magmatism of Sumba and Sulawesi are noted, indicating that the island was originally part of a volcanic arc situated near western Sulawesi from Late Cretaceous to Palaeogene. Palaeomagnetic data from Sumba show that the location of Sumba was at eastern Sundaland in the Late Cretaceous and has occupied its present position since the Early Miocene. Pb-Nd isotope characteristics of rocks from Sumba and its expected provenance areas show comparable isotopic signatures and affinities with Sundaland. Sumba contains a typical Eocene low-latitude Sundaland fauna of *Assilina*, *Pellatispira*, and *Biplanispira* and no Eocene high-latitude Australian *Lacazinella* fauna.

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Short Communication: No Jurassic Sediments on Sumba Island?

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Introduction and Summary

Roggeveen (1929) described a small ammonite fragment from SW Sumba Island, provisionally identified as a Middle Jurassic species. It is associated with *Inoceramus*-type bivalves. The presence of Jurassic age sediments within the intensely deformed Mesozoic section of Sumba was accepted by some authors (e.g. Van Bemmelen, 1949; Nishimura et al., 1981) and this presence of Jurassic ammonites and bivalves was used to support the presence of Australian continental basement crust on Sumba and South Sulawesi (Hall, 2011; 2012).

However, subsequent workers on the geology of Sumba have been unable to find additional fossil evidence for the presence of Jurassic sediments on Sumba; the oldest rocks that could be reliably dated are of Late Cretaceous age.

Three ammonite specialists were consulted to check the identification of the ammonite illustrated from Sumba by Roggeveen (1929). They concluded that the fragment could not be reliably identified and could well be a Cretaceous species, and also suggested that the associated *Inoceramus* looked like Cretaceous species. There is

therefore no reliable evidence for the presence of any rocks older than Late Cretaceous on Sumba, and it remains to be demonstrated whether basement of Sumba contains any Australia-derived continental material.

Plate Tectonic Setting of Sumba

The origin of Sumba island as a detached terrane from SE Sundaland (or a fragment of the Late Cretaceous–Paleogene 'Great Indonesian Volcanic Arc System' near the margin of SE Sundaland) has been accepted by most authors since Hamilton (1979) (Djumhana & Rumlan, 1992; Simandjuntak, 1993; Wensink, 1994; 1997; Soeria-Atmadja et al., 1998; Abdullah et al., 2000; Rutherford et al., 2001; Satyana, 2003; Harris, 2006; Prasetyadi et al., 2006; Satyana and Purwaningsih, 2011; and Hall, 2011; 2012).

For details on the similarities between the Cretaceous–Miocene stratigraphy of Sumba and SW Sulawesi (both with extensive evidence of Late Cretaceous and Paleogene arc volcanism), see the comprehensive review of Sumba Island by Satyana and Purwaningsih (2011). For detailed reference lists see Van Gorsel (2012).

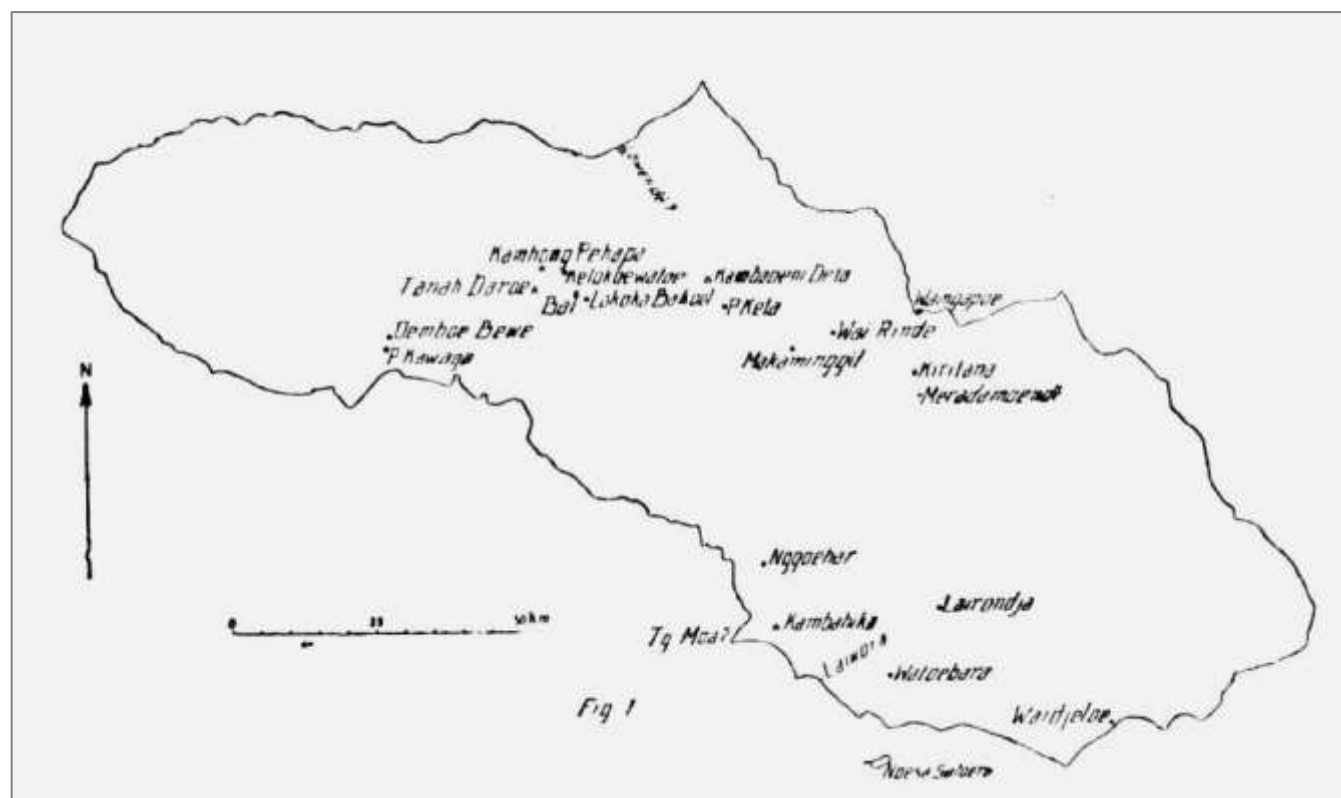


Figure 1. Map of localities visited by Witkamp, showing Oemboe Bene village in SW Sumba (from Roggeveen, 1932)

Pre-Tertiary Geology of Sumba

The Pre-Tertiary section of Sumba is represented by dark grey, intensely folded, mostly unfossiliferous 'flysch-type' clastic sediments with tuffs and volcanic agglomerates, named Lasipu Formation by Prasetyo (1981, in Von der Borch et al., 1983). There is widespread contact metamorphism around Late Cretaceous–Paleocene granite intrusions. They are unconformably overlain by relatively little-deformed Middle–Late Eocene shallow marine limestones and Miocene limestones, clastics and volcanics.

Burollet and Salle (1982), Von der Borch et al. (1983) and Effendi and Arpandi (1994) recognized these oldest beds on Sumba as submarine fan deposits, with principal fossils Late Cretaceous planktonic foraminifera and bivalve mollusks.

Jurassic- or Cretaceous-age of Macrofossils?

Roggeveen (1929) illustrated a small ammonite fragment, collected by Witkamp in 1910 from Oembu Bewe village near the south coast of West Sumba Island (Figures 1 and 2). It is associated with *Inoceramus*-type bivalves and fragments of shark teeth. In the opinion of Kruizinga it was "not quite impossible that it is a young *Hammatoceras molukkanum*", a species described by him from the Middle Jurassic of the Sula Islands in 1926. Roggeveen added that "considering the very fragmentary character...and the fact that the resemblance is not complete it is advisable not to give a specific determination".

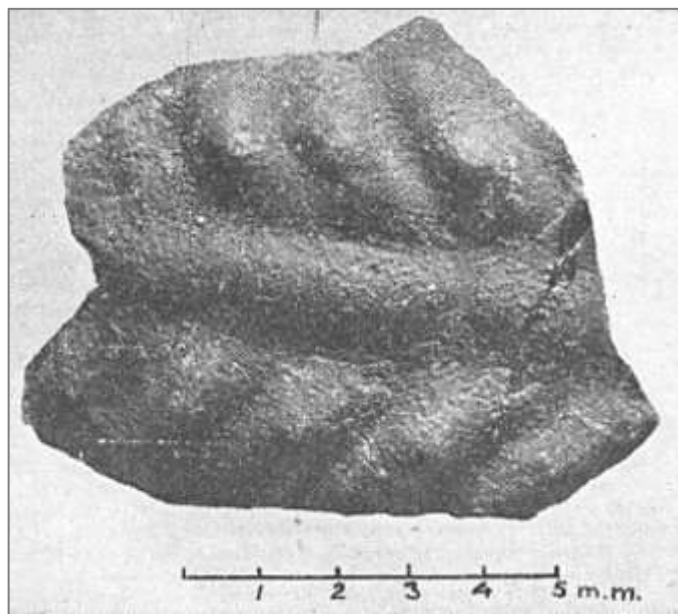


Figure 2. Fragment of ammonite from SW Sumba, provisionally identified as Jurassic *Hammatoceras molukkanum* by Roggeveen (1929)

Wanner (1931) described he had the opportunity to examine Roggeveen's ammonite fragment at the University of Utrecht. In his opinion the fragment is indeterminate, and looked more like a *Harporoceras* (also of Jurassic age).

Three ammonite specialists were consulted in July 2011 to check the identification and age interpretation of the Roggeveen (1929) ammonite from Sumba. They concluded that the fragment could not be reliably identified, and could also be a Cretaceous species:

- Dr. Jack Grant-Mackie (University of Auckland): "Roggeveen's illustration is most unlikely to be of *Hammatoceras*, which has a more compressed ventral area with a sub-triangular whorl section, not the broad venter shown in the photo. And there are Cretaceous genera with this type of venter";
- Dr. Fauzie Hasibuan (Geological Survey, Bandung): "small fragment of Ammonite is too small to be certain";
- Dr. Christian Meister (Natural History Museum, Geneva): "ventral area could correspond to a *Hammatoceras* s.l. but it also could be a part of a Cretaceous ammonite, like for example a *Mortoniceras*".

The associated *Inoceramus* described by Roggeveen (1929) (Figure 3) was believed to be an Upper Cretaceous species by its collector Witkamp. It also looks more like a Cretaceous species, possibly *Inoceramus everesti* or *Inoceramus carsoni*, to F. Hasibuan and J. Grant-Mackie (pers. comm., July 2011).

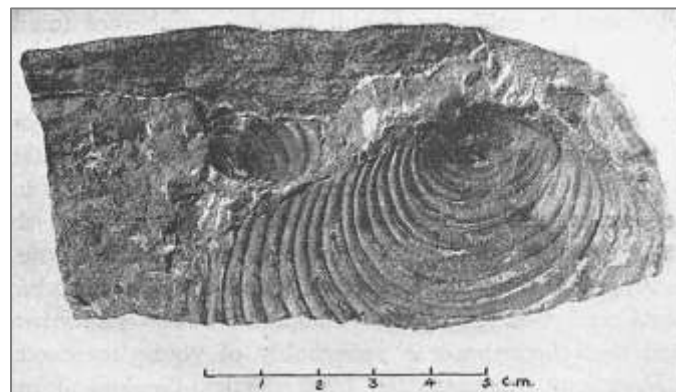


Figure 3. *Inoceramus* bivalves from SW Sumba (Roggeveen, 1929)

Kauffman (in Von der Borch et al., 1983) reported additional bivalve genera from the Cretaceous sediments of Sumba, including *Inoceramus*. He noted the tropical, Tethyan nature of the fauna, but offered no more precise age interpretations.

Conclusion

The presence of Jurassic sediments on Sumba Island has not been proven: (1) the 'Jurassic' ammonite fragment cannot be reliably identified and may well be a Cretaceous species; (2) associated *Inoceramus* suggest a more likely Cretaceous age and (3) all micropaleontological analyses of the Pre-Tertiary of Sumba by subsequent workers only yielded Late Cretaceous microfaunas. There is therefore no reliable evidence for the presence of any rocks older than Late Cretaceous in outcrops on Sumba.

Sumba is frequently viewed as a microcontinental fragment, but whether Sumba basement contains any Australia-derived continental material remains to be demonstrated. It may have simply originated as part of the Cretaceous accretionary melange/ volcanic arc complex along the SE Sundaland margin, called the 'Great Indonesian Arc' (Abdullah et al., 2000; Lytwyn et al., 2012, Rutherford et al., 2001; Harris, 2006; 2011).

The Mesozoic succession outcropping on Sumba may be entirely correlative to the Upper Cretaceous flysch-type successions of the Balangbaru and Malawa Formations of SW Sulawesi, which happens to be another area with a similar 'rumor' of Jurassic ammonites. Sukamto (1986) and Sukamto and Westermann (1992) reported the presence of Early Jurassic ammonites (*Funiceras*) in the 'Paremba Sandstone' of South Sulawesi. Descriptions of these ammonites were never published and the expert credited with identification in 1979 has no recollection of studying these (J. Grant-Mackie, pers. comm. July 2011). Here too, the presence of Jurassic ammonites has been used to support the presence of (Australian) continental crust, but real evidence of such continental basement in SW Sulawesi is still elusive.

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Short Note: Sedimentology of Bali Touristic Locations - Tanah Lot and Uluwatu

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Introduction

Tanah Lot and Uluwatu are famous touristic sites in the southern part of Bali (Figure 1), and part of the Sunda Volcanic Arc. Most visitors come to these places to enjoy the scenery and visit the temple. The uniqueness of these sites, however, is the result of the specific local geological setting in which they are located.

The Tanah Lot temple was built on top of Quaternary volcanic clastic deposits, and was separated from the main island because of erosional processes. Uluwatu which is well known for the temple was built on a Miocene limestone cliff (Figure 2). Due to the excellent exposure of the geology, both localities allow for studying the sedimentary history which has resulted in these remarkable sites.

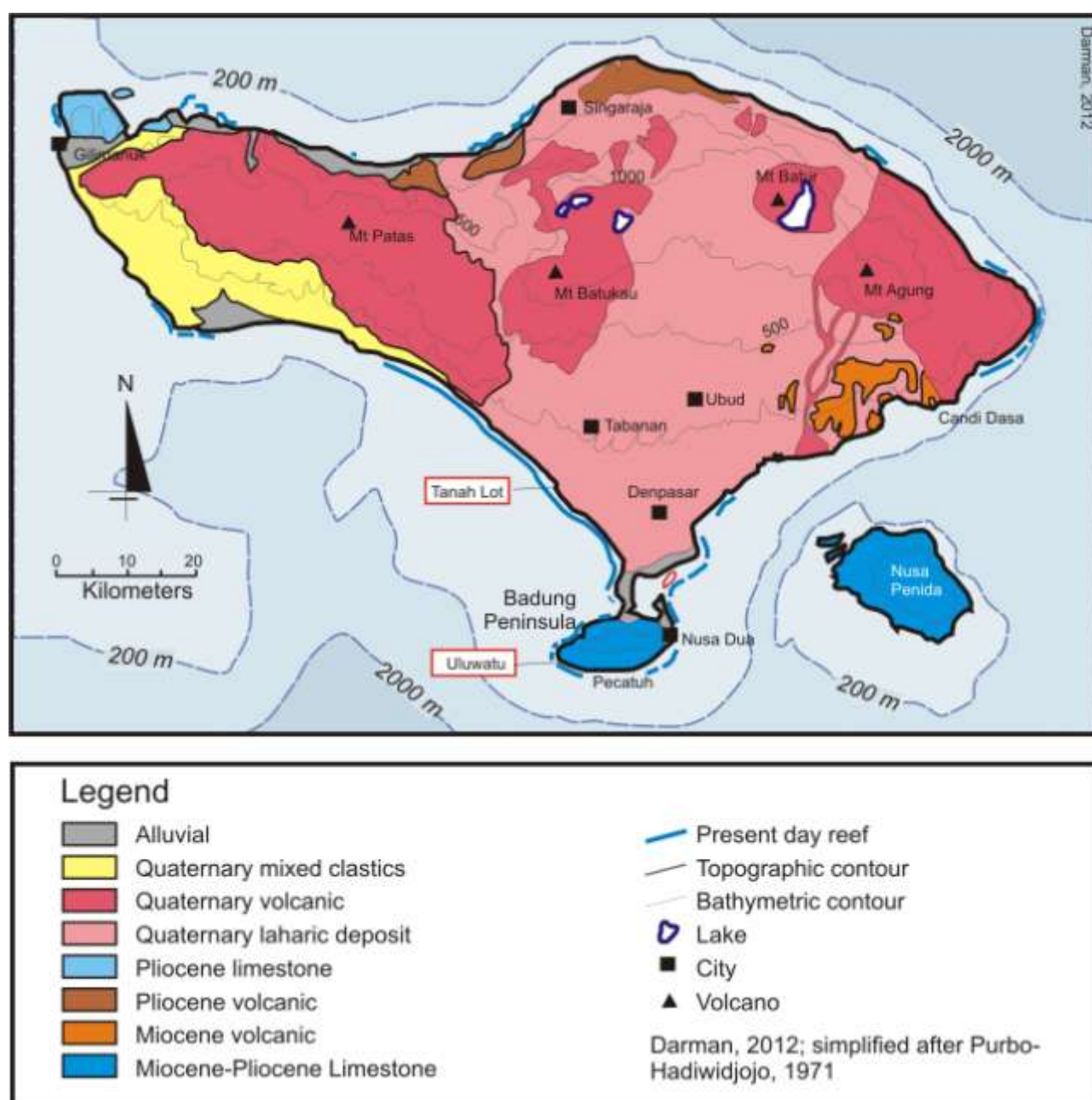


Figure 1. Simplified geological map of Bali, after Purbo-Hadiwidjojo (1971)

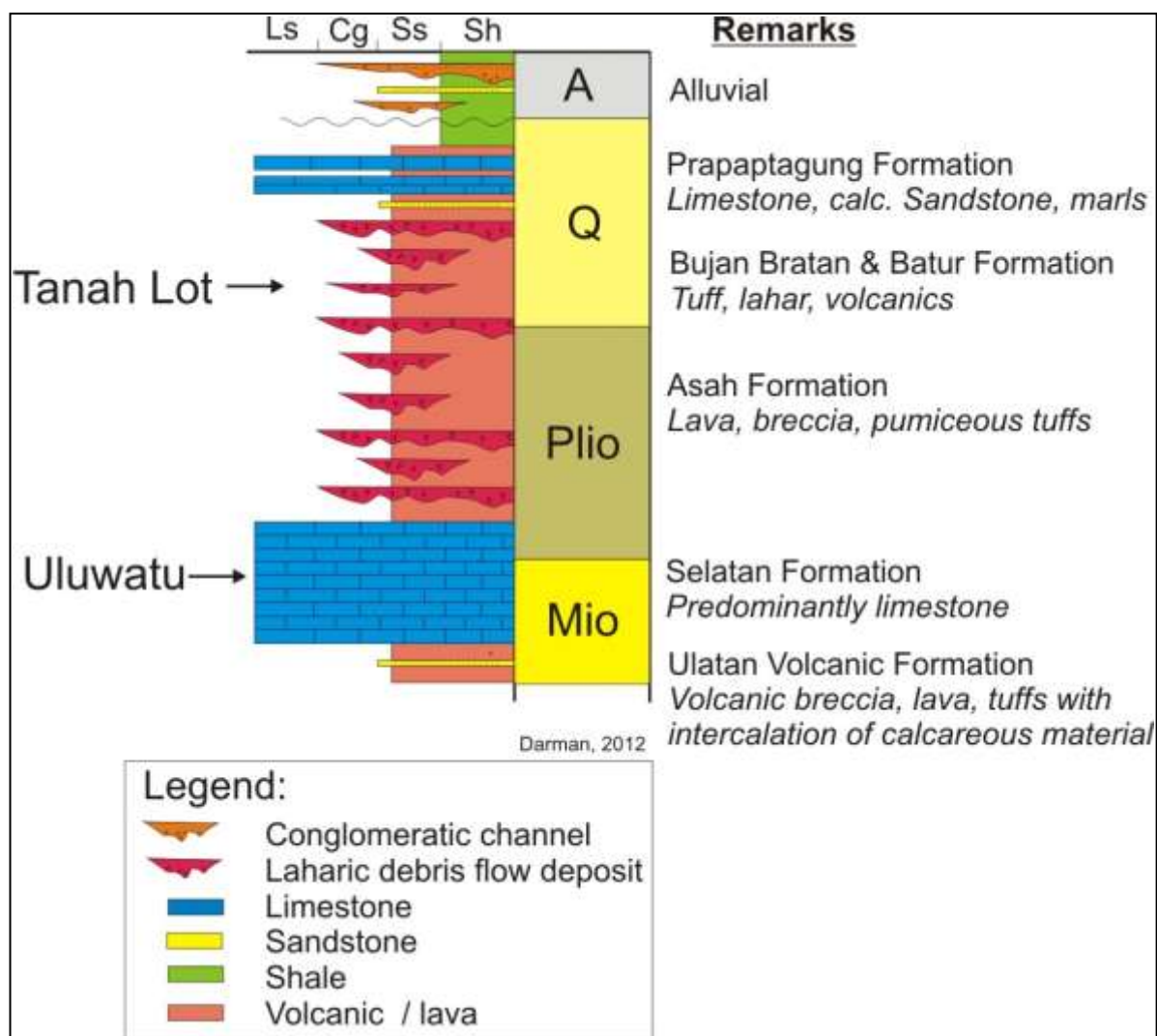


Figure 2. Proposed simplified stratigraphy of Bali Island based on Purbo-Hadiwidjojo (1971) map showing relative stratigraphic position of Tanah Lot and Uluwatu sites

This article discusses the stratigraphy and sedimentological features seen on these two locations. Despite the excellent exposure, both locations have received very little attention and only few studies have been reported. Both sites but especially the Uluwatu cliff, provides an excellent lateral exposure, allowing to discuss the depositional in a spatial framework. The outcrops in both locations show close relationship between volcanic activity and carbonate deposition

Regional Geology

The island of Bali is part of the Sunda volcanic arc which is curving from the West to the South of Indonesia. The Western part of the arc is dominated by large islands of Sumatra and Java, and is commonly called the Greater Sunda arc. Towards the East, the arc is characterized by smaller volcanic islands known as the Lesser Sunda Islands. Bali Island is located in the far West of the Lesser Sunda Islands. Most islands in this arc were generated cored by active volcanoes.

The island of Bali is one of those islands which are cored by quaternary volcanic and lahar deposits. Active volcanoes are located at the centre of the island, e.g. Mt.

Batur and Mt. Agung (Figure 1). Pliocene carbonate systems and Pliocene volcanics are located in the North of the island. Older units, such as the Miocene limestone deposits and Miocene volcanics, are located in the South side of the island.

Tanah Lot

The Tanah Lot temple is located in the West of Denpasar. The temple was built on relatively flat beds, exposed on the South coast of Bali (Figure 3). Purbo-Hadiwidjojo (1971) mapped this area as a part of the Bujan-Brata and Batur Formation which is dominated by tuff and lahar deposits. The cliffs show layered sandstone beds with breccia lenses with thickness ranging from 0.2 to 1 metre. The sandstone beds exhibit significant lateral grain size and thickness variation. Many beds are in fact discontinuous (Figure 4A).

The breccia lenses are isolated sedimentary bodies characterized by sub-angular coarse gravel, poorly sorted, with sand matrix (b unit in Figure 4B). Lateral variation in grain size, ranging between coarse gravel and sand, is visible predominantly at the base of the breccia lenses. At several locations, breccia pebbles show high-angle cross bedding as seen in unit "a" in Figure 4C. This unit has an



Figure 3. The temple in Tanah Lot, built on top of sub-horizontal beds, mainly composed of volcanoclastic sandstones with breccia lenses in places. Due to erosional processes, it became an island during high tide

erosional base above unit “b” and “d”. Unit “c” has been cut out by unit “b”. The sand beds in Tanah Lot are composed of medium to coarse volcanic sand grains and moderately sorted. The grains are dark grey in color. Some horizontal sand beds were cut by gravel beds, which indicate erosional processes (Fig. 4D). Based on field observations, the grains, both minerals and lithoclasts, in these beds are of predominately volcanic origin. Several coral fragments are present in this unit. Figure 4E shows a coral fragment, about 14 cm in diameter, within the breccia unit.

The breccia lenses are interpreted as a laharic debris flow deposit in a very proximal setting. The grain size in the breccia units indicated a high energy environment of deposition. The Tanah Lot outcrop section mainly composed of poorly sorted and generally angular to sub-angular grains, which indicate short distance migration. The coral fragments in Tanah Lot section suggests that this lahar was probably deposited nearby the coast line.

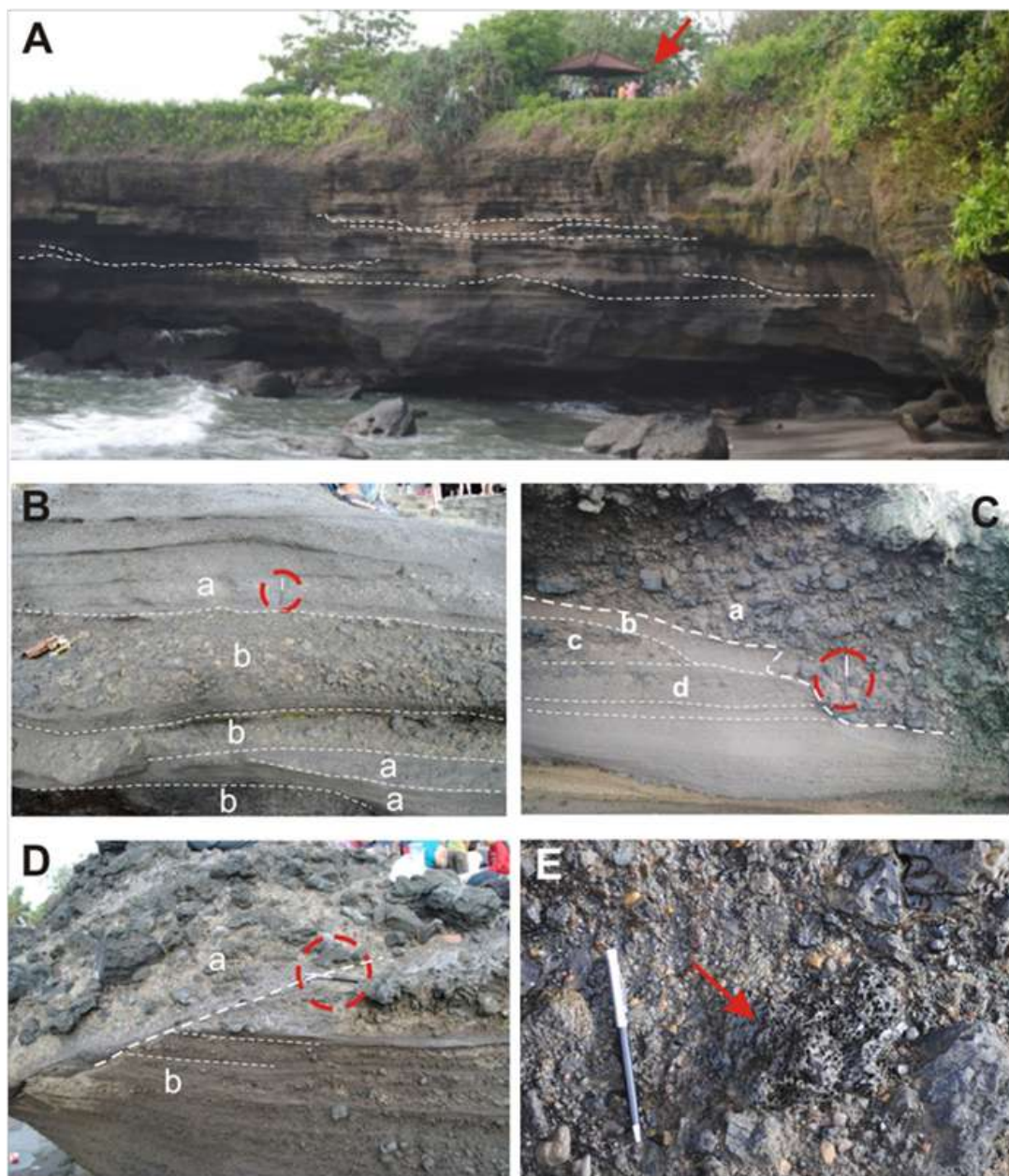


Figure 4. Outcrop pictures from Tanah Lot location. **A)** An outcrop section shows the sand body discontinuity; **B)** A detail picture of the rock layers with sandstone beds (a) and breccia (b); **C)** Erosional base of the breccia (a) which cut through sandstone beds (b and d). The (c) bed was eroded by (b) bed; **D)** A high angle erosional surface where (a) breccia cut deeply into (b) unit, which composed mainly of sands with large volcanic fragments at the lower part and change to breccia in the upper part; **E)** Coral fragment (pointed by red arrow) within the poorly sorted breccia unit, indicate the process was very close to the sea. Note a pen as scale in red dashed circle

Uluwatu

The limestone outcrops exposed at the Uluwatu location and generally in the Southern part of Bali and Nusa Penida Island are Miocene-Pliocene in age, and referred to as Selatan Formation (Purbo-Hadiwidjojo, 1971). The limestone cliffs are up to 200 m high. In the South of Bali Island, the limestone outcrops are located in the Western and Southern part of Badung Peninsula (Figure 1 and 5).

The cliff height decreases from South to the Northwest and East of the peninsula. The limestone beds characterized by their lighter grey shade are clearly visible on the cliff. In the sequence of these enormous exposures the lower half of evenly stratified limestones are shallowing upward into a reef facies (Boekschoten et al, 2000).

The cliff section in the Uluwatu area is about 70 m high (Boekschoten et al, 2000). The limestone beds are

relatively flat and fairly continuous. (Figure 6A & B). Figure 6A shows an outcrop profile in the Pecatuh Beach, south of Badung Peninsula. The lower section (unit “c” in Figure 7A) is composed of coral rudstones, characterized by abundant coral fragments which are up to 10s of cm in diameter (Figure 7B). Bedding is poorly visible and rudstones have formed a hard outcrop which is relatively resistant to wave erosion.

Above the unit “c”, limestone beds of unit “b” are show stratification. The beds are composed of finer grained limestone with smaller coral fragments. The boundary between “c” and “b” unit is sharp (see Figure 7C). Volcanic fragments which are up to a couple of centimeters in diameters are common in the Selatan Formation (Figure 7D). This implies volcanic activity at times of carbonate growth and deposition.

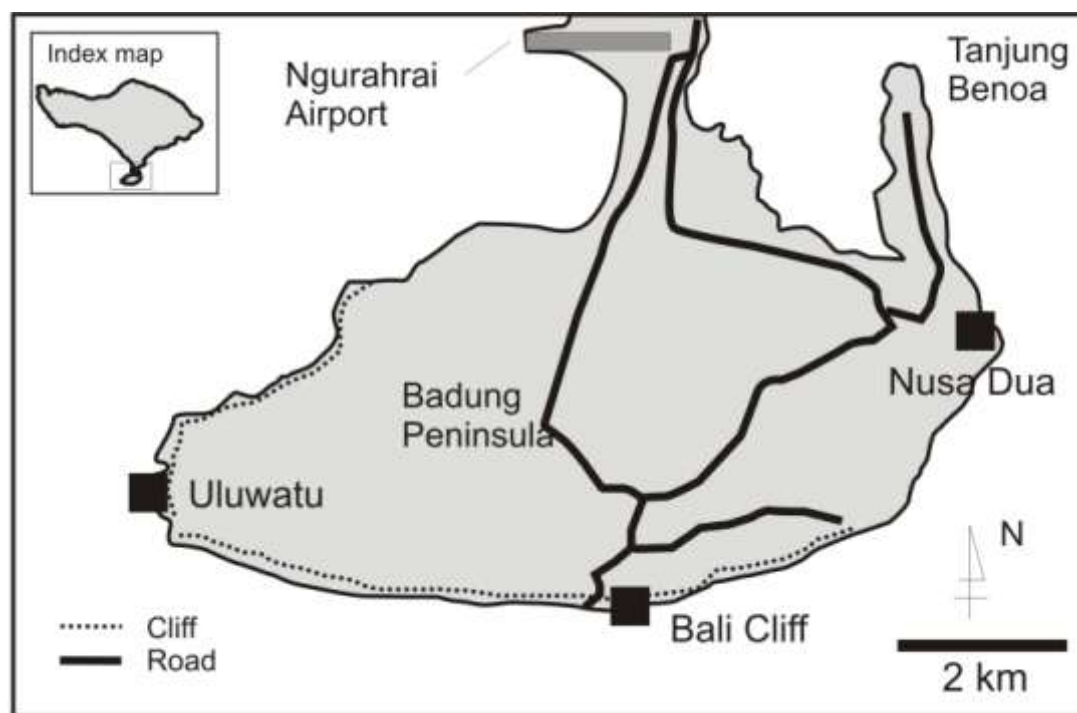


Figure 5. A map of Badung Peninsula in the south of Bali, showing the limestone cliff distribution in the west and south part



Figure 6. A) Aerial photo of Uluwatu cliff with the temple (pointed by arrow) as a scale. Some part of the cliff can reached more than 90 meters; **B)** A cliff picture from the side showing the lateral extension of the relatively flat beds

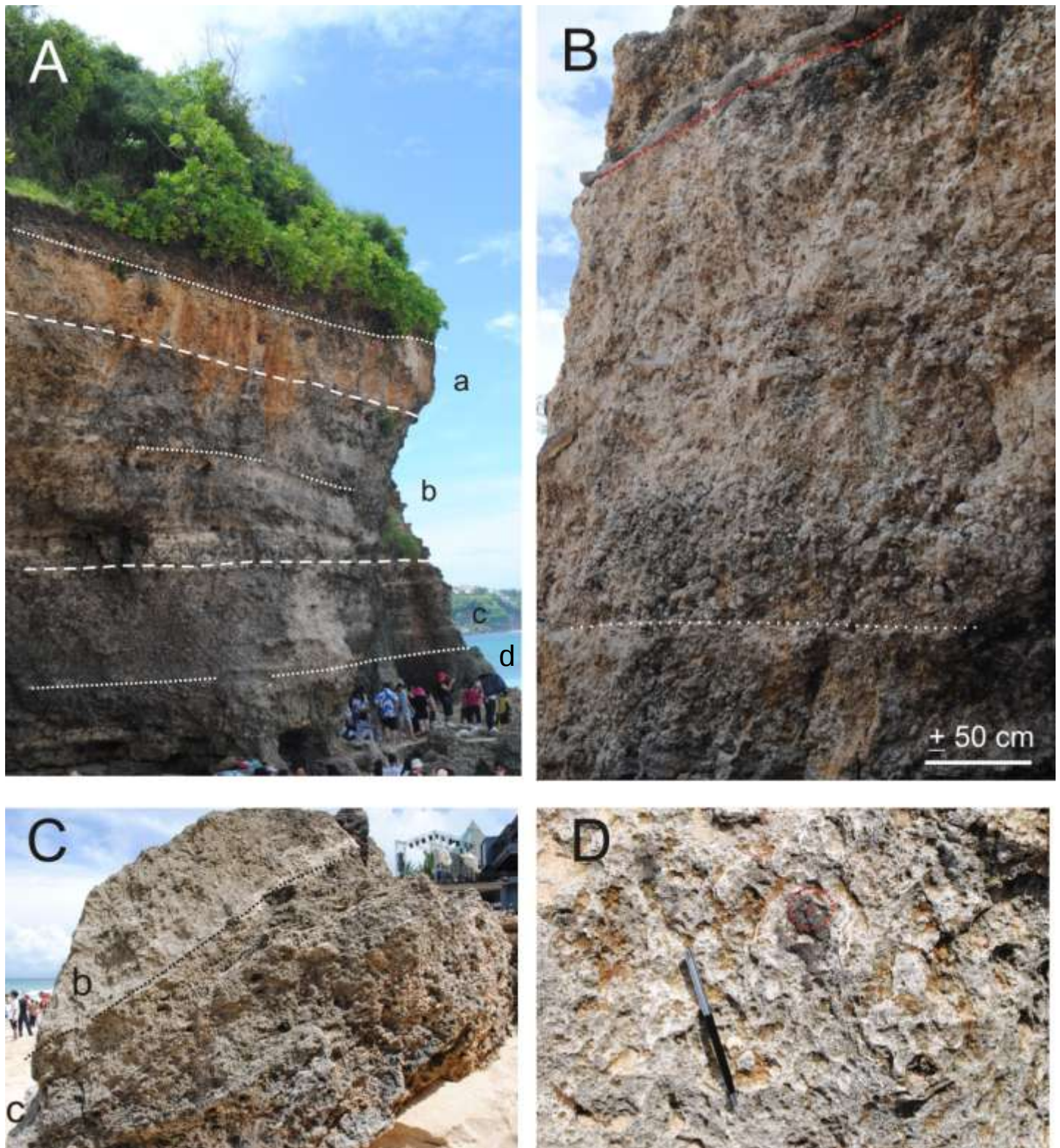


Figure 7. **A)** Selatan Limestone Formation in Pecatub Beach. The cliff profile may indicate the rock hardness. The 'c-d' sequence is relatively hard, with abundant of large coral fragments with poor beds on the left and well bedded unit on the right with smaller fragments. The sequence above it is relatively softer (especially around 'b' horizon) with much finer limestone fragments. Above 'a' horizon the beds are heavily mixed with soil; **B)** A detail picture close to 'd' horizon in Figure 7A, showing the large fragments of corals which is commonly called as Rudstone; **C)** A boulder large coral fragments at the bottom part (bottom right) and well layered limestone in the upper section (upper left); **D)** A volcanic rock fragment (red circle) within the limestone bed.

Conclusion

In the Lesser Sunda Islands, volcanic activity and carbonate deposition took place simultaneously and very close to each other. These two depositional systems shaped Bali Island, and appear both in present day and in the rock records. Uluwatu and Tanah Lot outcrops are

good example for these depositional systems. In these sites, limestone fragments are found in volcanic deposits and vice versa. It is therefore concluded that although volcanic eruptions may disturb the growth of a carbonate system, it is not a continuous process. The volcanic activity, therefore, won't kill the carbonates.

Recommendation

Both Uluwatu and Tanah Lot outcrops are excellent exposures for detailed studies of the relationship between volcanic activities and limestone depositional processes in Bali. The lateral variation of the long cliff in the southern part of Bali may also worth to be investigated in further detail. Unfortunately there were not many geological research and studies on these outcrops. These issues may come as projects which could be done by Indonesian universities.

Acknowledgement

The author would like to thank Bram van der Kooij and Cynthia Darman for reviewing the earlier version of this article.

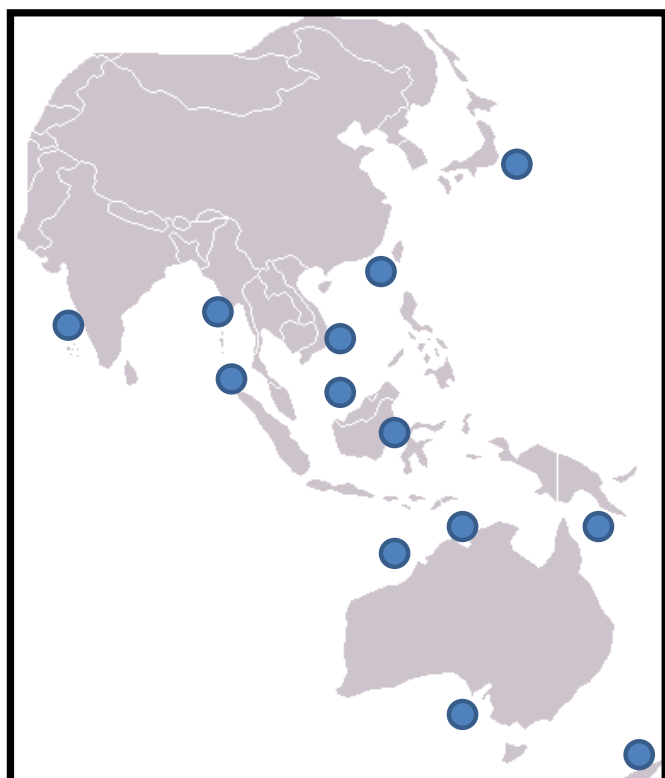
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Short Note: Well Rounded Kuta and Tanjung Aan Lombok Beach Sand

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Introduction

Coarse, well rounded carbonate sand grains are found in Kuta and Tanjung Aan beach Lombok (Figure 1). These kinds of sands are also common on Sanur Beach and other localities along the East coast of Bali, where many visitors believed them to be ooids (oolites). The grains are generally about 3-4 mm in diameter and well rounded. The colors of the grains are white to light-brownish white. In

places they are mixed with coral remain and other small shells which are angular to sub-angular or sub-rounded to oval shape, with generally the same grain size or larger (Figure 2).

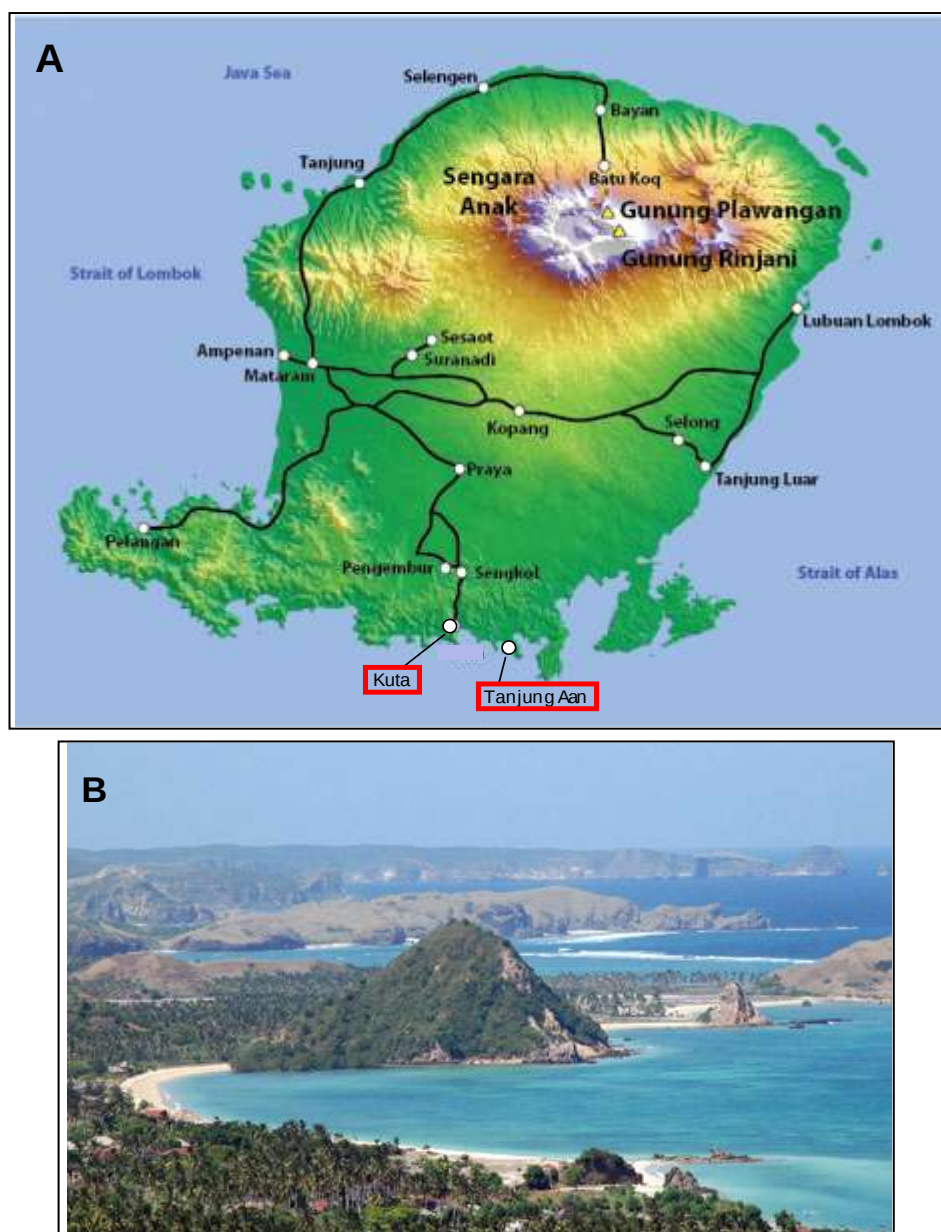


Figure 1.A) Map of Lombok Island, showing the location of Kuta and Tanjung Aan beach in the south coast of the island. **B)** Aerial view of Kuta beach, one of the most famous holiday destination in Lombok



Figure 2. A photo of the sand grains in Kuta beach, Lombok. The beach sands are dominated by rounded grains, few millimeters in size, with light colors. Source: Wikimedia Common, photo courtesy Midori

White Beach Sands of Lombok and Nearby Islands

R. P. Koesoemadinata took some beach samples from Kuta, Lombok and evaluated them under the microscope. Figure 3 shows clearly the surface texture of the grain. A thin section of one of the grains (Figure 4) shows it is not an ooid grain, but a larger foraminifer composed of chambers and pillars.

Han van Gorsel identified these as reef-flat foraminifera, first described by Schlumberger (1896) as *Baculogypsina floresiana*, from the south coast of Flores. Today these are generally called *Schlumbergerella floresiana*. Han mentioned that a few papers have been published on these Recent foram sands from Bali, Lombok, Flores, Sumbawa, etc. (Barbin et al. 1987, Adisaputra 1991, 1998, Renema 2003). Apparently these types of sands are also found on some W Pacific tropical island.

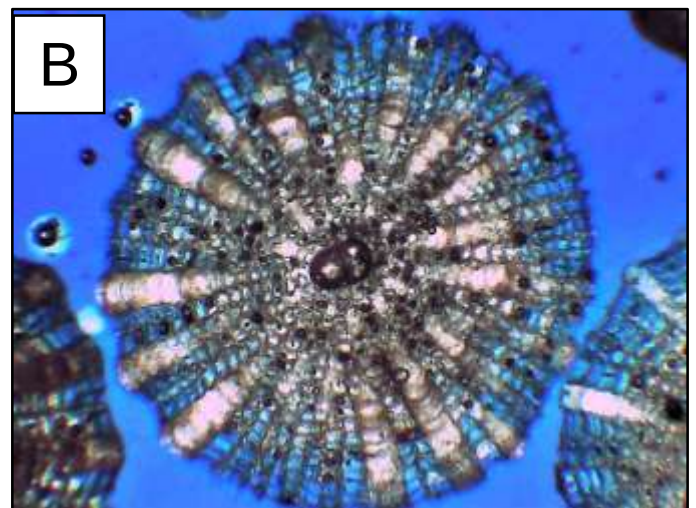


Figure 3. A) A photo of the grain under microscope and **B)** A section of the grain under optical microscope. Photo courtesy (R. P. Koesoemadinata)

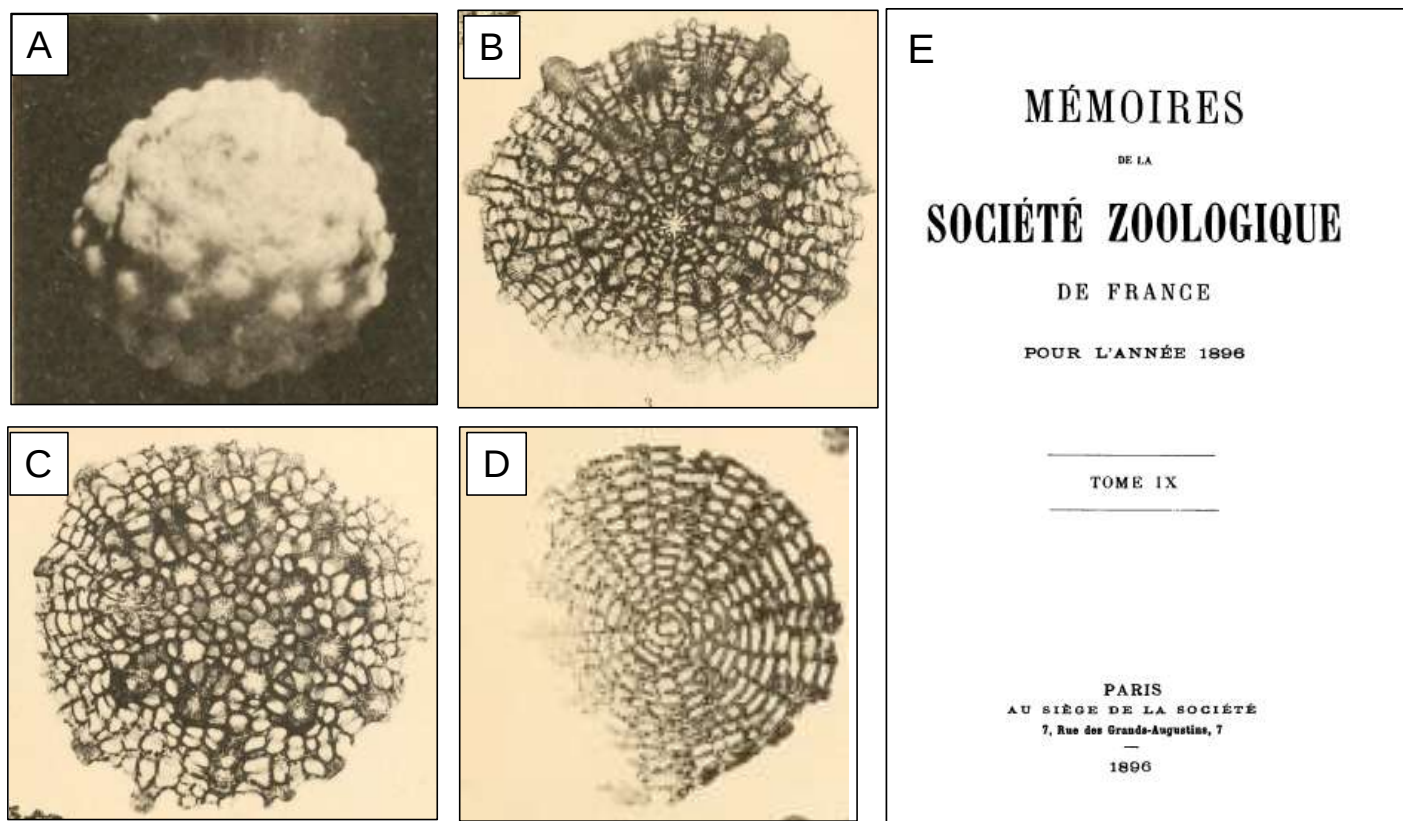


Figure 4. **A)** A photo of the *Baculogypsina Floresiana* Schlumberger under microscope and **B)** A section of the grain under optical microscope showing arrangement of the pillars and **C)** A section perpendicular to the core. **D)** A section of *Gypsina globulus* Reuss. **E)** Source: Societe Zoologique, Paris, 1896.

This sand has also been discussed by Adisaputra (1991, 1998) from the tourism view point. In her paper Adisaputra mentioned that the 'white sands' along the coasts of E Bali, W Lombok, N Sumbawa and S Flores are composed mainly of rounded foraminifera *Schlumbergerella floresiana*, which were derived from adjacent coral reef flats. These benthic foraminifera live in waters down to 90m (Adisaputra, 2000).

The unusual dominance of *Schlumbergerella* on coral reefs of the Lesser Sunda Islands area over the normally more abundant large imperforate miliolid benthic foraminifera in other parts of Indonesia is probably due to climatic or oceanographic parameters, most likely periodic upwelling, which causes seasonal seawater temperature drops (Renema, 2003)

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Remarks:

Related link to the Indonesian Marine Geology Research and Development Centre: <http://www.mgi.esdm.go.id/content/panorama-nan-indah-sebuah-aset-wilayah-pantai-dominasi-schlumbergerella-floresiana>

Volcano Tourism of Mt. Rinjani in West Nusa Tenggara Province, Indonesia: a Volcanological and Ecotourism Perspective

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Abstract

Indonesia has nearly 500 volcanoes and 129 of them are currently active. The active volcanoes are spread out along a 7000 km volcanic belt from Sumatra to Java, Bali, Nusa Tenggara, Banda, Halmahera and Sulawesi. Each volcano possesses its own natural characteristics that usually include beautiful landscapes and sceneries, fresh air and fertile lands. One of the volcanoes is Mount (Mt.) Rinjani (+3726 m) in Lombok island, West Nusa Tenggara. It is the second highest volcano in Indonesia after Mt. Kerinci (+3800 m) in Sumatra. Mt. Rinjani is situated at latitude 8°25' S and longitude 116°28' E. The Rinjani volcano complex has potential to be developed for volcano tourism and natural volcanic museum.

Currently, volcano tourism in Indonesia is still poorly developed and it relies on resources-based tourism only, not on knowledge-based tourism. Now is the moment for volcano tourism stakeholders, including travel guides, to prepare themselves by gaining more knowledge, specifically in term of scientific knowledge of a volcano and its environment. By doing so, they can make volcano more interesting as a tourist attraction and more appealing to both domestic and foreign tourists. The tourists eventually can have better understanding of a volcano including the landscapes, sceneries and panoramas, calderas, lakes, hotspots, waterfalls, caves, etc.

This paper discusses the volcano-tourism potential of Mt. Rinjani, focusing on volcanic and geological aspects as the main tourist attraction, and environmental aspect as a secondary attraction. The volcano-tourism attractions can include specific or general activities, depending on a visitor's interest, for examples for recreation, adventure or cultural activities.

Introduction

West Nusa Tenggara is a province that has three A-type active volcanoes, which include Rinjani in the Lombok Island, Tambora in the Sumbawa island and Sangeangapi in the Sangeang Island. Mt. Rinjani (+3726 m) lies at the northern part of Lombok Island, administratively within the East Lombok District.

Mt. Rinjani National Park, one of 39 national parks in Indonesia (Figure 1), is a representative of the best areas in natural landscape and wildlife biodiversity. National parks are

important tourist attractions and can significantly contribute to regional and national economies. The parks are managed nationally by the Ministry of Agriculture and Forestry, Directorate General of Nature Conservation and Protection from its central office in Bogor, West Java.

The Rinjani Park includes calderas, a lake, cones and a crater. The calderas include three cones of A-type volcanoes, which consist of Barujari (+2376 m), Rombongan (+ 2110 m) and Anak Barujari (+2112 m), with a lake called Segara Anak (Baby Sea). The Rinjani belongs to B-type active volcano in the form of strato in the eastern part of the calderas. Over its top, there is a crater of 860m x 650m in size and 300m deep, whose explosion history has never been recorded. Its last explosion was in 1994, when the Barujari crater produced lava flows and volcanic materials of ashes up to bomb size (Rachmat, 1994).

Approximately 1175m to the west of the top of Barujari, there is a small hill that was a product of flank eruption, with a height of more than 2112 m. To get to the top of Barujari and the 1994 lava flows, trackers can walk it up through the Putih (White) river head and walk up the cliff/northern part of the lake for approximately three hours. The 1994 eruption produced a piling up of volcanic materials, such as ashes and rocks over the southeastern part. A rainy season in November 1994 cause a large flood and led to 31 deaths and 7 injuries, as well as destroying agricultural fields, mills, a small shop and irrigation channels.

In 1994, the Mt. Rinjani observatory post was built at Sembalun Lawang. The observatory is now furnished with a seismograph, a thermometer and a telescope. The volcano is being continuously monitored by two persons working on shift, who have been specially trained in volcanic observation. These people would monitor Mt. Rinjani's volcanic activities persistently, visually and seismographically. Assuming an eruption occurred at Mt. Barujari, the danger zone from the eruption extends over an area of 196 km², which is populated by people living in Bayan (eight villages), Aikmel (three villages) and Sambelia subdistricts (five villages). Mt. Rinjani can throw out disastrous materials, which primarily include glowing cloud, blazing lava flows, stone rains, ash rains and poisonous gas. Secondary disastrous materials include lahar flows, stone flood and large flood. However, the volcano can also bring advantages, such as for geotourism and volcano tourism attractions and flora and fauna development.

Historically, the eruption of Mt. Rinjani often came from Mt. Barujari and Mt. Rombongan, which form the northern chain of Mt. Rinjani. There were no fatalities in the last eruption, however lahar flood as a secondary impact of the eruption claimed some victims.

Ecotourism development cannot be separated from conservation. The joint partnership concept is essentially an example of pure ecotourism, developing styles of tourism that benefit local communities and strengthen conservation objectives of a protected area. The Rinjani Trek has the potential of becoming an ecotourism model in Indonesia.

There are some interesting locations on Mt. Rinjani, which are scattered from its slope up to the summit, that can become the main tourist attraction and potentially support tourist attractions in the area. These include the crater/caldera at Mt. Rinjani and Mt. Barujari. The crater/caldera and its walls consist of alternating and cross cut of lava flows and pyroclastic layers including lava product of the Mt. Barujari's latest eruption, creating an amazing scenic view. Other objects to the upstream of Kokok Putih, Susu cave and at the foothills of Mt. Barujari are calderas with beautiful views and hot springs, while in the Segara Anak Lake, people can do fishing. When this area is developed into a volcano tourism destination in the future, activities can include cross country, travelling around the lake, wall climbing, tracing calderas walls to watch the lava flows and visiting hot springs and the new crater hole produced after the Mt. Barujari's eruption in June 1994.

Geological Setting

Geology

Van Bemmelen (1949) suggested that the northern part of Lombok Island is a continuation of the Solo Zone of Java Island. This zone represents the former top part of a geanticlinal belt, which broke off the south flank (represented by the Southern Mountains) and slipped northward. At the top part of the geanticline, granodioritic plutonic rocks were emplaced during the intra-Miocene phase of diastrophism. The basic roof part of such an intrusion is exposed on Java Island in the Jiwo Hills (west of Surakarta, Central Java), but farther eastward this older basement of the Solo Zone is not exposed anywhere. It appears in the western part of North Lombok, where the basic roof part of a plutonic intrusion is also exposed.

Geomorphology

According to van Paddang in *Data Dasar Gunungapi* (Kusumadinata, 1979), Rinjani is a composite volcano protruding high up at the northern part of Lombok. It is mostly composed of young volcanic rocks. The Rinjani cone (3726 m asl) is the steepest and highest peak in the area, consisting of mostly loose materials with a crater on its summit. To the west of this volcano, there is a caldera containing water which is elliptical in shape and is called Segara (Figure 2).

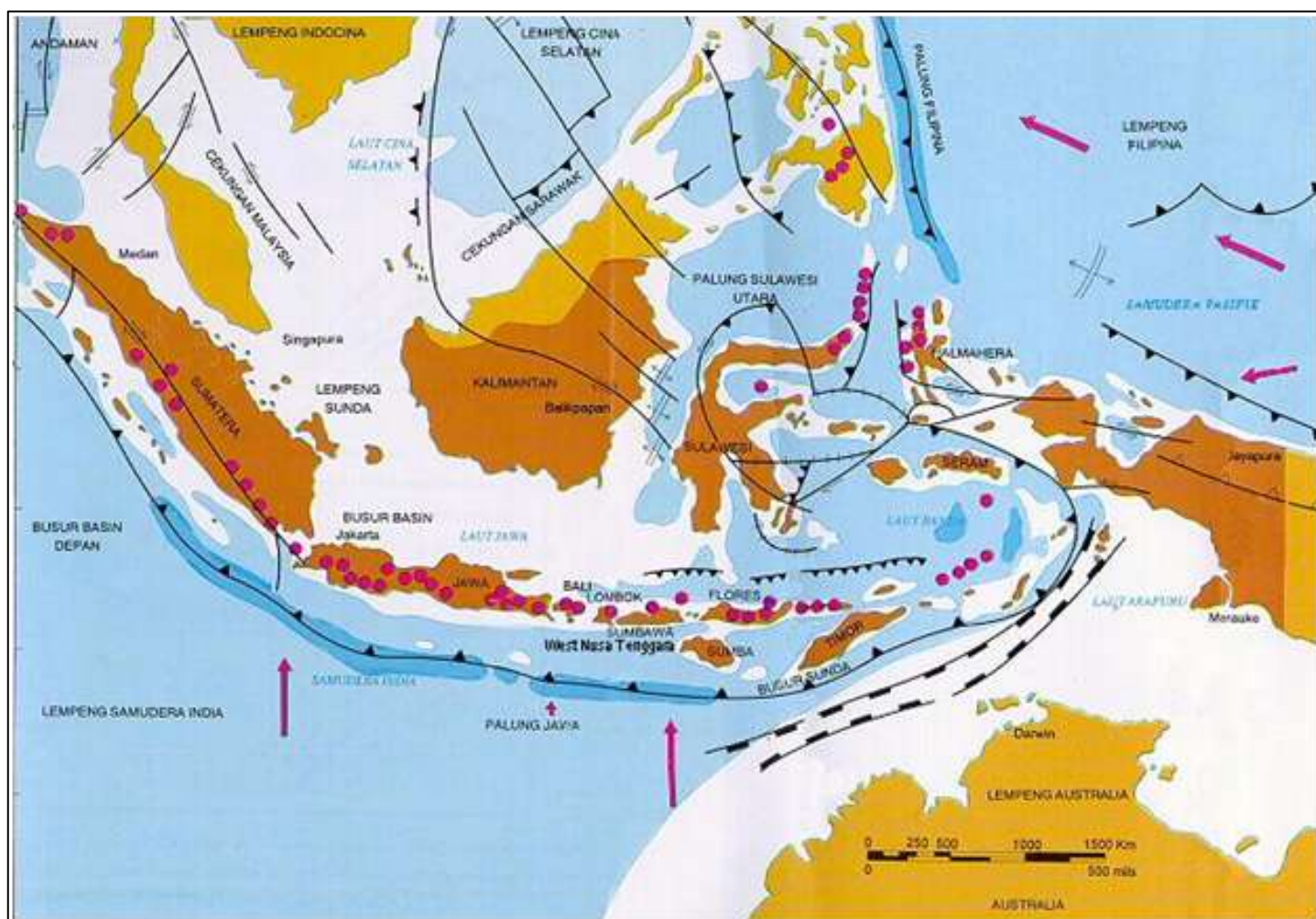


Figure 1. Volcanoes in Indonesia



Figure 2. *Calderas morphological unit of the volcano complex*

At the eastern part of Segara Anak Lake, there is a new volcanic cone called Barujari (2376m. asl), whereas to the west of it, there is another volcanic cone called Gunung Rombongan (2110 m asl). Both young volcanic cones are composed of lava flows and loose materials resulted from strombolian eruptions.

Other volcanic cones in the surrounding area are Mt. Kondo (2914 m asl) at the SW part of the calderas, Mt. Sangkareang (2914 m asl.) at the NW part of the calderas, and Mt. Plawangan (2658 m asl.) at the NNE rim of the calderas. In the northeast flank of Rinjani, there is a plateau called Sembalun Lawang, which is located at an elevation of 1000 m above sea level. Compared to the northern flank, the southern flank of Rinjani is more perfectly developed, while at the eastern and western flanks other old volcanic bodies bound the developments of Rinjani.

Stratigraphy

The stratigraphy of the Rinjani complex can be subdivided into units of eruption products that consist of several eruption sources, namely: Old Rinjani, Mt. Kondo, Mt. Sangkareang, Mt. Rinjani, Mt. Barujari, Mt. Mas and Mt. Manuk. Some of them, such as Old Rinjani, Kondo, and Sangkareang, no longer have craters because they were blown off during caldera formation. But, there are still indications showing that there used to be eruption sources, for example the eruption products, dykes, hot spring and alteration of the surrounding rocks (Hendrasto et al., 1990). In general, the eruption products are distributed to the northern and southern flanks, while to the east and western flanks the distribution is bounded by older Punikan and Anak Dare volcanic complexes.

Determination of the stratigraphic succession is based on lithological contact and super position of rock units. But, when a contact cannot be observed, the stratigraphy is determined by comparing lithology types and the degree of weathering and erosion. Distribution of the rock units was determined by using aerial photograph analysis.

Tectonics

Van Bemmelen (1949) interpreted the older basement of Solo Zone as the geanticline of East Java which re-appears in the western part of North Lombok. He suggested that the pattern of Java seems to end in this Island. The

development of tectonic activity of Lombok was the result of an uplift, volcanic activity and intrusion.

It is inferred that the oldest tectonic activity in Lombok took place in the Oligocene and was later followed by submarine volcanic activity of basaltic andesite composition, resulting in deposition of volcanoclastic rocks of Pengulung and Kawangan Formations. These two formations interfinger each other. The volcanic activity took place until Early Miocene and during Middle Miocene, a postmagmatic-activity occurred in the form of dacite intrusion into the Pengulung and Kawangan Formations.

Petrology and Geochemistry

Based on petrographic and chemical analysis of some lava flows of Rinjani carried out by Santosa and Sinulingga (1994), there are some similarities between lava flows of Rinjani and those from the Java Island. Generally, these lava flows are porphyritic and have intergranular texture with plagioclase, pyroxene and olivine phenocrysts. For those that have intergranular texture, the pyroxene and olivine minerals are frequently found amongst the irregular and elongated plagioclase minerals. Apart from phenocryst, the plagioclase is also found as ground mass in microlite forms. This plagioclase is also often associated with opaque minerals, pyroxene and glassy ground mass. The crystals are generally subhedral to euhedral shaped. Based on the extinction angle of the albite twin and lots of zoning, they are mostly labradorite.

The pyroxene of Rinjani lava flows is mostly found as phenocrysts (20%), subhedral-euhedral crystals with prismatic shaped, simple twinning and poly synthetic, varying from ortho- to clino- pyroxene. The olivine minerals are subhedral-anhedral, and they are found as phenocrysts (in relatively small amounts ranging between 1-5 %). The olivine minerals are usually found between plagioclase minerals. The opaque minerals are found almost in all thin sections as the ground mass in anhedral crystals. From the thin sections it is found that the lava flows of Rinjani range between basalt-to basaltic andesite.

Chemical analysis of some rock samples of Rinjani volcano shows that silica content varies from 48.95 %-56.86 %. The TiO content is less than 1 % and there are only 2 samples showing 1.02 % and 1.04 %, which indicate that the lava flows are characteristic of an island-arc lava (Santosa and Sinulingga, 1994).

Geothermal Energy

A geothermal field occurs at the Sembalun Lawang area, east-northeastern part of the Rinjani Volcano. The geothermal manifestation of Sembalun area is shown by the presence of hot springs and an altered volcanic zone. There are three hot springs found in the outer side of Sembalun calderas, while an alteration of volcanic rocks is found in the Sembalun lava flow unit, named Aik Orok altered zone. These three hot springs are Aik Kukusan, Aik Kalak and Aik Sebau.

The geothermal field is part of a volcano depression that resulted from calderas forming eruption of Sembalun volcano during pre-historic time/Early Quaternary (Sundhoro, 1992). This big eruption was characterized by its big volume of andesite pyroclastic flows associated with andesite-dacite pumice fall.

The collapse of the roof of magma chamber resulted in calderas structures that formed a ring fracture system. The Sembalun calderas have an elliptical shape which is 7km x 4 km in size, facing northwestward.

History of Mt. Rinjani Complex

Various reconstructions of the paleo-Mt. Rinjani Complex indicate that an old Rinjani volcano situated to the west of the present Mt. Rinjani, had existed with the height of 5000 m above mean sea level (Figure 3).

In the Pre-Quaternary time (>1.6 my), Rinjani area consisted of sedimentary rocks, then when volcanic activities occurred in the Pleistocene time (<1.6 my), the mountain underwent volcano tectonic activities. As a result of intense activity in the form of huge and strong explosions (paroxysmal explosion) followed by the collapse of the mountain body, the mountain lost most of its body and the rest was left in the form of Segara Anak calderas. This was followed by the forming of Mt. Barujari, Mt. Rombongan, and the emergence of Anak Barujari Hill.

Mt. Barujari is 170m x 200m in size, with the height of 2296 - 2376 m, or appears approximately 600m over the calderas base. The latest eruption of this mount was in June 1994, which resulted in ash rain, lahar, lake water surface declined to 4 m and an increase in the water temperature from 18°C to 40°C for 3 months. As a result of heavy rain over its top part, the pile of ash and sand caused a lahar flood along the Tanggik River and approximately 31 people died, 7 people were badly injured, agriculture fields and dam were destroyed and irrigation ways were silted up.

There were eight eruptions since 1847, all of them in Rinjani (Segara Anak) calderas. Based on its history record, Mt. Rinjani has never erupted, so Mt. Rinjani belongs to the B-type of active volcanoes. The types of eruption in Rinjani calderas were effusive (lava flows) and explosive (pyroclastic falls) which formed strato type volcano. Eruptions were recorded 8 times, i.e in 1847; 1884; 1901; 1905; 1915; 1944; 1966 and 1994 (Figure 4).

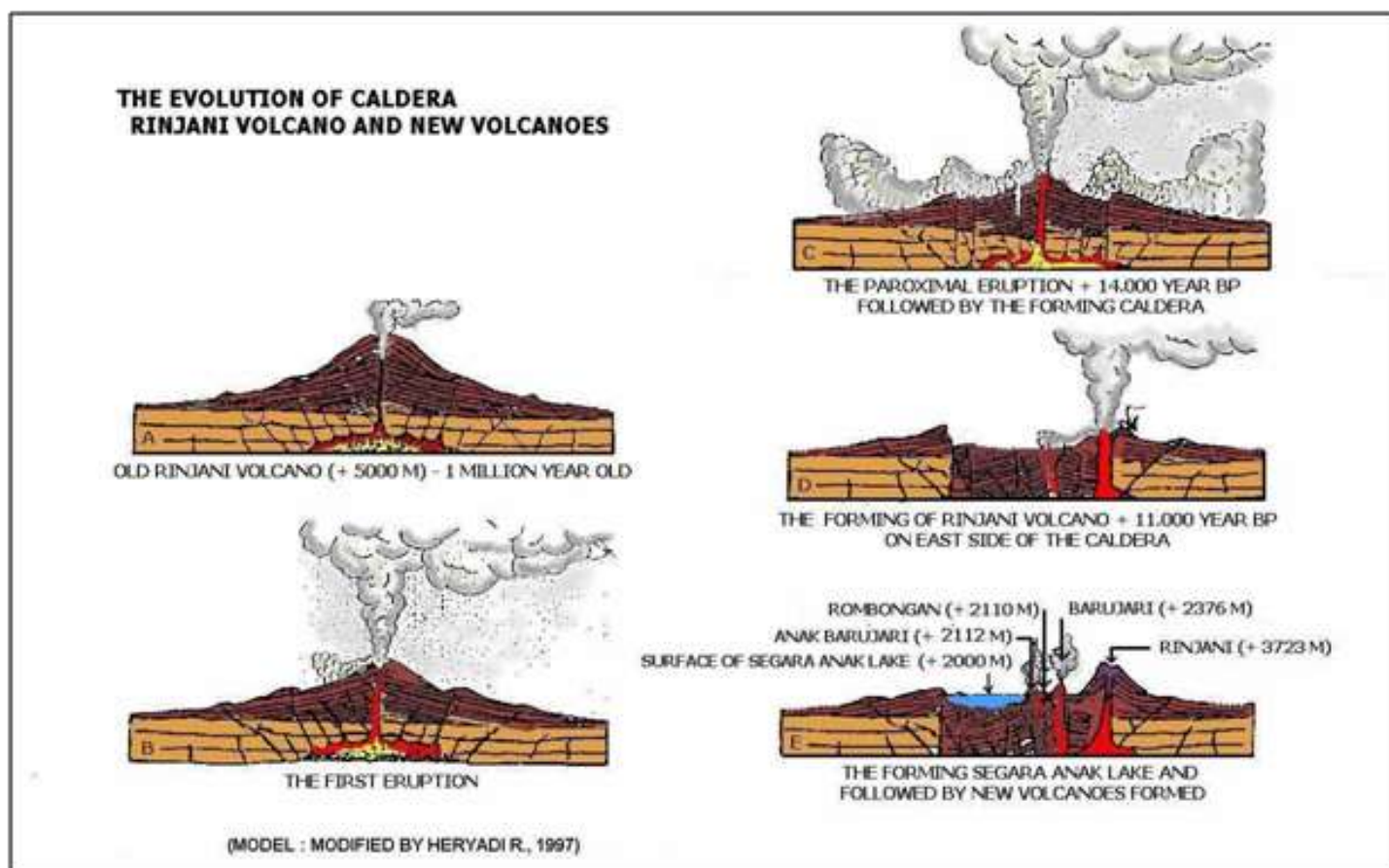


Figure 3. Evolution of Mt. Rinjani

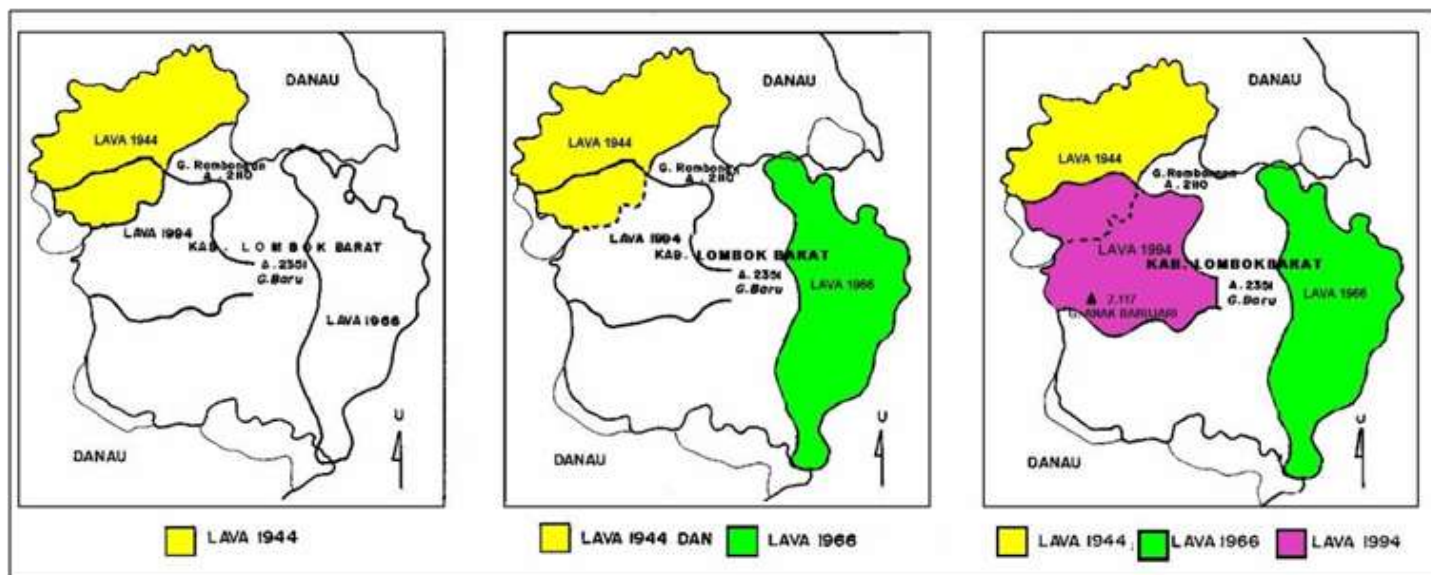


Figure 4. Lava flows in Segara Anak Caldera in 1944-1994

Only three explosions were recorded, *i.e.* in 1944, 1966, and 1994. The first explosion in 1944 formed the new cone of Mt. Rombongan, which emerged from the caldera's lake situated in northwest part of Mt. Barujari feet, which became wider to the north and west. The second explosion in 1966 produced lava, which came out from the eastern part of Mt. Barujari slope and reached the lake in the north and south. The last explosion in 1994 also came from Mt. Barujari, which produced lava in the west through the lake and caused the emergence of the Mount Anak Barujari and also resulted in the increasing of Mt. Barujari activities.

Volcano Tourism Potential

There are three relevant potential resources for volcano tourism in Mt. Rinjani that can be developed to be tourist destinations, that is geotourism/volcano tourism, flora/fauna and community development (Rachmat, 1998; 2001).

The Top/Calderas of Mt. Rinjani and Mt. Barujari
The highest point in the Mt. Rinjani area is situated in the eastern side of the elliptical Rinjani calderas (4.8 km and 3.5 km in diameters). When this point is seen from the distance, it appears as the top of Mt. Rinjani. The beautiful scene of Mt. Rinjani crater can be clearly seen from this point and a beautiful sea view can also be seen to the northern and eastern side.

Segara Anak Lake

The present crescent-shape of Segara Anak Lake lies at the height of ± 2008 m asl, which has an area of $\pm 11,126$ ha and depth 160 up to 230 m, even though data measured in 1925 yields ± 250 m in depth. After the explosion in 1944, the lake depth measured in 1951 was 200 m, with the area of 11,000 ha as a result of silting of the lake (Figure 4). It is

deduced that this occurred because of sedimentation of rock erosion from the upper part of the crater and the other products of explosion. This lake/caldera historically occurred as a recent of huge explosion that formed a big hole and rain for a period of time filled the hole with water creating a lake called Segara Anak. Fishing activities are carried out in this Lake, because there is a huge number of fresh water fish like mujair and karper. The weight of a single karper can reach 4 kg. Residents and tourists travel around the lake by rowboat.

Waterfalls and Caves

There are three main waterfalls in the Kokok Putih River stream, *i.e.* near Goa Susu (Susu Cave), in Mayung Putih, and in the proximity to Segara Anak Lake (Figure 5). Another waterfall in Sendang Gile comes from Mt. Rinjani hills indirectly. The waterfalls along Kokok Putih stream are a result of stopped lava flow, and the height of these waterfalls depend on the thickness of the lava flow when it stopped. All of these places attract many tourists, particularly on holiday.

The 1944, 1966, and 1994 Lava Flows

The new lava flows that can become another tourist objects are the lava flow from Mt. Barujari which erupted in 1944, the lava flow of the 1966 Mt. Rombongan eruption, and the lava flow of the 1994 Mt. Barujari eruption. The lava shapes are sharp corners in blocks with deep holes with lava flows which have become and harden. It occurred as a result of accumulation of gas pressure with magmas from the depth, which came out to the surface through weak zones or crater holes. Theoretically, if the gas pressure is very high, it will be accompanied by a huge explosion which throws out hot materials of ash with a size of about 12 m in diameter. If the gas pressure is weak, the lava just flows with temperature around 800°C .



Figure 5. *Susu Cave and Hot Spring*

Hot Springs

Hot springs are formed by surface water that flows deep down in the earth through cracks and contacts with magma, then the water rises to the surface as hot springs.

- Susu cave hot spring. This hot spring is situated at ± 1750 m msl with temperature of $52-45^{\circ}\text{C}$ in ambient air temperature at 19°C and pH 6-7. The water is clear, steamy and has a bad smell like H_2S with spots of yellow sediments and sinters.
- Foot of Mt. Barujari. This spring has a temperature from $42.4-44^{\circ}\text{C}$ and pH 7.6 with clear and bubbly water.
- Payung cave Pengekereman Umar Maya. This spring is found along the Kokok Putih River with a temperature of 50°C in 12°C ambient air temperature and pH 6-7. The water of the spring is clear, very steamy, with continuous and large amount of bubbles, and has orange and yellow colours of sediments (iron oxide) that might have arisen from basaltic andesite of lava blocks (Figure 6).



Figure 6. *Payung cave hot spring and small waterfall of Kokok Putih*

Cross Country/Wall Climbing/Glider Flying

The Rinjani complex can be reached from Mataram (the main city of Lombok) by car to Senaru (2.5 hours) or to Sembalun Lawang (3.5 hours) and continued on foot through several tracks from Senaru to Segara Anak Lake (9.5 hours) or from Sembalun Lawang to Segara Anak Lake (10.5 hours). The top of Mt. Rinjani can be reached out from two locations, i.e. from Plawangan Sembalun, which needs ± 2.5 hrs, climbing and directly from Aikmel. However, the second one is very hard because this route is longer and people will not find any water. Other activities in Mt. Rinjani area can be wall climbing along calderas walls, which surround the Segara Anak Lake and glider flying from the top of Mt. Rinjani to Sembalun Lawang.

There are several routes when people want to tracking around the Mount Rinjani to get some experiences and enjoy the view of Mt. Rinjani and Segara Anak Lake. Some routes can be described as follows (Figure 7) :

North Route: Bayan - Senaru

Senaru - Pelawangan (north side of calderas edge) - Kokok Putih needs around 9.5 hrs. This is the easiest route with smooth slope and the best view of a new stream of lava of Babanan.

North northeast Route: Bayan - Torean

This more difficult route can be completed in a day from Bayan to the caldera base.

Southeast Route: Sembalun Lawang

There are two routes: Sembalun Lawang-Pelawangan-Summit; and Sembalun Lawang-Plawangan-Kokok Putih. These two routes need the same length of time to complete, which is around 10.5 hrs. Even though the second route is more difficult, people prefer to use this route because it is easier to reach the top of Mt. Rinjani.

Sajang Route

This route is similar to the Sembalun Lawang Route because the footsteps meet the Sembalun Lawang Route on the western side.



Figure 7. The Rinjani Mountain Track

Geothermal

A geothermal is formed by near surface magma sources that, due to the magma heat, reaching the surface through the weakness of the cracked earth. The heat can appear as steam, gas or a hot spring. There are five potential geothermal fields in Mt. Rinjani, all of them situated in Sembalun sub-regency East Lombok Regency. The fields appear as hot watersprings and fumaroles, *i.e.* in Sambelia, Aek Sebau, slope of Mt. Anakdare, and Putih River of Segara Anak Lake. All these five geothermal fields located between 1500 and 2500 m asl, and have temperatures ranging from 41°C to 47°C, debit 0,3 to 2 l/s and pH6 to 7.

The Geology and Volcano Information

The Volcano Observatory Station has been built in Mt. Rinjani area, situated in Sembalun Lawang. There are two guards in this post everyday in the shift of 24 hour. Their task is to monitor volcano activities visually and seismically (Figure 8). The station has been equipped with several monitoring and communication tools which are connected to the Directorate of Volcanology and Geological Hazard Mitigation in Bandung twice a day. This station also has been equipped with information, photos and maps such as the Dangerous Zone Maps of Mt. Rinjani, posters, and some photos related to the activities of Mt. Rinjani. This station is very important as supporting volcanotourism objective in which the tourists can get more detailed information about many things that relate to volcanoes.



Figure 8. Rinjani volcano observatory and seismograph

Flora and Fauna

Mount Rinjani National Park covers an area of 41.330 ha. The park is surrounded by a further 66.000 ha of Protected Forest. Mount Rinjani is rich in the variety of flora, fauna and vegetation types (Figure 9).



Figure 9. Types of flora and fauna around Gunung Rinjani National Park

Notable flora include the everlasting edelweiss flower (*Anaphalis viscida*), tiger orchid (*Vanda sp.*), alang-alang grass (*Imperata cylindrica*), cemara tress (*Casuarina trifolia* and *Casuarina*). Wildlife found in the Park includes deer (*Cervus timorensis*) although they are hard to spot. Other mammals include black silver leafed monkeys or lutung (*Presbytis cristata*). Birds recorded in the park include eagles (*Spizæetus cerbatus*) and white cockatoos with yellow crests (*Cacatua sulphurea occidentale*).

Community Development

The main objective of the Mt. Rinjani Management is to foster community development on park boundaries bringing about benefits to rural women and men, in recognition of the link between national conservation and local development goals. There are other objectives of the Mt. Rinjani Management.

Firstly, to improve park management through training, developing management techniques and improving infrastructure, secondly to develop responsible park tourism by encouraging ecotourism based on trekking and Sasak culture.

Because of its geographic position which is close to each other, Lombok and Bali have similar culture and arts, nevertheless, there are still differences either in arts, culture or the life of Lombok people. The *traditional house, music, earth wear, art pattern, traditional clothes and handy crafts of Lombok* are also different from Bali (Figure 10).

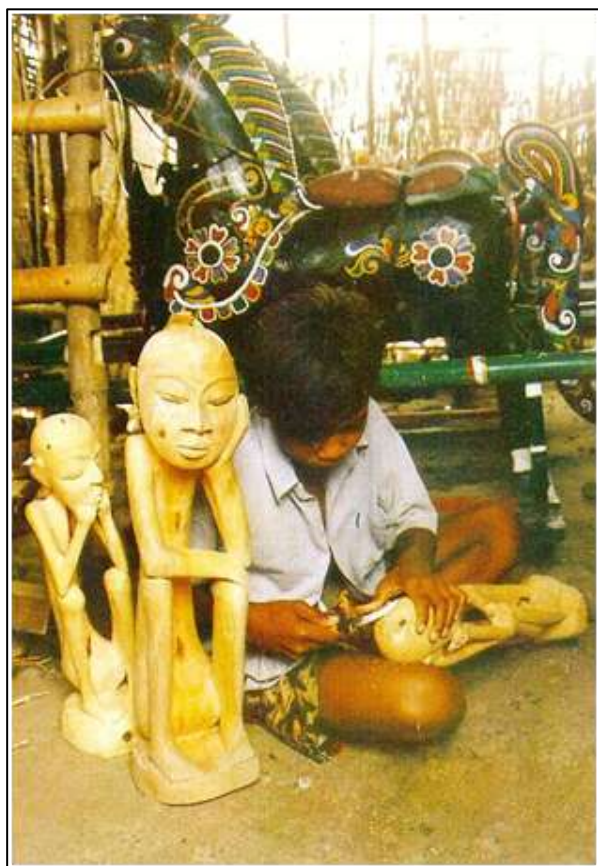


Figure 10. Traditional Handicrafts and Art Patterns

Conclusion

Mount Rinjani is the second highest volcano in Indonesia belonging to The 'Ring of Fire'. The dramatic landscape has been created over millions of years of cone-building and violent explosions. Eroded forested slopes rising directly from the sea create their own weather patterns and become a catchment area for the whole Lombok.

Mount Rinjani complex has variations in its natural resources (natural heritage) such as various types of flora and fauna. It also has other enticing charms, the uniqueness and beauty of nature known as geotourism or volcanotourism. The combination of all these makes Mount Rinjani a fascinating potential for volcanotourism and a specific vulcanotourism and specific unique type of nature tourism which stresses on its volcanological and geological elements. Over twenty villages surround Rinjani and there are many routes up to the mountain, but the main acceses are from Senaru in the north and Sembalun Lawang in the east. The challenging three-day Rinjani track route from Senaru to the crater rim (Plawangan), down to the stunning crater lake then on to Sembalun Lawang, is considered as one of the best track in Soth East Asia. Those heading for the summit usually prefer to start in Sembalun Lawang. If you want to know one of the fantastic volcanos in the world, come to the Rinjani volcanoes in Lombok Island, and West Nusa Tenggara Province, Indonesia. I believe you will find something new about this volcano.

The main objective of Mt. Rinjani Management is to foster community development on park boundaries bringing about benefits to rural women and men, in recognition of the link between national conservation goals and local development goal, based on an ecotourism programme.

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A Report from SEAPEX Evening Talk in Bangkok: Current Understanding of Sundaland Tectonics

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Introduction

Sundaland (Figure 1), the so called 'craton' and 'stable' core of SE Asia, may not be a real craton after all. New granite zircon dating, seismic tomography and heat flow data from the region all point towards relatively young, hot, heterogeneously assembled and easily deformed lithosphere with only local strong crusts. Ongoing research undertaken by Prof. Robert Hall and his team in the Southeast Asia Research Group (SEARG) of Royal Holloway, University of London (UK) shows strong evidences to argue that Sundaland is not a craton and neither are its characteristics similar to well-known cratons such Wyoming (US) and Gawler (South Australia). Their findings were presented by Prof. Hall in a recent SEAPEX Evening Talk that took place on the 31st of July 2012 in Bangkok, Thailand.

Reports

The Sundaland continental block was assembled mainly in the Triassic and Cretaceous from Tethyan sutures and Gondwana fragments (Hall et al., 2009). The Gondwana fragments were parts of the Australian continent that rifted in the Jurassic and arrived and collided with Sundaland in the Late Cretaceous (*ca.* 90–80 Ma). By this period, subduction was terminated and Sundaland was surrounded by mostly inactive plate margin, however local extension, subduction and strike-slip deformation still occurred. For example in the SW Borneo, which is considered as part of the Sundaland's core, local extension has led to the intrusion of Schwaner granites into pre-Carboniferous Pinoh metamorphics and formed the Borneo island. Age dating of detrital zircons within sandstones sourced from the Schwaner granites show consistent mid-Cretaceous age for the granite's emplacement.

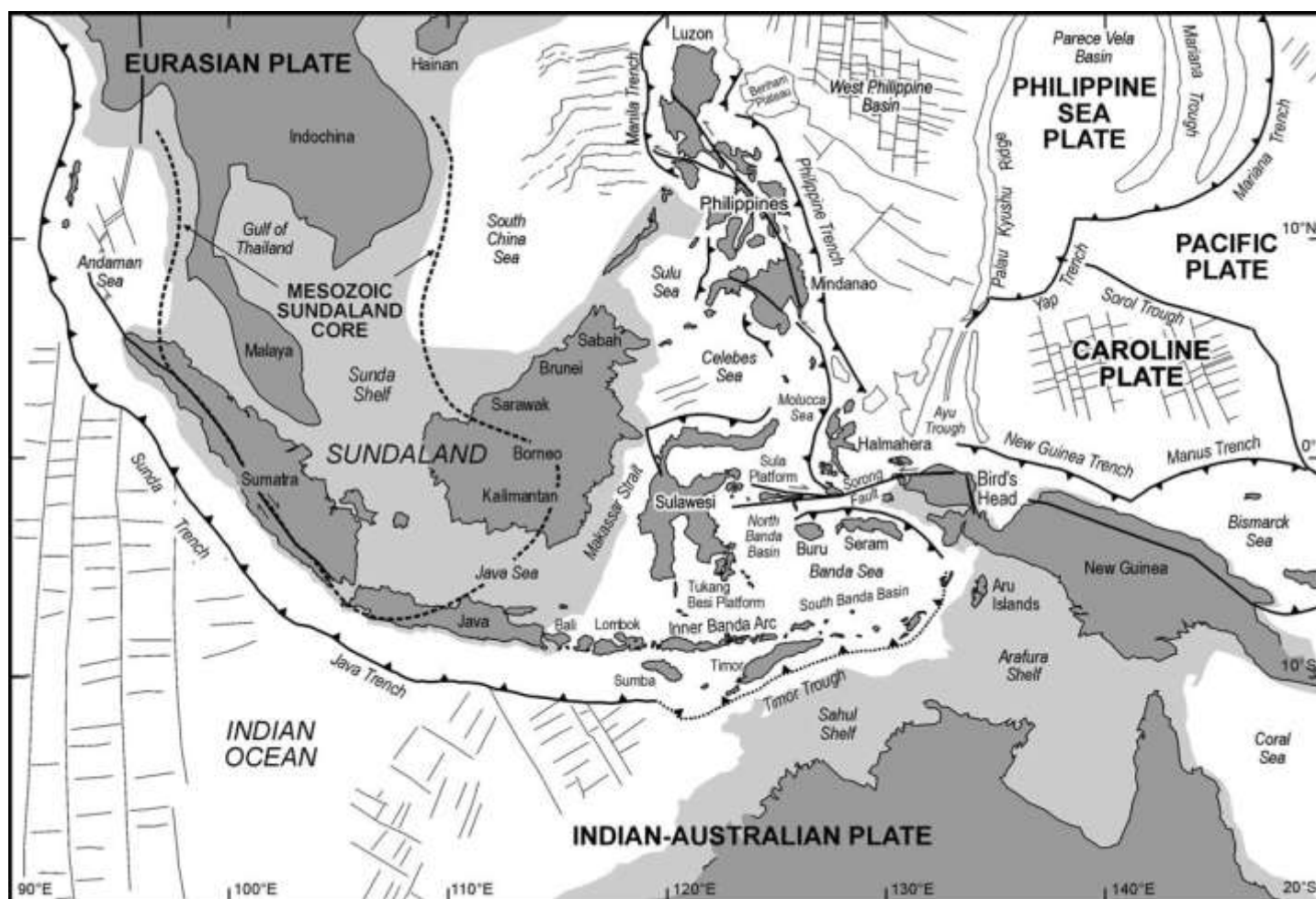


Figure 1. Sundaland and nearby geographical features (Hall, 2002)

Seismic tomography data show that at 150 km below surface, the Sundaland region has average seismic shear velocity (V_s). The low V_s occur mostly below mid oceanic ridge, suggesting thin and hot crust, while the high V_s are observed below continental crust such as Australia and India, which suggest thick and cold crust. The relatively low seismic V_s of the Sundaland's upper mantle indicate fairly thin, warm and weak lithosphere. This interpretation is supported by high present-day heat flow across much of the region, even in the area far away from volcanic belt such as the Gulf of Thailand. As a comparison, an average heat flow of a continental crust is approximately 60 mW/m², while across the Sundaland, it is mostly 80–100 mW/m².

The weak and unstable nature of Sundaland makes the region be easily deformed, as shown by the development of numerous Cenozoic extensional basins that captured thick sediments. Active deformation still takes place until the present-day in the form of fold and thrust belt (FTB) development that is also accompanied by subsidence on the opposite side of the FTB. This coupled FTB and extension are observed particularly at the NW Borneo-Palawan (offshore Brunei & Sabah), Sulu Sea and West Sulawesi (Makassar Strait). These FTBs all share some common features which include having onshore mountains, exposed young granites and deep crustal metamorphic rocks, rapid subsidence and rapid uplift, developing on areas that lack subduction slab evidence, have minimum seismicity and no volcanic activities.

Previous researchers attributed the formation of NW Borneo-Palawan and West Sulawesi FTBs to subduction and collision mechanisms, but Prof. Hall and his team believe that these FTBs were not formed by contractional mechanism. Instead, they proposed gravitational-driven mechanism through the rise of nearby mountains, such as Kinabalu Mountain in the case of NW Borneo-Palawan

FTB; and Central Sulawesi Range for the West Sulawesi FTB.

Subduction in the NW Borneo-Palawan was taking place most likely until Early Miocene when the South China Sea was forming, but from Middle Miocene onward, there is no evidence to interpret the offshore Brunei FTB as a product of contraction due to a subducting slab. Likewise, interpretation of newly acquired seismic data around the Banggai-Sula continental block found no evidence to suggest that the block was transported from the Bird's Head by a major, left lateral, strike-slip fault (Sorong Fault). The strike-slip fault segments mapped around the Banggai-Sula block are disjointed and furthermore, they have right lateral sense of movement rather than left-lateral. Therefore, it is unlikely that the Banggai-Sula block travelled a long way to the west and then collided with the eastern arm of Sulawesi to form the West Sulawesi FTB on the other side of the island.

Current understanding of the Sundaland's tectonics as advocated by Southeast Asia Research Group promotes extension, not contraction, as more important in shaping basin evolution in the region. The upper crust of Sundaland may have gone up and down, moving vertically to create various deformations, including young fold and thrust belts that are active until the present-day.

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