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).

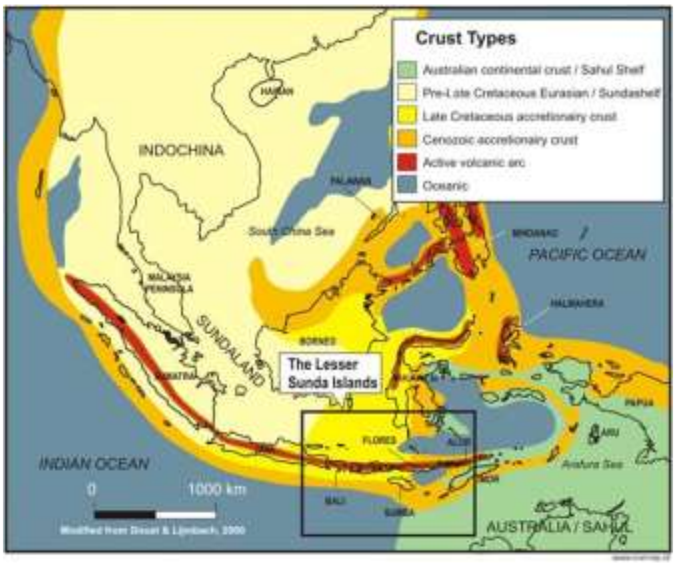


Figure 1 *Map of Southeast Asia showing the different crustal type in the region and the location map of the Lesser Sunda Islands (after Doust & Lijmbach 1997).*

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 (Krabbenhoeft, A., 2010) for bathymetric data acquisition.

- 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

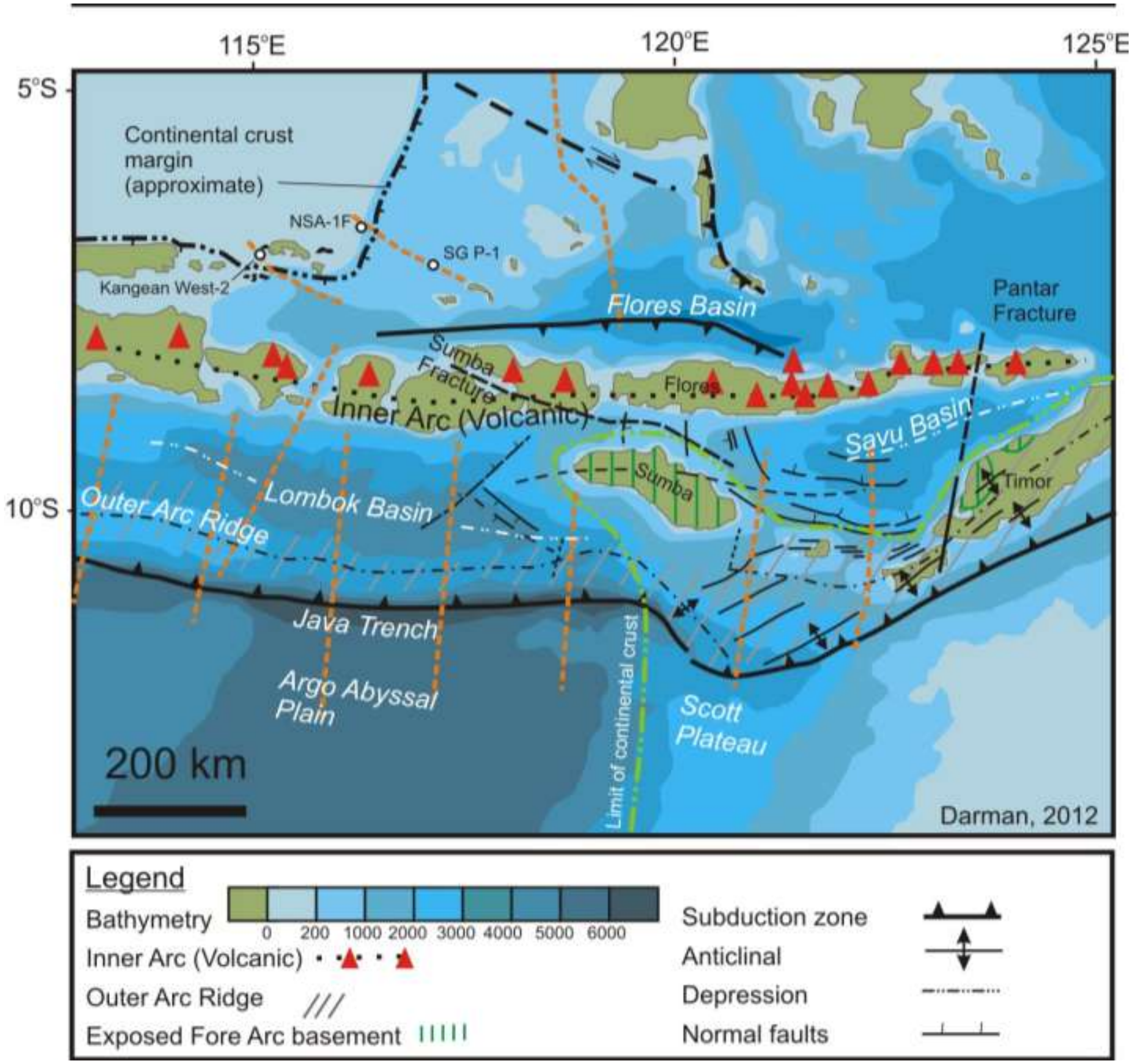


Figure 2 *Tectonic map of the Lesser Sunda Islands, showing the main tectonic units, main faults, bathymetry and location of seismic sections discussed in this paper.*

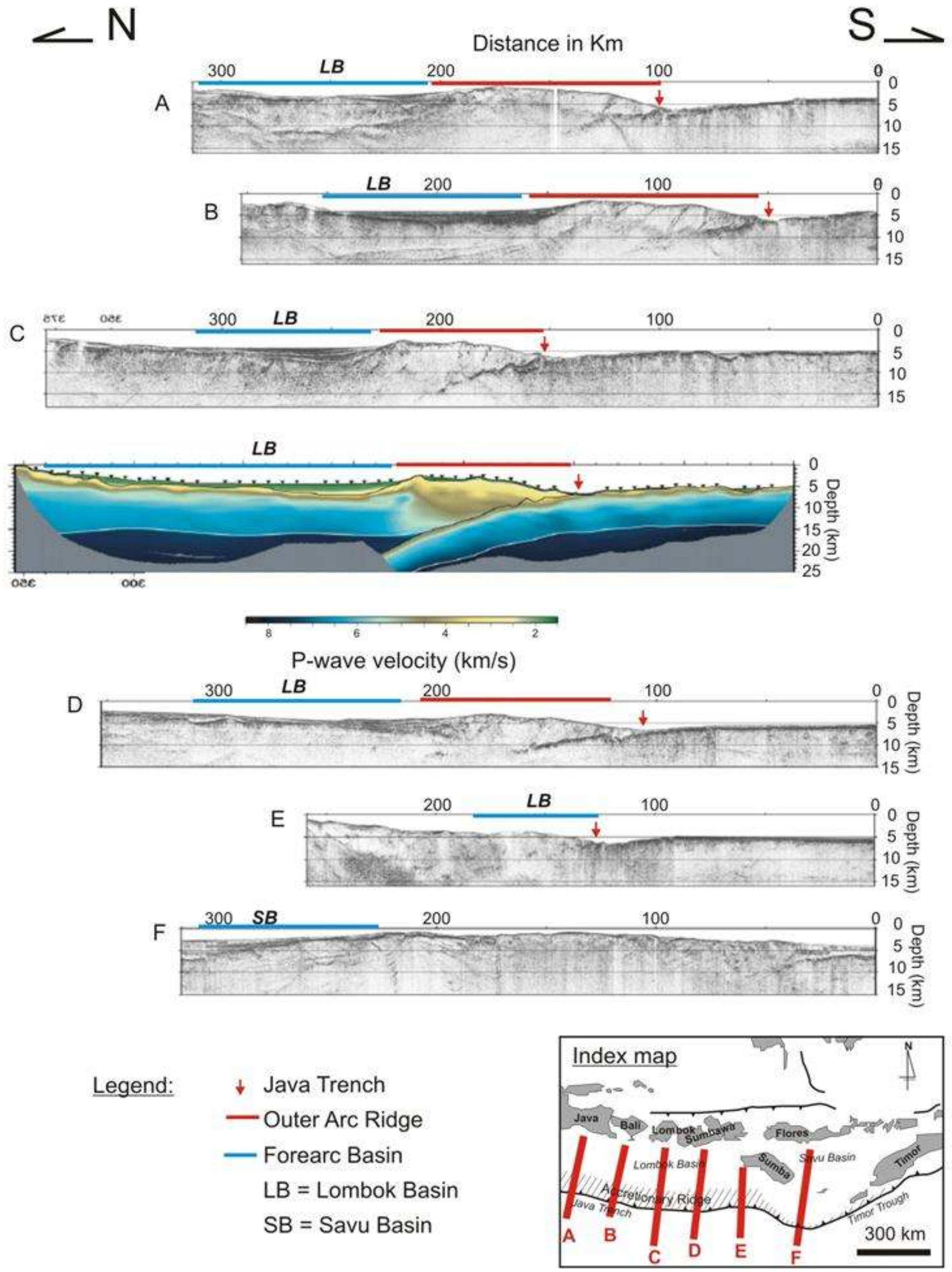


Figure 3 *Six 15 km deep seismic sections acquired by BGR from west to east traversing oceanic crust, deep sea trench, accretionary prism, outer arc high and fore-arc basin, derived from Kirchoff prestack depth migration (PreSDM) with a frequency range of 4-60 Hz. Profile BGR06-313 shows exemplarily 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 aerially 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.

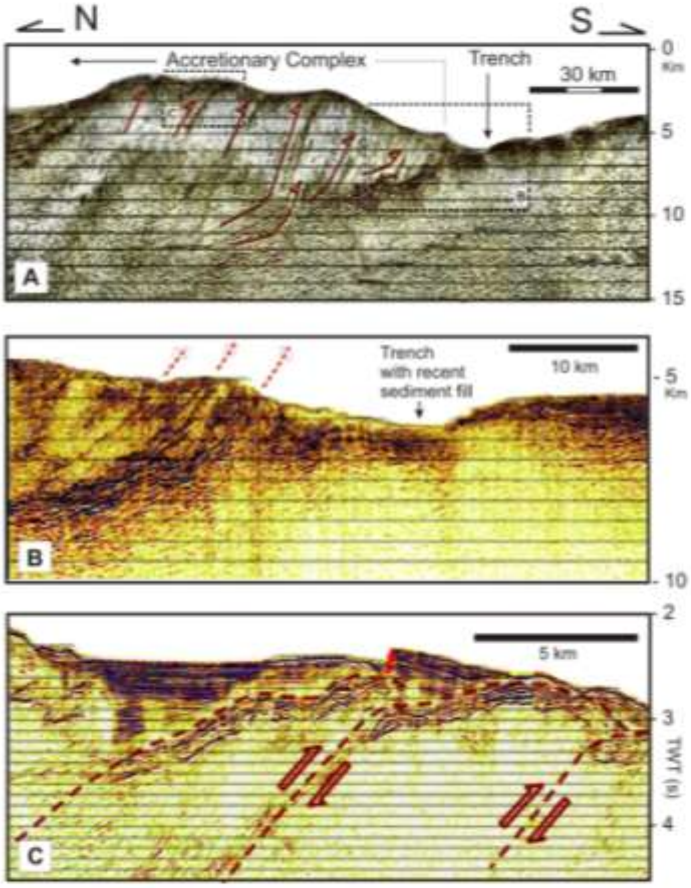


Figure 4 *Detail sections of BGR06-303. A) Outer-arc ridge with thrust faults which formed the accretionary complex. B) Detail section of A) showing the trench sediment fill and the thrust faults in the north of the section. C) Detail section of A) showing the sediment fills of the Piggy-Back Basin, 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 thoughout 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

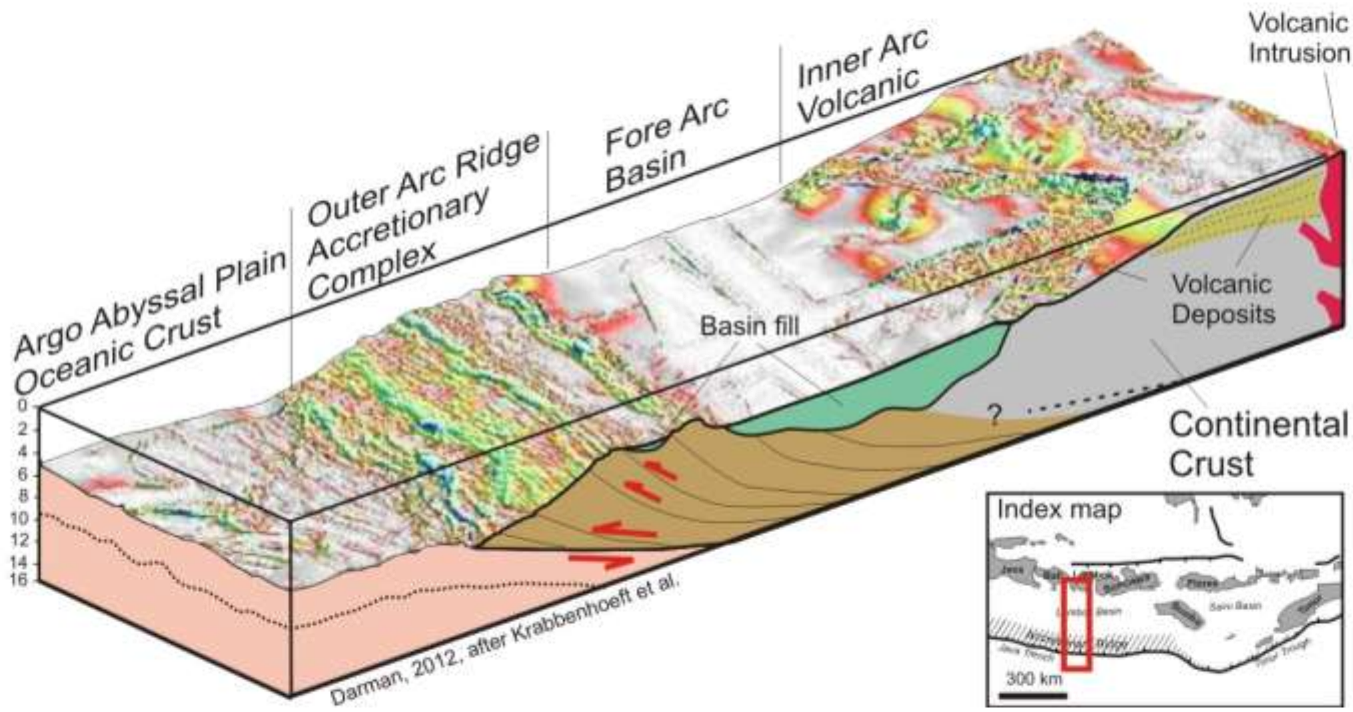


Figure 5 *Block diagram of the southern part of Lombok Island. The surface is a gradients map of bathymetric data. Gradients are draped on perspective view of bathymetric relief. Trench, outer wedge, slope break and inner wedge are indicated. The section is modeled based on sea bottom profile (after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

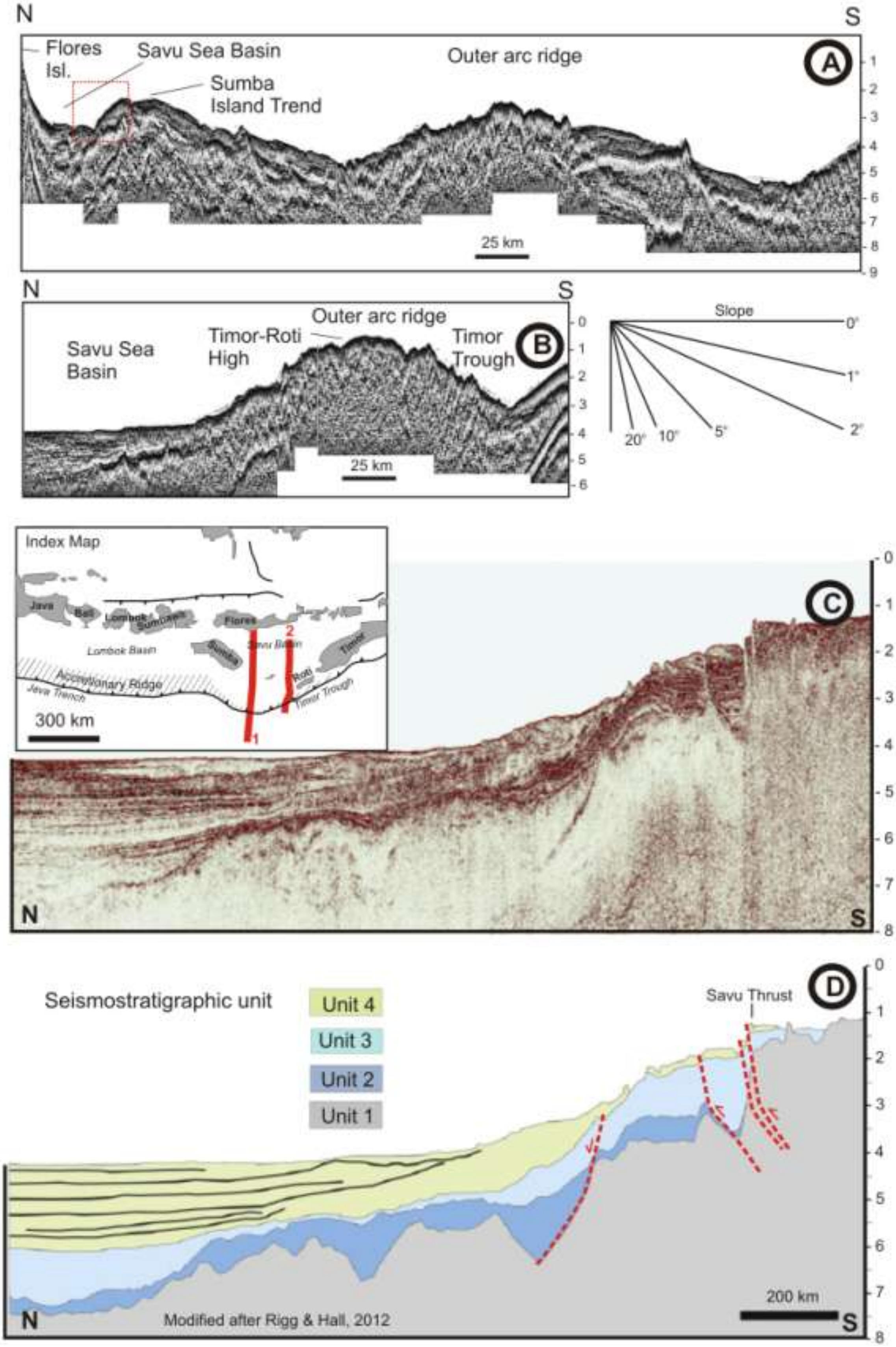


Figure 6 *North-south seismic sections across the Savu Basin. A) Rama expedition seismic, shows the relationship of the outer-arc ridge, Sumba Island high, Savu basin and Flores Island in the north. B) Another Rama expedition seismic in the centre of Savu Basin. C) A CGG Veritas seismic lines parallel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

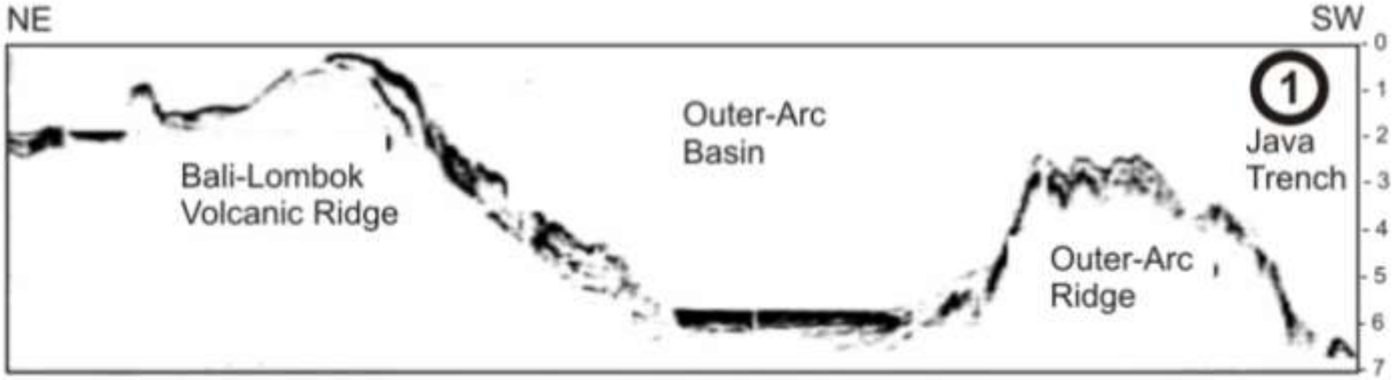
and the outer-arc are known as fore-arc basins. The fore-arc basin in the west is called the Lombok Basin (Fig. 2). Further east, the Savu Basin is a continuation of fore-arc basin located in the eastern Lesser Sunda Islands, separated from the Lombok Basin by Sumba Island.

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 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 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 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?



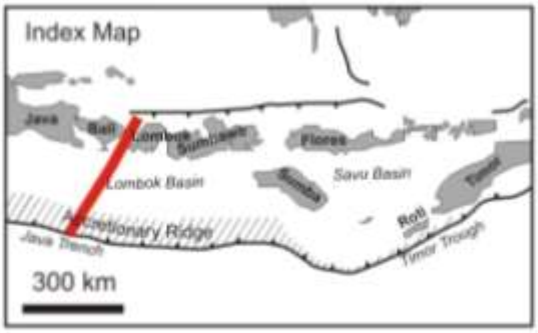


Figure 7. *Seismic-reflection profile across Bali-Lombok volcanic ridge, acquired by R. V. Robbert Conrad cruise 11 (Hamilton, 1979). The crest and north flank of the outer-arc ridge are mantled by pelagic sediments, whereas the south flank is not; this may record increasingly intensity of deformation 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.*

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 to shallow or impaired quality to see of the edge of the Australian Continent Shelf.

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

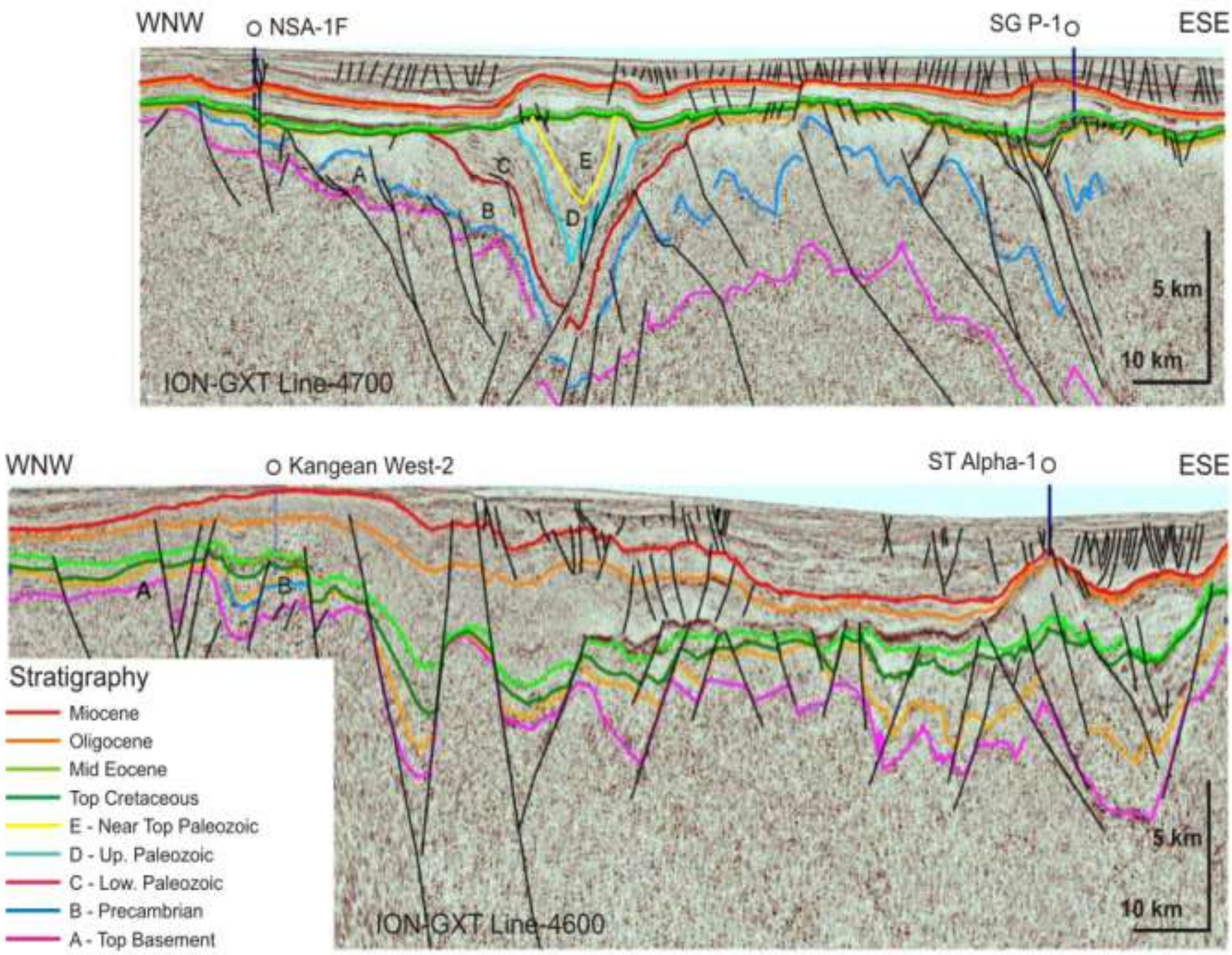


Figure 8. *Two WNW-ESE seismic lines in the north of the Lesser Sunda Islands showing the potential margin of the Sunda Shelf or Eurasian Continental crust margin. These seismic sections were acquired by ION (Granath et al, 2011). A) Seismic line between NSA-1F and SG P-1 well with significant drop of 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.*

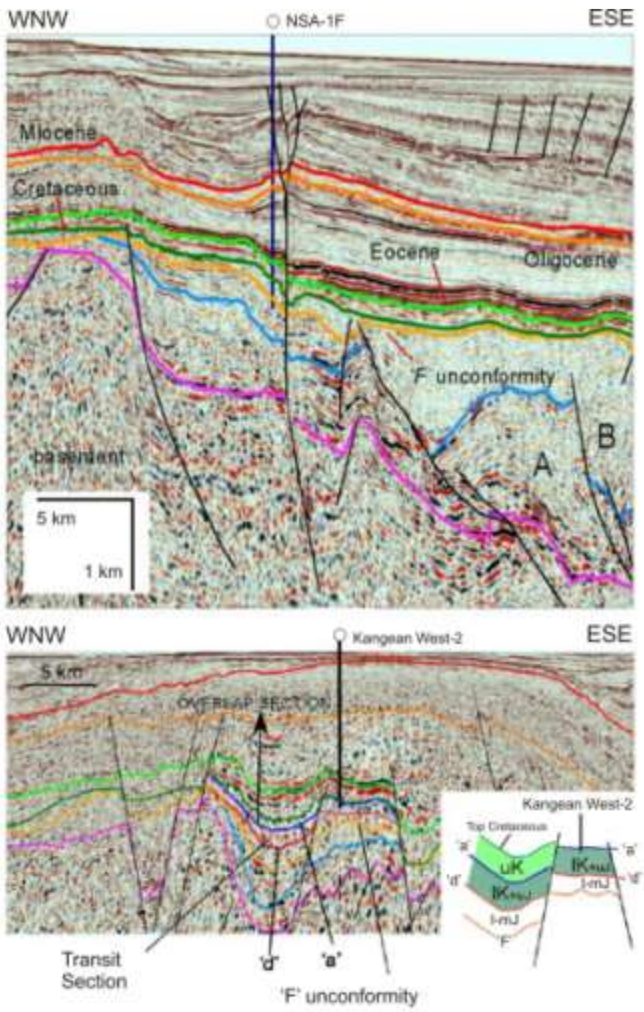


Figure 9. *Detail sections of the profiles shown in Figure 7. A) A section located near to NSA-1F and B) A detail section located near to Kangean West-2 well.*

acquired by ION (Fig. 8B) and allowed definition of top basement on this area area Granath et al (2011). To the WNW, shallow basement ibeneath 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.

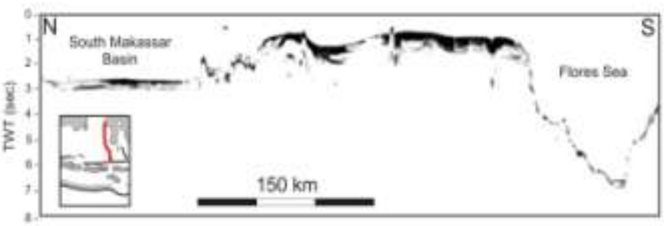


Figure 10. *A N-S seismic section from Lamong Doherty Geological Observatory, acquired by R. V. Robert Conrad cruise 11 (Hamilton, 1979). This section shows little sediment on the narrow floor of the Flores Sea or Flores Basin, in contrast to the thick strata on the platform between that sea and the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

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

Neo-Tectonic activitity

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 N11oE 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)

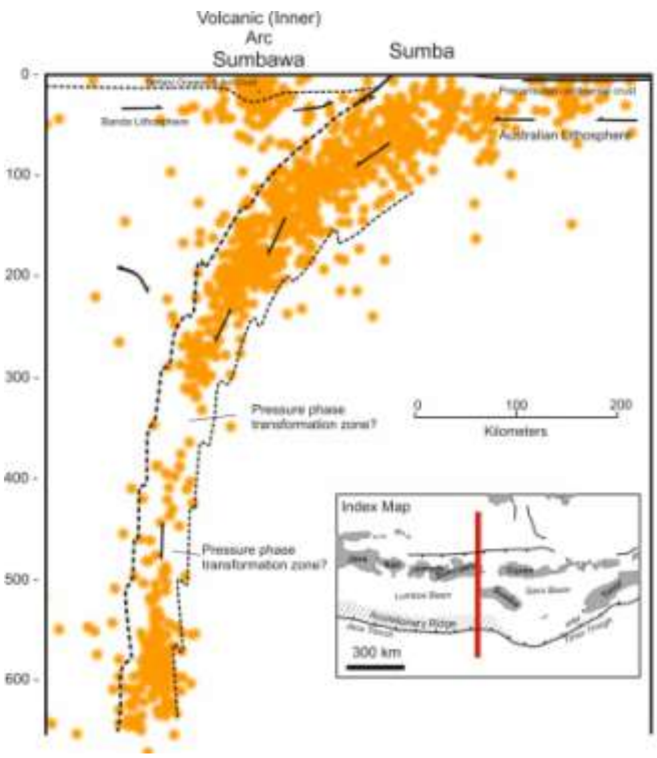


Figure 11. *This plot shows the earthquake localizations on a South-North cross section for the lat -14°/-4° long 114°/124° quadrant corresponding to the Lesser Sunda Islands region. The localizations are extracted from the USGS database and corresponds to magnitude greater than 4.5 in the 1973-2004 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 continenet (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-ar 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

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