Oblique Intraplate Convergence of the Seram Trough, Indonesia

Konvergensi Intra-lempeng Miring Palung Seram Indonesia

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ABSTRACT: The Banda Arc which curves around through 180^o is one of interesting features in Eastern Indonesia, a complex area resulting from convergence of Indo–Australia, Eurasia, and Pacific plates with a number of microplates involved. Its complexity has led to debates on how the U–shaped geometry was attained. This study investigates seafloor morphology and seismicity around the Seram Trough which may help to give an insight into the tectonic setting of the area. We further discuss each model proposed for the Seram Trough by previous authors. Generally, there are two views on how many slabs are subducting beneath the Banda Arc, either double slabs or single slab. The Seram Trough, which is often linked to the Timor–Tanimbar Trough enclosing the Banda Arc, was interpreted in different ways, with many models by many authors, as a subduction trench, an intraplate foredeep and a zone of strike–slip faulting. We argue that the most plausible explanation is a single slab model to explain the nature of the Banda Arc. The most plausible model for the Seram Trough is a foredeep model which is associated with exhumation processes on Seram and the deep feature was caused by a subsidence, led by loading by the fold–thrust belt. The Seram Trough is significantly different to common subduction systems. It has shallower bathymetry, is less than 3000 m in depth and is an almost aseismic zone.

Keywords: Banda Arc, Buru Basin, convergence, fold–thrust belt, Seram Trough.

ABSTRAK: *Busur Banda yang melengkung 180^o merupakan fitur menarik di Indonesia bagian timur, suatu area kompleks hasil konvergensi lempeng Indo–Australia, Eurasia dan Pasifik dengan beberapa lempeng mikro terlibat. Kompleksitasnya mengarah pada perdebatan bagaimana geometri 'U' terbentuk. Studi ini menginvestigasi morfologi dasar laut dan kegempaan disekitar Palung Seram yang dapat membantu memberikan wawasan tentang tatanan tektonik area tersebut. Kami juga mendiskusikan setiap model yang diajukan untuk Palung Seram oleh beberapa penulis sebelumnya. Umumnya, terdapat dua penjelasan tentang berapa jumlah lempeng yang menunjam dibawah Busur Sunda, antara dua lempeng atau satu lempeng. Palung Seram yang sering dihubungkan dengan Palung Timor-Tanimbar menyelubungi Busur Banda telah diinterpretasikan dengan beberapa model oleh beberapa penulis sebagai palung subduksi, foredeep dalam satu lempeng dan zona sesar mendatar. Kami mengajukan bahwa penjelasan yang memungkinkan adalah model satu lempeng dalam penjelasan keadaan Busur Banda. Model yang dapat diterima untuk Palung Seram adalah foredeep di depan sabuk sesar anjak dan lipatan yang berasosiasi dengan exhumation processes di Pulau Seram dan fitur yang dalam diakibatkan oleh subsidence akibat pembeban jalur sesar anjak dan lipatan. Palung Seram memiliki batimetri yang lebih dangkal, kurang dari 3000m dan merupakan zona aseismik.*

Kata kunci: *Busur Banda, Cekungan Buru, konvergensi, jalur sesar anjak dan lipatan, Palung Seram.*

INTRODUCTION

The Banda Arc was described as U-shaped active subduction zone in Eastern Indonesia which consists of an outer-arc ridge and inner volcanic arc (Hamilton, 1979). Seram is part of the Outer Banda Arc and includes Australian Continental Crust (Audley-Charles *et al.*, 1979). Seram is the second largest island after Timor in the Outer Banda Arc and is characterized by mountainous topographic relief with elevation reaching more than 3000 m above sea level in Central Seram and has a relatively E-W trending elongated shape. The Seram Trough lies parallel to Seram in the offshore area north of Seram. To the east, the Seram Trough rotates into a N-S trend in the offshore area near the Kai Islands. The trough is often linked to the Timor-Tanimbar Trough, and commonly represented as a U-shaped trough in map view as continuation of the Java Subduction Trench. The sea water depth in the study area is generally shallower than 3000 m and the average depth of the Seram Trough is about 2000 m, except the Buru Basin which reaches 5300 m. To the north, the Seram Trough is roughly parallel to an irregular ridge between the island of Misool and the Onin-Kumawa Peninsula, known also as Misool-Onin-Kumawa Ridge.

The Seram Trough is located between Seram Island and the Bird's Head of New Guinea, in a complex area where convergence between the Eurasian, Indo-Australian and Pacific Plates has been active (Figure 1) since at least Late Oligocene (Katili, 1975; Hamilton, 1979; Hall, 2002; Hinschberger *et al.*, 2005; Spakman and Hall, 2010; Watkinson *et al.*, 2012; Hall, 2012). The interaction among those plates has controlled the present-day geological structures in the area. Based on study of seismicity, it is generally agreed that the Australian Plate (Proto-Banda Sea) is subducted beneath the Banda Sea Plate (McCaffrey, 1989; Milsom, 2001; Spakman and Hall, 2010; Špičák *et al.*, 2013). The Seram Trough is north of the outer arc ridge of the Banda Arc which has been interpreted as an accretionary wedge in the zone of subduction of Australian continental crust beneath Seram (i.e. Hamilton, 1979; Hinschberger *et al.*, 2005; Katili, 1991, 1989, 1975; Milsom, 2001; Stevens *et al.*, 2002). The inner volcanic arc is considered to have been active since the Late Miocene (Abbott and Chamalaun, 1981; Honthaas *et al.*, 1998). Alternatively, the Seram Trough has been interpreted in a different way as a foredeep underlain by Australian continental crust (Audley-Charles *et al.*, 1979; Audley-Charles, 1986; Pairault *et al.*, 2003; Patria and Hall, 2017; Hall *et al.*, 2017). Additionally, it has also been suggested that the Seram Trough is zone of strike-slip faulting (Linthout *et al.*, 1991).

Although many studies have been undertaken in the eastern part of Indonesia, especially the Banda Arc, focusing on geological evolution of the region it still remains problematical. This study discusses the region from the offshore area north of Buru to the Kai Arch south of the Bird's Head. This paper investigates morphological features of the Seram Trough and discusses modern seismicity of the region which may aid understanding of present-day tectonic activity around the Seram Trough. We also preview some interpretations of the tectonics of the Banda Arc and the Seram Trough presented in previous studies and discuss each previous interpretation.

REGIONAL TECTONICS

Major Geological Structures

The study area is surrounded by major geological structures. In some models, some of the structures influence the development of the study area. The regional structural elements are shown in Figure 2. The Seram Fold-Thrust Belt (also known as Imbricated Complex or Seram Duplex) has been interpreted as southward-dipping thrust sheet fault system which has a parallel trend to the Seram Trough and repeats the Mesozoic to Miocene sequences (Audley-Charles *et al.*, 1979; Kemp and Mogg, 1992; Hill, 2005). The age of initial thrusting and uplift was interpreted as Late Miocene to Early Pliocene (Audley-Charles *et al.*, 1979; Kemp and Mogg, 1992). In the offshore region anticlinal features have been interpreted as drag folds resulting from faulting which means that the fault system remains active (Darman and Reemst, 2012). The thrust faults also developed accommodation space with growth-strata filling piggyback basins (Pairault *et al.*, 2003; Patria and Hall, 2017). The Seram Trough trends WNW-ESE in the west and rotates to a NW-SE trend in the east. It is bounded by the Seram fold-thrust belt in the west and the Misool-Onin-Kumawa Ridge in the east. The Seram Trough is a relatively deep bathymetric feature in front of the Seram fold-thrust belt and is believed to have been the deformation front of active recent thrusting (Pairault *et al.*, 2003; Patria and Hall, 2017).

The Misool-Onin-Kumawa Ridge (MOKR) is a broad anticlinorium which is about 700 km in length and NW-SW trending (Figure 2), traceable from Misool Island to the Onin Peninsula (Pairault *et al.*, 2003; Darman and Reemst, 2012). The Misool-Onin-Kumawa Ridge is terminated by the Sorong Fault in the north and the Tarera-Aiduna Fault in the south and bounded by the Seram Trough and the Lengguru fold-thrust belt. Pairault *et al.* (2003) interpreted this ridge to consist of two types of anticlinorium with distinct axial traces. The first one is a series of folds and thrusts which formed in the Early Pliocene and is unconformably overlain by Late Pliocene sediments. The older anticlinorium has been suggested to have no relationship with the Seram Trough because its axial trace is not parallel to the trough. Later, the Early Pliocene Unconformity was folded to form a younger broad anticlinorium. The axial trace of the younger anticlinorium is parallel to the Seram Trough which indicates that it is related to loading of the Seram fold-thrust belt (Pairault *et al.*, 2003). In contrast, Sapin *et al.* (2009) argued that formation of the younger anticlinorium is not related to the Seram Trough because of variation in distance of its axis from the Seram Trough.

The Sorong Fault has been considered to be the tectonic boundary between the Molucca Sea and Philippine Sea Plates and the Australian Plate. The Sorong Fault trends broadly E-W and can be traced about 1500 km from Yapen Island towards the East Arm of Sulawesi via the Banggai Sula Islands. Its left-lateral displacement is believed to result from oblique convergence among plates (Hamilton, 1979; Hall, 2002; Hall, 2012). The movement of the Sorong Fault has influenced the evolution of the Seram Fold-Thrust

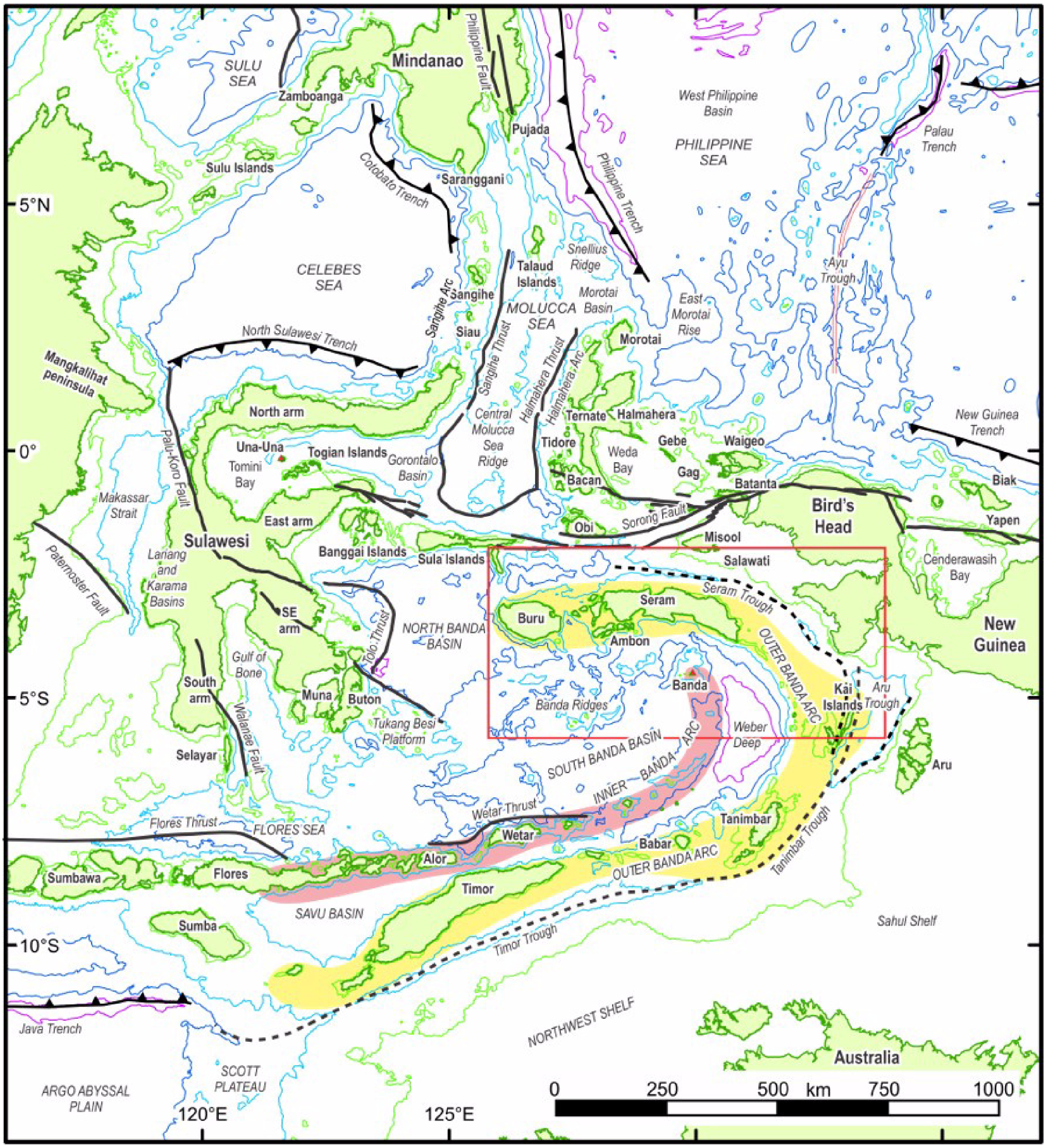

Figure 1. Tectonic elements of Eastern Indonesia (modified after Hall, 2012). Seram is one of the islands of the Outer Banda Arc. The Seram Trough is situated between Seram and Misool. Faults are marked by solid black lines; subduction zones are indicated by toothed black lines; the deformation front of the Banda Arc is marked by dashed black lines. The study area is marked by the red box

Belt and Misool-Onin-Kumawa Ridge (Linthout *et al.*, 1991; Sapiie *et al.*, 2012; Riadini *et al.*, 2012; Sapiie and Hadiana, 2014). The strike-slip system was active from the Early Miocene until the Early Pliocene (Dow and Sukamto, 1984; Hall and Wilson, 2000; Hall, 2002; Hall, 2012) and may be active at the present day (Puntodewo *et al.*, 1994).

Another large strike-slip fault zone in the south is the Tarera-Aiduna Fault. The Tarera-Aiduna Fault merges to the east with the Wandamen Thrust Fault (Dow and Sukamto, 1984; Pubellier and Ego, 2002) and can be traced from the Bird's Neck of Papua to the Seram Trough (Pubellier and Ego, 2002) as an E-W trending feature of about 700 km length. Teas *et al.* (2009) suggested that the Tarera-Aiduna Fault passes

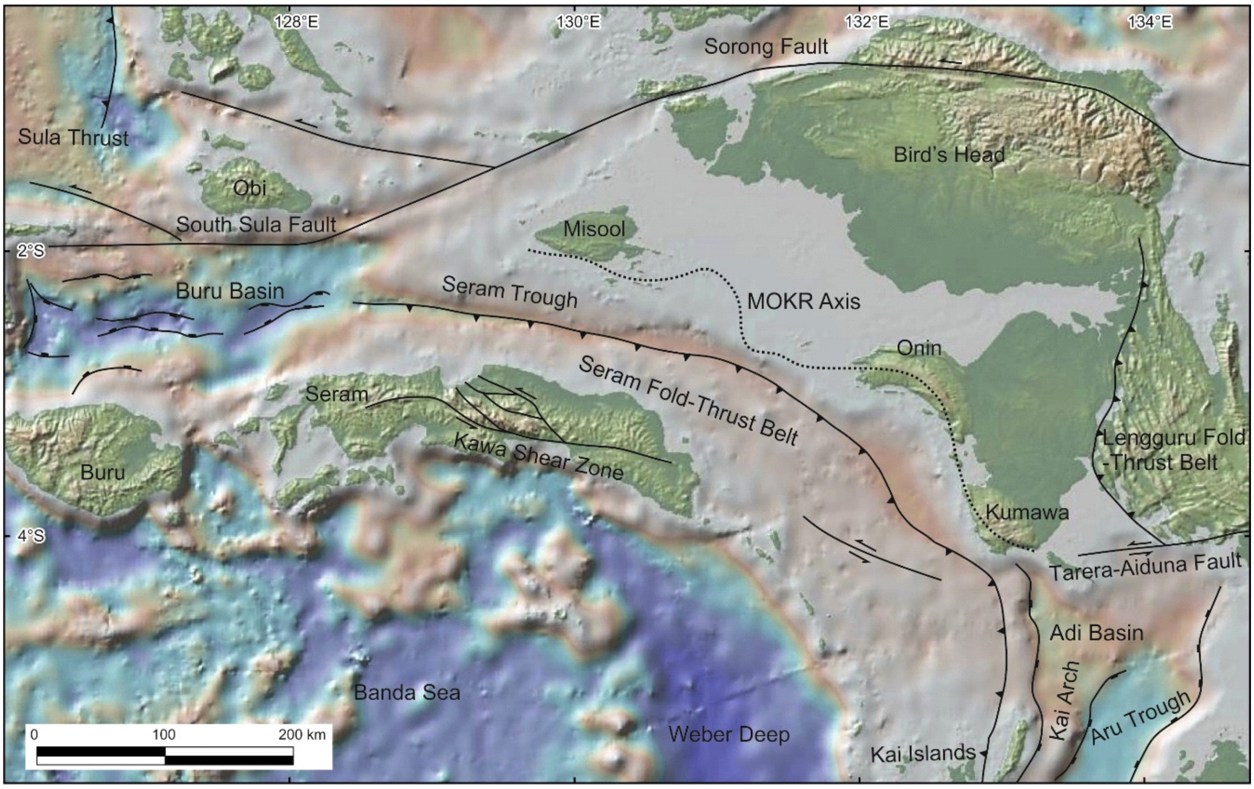

Figure 2. Structural map of the Seram region. The structural elements are compiled from several authors (Charlton, 2000; Hall, 2002; Pairault *et al.*, 2003; Watkinson *et al.*, 2011; Hall, 2012; Sapiie *et al.*, 2012; Pownall *et al.*, 2013; Patria and Hall, 2017).

through the Seram fold-thrust belt and bends into a NW-SE trend in front of Seram Island. The Tarera-Aiduna Fault records a similar movement to the Sorong Fault which is left-lateral displacement (Hamilton, 1979; Dow and Sukamto, 1984; Abers and McCaffrey, 1988; Bock *et al.*, 2003). The age of initial movement of the Tarera-Aiduna Fault is considered to be Pliocene (Hamilton, 1979; Cloos *et al.*, 2005). Both the Sorong Fault and Tarera-Aiduna Fault have been considered to have influenced deformation within the Seram fold-thrust belt due to oblique convergent strike-slip deformation (transpression) (Teas *et al.*, 2009; Sapiie *et al.*, 2012; Sapiie and Hadiana, 2014)

Tectonics of the Banda Arc

Eastern Indonesia geologically has a more complicated tectonic setting and sutures compared to western Indonesia. The complex geology has been caused by convergence of three major plates: Indo-Australia, Eurasia, and Pacific. Additionally, some microplates have involved which increased the complexity of eastern Indonesia. The Banda Arc, which is generally known as the zone of interaction between the Australian and Eurasian plates, is one of most interesting areas because the convergent margin of the Banda Arc forms a U-shaped geometry and has been studied for many years (Katili, 1975; Cardwell and Isacks, 1978; Audley-Charles *et al.*, 1979; Hamilton, 1979; Audley-Charles, 1986; Katili, 1989; McCaffrey and Abers, 1991; Katili, 1991; Hall, 2002; Hinschberger *et al.*, 2005; Nugroho *et al.*, 2009; Spakman and Hall, 2010; Hall, 2012; Špicák *et al.*, 2013; Porritt *et al.*, 2016). Especially in the Seram region, deformation and volcanism cannot be explained by a simple model of subduction.

Much controversy has centred on how the U-shaped geometry was formed. There are two different explanations concerning formation of the Banda Arc. Some authors have argued that there are two separate slabs dipping in opposite directions that formed the U-shaped geometry of the subducted slab (Cardwell and Isacks, 1978; Bowin *et al.*, 1980; McCaffrey, 1989; McCaffrey and Abers, 1991; Hinschberger *et al.*, 2005; Špicák *et al.*, 2013; Porritt *et al.*, 2016) while others interpret the geometry as a single slab which curves around the arc (Katili, 1975; Hamilton, 1979; Milsom, 2001; Spakman and Hall, 2010).

Many authors have proposed that only one plate which is curved 180^{o} was subducted beneath the Banda Arc (i.e. Audley-Charles *et al.*, 1979; Hall, 2012, 2002; Hamilton, 1979; Katili, 1975; Spakman and Hall, 2010). Additionally, the single slab (Proto-Banda Sea) plate is now subducting beneath the Banda Arc with rollback of subduction zone to the east with extension into the U-shaped oceanic embayment (Banda Embayment) within the Australian Continental Margin from 16 Ma (Spakman and Hall, 2010). This is a one-slab model in which there was no oceanic subduction beneath Seram from the Seram Trough. The Proto-Banda Sea Plate is considered as old, cold and negatively buoyant oceanic lithosphere which occupied the Banda Embayment. The Proto-Banda Sea Plate has collapsed into the mantle by advance of the Java Subduction Zone (Figure 3a) and initiated crustal delamination (Spakman and Hall, 2010). This delamination has also exhumed lithospheric mantle to Seram during ± 15-3 Ma (Pownall *et al.*, 2017). The trough is a foredeep, a topographic expression of the intersected by the Tarera-Aiduna Fault (Figure 3b) and it is also suggested that the Timor-Tanimbar-Seram Trough acts as a subduction trench (Cardwell and Isacks, 1978; McCaffrey, 1989; Hinschberger *et al.*, 2005). An alternative Neogene - Recent plate tectonic development has been proposed by Hinschberger *et al.* (2005). This presents a contrasting view of the development of the Banda Arc. In the Middle Miocene, the Sorong Fault Zone and Sunda subduction were connected by a transform fault in the Australian Plate with an ENE-WSW trend. In the Late Miocene, this transform fault developed into a Seram subduction zone connected to the Tarera-Aiduna Fault which was active from at least 9 Ma. The formation of the Banda Arc is considered as result of counter-clockwise rotation, based on paleomagnetic data from Haile (1978), of

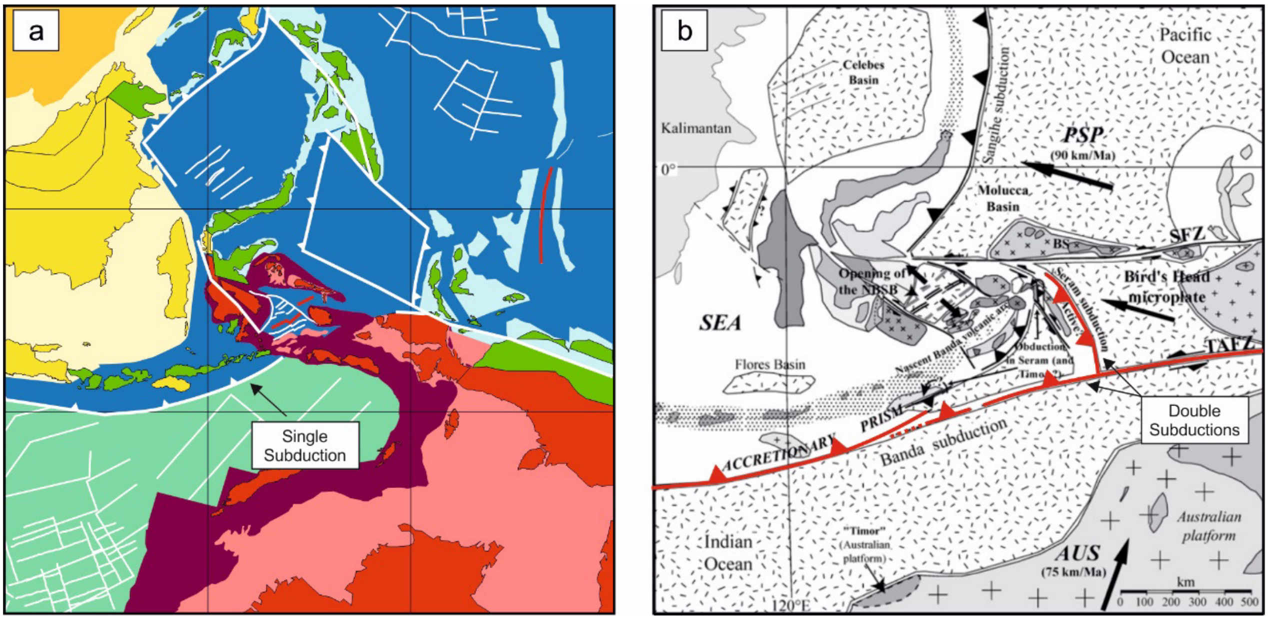

Figure 3. Two proposed models for Eastern Indonesia at 9 Ma. a) A one slab subduction rollback model with no subduction at the Seram Trough (modified after Spakman and Hall, 2010; Hall, 2012). The Tarera Aiduna Fault did not exist in this time. b). A two-slab model which interprets major subduction at the Seram Trough (modified after Hinschberger *et al.*, 2005). Note also significant subduction at the Tarera Aiduna Fault of more than 300 km since 9 Ma.

thrust-loaded Bird's Head Margin, and partly the limit of delamination of the crustal part of the continental margin. In this model there was no subduction at the Seram Trough and very young and little displacement on the Tarera-Aiduna Fault.

In contrast, double slabs with opposite polarity was proposed by some authors, mainly seismologists (Cardwell and Isacks, 1978; Bowin *et al.*, 1980; McCaffrey, 1989; McCaffrey and Abers, 1991; Hinschberger *et al.*, 2005; Špičák *et al.*, 2013). The U-shaped geometry of the Banda Arc is interpreted to reflect two separate slabs dipping in opposite directions Seram and the subduction trench. This is a two-slab model which interprets major subduction at the Seram Trough of at least 500 km since 9 Ma. It also proposes significant subduction at the Tarera-Aiduna Fault of more than 300 km since 9 Ma. However, this model is not obviously supported by geological evidence since, for example, oceanic crust does not appear between Bird's Head and Seram. There is no clear evidence that the Tarera-Aiduna Fault intersects the two slabs. If the Tarera-Aiduna Fault separates the two slabs, it ought to be a major structure in the region with prominent surface expression.

RESULTS

Seafloor Morphology

As the Seram trough lies in a complex tectonic area, the topography and bathymetry (Figure 4) reflect structural elements resulting from converging tectonic blocks. The Seram Trough curved through 90^{o} and is E-W trending to the north of Seram and rotates into a N-S trending direction in the Kai Arch. Seram Island has a mountainous topography, notably in central Seram, and is elongated E-W. Seram Island is significantly influenced by the major left-lateral strike-slip fault, namely the Kawa Fault (Pownall *et al.*, 2013) while Buru Island is mainly controlled by NE-SW Rana Fault (Watkinson and Hall, 2017). Buru and Seram Islands are separated by a deep bathymetric feature, more than 1000 m.

The northern slope of the Seram Trough is steeper than the southern slope (Figure 4). The area north of Seram to the trough has many lineaments, mainly following the trend of the Seram Trough indicating intense deformation in the area while that between the trough and south of the Bird's Head is relatively flat and less deformed (Figure 4), and the deformation is concentrated in Misool Island and the Onin-Kumawa Peninsula where topography is more elevated than adjacent areas. Subsided carbonate platforms are observed south of Misool and on the Kai Arch (Figure 4) at 400 – 1400 m and 900, respectively and indicate subsidence since late Pleistocene. The subsidence was likely due to the loading of fold-thrust belt. To the north of Seram the trough is narrow while the widest part of the trough is south of the Onin-Kumawa Peninsula. Close to the Kai Arch where the trough is N-S oriented, the width of the trough is practically 0 km. The fold-thrust belt zone is located south and west of the trough and widens towards the southeast reaching 50 km. In the Kai Arch area, the width of the fold-thrust belt unit is constant at about 12 km. Close to the Seram coast, the seabed has a smooth rounded-shaped morphology. To the west of the Seram Trough, the Buru Basin is situated north of Buru Island and it has a similar trend to the Seram Trough but morphologically it can be distinguished from the Seram Trough. It has much

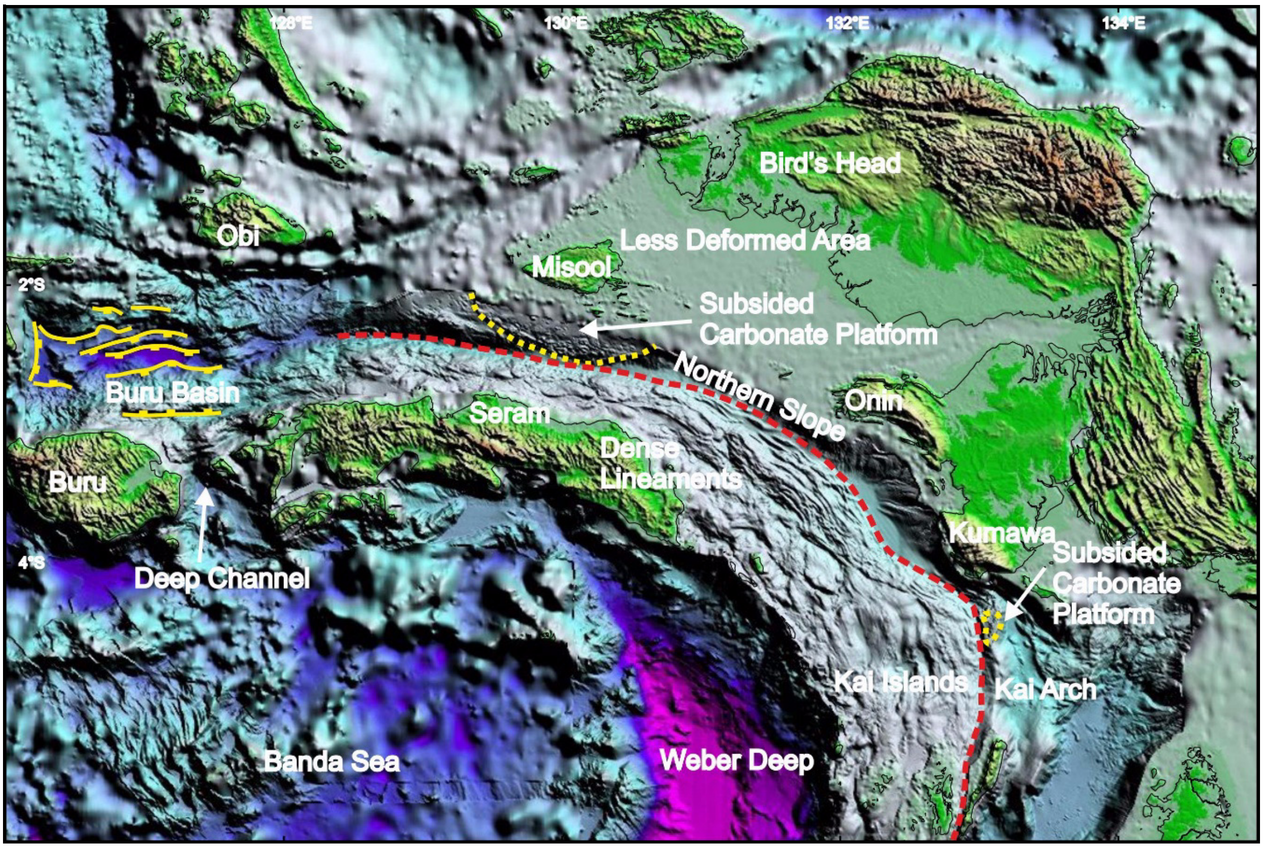

Figure 4. Principal features of the topography and bathymetry of the Seram Trough and surrounding region. Topography is from SRTM (NASA Shuttle Radar Topography Mission). Ocean data are from the Smith and Sandwell (1997) global 1-minute grid from satellite altimetry and ship depth soundings updated in 2014. For the area of the trough and nearby the global grid is merged with the high resolution multibeam bathymetry. Yellow lines mark the subsided carbonate platforms. Red line indicates the deformation front of Seram Fold-Thrust Belt. Yellow toothed lines indicate normal faults in Buru Basin.

deeper bathymetry and is bounded by normal faults in the north and the south, formed by rifting. South of Seram and Buru Islands, the Banda Sea area is the deepest area in the region. The Weber Deep is over 7000 m deep and it is bounded by the Outer Banda Arc in the east. In the eastern end of the Weber deep, there is a very steep slope representing an abrupt change in bathymetry from >7000 m to 500 m within 50 km.

The Seram Trough is not the deepest area in the region. The Banda Sea located south of Seram and Buru is deeper than the trough with the Weber Deep is the deepest area. Bathymetrically, the Seram Trough varies in depth from 900 to 3000 m (Figure 5). The depth of the trough generally becomes shallower from 3000 m in the west to 900 m in the southeast part. It is slightly deeper to the south of the Onin-Kumawa Peninsula. The Buru Basin is the deepest area within the study area with depth reaching 5300 m in the middle of basin. The depth of the Buru Basin suggests oceanic crust lying in the central part (Patria and Hall, 2017). The offshore Bird's Head which is relatively undeformed is typically less than 100 m deep (Figure 6). The bathymetry of the shallow part (less than 1000 m) of northern offshore Seram shows some variation in width. This shallow area is wider towards the SE and narrows westwards. North of Buru Island there is almost no shallower part around the island.

Modern Seismicity

Present-day shallow seismicity (less than 70 km) is concentrated in the area to the north of Seram, north of Obi Island and east of the Bird's Head and south of the Kumawa Peninsula (Figure 7). Unlike typical subduction zones, the Seram Trough itself is associated with very little seismicity and there are only a few shallow hypocentres in or near the trough. The area north of the trough (western offshore Bird's Head), where morphology is flat and little deformed, is an aseismic area. Deep seismicity (more than 70 km) is only observed in the Banda Sea Region and hypocentres become deeper to the south.

Active normal faulting activity can be observed mainly in western Seram and the Buru Basin (Figure 7). Many of the solutions classified as recording movement of normal faults are oblique with a strike-slip component. Pure dip-slip normal faults are limited to Buru Island, Buru Basin and south Seram Island. Many faults with strike-slip solution are observed in and

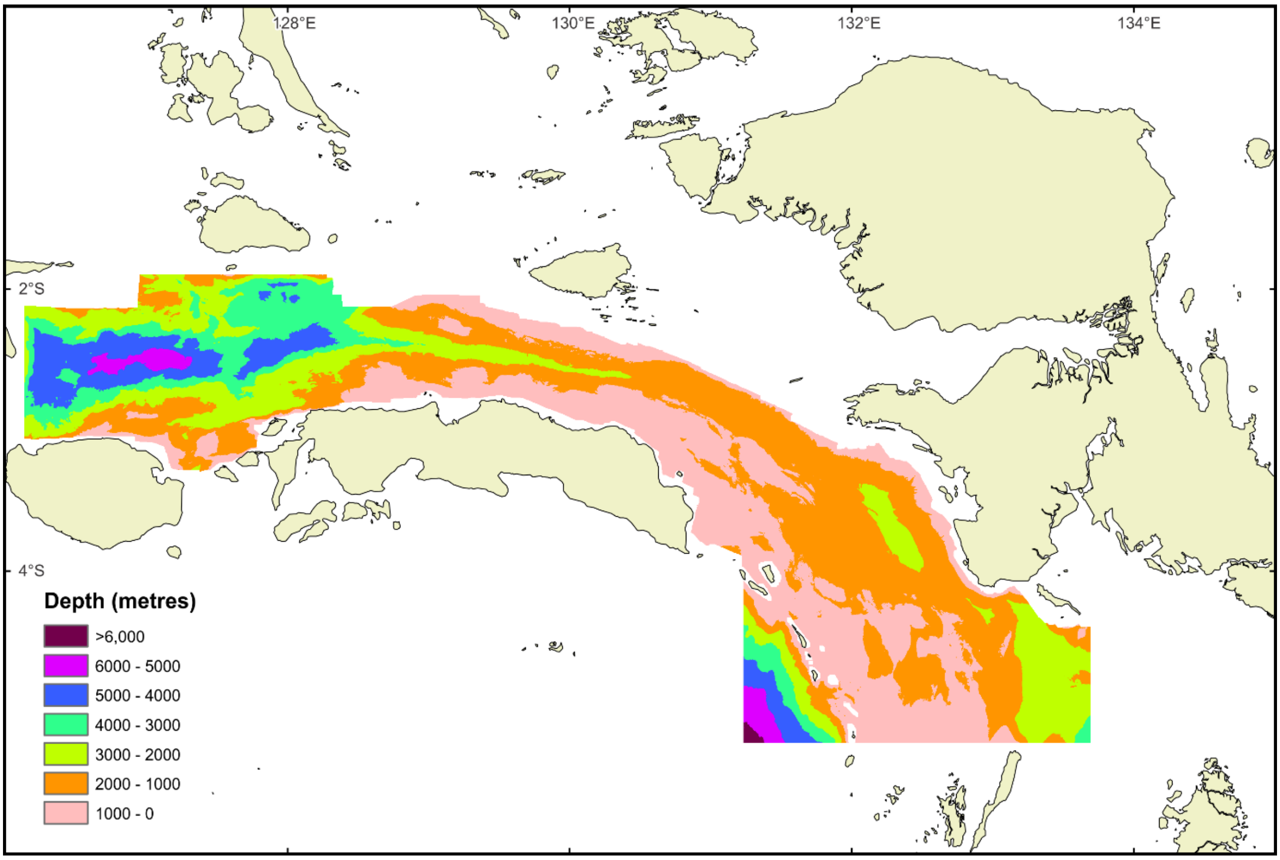

Figure 5. Bathymetry of the Seram Trough and surrounding region from the high resolution multibeam data coloured to show main features. The trough is much shallower than most subduction trenches and its depth is mainly less than 3000 m. Geographic locations refer to Figure 4.

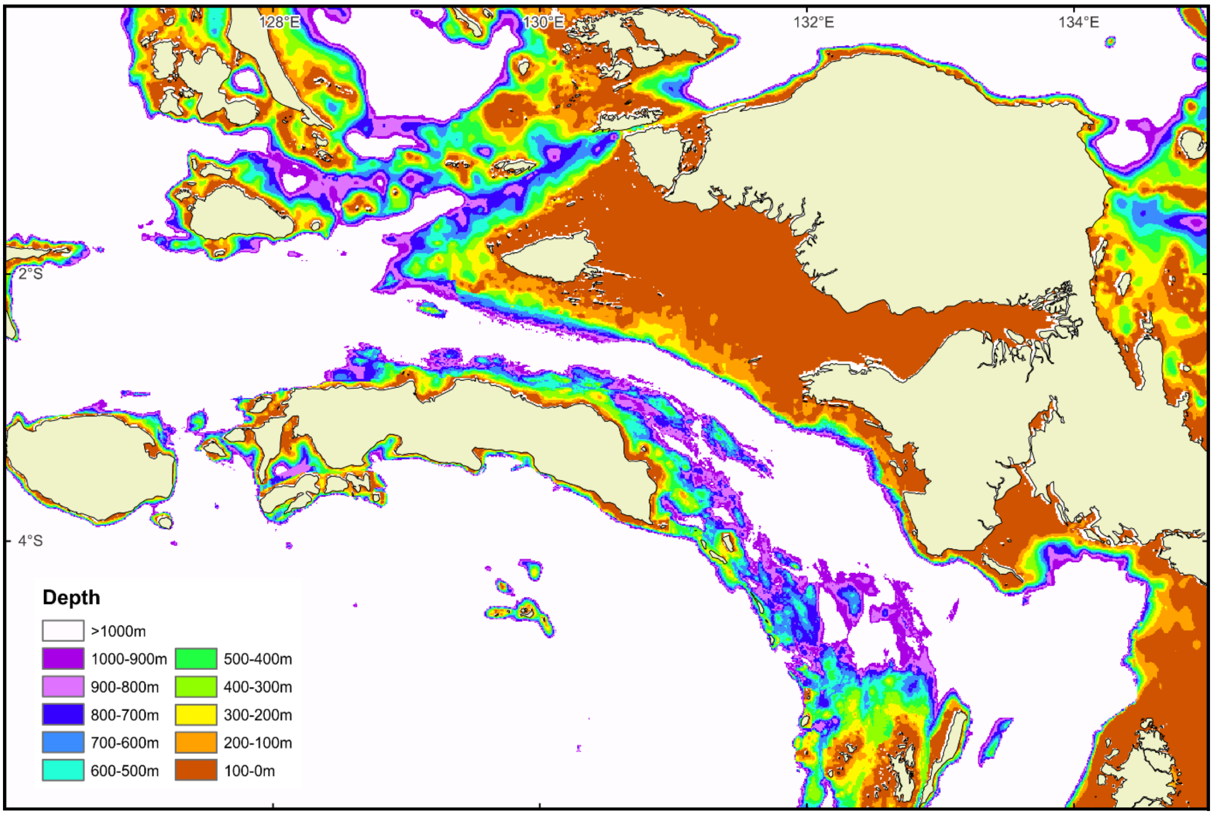

Figure 6. Bathymetry of the area surrounding the Seram Trough from the Smith and Sandwell (1997) global 1-minute grid coloured to display main features of the areas less than 1000 m deep. Geographic locations refer to Figure 4.

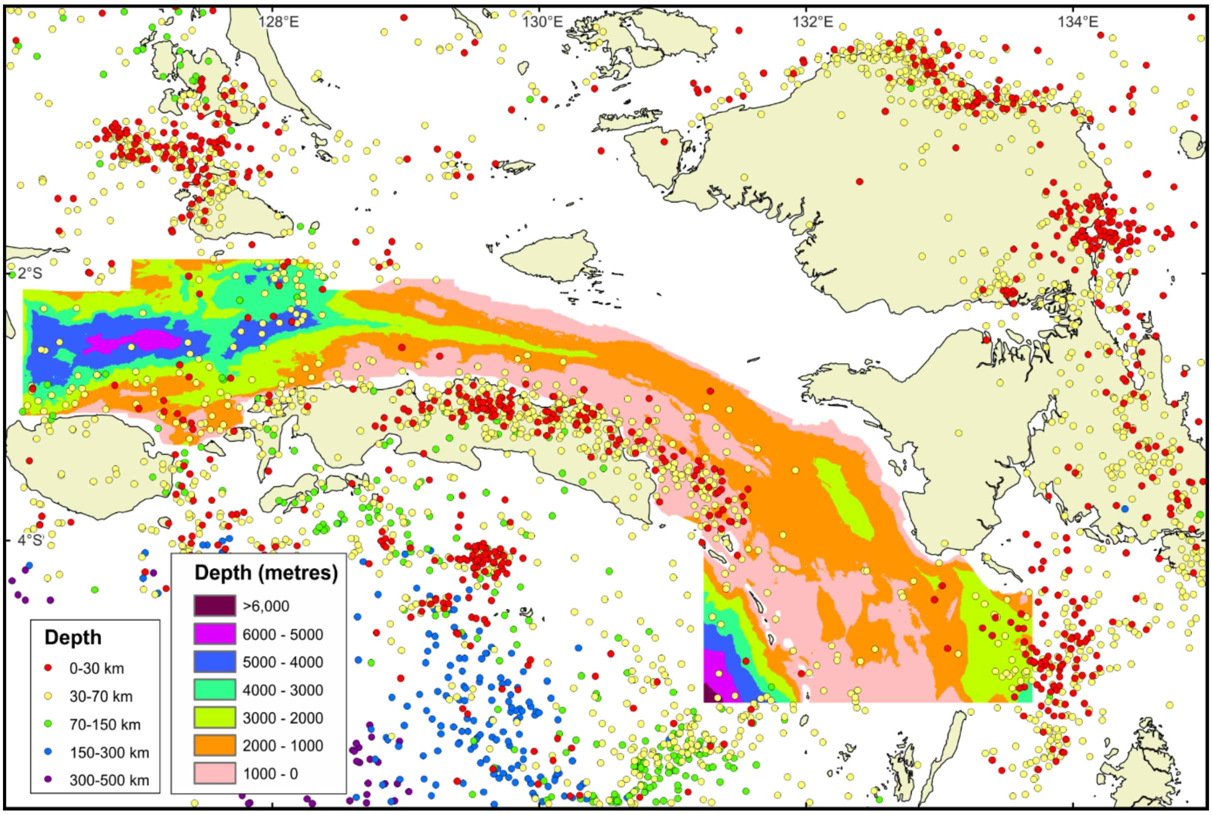

Figure 7. Seismicity of the Seram Trough and surrounding region from the USGS global catalogue (http://earthquake.usgs.gov/earthquakes/) showing all hypocentres with magnitudes greater than 4.5 between 1980 and 2016. The map shows there are very few earthquakes at the trough and the region north of the trough is almost entirely aseismic. Geographic locations refer to Figure 4.

offshore of north Seram (Figure 8). The area of the Kai Arch is characterised by similar solutions of strike-slip faulting. In the area between the Seram Trough and the Buru Basin, strike-slip faulting activity is common from Obi Island to east Buru Island. Most of the solutions suggest sinistral displacement on roughly E-W trending faults, broadly parallel to the trough from the Buru Basin to the Kai Arch. Thrust faults are the most common solutions in the region. They are observed to the south of the trough with fault planes mostly parallel to the trough (Figure 8). No earthquake is observed close to the Seram Trough eventhough the deformation front is recently active as indicated by growth strata (Patria and Hall, 2017). Anomalous thrusting activity is found in the Weber Deep, in which the thrusting is almost perpendicular to the trough.

Based on observation on focal mechanism solutions, the direction of S_{Hmax} for Seram Island region is ENE-WSW in the northern part while for the southwestern part is NE-SW. This corresponds to the changing orientation of the trough from roughly E-W to roughly NW-SE. In the Weber Deep, the S_{Hmax} trend is N-S. The variation of earthquake activity and deformation can be related to block movements in the region. The most recent GPS motion study by Bock *et al.* (2003) showed the northern Outer Banda Arc moves to the east relative to Bird's Head with 20 to 50 mm/yr velocity and Onin Peninsula moves more slowly to the NE with c. 5 mm/yr velocity (Figure 8). The difference in velocity results in convergence between these two areas. The direction of motion of the northern Outer Banda Arc is oblique to the trough. The GPS measured motions can explain the modern faulting activity which is mainly accommodated by thrust faults and strike-slip faults. In general, the GPS velocity survey shows that the southern Banda Outer Arc moves to NE, the northern Banda Outer Arc moves to E and the movement direction of New Guinea is to SE relative to Bird's Head. The variations of direction of movement controlled the direction of S_{Hmax}. Within this region, the Bird's Head area behaves as a stable block with very small movement and relatively undeformed. Thus, Bock *et al.* (2003) suggested that the Bird's Head area can be regarded as an independent rigid block (Figure 8).

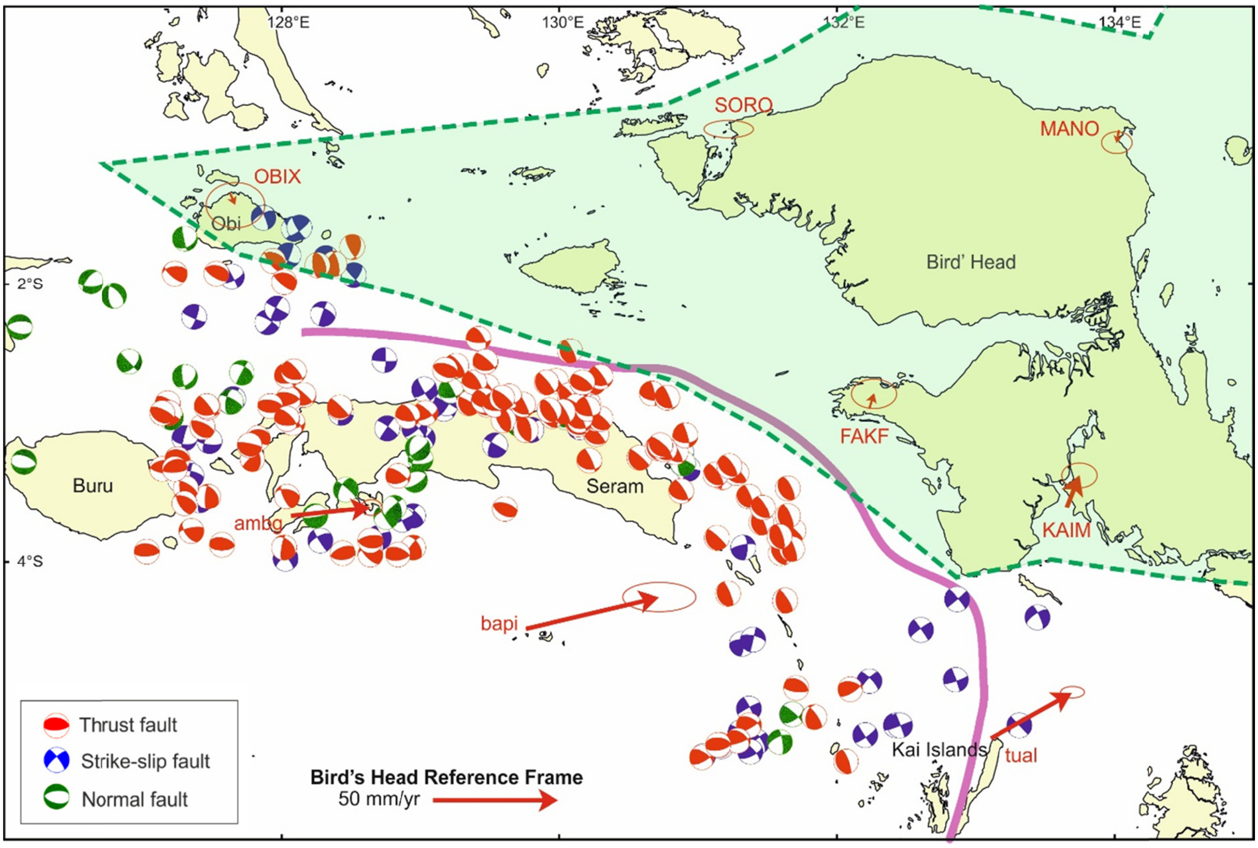

Figure 8. Seismicity of the Seram Trough and surrounding region showing hypocentres with focal mechanism solutions from the Global CMT catalogue (http://www.globalcmt.org/CMTsearch.html). Velocity field (Red Arrows) derived from GPS surveys (Bock *et al.* 2003)., in the Bird's Head Block reference frame Ellipses show 2D 95% confidence limits. The green dashed line outlines the area considered by Bock *et al.,* (2003) to form part of a single block. Note that the length of the arrow represents the rate of velocity.

DISCUSSIONS

The Seram Trough is generally agreed to be a product of deformation due to convergence between the Australian Plate and the Eurasian Plate (Katili, 1975; Hamilton, 1979; Katili, 1989; Katili, 1991; Hall, 2002; Hinschberger *et al*., 2005; Hall, 2012; Watkinson *et al*., 2012). However, the tectonic setting and significance of the trough has been discussed by many authors, and there are numerous different interpretations of its location, tectonic character and age which has led to different tectonic models.

Subduction Trench

The Seram Trough was interpreted as the surface expression of a new subduction zone that started in the Late Neogene (Katili, 1975; Hamilton, 1979; O'Sullivan *et al*., 1985; Katili, 1989; Katili, 1991; Charlton, 2000; Milsom, 2001; Stevens *et al*., 2002; Hinschberger *et al*., 2005). The subduction trench is often linked to the Timor Trough via the Tanimbar Trough forming a U-shaped suture. Seram was considered to be an accretionary wedge that consists of imbricated complex Mesozoic and Cenozoic continental material separated by clay material mélanges or olistostromes (Figure 9). One problem with this model is it cannot explain why the volcanic arc is very close to the supposed subduction trench in the Timor region. In the Seram region there is very limited evidence of a volcanic arc. However, the stratigraphy of Bird's Head can be extended across the trough, indicating that the region lies on same Australian crust (Pairault *et al*., 2003; Darman and Reemst, 2012; Patria and Hall, 2017). It should be noted than the depth of Seram Trough is quite different from trenches of subduction systems, Generally, the depth of a subduction trench is more than 5000 m in examples such as the Java, Japan and South Alaska Trenches, and often much greater (Philippine Trench is up to 10 km and the Mariana Trench up to 11 km deep) while the Seram Trough is shallower, less than 3000 m depth (Figure 5). The Seram Trough is also characterised by very few seismicity in the trough (Figure 7).

Alternatively, the Seram Trough was interpreted as a subduction trench of Himalayan type subduction zone (Kemp and Mogg, 1992) where the slab subducting beneath Seram is not oceanic lithosphere but Australian continental lithosphere which they suggested has resulted in the deepest subduction continental crust known on earth (Figure 10). Because of the positive buoyancy of continental lithosphere, the region must now be onland rather than in deep marine so that this model does not favour the present-day situation of the trough.

Foredeep in front of Fold-Thrust Belt

In contrast, the Seram Trough has been considered to indicate the same tectonic setting as the Timor Trough and be the product of shortening and loading of the Australian Plate (Audley-Charles *et al*., 1979; Audley-Charles, 1986; Pairault *et al*., 2003; Patria and Hall, 2017). Seram and Timor are interpreted as a series of thrust sheets consisting of Australian continental sediments with some Asian allochthonous material and the Seram Trough is interpreted as a foredeep at the front of an imbricate thrust sheet (Figure 11). In this model, the subduction trench was located to the south of Seram Island and the north of Timor Island. According to Audley-Charles *et al.* (1979) the collision in Seram began in the Late Miocene. They suggested the trough was an A-subduction zone which involves only continental lithosphere. Ampferer or A-subduction, results in shortening of only a few hundred kilometres

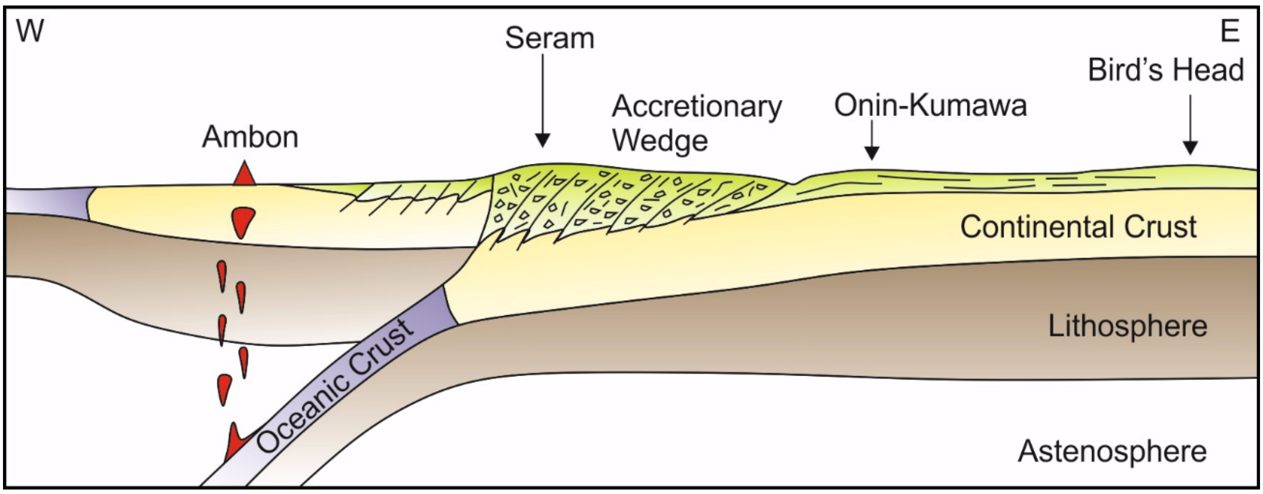

Figure 9. Model of tectonic setting for the Seram Trough as Subduction Trench (modified after O'Sullivan *et al.,* 1985). The Seram Trough is interpreted as subduction trench with Ambon as the volcanic arc. It should be noted that the distance between the trough and Ambon is about 140 km which is less than typical arc-trench distance.

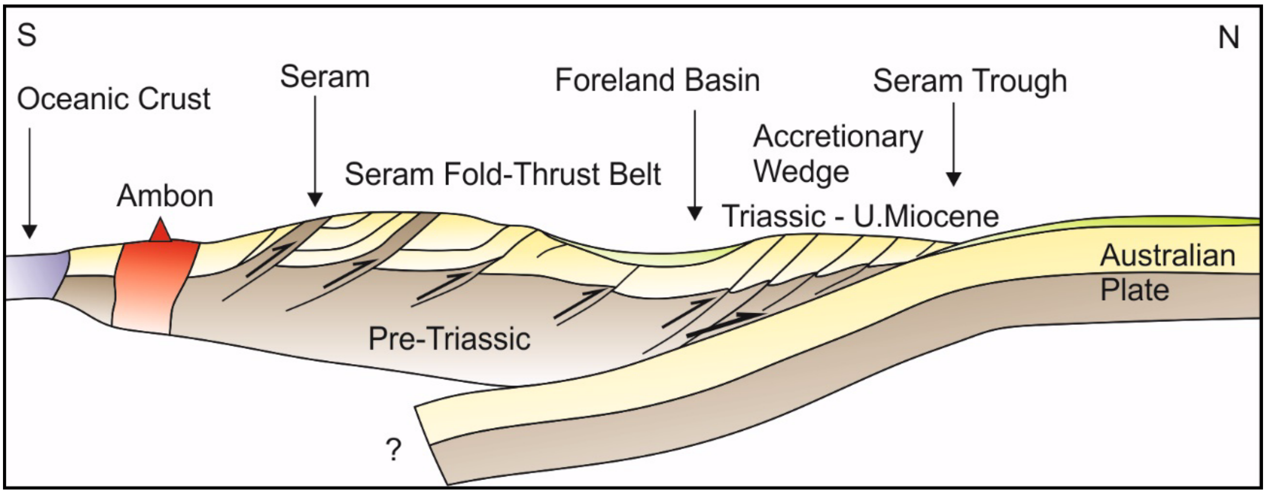

Figure 10. Model of tectonic setting for the Seram Trough as a result of continental-continental collision and subduction (modified after Kemp and Mogg, 1992). The Seram Trough is considered to be a subduction trench in front of an accretionary wedge.

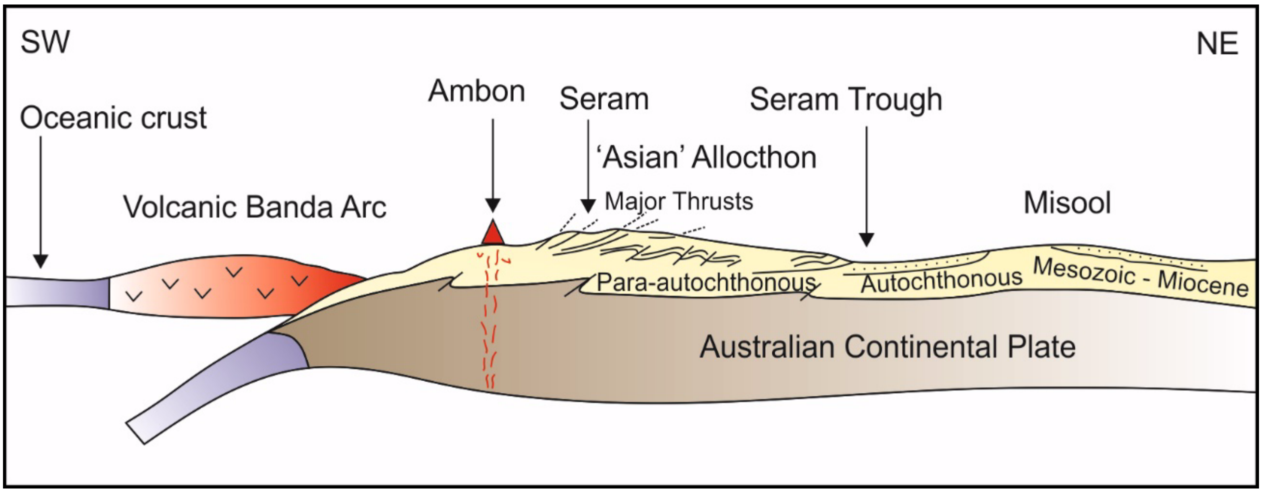

Figure 11. Model of tectonic setting for the Seram Trough as foredeep (modified after Audley-Charles *et al.,* 1979). T1- T6 are the major thrust sheets. The Seram trough is interpreted as a foredeep in front of fold-thrust belt but this model cannot explain the absence of volcanic arc except in the area of Ambon.

in contrast to Benioff or B-subduction, in which many hundreds or thousands of kilometres of oceanic lithosphere may be eliminated. Pairault *et al*., (2003) have added that the Seram Trough is a foredeep produced by loading of the developing fold-thrust belt with an associated peripheral bulge to the north, Misool-Onin-Kumawa Ridge, resulting from an oblique intraplate convergence between Seram and Bird's Head (Patria and Hall, 2017). The Seram Trough also has also been controlled by strike-slip faults, during and after formation fold-thrust belt (Teas *et al*., 2009; Patria and Hall, 2017). Furthermore, Hall *et al*., (2017) has proposed a major NW-SE trending left-lateral strike-slip fault and Kawa Shear Zone as major fault that have been active since at least 4 Ma which may occurred due to eastward subduction rollback of Proto-Banda Sea Plate.

Spakman and Hall (2010) agreed that the trough is a topographic expression of down-flexed and thrust-loaded Australian margin, rather than a subduction trench, but proposed that the trough is also the limit of delamination of the crustal part of the continental margin that permitted continued subduction of the deeper continental lithosphere without a subduction fault reaching the surface. Pownall *et al.* (2013) showed the topographic low as due to extensional exhumation, and thrusting resulting from subducting slab-mantle interaction during rollback. A study by Pownall *et al.* (2013) has shown a topographic low as due to extensional exhumation (Figure 12). They proposed two models based on existence of peridotite and high-grade metamorphic rock in Seram. The peridotite which was previously believed to be part of ophiolite from oceanic crust is interpreted as subcontinental lithospheric mantle (SCLM). This is supported by the low-angle normal fault contact between the peridotite below the metamorphic complex. The exposure of deep mantle is explained by crustal-scale exhumation due to subduction rollback. This model favours present-day situation where intense deformation were observed in between Seram and the Seram Trough (Figure 4), and the evidence of flexural bending was found on the southwest of Misool and Kai Arch as a subsided carbonate platform (Patria and Hall, 2017; Adhitama *et al.*, 2017; Figure 4). Modern seismicity also shows that intense thrust faulting activity is mainly observed in northeast Seram and offshore northeast Seram, close to coastline (Figure 8). The strike-slip faulting activity in central Seram may relate to the Kawa Fault (Figure 8). This deformation can be explained by the movement of Seram towards east relative to Bird's Head, oblique to the Seram Trough as shown by GPS data from Bock *et al.*, (2003).

Zone of Strike-slip Faulting

It has also been suggested that the Seram Trough and Seram mark zones of right-lateral strike-slip faulting, resulting from counter-clockwise rotation since Late Miocene (Haile, 1978) due to E-W strike-slip dominated movement of the Sorong Fault in the north and the Tarera-Aiduna Fault in the south (Linthout *et al.*, 1991). The right-lateral strike-slip faults may have started as west-dipping thrust faults which exposed older metamorphic rocks on Seram (Figure 13). As the Papua moved eastward, the thrust faults turned into right-lateral strike-slip faults. For this model, it requires the Tarera-Aiduna Fault to have been active since late Miocene and 1000 km in length in an E-W direction south of Seram. No structure of this type is observed to the southeast of Seram and the Tarera-Aiduna Fault is likely to be younger structure as it does not cut the Seram Fold-Thrust Belt. Although the interpretation is based on paleomagnetic data from Haile, 1987,

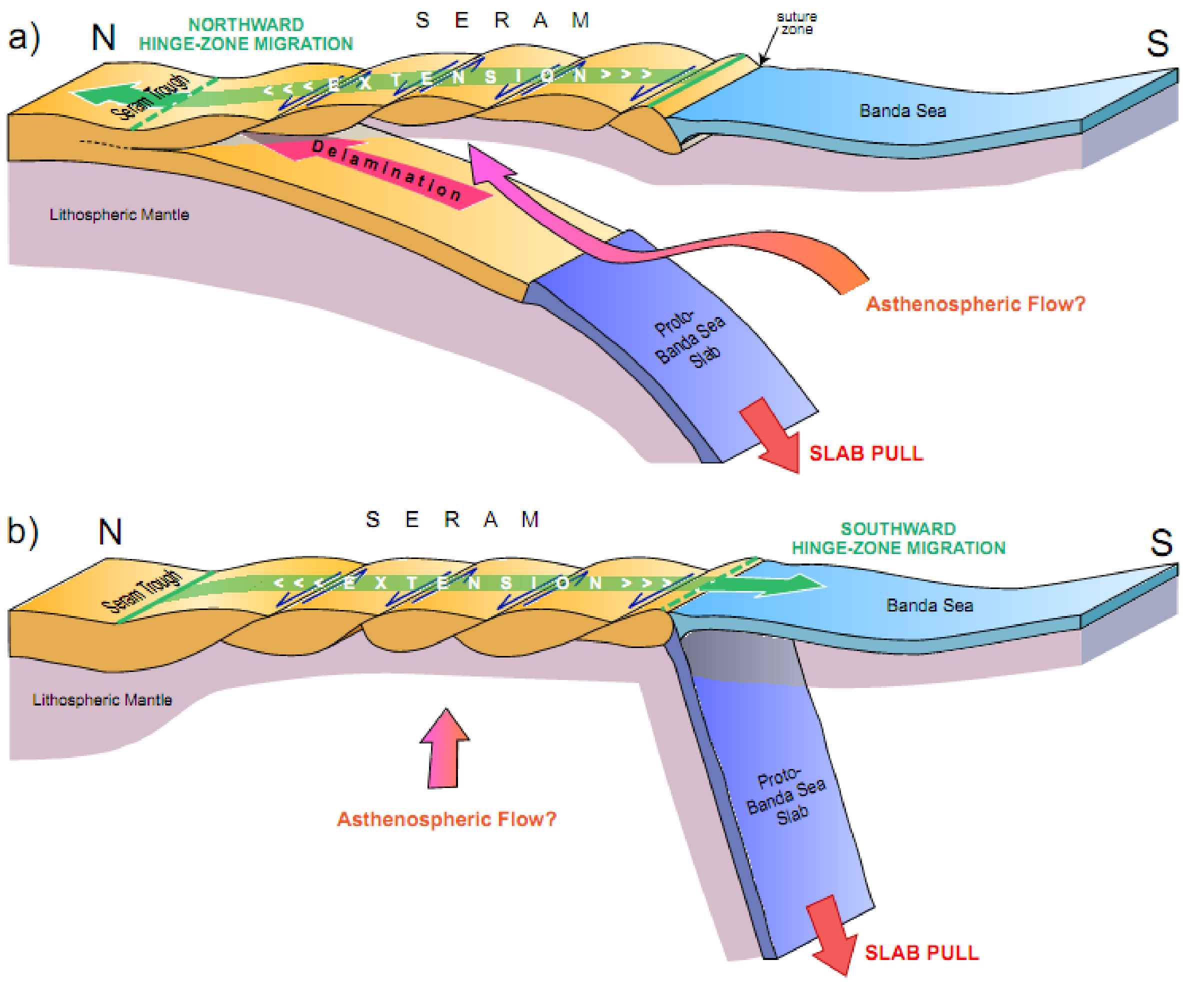

Figure 12. Two possible tectonic models for the Seram Region (Pownall *et al.,* 2013). a). Extensional exhumation was caused by delamination that allowed hot asthenosphere to escape from beneath the subducting Proto-Banda Sea; b). Slab pull caused by the Proto-Banda Sea slab stretched and thinned the crust.

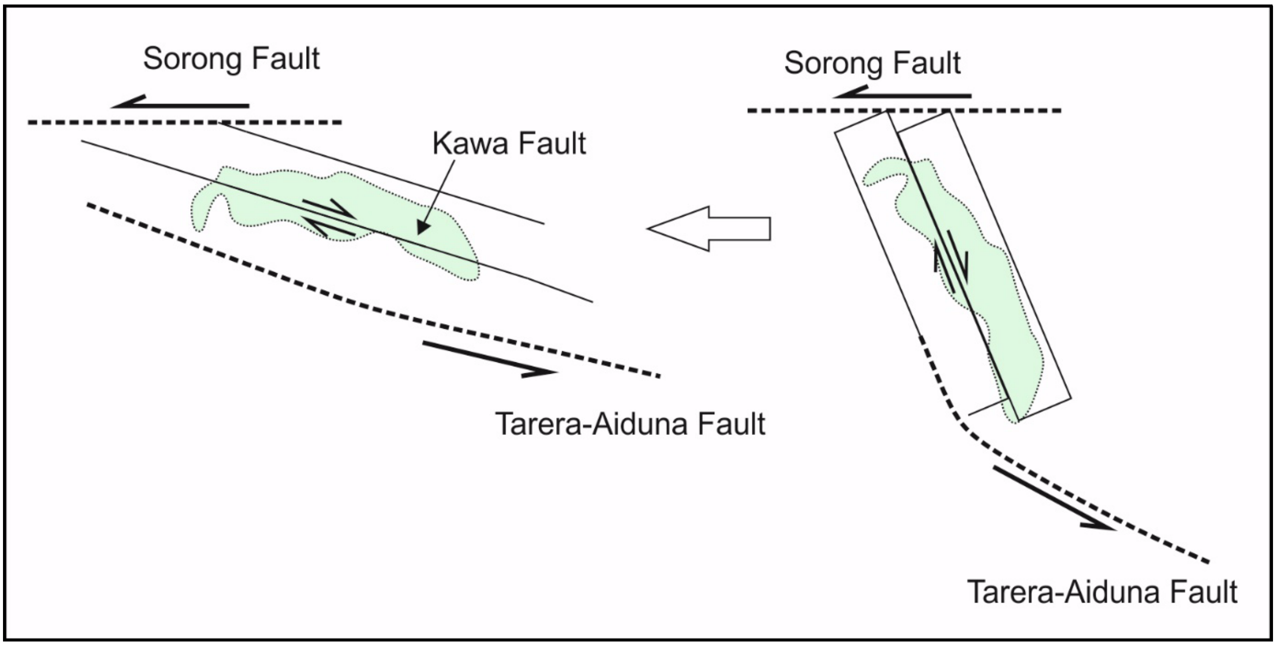

Figure 13. Model of the Seram and the Seram Trough as right-lateral strike-slip faults (modified after Linthout *et al.,* 1991).

kinematic evidence is shows mainly a contrasting a sense of movement, left-lateral in the Kawa Shear Zone (Pownall *et al*., 2013). Few number of strike-slip faulting activity on Central Seram also shows sinistral movement for NW-SE nodal plane while north of Seram and offshore Seram are dominated by thrust faults (Figure 8).

Another model also has been postulated using sandbox modelling by Sapiie *et al.* (2012), who argued that deformation in the Seram fold-thrust belt, including the Seram Trough, can be described as oblique convergent strike-slip tectonic (transpression) (Figure 14). Again, the Sorong Fault and Tarera-Aiduna Fault act as strike-slip bounding fault in the north and south,

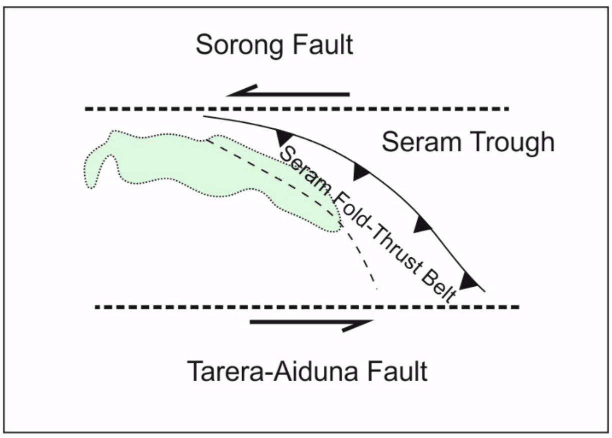

Figure 14. Model of tectonic setting of the Seram Trough as transpressional structures, based on sandbox modelling (Sapiie *et al.,* 2012; Sapiie and Hadiana, 2014).

respectively. In contrast to previous models, the Tarera-Aiduna Fault is connected to a NW-SE left-lateral strike-slip in the southeast of Seram within the Seram Fold-Thrust Belt (Teas *et al*., 2009). The problem for this model is that the Seram Fold-Thrust Belt must be bounded by the Tarera-Aiduna Fault but it actually extends further south in west of Kai Islands (Figure 4).

Other Models

Sapin *et al*., (2009) proposed another explanation of the formation of the Seram Trough. The thin-skinned thrusting begun in the late Miocene and developed the fold-thrust belt along Seram and Misool-Onin-Kumawa Ridge. Then based on observation on gravity anomaly beneath Misool-Onin-Kumawa Ridge, it was interpreted that northeastward-moving crustal scale thrust fault which detached at the top of ductile crust (12 km depth) has uplifted the Misool-Onin-Kumawa Ridge since the late Pliocene (Figure 15). This tectonic evolution is not in line with evidence of subsidence of Misool-Onin-Kumawa Ridge since Late Pleistocene (Patria and Hall, 2017; Adhitama *et al*., 2017). If the region was uplifted, the carbonate platform in the southwest of Misool and Kai Arch (Figure 4) would be exposed on land.

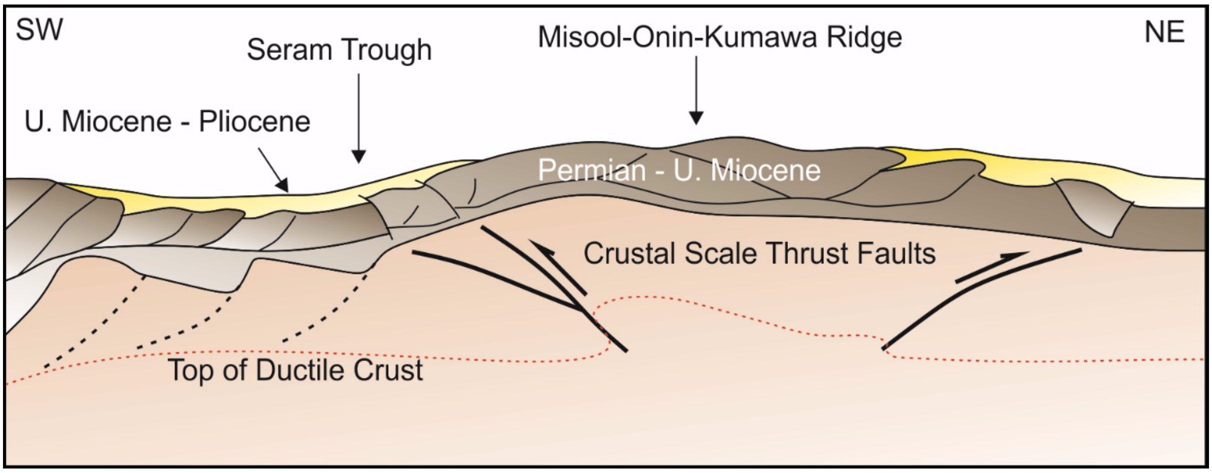

Figure 15. Development of the Misool-Onin-Kumawa Ridge and The Seram Trough in Late Pliocene due to crustal scale thrust faults (modified after Sapin *et al.,* 2009).

CONCLUSIONS

The Seram Trough curves 90°, from an E-W direction in North Seram to a N-S trend in the Kai Islands. Bathymetrically, the Seram Trough is shallower than common subduction zones elsewhere in the world ranging with depth from 900 to 3000 m and does not extend to the Buru Basin. The Buru Basin has deeper bathymetry reaching 5300 m and is bounded by normal faults. The Weber Deep is the deepest within region, more than 7000 m deep.

The Seram Trough is an almost aseismic zone, different to known subduction systems. Seismicity is concentrated in the north of Seram Island and the western offshore region north of Seram with hypocentres less than 70 km depth. The dominant earthquakes are due to thrust faulting; there are many earthquakes related to strike-slip faults. Normal fault solutions are rare and predominantly observed in the Buru Basin. The lack of significant extensional faulting on each side of the trough, and the absence of earthquakes in the trough itself are quite unlike modern subduction zones such as the Java Trench. The deformation relates to the movement of the outer Banda Arc towards east.

Among the many interpretations of the tectonics of the Banda Sea and especially the Seram Trough, we prefer the foredeep model and contemporaneous exhumation processes on Seram. Tectonics of the Banda Arc can be explained by a single slab model which includes eastward subduction rollback of the Proto-Banda Sea Plate and exhumation in Seram. The Seram Trough is a foredeep in front of fold-thrust belt and acts as a deformation front. The plausible cause of the subsidence is loading of Seram fold-thrust belt which formed due to oblique intraplate convergence between Seram and the Bird's Head. The bending of the Australian Plate in the Seram Trough is supported by existence of former carbonate platforms in the southwest of Misool and Kai Arch now in a deep marine environment (Patria and Hall, 2017; Adhitama *et al.*, 2017). This interpretation favours the absence of oceanic crust in between Seram and Bird's Head and agrees with evidence that the Tarera-Aiduna Fault is a young structure as it does not cut the Seram fold-thrust belt.

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