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**NEOGENE EXTENSION ON SERAM:  
A NEW TECTONIC MODEL FOR THE NORTHERN BANDA ARC**

**Jonathan M. Pownall\***  
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**ABSTRACT**

It has long been argued that Seram's Neogene tectonic evolution was dominated by thrusting and crustal shortening due to collision of the northern Banda Arc with the Australian passive continental margin. This collision model considers voluminous peridotites, which crop out in western and central Seram and on Ambon, to be part of a large dismembered ophiolite that was allegedly obducted from the Banda Sea, with associated granitoids explained as the melting beneath the ophiolite during emplacement.

However, new field, geochronological, and thermobarometric data question this model, with potentially important consequences for the interpretation of sedimentary basin development both onshore and in the Seram Trough. Based primarily on structural mapping of western Seram, we interpret the peridotites to represent subcontinental lithospheric mantle (SCLM) beneath Seram, which was rapidly exhumed beneath low-angle detachment faults during a period of extreme crustal extension.

Mantle exhumation is linked to widespread crustal anatexis and the formation of an extensive migmatite complex—the Kobipoto Complex—which records ultrahigh (UHT) temperatures of ~950°C at ~8 kbar pressure (25–30 km depth). Granitic rocks on Seram and Ambon, and unusual cordierite + garnet dacites (ambonites) also exposed on Ambon, all preserve evidence for their generation in the Kobipoto Complex at temperatures far in excess of that predicted by the ophiolite model. SHRIMP U–Pb zircon dating has revealed that melting and UHT metamorphism of the Kobipoto Complex was underway by 16 Ma, with granitoids produced episodically across Seram and Ambon from 16 Ma (Kobipoto Mountains, central Seram) until 3.5 Ma (Ambon).

We propose that Seram has experienced a history of extreme extension by detachment faulting that is best explained by eastward rollback of the Banda slab into the Banda Embayment since 16 Ma.

**INTRODUCTION**

The island of Seram (Figures 1 and 2) originated as part of the Sula Spur (Klompé, 1954) a promontory of Australian crust located at the leading edge of the Australian Plate (Figure 3) that collided with part of Sulawesi after subduction of the eastern Cenozoic Tethys beneath the North Sulawesi-Philippines-Halmahera volcanic arc (Audley-Charles et al., 1972; Hamilton, 1979; Bowin et al., 1980; Hall, 1996, 2002, 2011, 2012; Charlton, 2000; Spakman and Hall, 2010). The Australian–SE Asian collision, which began at c. 25 Ma (Hall, 2011), is still underway.

However, there are many contrasting models for the Neogene tectonic evolution of the region, especially regarding the nature of subduction around the Banda Arc (see discussions in Hall and Wilson, 2000; Milsom et al., 2001; Pownall et al., 2013), and the affinities of, and relationships between, different tectonic units comprising Seram and the surrounding islands (e.g. Audley-Charles et al., 1979; Tjokrosapoetro and Budhitrisna, 1982; Linthout et al., 1989; Kemp and Mogg, 1992; Linthout and Helmers, 1994; Hill, 2005; Pownall et al., 2013).

Seram has commonly been interpreted as a fold-and-thrust belt resulting from arc-continent collision (e.g. Audley-Charles et al., 1979; Bowin, 1980; Jongsma et al., 1989; Charlton, 2004; Hill, 2005). Audley-Charles et al. (1979) proposed a tectonostratigraphic scheme for Seram that involved allochthonous units of Asian affinity having been thrust over Australian para-autochthonous sequences. Ultramafic rocks, which crop out over western and central Seram and on Ambon (see Figure 2), were originally ascribed to an

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allochthonous thrust sheet and were therefore interpreted to comprise part of an extensive ophiolite that had been thrust from the Banda Sea. Work by Linthout et al. (1989), Linthout and Helmers (1994), Sopaheluwakan (1994), and Monnier et al. (2003) built further on this 'Seram Ophiolite' concept, arguing that its obduction over the metamorphic 'basement' of the Tehoru Formation had induced sub-ophiolite metamorphism and the generation of cordierite-bearing granites. Thus, the concept of Seram representing a collisional complex dominated by long-distance thrusting was developed. Indeed, fold-and-thrust-belts have been described for northern and eastern Seram (Zillman and Paten, 1975; Tjokrosapoetro and Budhitrisna, 1982; Kemp and Mogg, 1992; Hill, 2005) and the Seram Trough (Pairault et al., 2003a,b; Teas et al., 2004), but good evidence for this collisional tectonic style in western Seram is lacking.

Hall and Wilson (2000) questioned the ophiolite concept for Seram; they suggested that the ultramafic rocks may have instead been derived from the subcontinental mantle, and that extension may have been more important in the tectonic evolution of western Seram than collision and thrusting. Spakman and Hall (2010) later provided further evidence for an extension-dominated history for the island in the context of plate reconstructions utilising new tomographic models for the Banda region. More recently, Pownall et al. (2013) mapped out low-angle detachment faults in western Seram (Figure 4) that were shown to have facilitated the exhumation of subcontinental lithospheric mantle, providing evidence for significant lithospheric extension having occurred across the island. Furthermore, Pownall et al. (2013) found no evidence for significant thrusting in western Seram.

## THE GEOLOGY OF SERAM

Field relations on Seram and Ambon have previously been described by several authors (Valk, 1945; Germeraad, 1946; van der Sluis, 1950; Audley-Charles et al., 1979; Tjokrosapoetro and Budhitrisna, 1982). The summary here is based the observations by these authors and new field observations by Pownall et al. (2013).

Western Seram mainly comprises lower-greenschist to upper-amphibolite facies phyllites, schists, and gneisses of the Tehoru Formation. Garnet mica-schists are widespread, which are often intercalated with amphibolites. Scarce kyanite-grade schists (containing also staurolite and garnet) represent the

highest grade part of the complex; however, large areas are of a low metamorphic grade and preserve original sedimentary structures (Audley-Charles et al., 1979; Tjokrosapoetro and Budhitrisna 1982; Linthout et al., 1989; Pownall et al., 2013).

The Tehoru Formation is associated with complexes of peridotites and cordierite + garnet-bearing granitic rocks (see next section). The term 'cordierite granite' has long been used in the literature to describe the granitic lithologies (e.g. Priem et al., 1978); however, these rocks contain abundant mm-scale (and more rarely cm-scale) schlieren of granulite-facies mineral assemblages (sillimanite + spinel + cordierite) that demonstrate the rocks are part of a migmatite complex, and have not migrated from their source region to form separate granitoid plutons (Pownall et al., 2013, 2014).

These leucosome-rich migmatites (diatexites) and associated peridotites comprise part of the Kobipoto Complex, which has been exhumed beneath low-angle lithospheric detachment faults mapped on the Kaibobo Peninsula (Figure 4; see Pownall et al., 2013) in response to major lithospheric extension.

Gneisses adjacent to the Kobipoto Complex peridotites that crop out on the Kaibobo Peninsula, previously interpreted by Linthout et al. (1989) and Linthout and Helmers (1994) to comprise a metamorphic sole, certainly have been overprinted by sillimanite-grade metamorphism and intensive shearing. However, we interpret these metamorphic rocks to form the hanging wall above the exhumed Kobipoto Complex, not the footwall. As outlined by Pownall et al. (2013), the Taunusa Complex is an overprint of Tehoru Formation rocks in response to high-temperature exhumation of the underlying Kobipoto Complex.

In central Seram, the dominantly left-lateral Kawa Shear Zone (KSZ) is oriented roughly parallel to the strike of the detachment faults in western Seram (Figure 5) and there is evidence from fault-bounded lenses of serpentinised peridotites that are incorporated within the KSZ that these faults may have re-activated similar lithospheric-scale detachments (Pownall et al., 2013). The Kobipoto Mountains are a left-lateral pop-up structure that links with the KSZ, and the Kobipoto Complex rocks that crop out in the mountains have evidently been exhumed by left-lateral transpression.

The 3 km high Manusela Mountains, bounded along their southern margin by the major strike-slip Kawa

Fault (Figure 2), are formed from the Upper Triassic Manusela Mountain Limestones (Martini et al., 2004). Between them and the Kobipoto Mountains to their north are outcrops of the Triassic-Jurassic Kanikeh Formation deep-water clays, siltstones, and micaceous carbonaceous sandstones (Tjokrosapoetro and Budhitrinsa, 1982), which are separated from the Tehoru Formation by slates and marbles of the Saku Formation.

In northern Seram, the Mid-Upper Jurassic to Miocene Nief Beds are exposed, comprising a passive margin sequence of deep water carbonates and turbidites (Kemp and Mogg, 1992). The Nief Beds are highly imbricated (Kemp and Mogg, 1992; Hill, 2005), and are interpreted to rest on the Kola Shales, suggested by Hill (2005) to be cut by a major basal décollement beneath which the Bird's Head may have underthrust northern Seram.

Much of northern and eastern Seram is covered by extensive mélanges of the Salas Block Clay (interpreted by Audley-Charles et al. (1979), Tjokrosapoetro and Budhitrinsa (1982), and O'Sullivan et al. (1985) as an olistostrome) and Plio-Pleistocene sedimentary deposits of the Wahai Beds and Fufa Formation (Zillman and Paten, 1975). Uplifted Quaternary reefs flank the island.

## **UHT METAMORPHISM IN RESPONSE TO MANTLE EXHUMATION**

The Kobipoto Complex consists of peridotites and a granulite-facies migmatite complex comprising highly residual aluminous granulites (Pownall et al., 2014), stromatic metatexites, and melt-rich granitic diatexites (described previously as 'cordierite granites'). All rocks in the migmatite complex are characterised by aluminous sillimanite + spinel ( $\pm$  corundum) bearing assemblages which represent the residual component; the cordierite granites are peppered with schlieren of sillimanite + spinel as well as schollen of metatexite. The cordierite granites in the Kobipoto Mountains are equivalent to those in western Seram (e.g. on the Kaibobo Peninsula) and on Ambon which are similarly associated with peridotites.

In the Kobipoto Mountains, the peridotites are mainly spinel lherzolites (Pownall et al., 2013), although plagioclase lherzolites have been reported by Monnier et al. (2003) from Ambon and from the Kaibobo Peninsula, western Seram.

It has been suggested that the peridotites of eastern Seram are ophiolites which were emplaced at low

temperature (Charlton, 2004), but this is ruled out by the extremely high temperatures recorded by metamorphic rocks at their contacts. The peridotites are also unlike the depleted harzburgites typically found in ophiolite complexes and are dominantly fertile lherzolites without products of mantle partial melting including basaltic dyke complexes and large-volume gabbros. A subcontinental lithospheric mantle origin (SCLM) is much more likely.

Widespread partial melting was accompanied by ultrahigh-temperature (UHT  $\geq 900^\circ\text{C}$ ) metamorphism of the residuum; peak P-T conditions experienced by spinel + quartz and sapphirine-bearing granulites are inferred to be  $\sim 950^\circ\text{C}$  at a pressure of  $\sim 8$  kbar based on phase equilibria modelling (Pownall et al., 2014). This demonstrates the existence of an extremely high (apparent) geothermal gradient of  $\sim 120^\circ\text{C kbar}^{-1}$  ( $\sim 35^\circ\text{C km}^{-1}$ ). Diatexites of the Kobipoto Complex are always found in direct association with voluminous spinel lherzolites (whether they be in the Kobipoto Mountains, the Kaibobo Peninsula, the Wallace Mountains, the Hoamoal Peninsula, or on Ambon); these hot mantle rocks are interpreted to be the driver of UHT metamorphism, and melting appears to have been short-lived event. Assuming that the granulites were close to being in thermal equilibrium with their heat source, in order to have experienced metamorphism at  $950^\circ\text{C}$  the neighbouring lherzolites must have been close to typical subcontinental lithospheric mantle (SCLM) temperatures of  $\sim 1300^\circ\text{C}$ .

Most authors who supported the idea of the 'Seram Ophiolite' applied the concept exclusively to western Seram and Ambon and never attempted to explain isolated outcrops of peridotites exposed in the Kobipoto Mountains or in eastern Seram around Gunung Langget (e.g. Linthout et al., 1989, 1996; Sopaheluwakan, 1994; Linthout and Helmers, 1994; Monnier et al., 2003). If further proof were needed that the lherzolites are not part of an obducted ophiolite, then their juxtaposition against the Kobipoto Complex without cooling below upper mantle temperatures is the evidence. In the Kobipoto Mountains, if the lherzolites had been obducted from the Banda Sea to have generated the 'cordierite granites' by anatexis within a metamorphic sole (cf. Linthout et al., 1989; Linthout and Helmers, 1994), they would have had to have been thrust for  $> 50$  km over the Tehoru Formation and the cold carbonates of the Manusela Formation without any significant cooling.

Sensitive High Resolution Ion Microprobe (SHRIMP) U-Pb dating of zircons from Kobipoto Complex granulites sampled from the Kobipoto Mountains has revealed a ~16 Ma age for UHT metamorphism (Pownall et al., 2014). Importantly, this age is significantly younger than the Permian (or Precambrian) age that has often been assumed for the complex (see Figure 2 and references in Pownall et al., 2013). Furthermore, the presence of Triassic detrital zircon grains demonstrates a protolith age that is also younger than these earlier estimates. Cordierite diatexites present on the Kaibobo Peninsula have been dated at ~5.5 Ma (40Ar/39Ar biotite age; Linthout et al., 1996) and voluminous cordierite diatexites and related granites present on Ambon are younger still, at ~3.3 Ma (Rb–Sr age; Priem et al., 1978). Cordierite + garnet dacites (or ‘ambonites’), which are in part sourced from the Kobipoto Complex, were erupted on Ambon shortly before ~2.4 Ma (K–Ar age for the groundmass; Honthaas et al., 1999).

## **INTERPRETATION OF THE SERAM TROUGH**

Hamilton (1979) presented the first seismic profiles across the Seram Trough. He interpreted the zone as the surface trace of southward subduction of the Bird’s Head, describing Seram as an accretionary prism of Australian-derived terranes chamfered off the top of the subducting slab – a model adopted by several later authors (Bowin et al., 1980; Tjokrosapoetro and Budhitrinsa, 1982; Hartono and Tjokrosapoetro, 1984; O’Sullivan et al., 1985). It was also later suggested that the Seram Trough is primarily a zone of strike-slip faulting associated with the Tarera-Aiduna and Sorong fault zones (Linthout et al., 1997; Milsom et al., 1983).

However, in recent years these interpretations have been challenged both by greatly improved seismic profiles (Pairault et al., 2003a,b; Teas et al., 2009; Darman and Reemst, 2012) and high-resolution multibeam bathymetry (Teas et al., 2009) which have led to the interpretation of the Seram Trough as a foredeep basin flanking the Seram fold-and-thrust belt. Pairault et al. (2003a,b) described the Seram Trough as a very young zone of thrusting in the Australian continental margin resulting from southward underthrusting of the Bird’s Head beneath Seram. A major décollement is clearly imaged on seismic sections shot perpendicular to the trough along which a series of steep reflectors, interpreted to be reverse faults within the imbricated Triassic to Miocene Nief Beds, are shown to terminate. A Permian to Pliocene sedimentary

succession overlying Australian ‘basement’ is shown to dip southwards into the Seram Trough where it is seemingly overthrust by ‘Seram’ beds riding the décollement. A cross-section published by Hill (2005) depicts this interpretation, with the detachment fault having propagated through the Kola Shales, as previously mentioned. Although Pairault et al. (2003b) strongly favoured a foredeep model for the Seram Trough, they concluded a subduction model cannot be ruled out entirely due to the poor quality of seismic data at depth.

Teas et al. (2009) presented high-resolution bathymetry of the Seram Sea which clearly shows an E–W-trending offshore fold-and-thrust belt developed immediately south of the major décollement. In agreement with Pairault et al. (2003a,b), the authors concluded that the deformation is due to convergence of the Bird’s Head with Seram and that no large-scale strike-slip faulting is present. However, in the eastern offshore fold-and-thrust belt, Teas et al. (2009) identified many localised E–W oriented sinistral shear zones which they attributed to a possible diffuse termination of the left-lateral Tarera-Aiduna Fault Zone which runs south of the Bird’s Head. The fold belt narrows at the western end (Teas et al., 2009; Darman and Reemst, 2012), where deformation is dominated by detachment faulting and block rotation rather than the thin-skinned deformation in the east. Teas et al. (2009) suggested that the evolution of the fold belt was dictated by the relative movement between the Bird’s Head and Australia, calculated by Stevens et al. (2002) to be occurring along an azimuth of 252°. The Seram Trough has been infilled with unconformable horizontally-bedded sediments during the Pleistocene (Darman and Reemst, 2012).

## **BANDA SUBDUCTION**

The Wadati-Benioff Zone for the subducted slab around the Banda Arc, as inferred from seismicity (e.g. Cardwell and Isacks, 1978; McCaffrey, 1988, 1989; Das 2004) and tomographic models (e.g. Widiyantoro and van der Hilst, 1997; Spakman and Hall, 2010) is shown to have acquired a highly concave spoon-shaped or prow-shaped morphology within the 180°-curved arc. Early models proposed that the Banda Arc formed by the bending of an originally straight subduction zone through 180° (Audley-Charles et al., 1972; Katili, 1975), but most authors now agree that slab rollback has played a role in the formation of the tightly-curved arc (e.g. Hall, 1996; Charlton, 2000; Hall and Wilson, 2000; Harris, 2006; Spakman and Hall, 2010), although

opinions are still divided over whether one or two slabs are involved. Those authors that have invoked two separate subduction zones (e.g. Cardwell and Isacks, 1978; McCaffrey, 1988, 1989; Das, 2004; Špičák et al., 2013) have often done so in order to explain a lineament of high-seismicity across the southern margin of the arc that is interpreted to link with the Tarera-Aiduna Fault Zone to the south of the Bird's Head (West Papua); it has been argued that this zone represents a suture between two separate slabs with opposing dip directions. However, a single-slab model arguably is better supported in the context of plate reconstructions for the region (e.g. Hall, 2011, 2012), and the high-seismicity zone can be explained by a tear in a single, albeit highly contorted, slab.

The interpretation of seismicity data (Das, 2004) combined with the Spakman and Hall (2010) tomographic model were used to construct the 3D diagram of the Banda Arc (Figure 6). The slab appears to be detached from the northern margin at a point between Buru and Seram, and further west, it has fully collapsed into the mantle to form a flat-subducted surface at 660 km depth. The slab is thus interpreted to have torn from the northern margin, supported by the presence of an aseismic zone, during eastward rollback of the arc into a pre-existing D-shaped oceanic embayment (Spakman and Hall, 2010).

### **Present-day seismicity**

Recent (1976-present) shallow-level (< 80 km depth) earthquakes recorded for Seram and the northern Banda Arc, catalogued in the Global Centroid-Moment-Tensor (CMT) database (Ekström, 2006), were plotted using the UNAVCO (2012) Integrated Data Viewer (IDV) – see Figure 7. The northern coast of Seram and the southern extent of the Seram Sea is currently the most seismically-active region, with earthquakes typically recording high-angle thrust faults with components of right-lateral transpression. In central Seram, several focal mechanisms can be interpreted as displaying strike-slip motions on fault planes striking ESE–WNW, roughly parallel to the Kawa Shear Zone and the detachment faults in western Seram. A single earthquake in the Manusela Mountains recorded left-lateral strike-slip motion, but two earthquakes further west indicate right-lateral strike-slip. A number of focal mechanisms showing ENE–WSW-striking extensional faulting perhaps correlate with the youngest set of normal faults interpreted in Figure 5 (shown in blue). A series of earthquakes in the Banda Sea indicate

purely north- or south-directed thrusting. The cluster of earthquakes around the eastern coast of Buru mark the site of the largest shallow-depth earthquake in the dataset—an Mw 6.7 left-lateral strike-slip earthquake just 13 km below the surface.

It can be seen in Figure 7 that present-day deformation across northern and eastern Seram is in response to maximum principal stress directions that are oriented roughly perpendicular to the Seram Trough, with the pressure axes (shown in white) rotating clockwise to a more E–W-aligned orientation further to the east. This shortening is responsible for the formation of the fold-and-thrust belt in the southern Seram Trough, although this is arguably a very recent feature.

### **DISCUSSION: A NEW TECTONIC MODEL FOR THE NORTHERN BANDA ARC**

As outlined by Pownall et al. (2013, 2014), a major extensional episode is interpreted to have thinned the lithosphere and to have exhumed the subcontinental lithospheric mantle beneath the protolith of the Kobipoto Complex at temperatures sufficient to have induced UHT (> 900°C) metamorphism. From the phase equilibria modelling described by Pownall et al. (2014), a depth of 25–30 km (based on a pressure of ~8 kbar) can be considered as the depth of heating to UHT conditions, which is consistent also with the equilibration of the Iherzolites in the Cr-spinel stability field at a pressure of 7–18 kbar (Gasparik, 1984). As demonstrated on the Kaibobo Peninsula, mantle exhumation was in part facilitated by low-angle detachment faults; however, at deeper structural levels upon transition into the ductile regime, it is also plausible that exhumation and extension by pure shear may have also operated. Alternatively, a combination of brittle normal shear and ductile pure shear (cf. Lister and Davis, 1989), may best explain crustal extension in this core-complex-type scenario. However, the very high ~35°C km<sup>-1</sup> apparent geothermal gradient, and the exhumation of hot SCLM, demonstrates a heat flow which surpasses that of typical 'hot crust' core complex models (cf. Whitney et al., 2013).

The initial mechanism for Kobipoto Complex exhumation in the Kobipoto Mountain is unclear, because the rocks have subsequently been exhumed by transpression and incorporated into the Kobipoto Mountains pop-up structure. Field relations in Western Seram may therefore more clearly demonstrate the style of extensional tectonics. In

Figure 8, the extension is depicted primarily as slip along low-angle detachment faults (as mapped on the Kaibobo Peninsula; see Pownall et al., 2013) that flatten and disappear into the weak, melt-rich ductile zone, which in turn has been exhumed by the next detachment fault in the sequence (shown more clearly in the 2D schematic cross-section of Figure 9). The net effect would have been similar to a boudinaging of the crust as it stretched, with individual blocks (or giant boudins) having rotated backwards into a flatter (thinner in cross-section) orientation. This mechanism permits both hot SCLM and lower-crustal granulite-facies migmatites to be exhumed beneath the detachment faults as the blocks rotate, and also accounts for how Tehoru Formation rocks in the hanging wall (that are rotating downwards onto the upward-rotating footwall of the next block) have been overprinted by localised heating and shearing by the Kaibobo Complex granulites and lherzolites.

A further implication of this model is that the protoliths of the Kobipoto Complex migmatites and the Taunusa Complex gneisses are very likely in both instances the Tehoru Formation; therefore, all metamorphic complexes on Seram may share a common origin. Furthermore, following this model, Taunusa Complex gneisses located in the hanging wall are equivalent to upper-amphibolite-facies rocks that presumably separate the Kobipoto Complex migmatites from ‘normal’ Taunusa Formation schists in the respective footwall.

That only localised anatexis is observed in the hanging wall demonstrates that the lherzolites and migmatites must have been cooled by several hundred degrees as they were exhumed beneath the detachment faults.

Spakman and Hall (2010) proposed that slab rollback into the Banda Embayment, which initiated at ~15 Ma, caused the Sula Spur to extend and fragment as the slab rolled back eastwards (Figure 10). Slab rollback is certainly the most probable mechanism to have driven this extensional episode on Seram, and the proposed initiation time of this rollback by Spakman and Hall (2010) and Hall (2011, 2012) coincides fairly well with the age of UHT metamorphism. Perhaps, due to the requirement of having to extend the crust in advance of UHT conditions being produced (Schenker et al., 2012), that the rollback initiation may have occurred at a few Myr earlier than previously suggested, and also that Seram and Buru may have originated further west, bordering the SE arm of Sulawesi before 16 Ma.

The strike-slip Kawa Shear Zone (KSZ) has evidently operated most recently in the sinistral sense, as is apparent from viewing the digital elevation models (DEMs) of the island (see Figure 5). However, as described by Pownall et al. (2013), both left- and right-lateral kinematic indicators are present when investigated in the field, indicating that the history of the KSZ is very likely more complex. The incorporation of thin lenses and boudins of serpentinitised spinel peridotites within the wide fault core of the main Kawa Fault demonstrates it is a major lithospheric-scale feature. Furthermore, the main section of the KSZ that runs the length of the Wai Kawa into Teluk Taluti (near Tehoru Village) has an identical strike (120°–300°) to the Kaibobo Detachment, suggesting that possibility that the KSZ could have formed through reactivation of similarly-oriented detachment faults in central Seram. By this mechanism, peridotites that were initially exhumed along the base of the detachment could then be incorporated into the shear zone after it reactivated with a dominantly strike-slip motion. Repeated cycles of strike-slip faulting could then have further exhumed the peridotites by ‘shuffling’ them upwards from depth (cf. Lister and Forster, 2009).

This proposal for the reactivation of low-angle detachment faults as lithospheric strike-slip features is illustrated in Figure 8. Feasibly, the KSZ may have operated with both dip-slip and strike-slip components to its motion during its early history. Linthout et al. (1991) suggested that the KSZ acted as a right-lateral antithetic shear that facilitated an anticlockwise rotation of the island eastwards into the northern limb of the Banda Arc; however, this interpretation would seem unlikely given the evidence presented here for a dominantly left-lateral history.

Furthermore, this interpretation does not make sense in the context of rollback-driven extension. As previously stated, the 16 Ma age for UHT metamorphism (suggesting that extension must have initiated > 16Ma) would locate Seram against the SE Arm of Sulawesi at this time, not along the NE margin of the Banda Embayment as implied by Linthout et al. (1991, 1997). Eastward slab rollback is consistent with it having driven E–W-striking left-lateral shear, as would have been required to drag Seram towards to its present location further east. This migration may, or may not, have been accompanied by an anticlockwise rotation through about 90° as proposed by Haile (1978) in light of his reconnaissance palaeomagnetic survey, although if Seram had undergone significant rotation, an

anticlockwise direction would be probably most likely, as proposed by Lonergan and White (1997) to explain the development of the Betic-Rif Arc in the western Mediterranean.

As demonstrated by modern-day seismicity (see previous section and Figure 7), the KSZ still shows signs of both left- and right-lateral strike-slip faulting; however, most of the seismicity is concentrated around the northern Seram coast in response to E–W-striking thrust faulting. As shown by high-resolution bathymetry for the Seram Sea (Teas et al., 2009), this fold-and-thrust-belt is also affected by left-lateral transpression. The geometries and orientation of transpressional and transtensional structures in central Seram (i.e. the Kobipoto Mountains and ‘Central Valley’) are similar to those imaged offshore. Thus, active left-lateral shear across this portion of the northern Banda Arc can be interpreted. However, the fold-and-thrust belt off northern Seram is possibly very young and not representative of the dominantly extensional tectonic history that has affected the island over the last 16 Ma.

## CONCLUSIONS

Our observations do not support models that invoke collisions of arcs with the Australian margin, emplacement of hot ophiolites, nor thrusting that began in the Late Miocene. At the present day, seismicity and structures on Seram and in the Seram Trough do indicate north-directed thrusting but we suggest the thrusting began only during the Pliocene. Seram preserves a record of extreme crustal extension which continued during the Neogene until about 2 million years ago.

Subduction rollback into the Banda embayment is indicated by mantle structure and is supported by the presence of young UHT rocks exhumed on Seram, intrusive peridotite-granite contacts, and the exhumation of subcontinental mantle lithosphere.

East Indonesia has been widely interpreted for many years in terms of collision and slicing of continental fragments from New Guinea. These interpretations need to be reconsidered. Seram is a spectacular example of prolonged extension, driven by subduction, which is increasingly recognised to be of major importance in eastern Indonesia.

The importance of extension cannot be over-emphasised but at present it is incorporated in few structural and tectonic models in a significant way. It was this extension that fragmented the former

Sula Spur, created the deep oceanic basins of the Banda Sea, and left extended remnants of continental crust throughout the region from Sulawesi to the Banda forearc islands. Extension is manifested on land in many areas by unusual and very young igneous and metamorphic rocks but offshore by deep sediment-filled basins which are of major interest to the hydrocarbon industry. Our knowledge of the basin-forming mechanisms, rates of vertical motions and heatflow implications is still limited and more work is required to better understand the implications of regional extension.

Seram also illustrates one other important feature of Indonesian geology: the need for many more new field-based investigations. The unusual UHT rocks of Seram are known elsewhere in the world (with one or maybe two known exceptions) only from Precambrian–Palaeozoic terranes, and consequently mechanisms for their formation are the subject of controversy and speculation. Seram offers an example of a field study in an understudied area yielding surprising and exciting results which will contribute to new thinking about tectonic models of orogenic belts with implications for basins and hydrocarbons. There are many other parts of Indonesia where new field-based studies offer similar opportunities.

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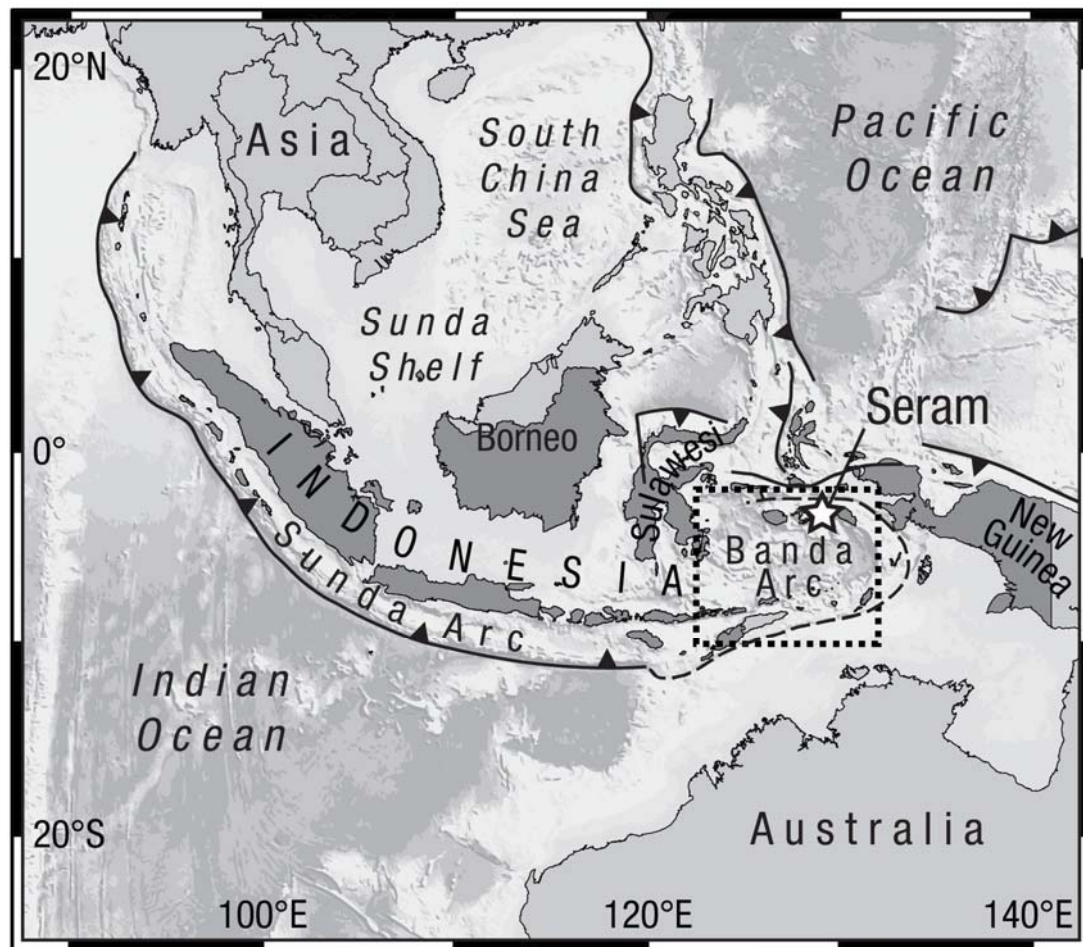
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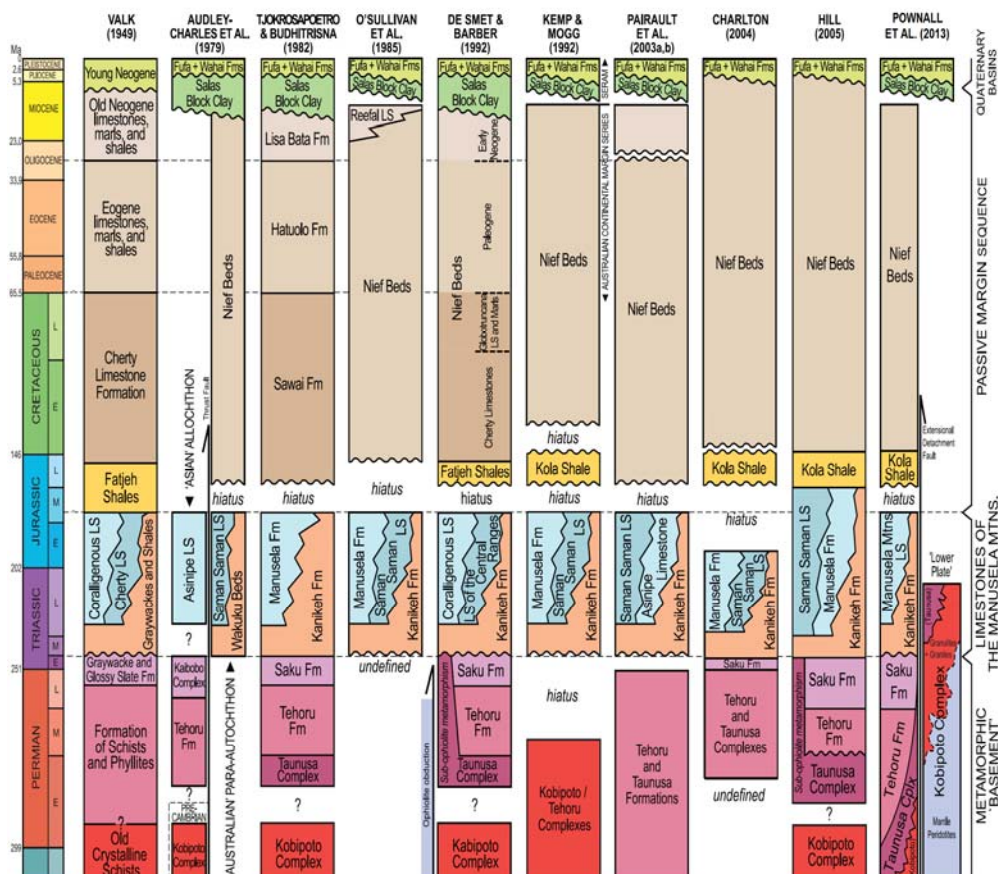
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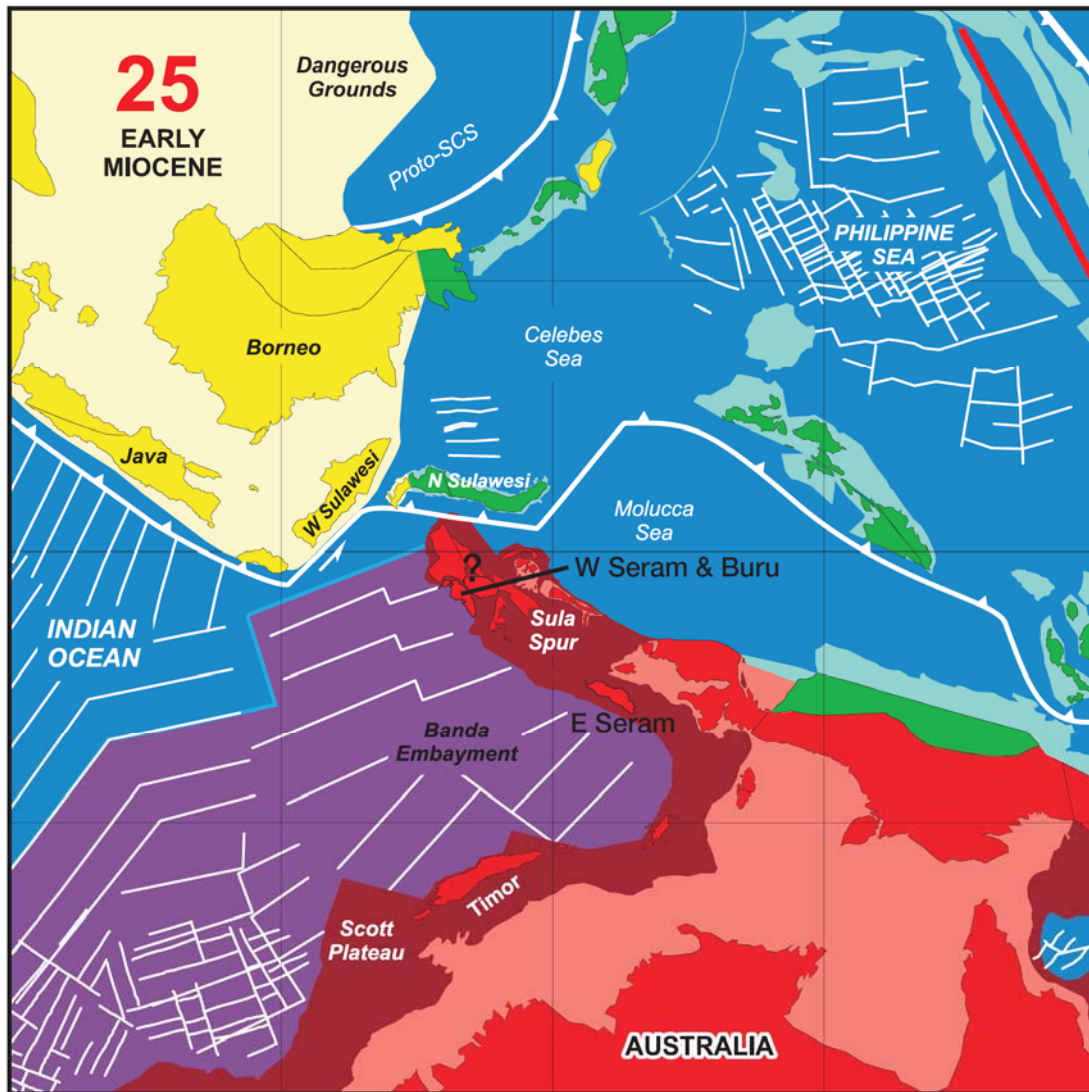


**Figure 1** - Map of eastern Indonesia. Seram is marked by the star. The location of Figure 6 is shown by the box.

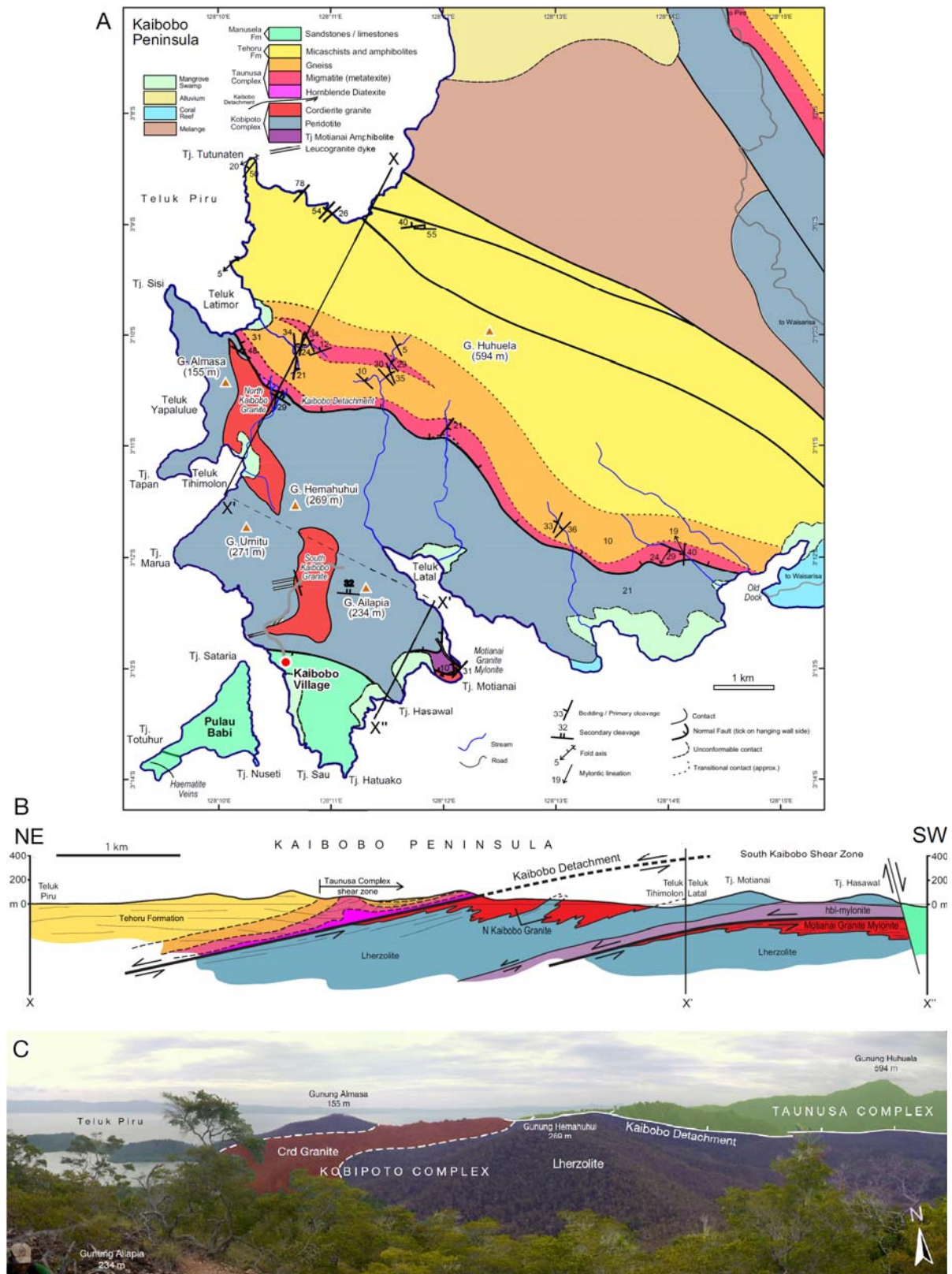


**Figure 2 -** Geological sketch map of western and central Seram and Ambon (after Pownall et al., 2013). The stratigraphic columns shown below (which can be used as a key to the map) show a comparison between previous stratigraphic proposals. Equivalent (and approximately equivalent) units are shown in the same colours. Note that the stratigraphic position of the metamorphic units relates to the protolith age and not necessarily the age of metamorphism.

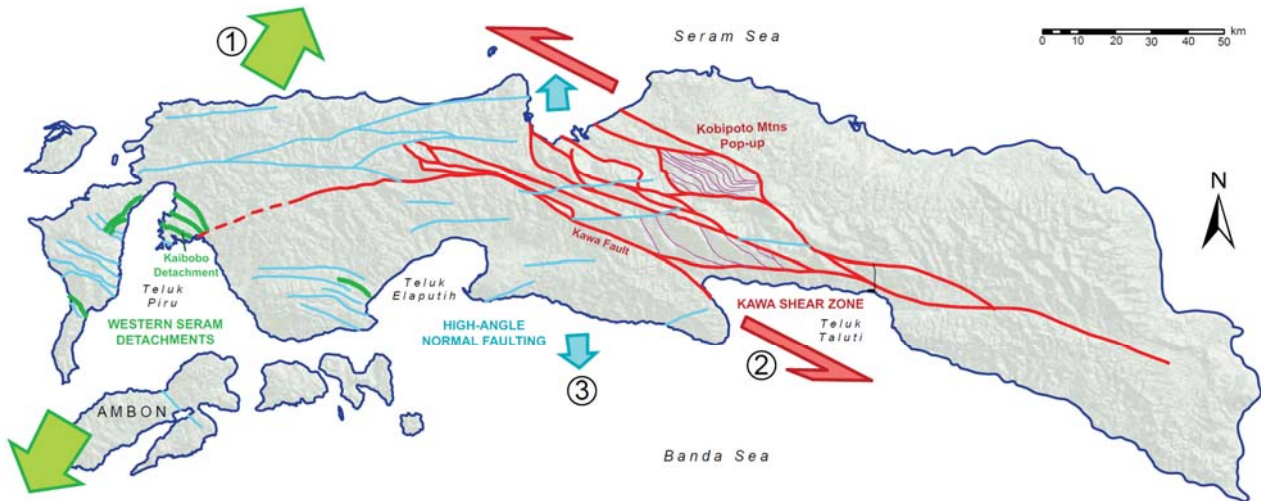




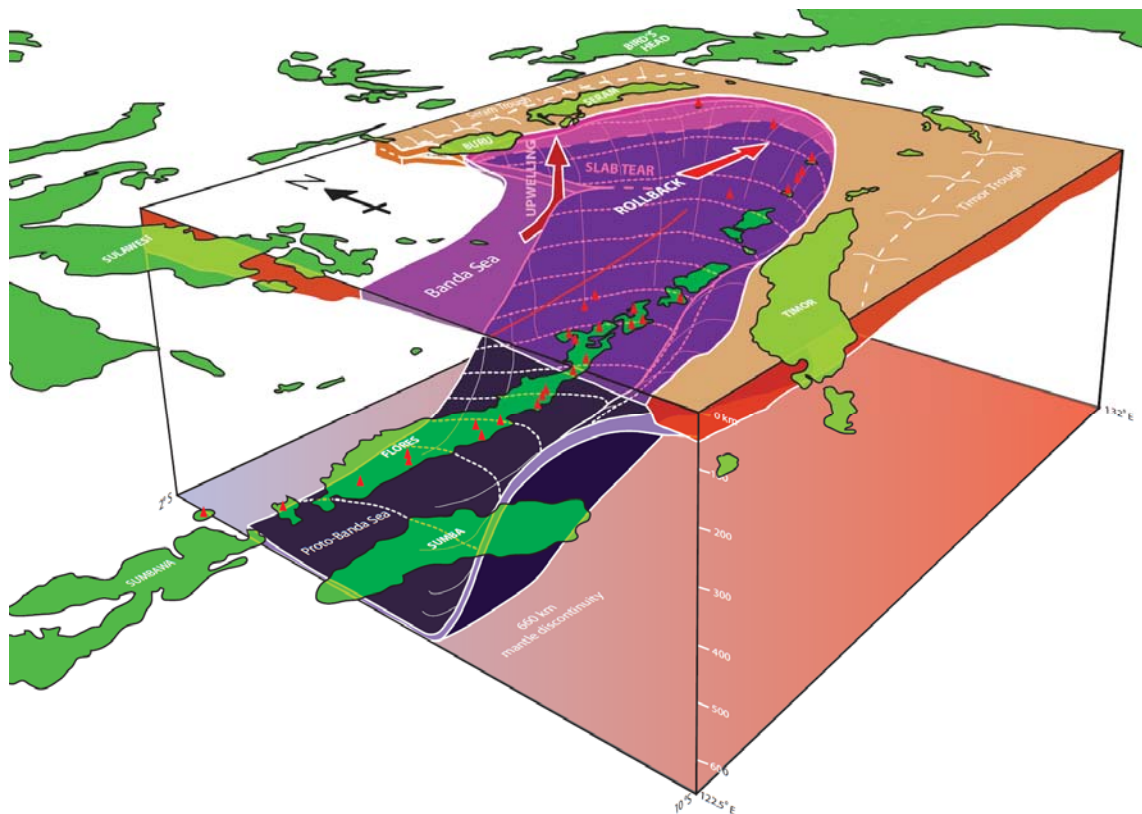
**Figure 3** - Australia-Asia collision at 25–23 Ma. Figure modified slightly from Hall (2011) with western/central Seram and Buru positioned further west (although the exact configuration of the Sula Spur is unknown). Purple—oceanic crust > 120 Ma; blue—oceanic crust < 120 Ma; green—volcanic arcs; yellow—SE Asia; red—Australia.



**Figure 4** - (a) Geological map of the Kaibobo Peninsula, western Seram (after Pownall et al., 2013); (b) Cross-section through the Kaibobo Peninsula along profile X–X'–X''; (c) Annotated panoramic photograph taken from the top of Gunung Ailapia showing the Kobipoto Complex located beneath the Kaibobo Detachment.

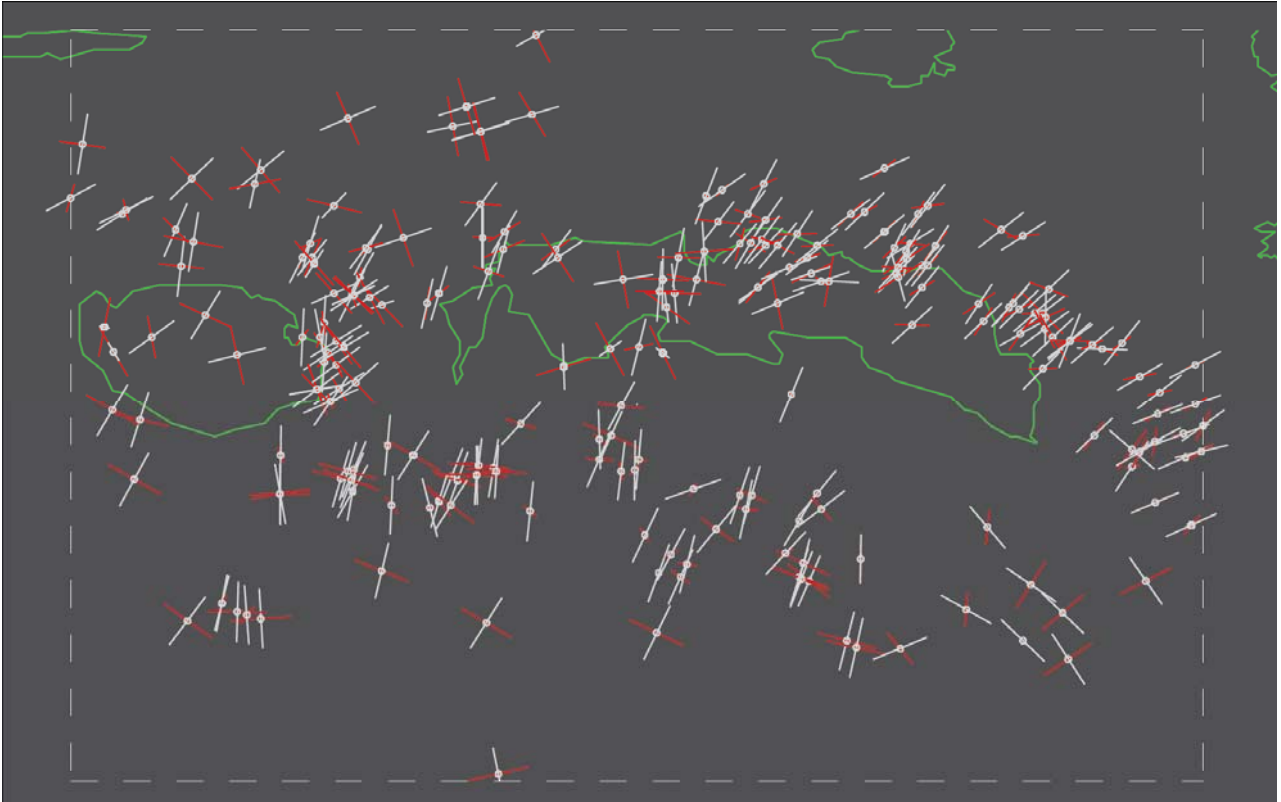


**Figure 5** - Structural sketch map of Seram (from Pownall et al., 2013) showing detachment faults (green), strike-slip faults (red), high-angle normal faults (blue), and faults within the Kobipoto Mountains strike-slip pop-up structure (magenta) inferred from field observations and DEM interpretation. The relative timings of these three faulting episodes is indicated: Detachment faults strike normal to an inferred NNE–SSW initial extension direction (1); possible subsequent reactivation of detachment faults in central Seram by WNW–ESE left-lateral shear (2) forms the Kawa Shear Zone and Kobipoto Mountains pop-up; late-stage normal faulting in response to slight N–S extension (3) cross-cuts all other structures.

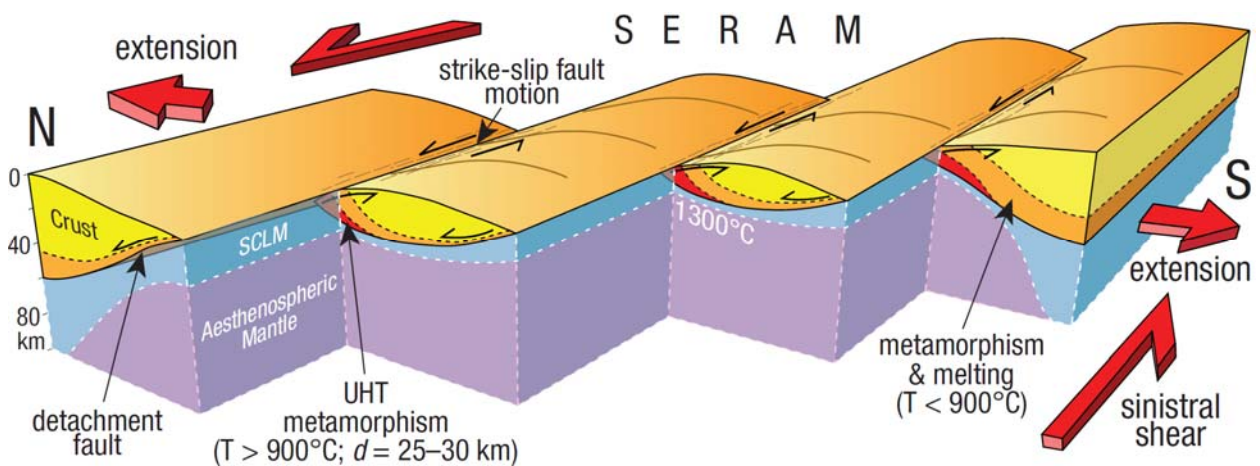


**Figure 6** - 3D model of the Banda Arc (after Pownall et al., 2013) based on earthquake hypocentre locations (Das, 2004) and seismic tomography (Spakman and Hall, 2010). The box is drawn between 122.5–132°E and 2–10°S to 660 km depth.

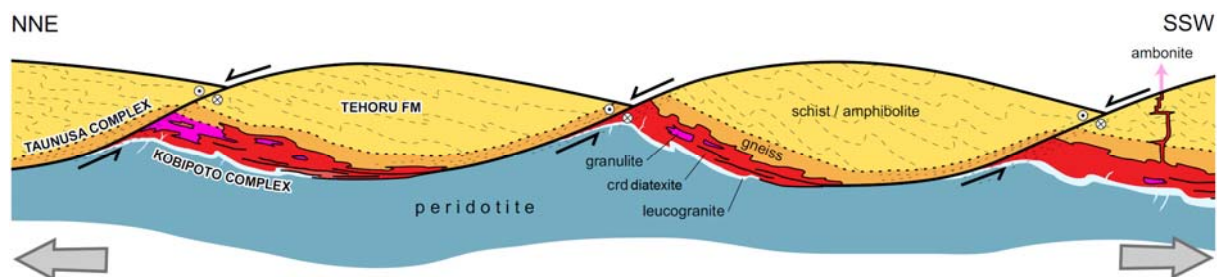




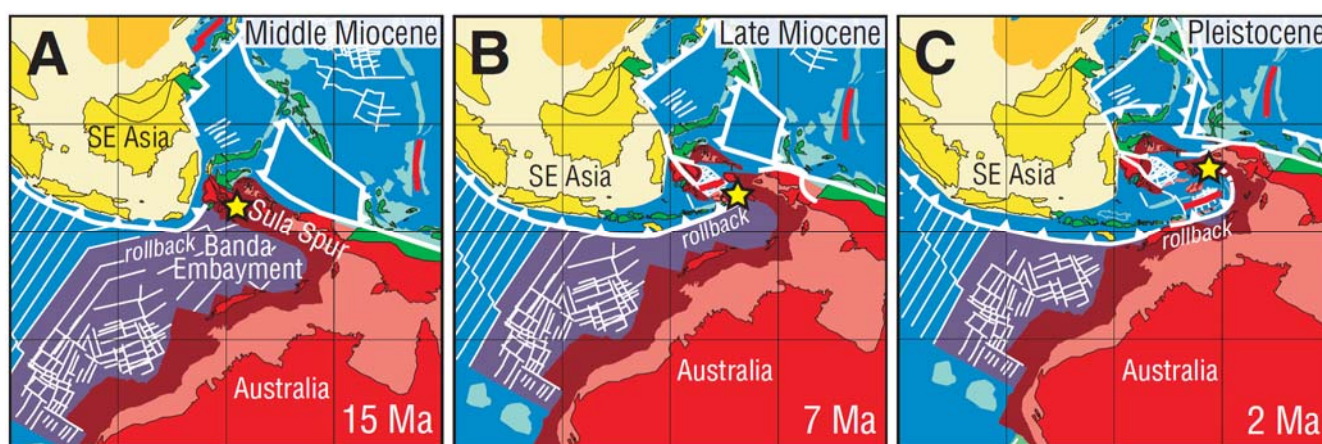
**Figure 7** - Seismicity of the northern Banda Arc. Pressure (white) and tension (red) axes are shown for earthquakes shallower than 80 km depth. CMT solutions were obtained from the Global CMT database at [globalcmt.org](http://globalcmt.org) (Ekström, 2006), and plotted using the UNAVCO Integrated Data Viewer (UNAVCO, 2012). The dashed box shows the limits of the area of interest (126.0–131.7°E; 1.8–5.5°S).



**Figure 8** - Schematic 3D block model (from Pownall et al., 2014) demonstrating the generation of ultrahigh-temperature (UHT) conditions (red) by extreme extension accommodated by lithospheric detachment faults and their subsequent strike-slip reactivation. See Figure 9 for a 2D version.



**Figure 9** - Schematic 2D model (from Pownall et al., 2013) proposed for Seram to explain mantle exhumation by extreme extension driven by Banda Arc slab rollback. The relationship between the Kobipoto Complex, the Taunusa Complex, and the Tehoru Formation is shown. The detachment faults may have subsequently been reactivated as left-lateral strike-slip faults as observed in the Kawa Fault Zone. See Figure 8 for a 3D version.



**Figure 10** - Tectonic reconstructions for the Banda region at (A) 15 Ma, (B) 7 Ma, (C) 2 Ma showing slab rollback into the Banda Embayment (adapted from Hall, 2012; Pownall et al., 2014). Yellow star indicates the location of Seram. Oceanic crust is shown in purple (older than 120 Ma) and blue (younger than 120 Ma); submarine arcs and oceanic plateaus are shown in cyan; volcanic island arcs, ophiolites, and material accreted along plate margins are shown in green.