Tectonic and Regional Structure of Seram and the Banda Arc

Kevin C. Hill
Oil Search Ltd., Sydney, NSW, Australia
E-mail: **kevin.hill@oilsearch.com**

ABSTRACT

Seram and the Banda Sea lie between the passive margin tectonics of Australia's Northwest Shelf and the active margin tectonics of New Guinea, both of which have played an important role in the structure, facies distribution and hydrocarbon prospectivity of the area.

A restored cross section across Seram and a 3D model reconstruction of the Miocene evolution of the Banda Arc reveal the history of the area. The Proto-Banda Sea is considered to have formed in the Permian, including a marginal basin with Permian oceanic crust. Extension was terminated by Triassic orogenesis in New Guinea supplying vast amounts of Triassic detritus (Kanikeh) to the stretched Banda margins. In the Late Triassic, the sediment supply was diminished in part due to the renewed onset of extension along the New Guinea margin. It is notable that the Triassic orogeny was very similar to the Miocene to Recent orogeny in New Guinea. As Triassic sediment supply was reduced, carbonate banks were locally built up (Manusela reservoir) surrounded by starved source rock facies. The margin subsided in the Jurassic and was starved of sediment until the Tertiary when renewed tectonic activity in New Guinea supplied distal carbonates and marls, mainly in the Miocene. Around 10 Ma, the Indonesian Arc impinged on the Permian oceanic lithosphere of the Proto-Banda Sea, which was then rapidly subducted, sinking under its own weight. The Arc advanced rapidly eastwards towards Timor and Seram, generating a collisional margin in Timor, but a strongly transpressional margin in Seram. The first phase of collision in Seram at ~6 Ma involved overthrusting of an accretionary prism, largely comprising Kanikeh sediments, but also some oceanic fragments. The second phase of orogenesis in Seram involved thrusting of the continental margin beneath the overthrust, creating highly fractured antiformal stacks in the Manusela encased in Kanikeh seal and source rocks, as in the Oseil oilfield. To the east an imbricate thrust zone has formed in the Cretaceous and Tertiary sequences which is now impinging on the Misool-Onin Arch.

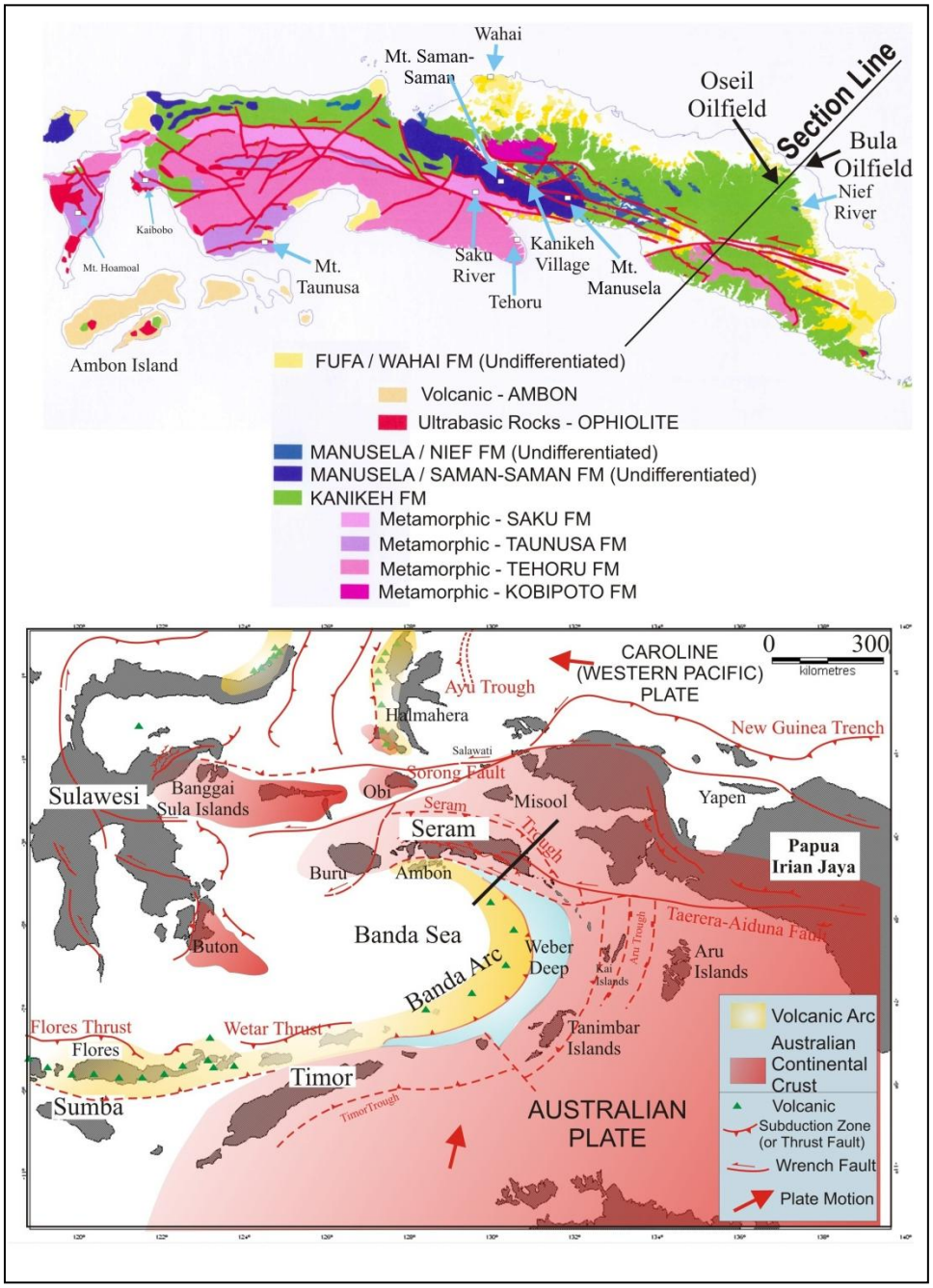


Figure 1. Tectonic setting of the Banda Arc and simplified geology map of Seram, courtesy of Kufpec (Indonesia) Limited, showing the location of the regional cross section.

INTRODUCTION

Seram and the Banda Sea area lie between the passive margin tectonics of Australia's NW Shelf and active margin tectonics in New Guinea (Figure 1). The stratigraphy and tectonics of both areas need to be taken into account. Here, we draw on the tectonics and stratigraphy of the Browse Basin on the NW Shelf (Hill & Hoffman 2004; Hoffman & Hill 2004), the nearest area unaffected by Mesozoic and Tertiary orogenesis, and compare it to the tectonics and stratigraphy of New Guinea (Hill & Hall 2003). It is necessary to make comparisons with such regions as the stratigraphy and facies variations around the Banda Arc are poorly known and there is relatively little structural data.

To fit the Seram stratigraphic section (Figure 2) into a regional context it was compared to that in the Browse Basin along Australia's NW Shelf. A 500 km long cross-section from the Browse Basin was balanced and restored showing the evolution of the margin and growth of the stratigraphic sequences (Hoffman & Hill 2004). For the Browse Basin region Struckmeyer et al (1998) indicated:-

- Upper Carboniferous to Lower Permian extension
- Upper Permian to Lower Triassic subsidence
- Upper Triassic to Lower Jurassic compression and inversion
- Lower to Middle Jurassic extension
- Upper Jurassic to Paleogene thermal subsidence
- Middle to Upper Miocene inversion.

Hill & Hoffman (2004) showed substantial thinning of the outer margin crust (the Scott Plateau) in the Middle Jurassic, as it stretched from 60 to 120 km in length and subsided permanently into 2-3 km water depth. Towards the continent, this was bound by a long-lived crustal scale fault marking a fundamental change in crustal thickness such that the continentward margin remained in relatively shallow water, usually shelfal and always <500 m deep. Between the Scott Plateau and Callovian oceanic crust Hill & Hoffman (2004) showed

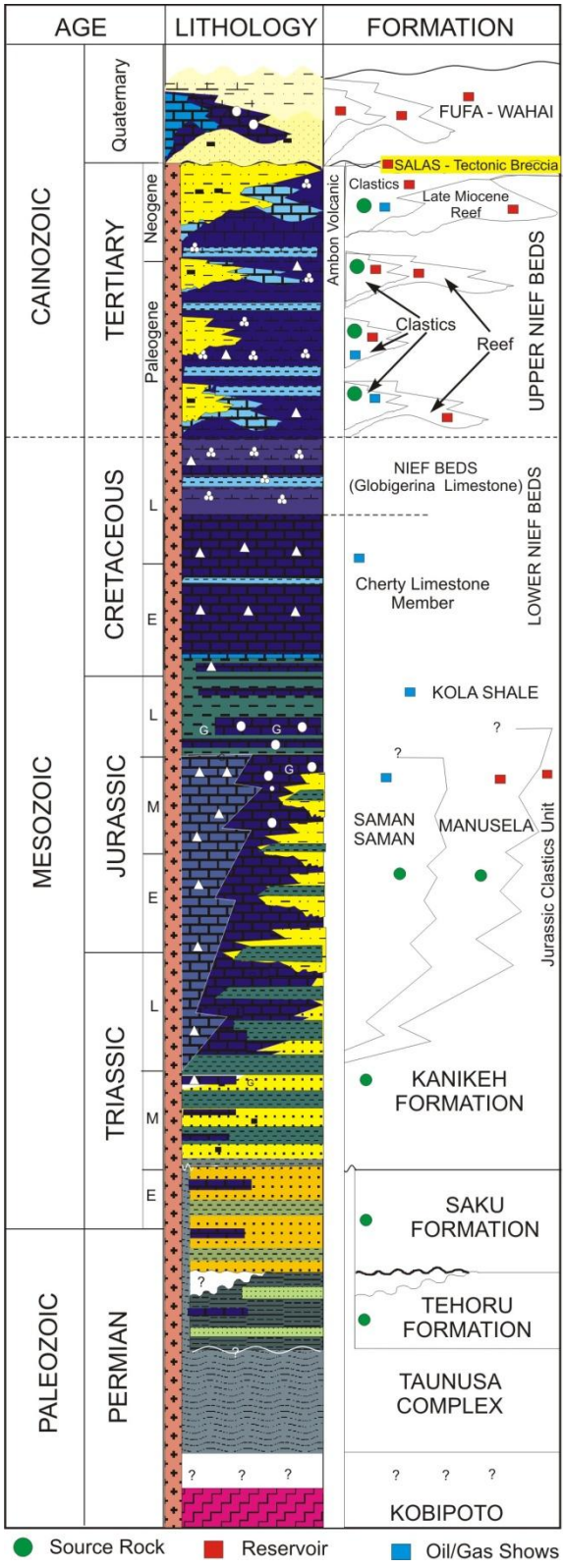


Figure 2. **Simplified stratigraphy for Seram courtesy of Kufpec (Indonesia) Limited.**

the presence of an outer margin higher, probably of intruded and thinned continental crust. This High may include metamorphic core complexes as recorded along Australia's southern margin along the Continent-Ocean Boundary (COB) (Sayers et al. 2001).
This sequence is significant as, here, we interpret a similar crustal morphology along the Seram margin prior to Pliocene compression. However, the timing of events is not the same as in the Browse Basin in part due to the tectonism in neighbouring New Guinea.

For Northern and Eastern New Guinea, Hill & Hall (2003) reported:

- Late Devonian Tasman orogenesis (including the Birds Head), with Carboniferous strata absent
- Permian extension in the west (Hill et al 2002)
- Early Triassic orogenesis
- Middle Triassic granitic intrusions
- Late Triassic extension and orogenic collapse
- Jurassic rifting and Cretaceous passive margin
- Paleocene rifting in eastern New Guinea and the Birds Head
- Neogene orogenesis, with the acme in the Early Pliocene (e.g. Kendrick et al 1995; 1997; 2003)
- Pleistocene post-orogenic collapse in the Birds Head and eastern New Guinea.

This has particular relevance to the Seram-Banda area as the margin to the north was in compression in the Early and Middle Triassic so was uplifted and eroded supplying significant volumes of Triassic sediment.

The Neogene tectonic model used here follows that of Hall (2002), which shows old oceanic crust in the Banda Sea consumed by subduction rollback from 10 Ma to the Present. Hall's (2002) model shows over 1000 km of oceanic crust consumed in ~6 Ma, indicating very fast microplate movements of ~10-15cm/year. This subduction rollback was the main driving force for the Pliocene to Recent tectonism around the Banda Arc causing rapid and changing deformation.

Hall's (2002) restoration at 10 Ma symbolically shows Seram and Timor overlying thinned continental crust and Seram is shown further away from the continental margin than at Present to take account of Pliocene to Recent shortening. However, the Timor margin is not similarly restored. At 10 Ma the subduction zone beneath the southward migrating Indonesian Archipelago had just reached the Banda Sea old oceanic crust. Hall (2002) shows that the subduction zone jumped to the south from 10-8 Ma, possibly trapping a portion of the old crust in the overriding plate, which ends up in the Weber Deep. The subduction jump initiated a new subduction zone in which the very old, cold, thick and dense Banda Sea oceanic crust was subducted. This crust then sank of its own accord and pulled the subduction zone across the Banda Sea area in a horseshoe shape. The overlying arc migrated south and east and the northern margin was largely a strike-slip margin. Backarc spreading occurred NW of the arc in the present Banda Sea. Hall (2002) infers that the subduction zone and backarc spreading ridge swept along the southern margin of Seram from 6-4 Ma and that most of the old Banda Sea oceanic crust was consumed by 3 Ma, the time of orogeny in Timor. From 3 Ma to the Present, Hall (2002) shows movement of the Birds Head and expansion of the Banda Sea producing compression and shortening in Seram.

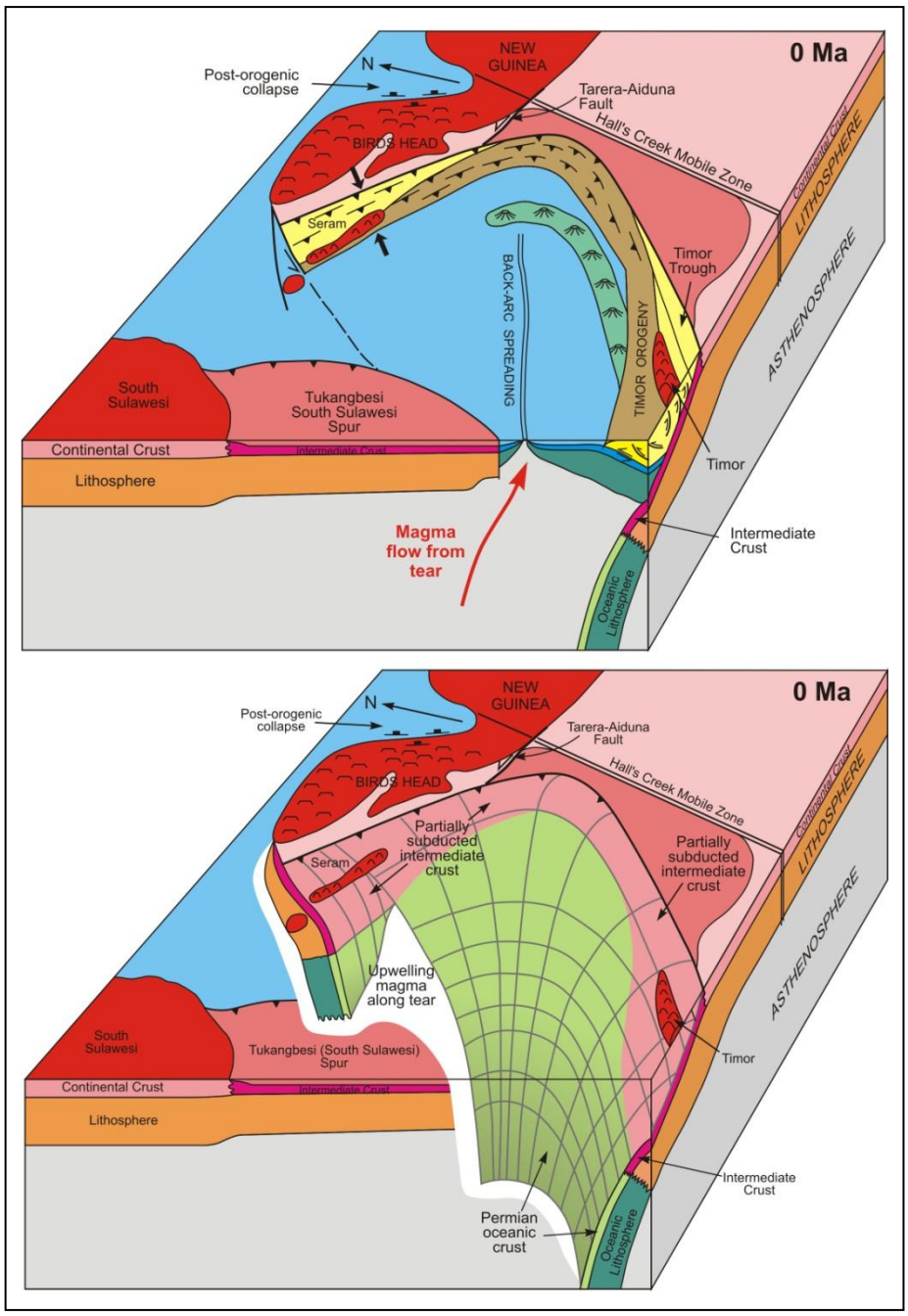


Figure 3. 3D visualisation of the present tectonic setting of the Banda Arc, firstly with the overriding plate and then with the overriding plate removed to reveal the subducting slab.

OBSERVATIONS

A crucial observation to be tied into the Hall (2002) model is that the overthrust sediments in Seram comprise a thick Triassic sequence, mostly deposited in deep water (Kemp & Mogg 1992). It is here inferred that this deep water Triassic section was thrust over Seram around 6-4 Ma when the oceanic crust to the south was subducted.

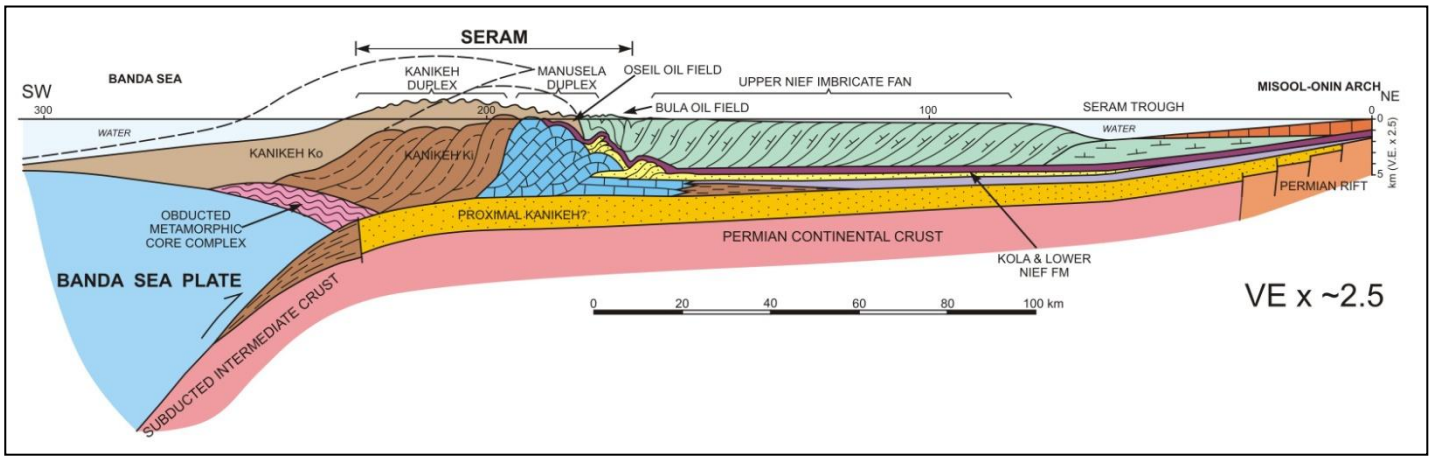


Figure 4. Schematic regional cross-section across Seram, with a vertical exaggeration of x ~2.5. See Figure 1 for location.

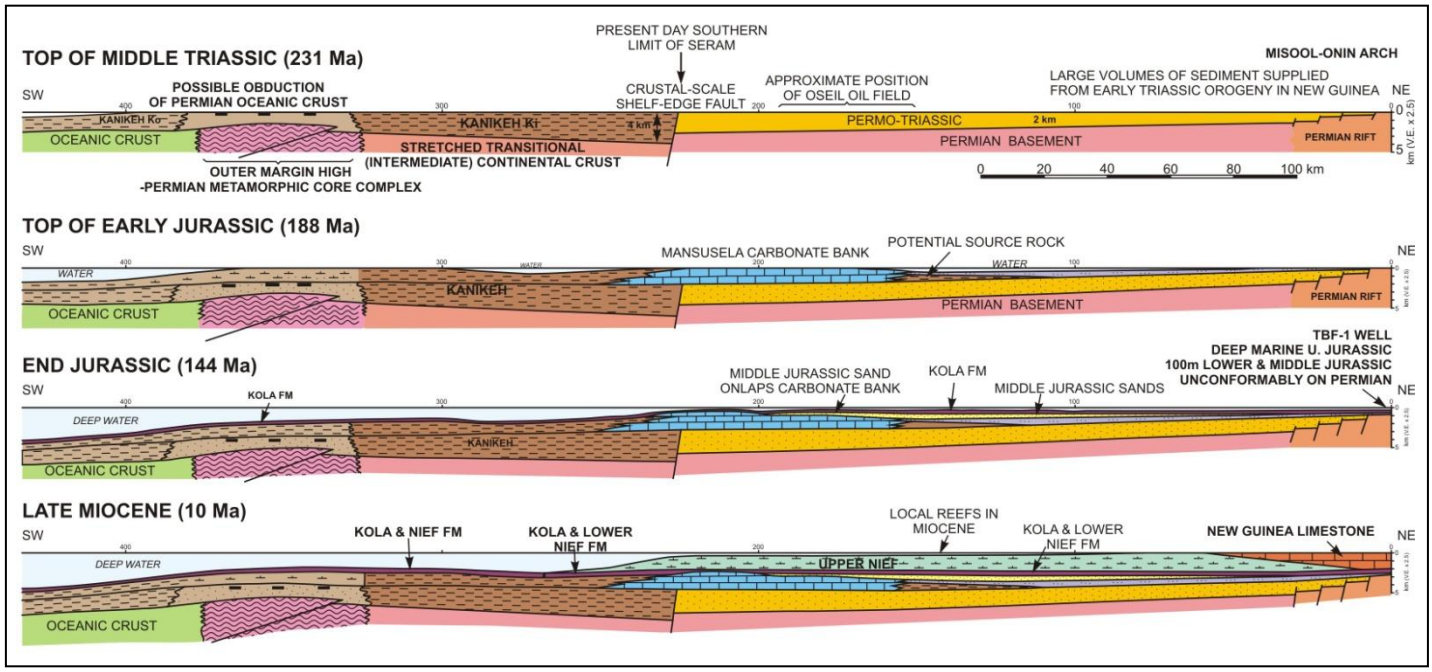


Figure 5. Schematic cross sections of the Triassic to Miocene evolution of the Seram margin (VE x 2.5).

This is consistent with the 6-5 Ma cooling age on the Seram Ultramafic complex in SW Seram (Linthout et al. 1996). Further, we suggest that the Triassic section was scraped off the downgoing slab as an accretionary prism and emplaced onto the adjacent margin. Importantly, this implies that the underlying oceanic crust was Permian or older. Snyder et al (1996) show subsea contours in depth on the downgoing oceanic plate south of Seram, based on earthquake seismology. It is clear that the slab is broken to the south of western Seram, consistent with the strike-slip margin. Projecting the slab upwards towards eastern Seram it meets the island at the present south coast (Figure 3).

Other important observations include:

1. The offshore Seram seismic data to the north of east Seram show multiple thrust repeats of Tertiary to Recent sediments (Pairault et al 2003a/b) indicating >50 km shortening. This observation is crucial to the structural interpretation as it indicates thin-skinned deformation and a large amount of shortening.
2. The geological map of NE Seram shows a 3D 'window' of Triassic outcrop in the Nief sediments consistent with an underlying antiformal stack.
3. The Triassic to Early Jurassic Kanikeh sediments were regionally thrust over the deep water Nief beds in the earliest Pliocene (e.g. Kemp & Mogg 1992). This most likely occurred as an accretionary prism in deep water, similar to the Liguride sequences in northern Italy (e.g. Hill & Hayward 1987).
4. Effective basement in the Seram area is Permian. Along the Misool-Onin Arch, a thin Jurassic sequence overlies the Permian Ainim sedimentary section. To the southwest, a thick Triassic section is preserved, suggesting Permian rifting.
5. Contours on the downgoing slab beneath the Banda Arc indicate that it projects up to the southern end of Seram Island. This is interpreted to show that the southern end of Seram Island was a long-term crustal and/or lithospheric boundary with stronger, thicker and more buoyant continental crust to the north.
6. Regional structural restoration of the duplex in Late Triassic to Mid

Jurassic Manusela beds indicates that prior to compression the southern limit of the Manusela coincided with the southern margin of the island. There it passed into thick Triassic Kanikeh beds, suggesting a major crustal scale normal fault along what is now Seram's southern margin.

Between the axis of the Seram Trough and the northern coast of Seram an imbricate stack of Paleogene and Neogene Upper Nief beds is interpreted. In some places the imbricate Upper Nief Beds have been cut by late stage normal faults, creating local basins above it in which Pleistocene Fufa Beds were deposited.

These faults probably sole into the same regional detachment and contribute to toe-thrusts in the Seram Trough (Pairault et al 2003a/b). The late stage normal faults are not illustrated on the regional section, in order to clearly illustrate the inferred compressional tectonics. The regional detachment is interpreted to lie within

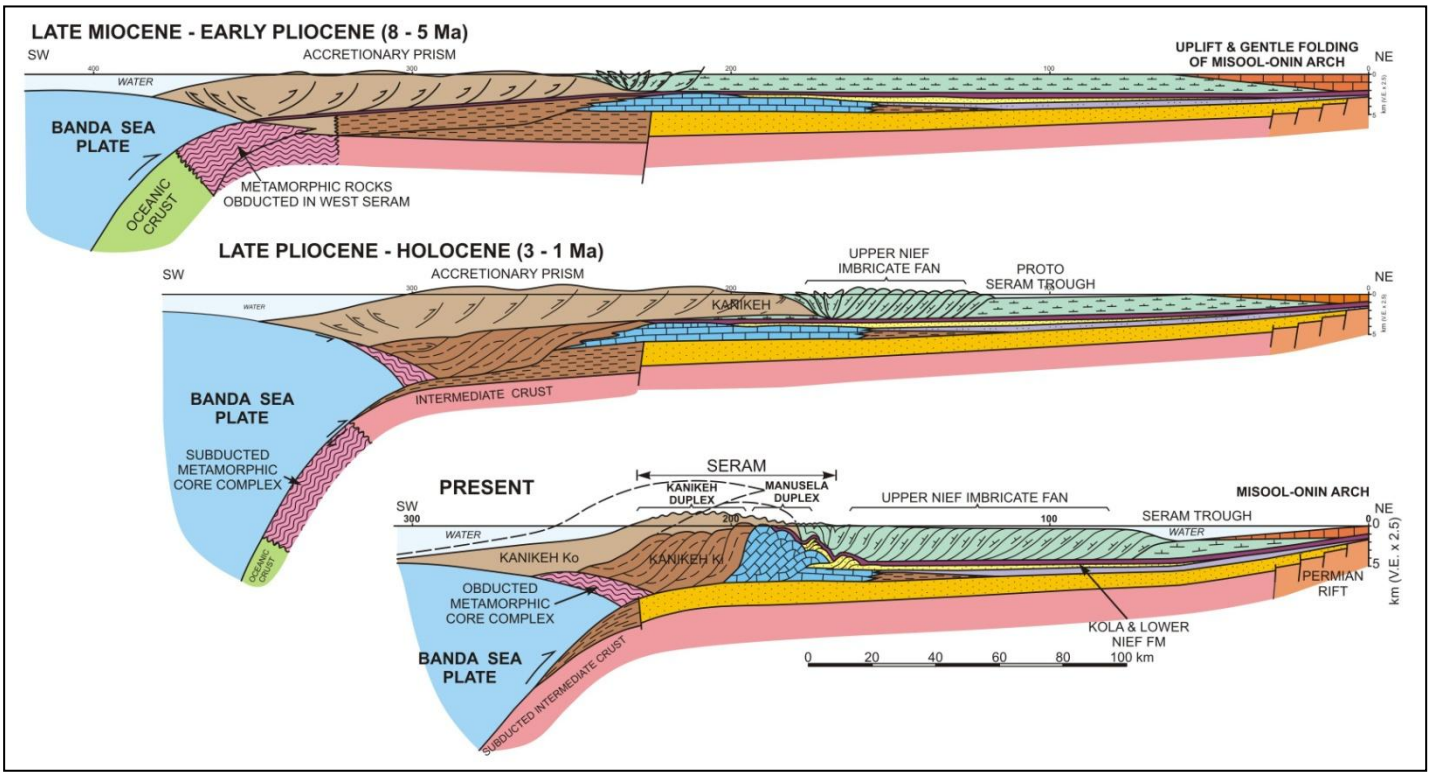


Figure 6. Schematic cross sections of the Late Miocene to Present evolution of the Seram margin (VE x 2.5)

REGIONAL CROSS SECTION

The section trends 040-220^{O}, from the Misool-Onin arch in the northeast to the subducted crust southwest of the island of Seram (Figure 4). The NE end of the section shows the Misool-Onin High, which was uplifted and eroded in the Late Miocene (e.g. Pairault et al 2003a/b). This area is interpreted to lie on continental crust of 'normal' thickness. The morphology of the High and the regional dip into the Seram Trough are constrained by the seismic sections published by Pairault et al (2003a/b). The thin Pleistocene sediments in the Seram Trough have been mildly folded and thrust (Pairault et al 2003a/b) as the deformation continues to the present day, although this detail is not shown on the regional section.

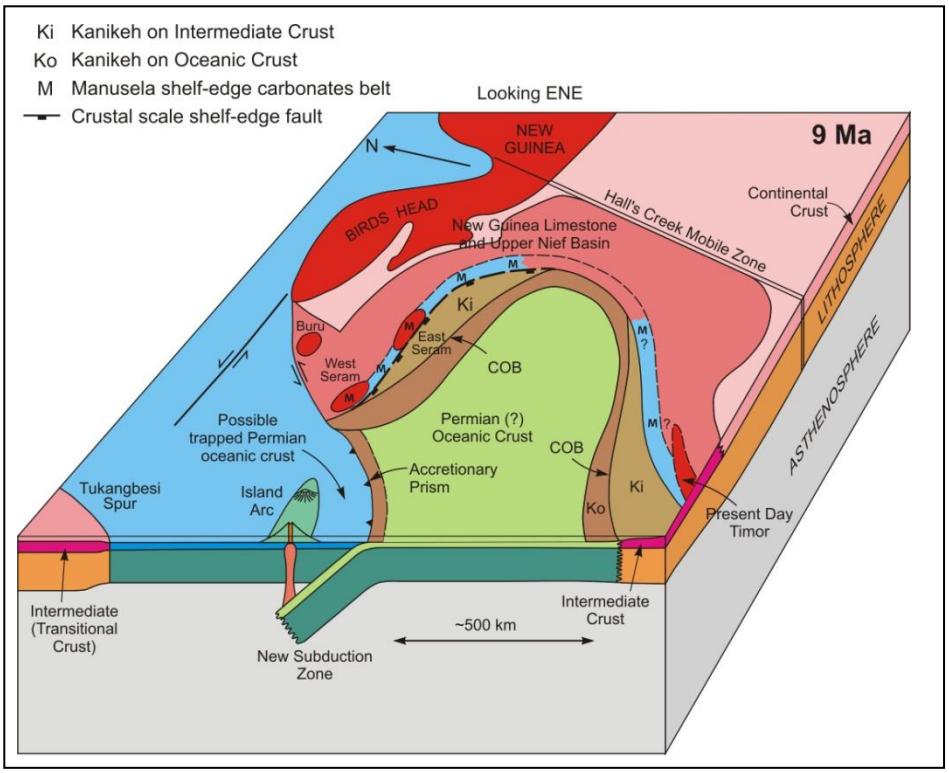


Figure 7. 3D visualisation of the inferred tectonic setting of the Banda Arc at 9 Ma.

the Jurassic and Cretaceous Kola and Lower Nief beds, thin regional deep-water deposits (Figure 4).

Beneath the northern part of the island of Seram lies the Manusela duplex. The East Nief well clearly show that the Manusela Limestone is overlain by conformable Late Jurassic Kola Shale and Cretaceous Lower Nief beds and then a few hundred metres thick imbricate zone of mixed Upper Nief and Triassic Kanikeh Beds (Kemp & Mogg 1992). This is all overlain by a thick sequence of deformed Triassic Kanikeh beds, usually deep-water deposits, but reported to contain some thin coals. The Triassic Kanikeh Beds are here interpreted to have been thrust over the Manusela carbonates when the latter were flat, resulting in some of the Upper Nief beds being incorporated into the regional thrust zone to make the 'imbricate zone'. Subsequently the Manusela duplex developed beneath, with the 'imbricate zone' as a roof-thrust.

The SW limit of the Manusela duplex corresponds to a facies change to time-equivalent Kanikeh beds. The deformation shown in the Kanikeh beds on the cross-section is highly stylolised as it is very complex and poorly constrained by sparse dip data and no seismic data. Many other interpretations are possible, including involving basement thrusts and/or ophiolites. The interpretation shown here is simply a model based on the assumption that thick Kanikeh (Ki) beds were originally deposited on thinned continental (intermediate) crust and thinner Kanikeh (Ko) beds were deposited on Permian oceanic crust.

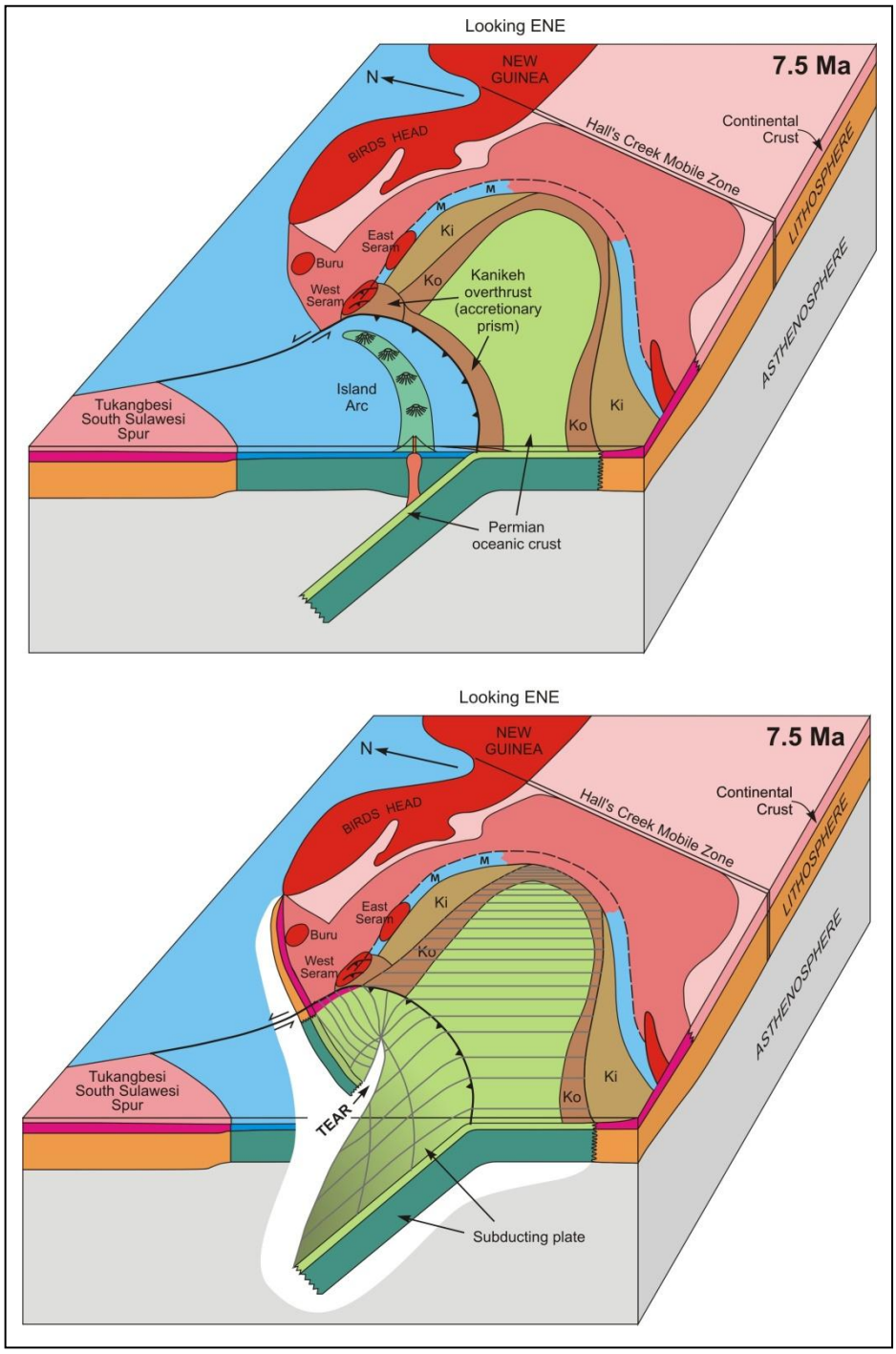


Figure 8. 3D visualisation of the inferred tectonic setting of the Banda Arc at 7.5 Ma, firstly with the overriding plate and then with the overriding plate removed to reveal the subducting slab.

TECTONIC MODEL

The tectonic model presented here is illustrated by regional schematic structural sections shown at ~2.5:1 V.E. (Figures 5 and 6) and by a series of block diagrams illustrating the Late Miocene to Pliocene evolution of the Banda Sea (Figures 7-12), following the model of Hall (2002).

Permian

Rifting occurred in the area that is now the Banda Sea, probably by NE movement of the Bird's Head along the long-lived Hall's Creek Mobile Belt, possibly associated with clockwise rotation of the Bird's Head (Norvick 2003a/b, Metcalfe 1996, 2002 Charlton 2001). This is interpreted to have led to the formation of ?Middle to Late Permian oceanic crust in the Banda Sea area. A major SW-dipping normal fault was generated along the southern margin of the Misool-Onin High, allowing subsequent deposition of Triassic and Jurassic sediments to the southwest, with no Triassic and little Jurassic on the High (e.g. TBF-1 well; Perkins & Livsey 1993). A second SW-dipping, crustal-scale normal fault was generated in the area of what is now the southern margin of Seram with thinned continental crust to the south allowing deposition of very thick Triassic and Jurassic sediments to the southwest. Prior to the formation of oceanic crust even further to the south, Permian metamorphic core complexes may have been emplaced, probably in shallow water or emergent. At this

stage the margin was similar to those along strike to the southwest in the Browse Basin.

Triassic

The major event in the Triassic was the orogeny along the New Guinea margin continuing into the New England orogeny down the east coast of Australia (Hill & Hall 2003). Triassic orogenesis in New Guinea was probably similar to that in the Late Miocene to Pliocene that is apparent today. Regional compression and mountain building took place in the Early Triassic followed by granitic intrusions in the Middle Triassic and extensional collapse in the Late Triassic.

Triassic orogenesis placed the Banda Sea area into compression, inhibiting further subsidence and possibly causing partial obduction of Permian oceanic crust and local inversion. However, the main effect was a massive influx of Triassic detritus from the mountains in New Guinea, filling the basins with Triassic 'Kanikeh' sediments, mainly regional turbidites (Figure 5). It is probable that a considerable portion of the detritus entered the basin from the east along the axis of the Banda Sea.

Extensional collapse in New Guinea in the Late Triassic gradually reduced the sedimentary supply and promoted regional subsidence in the Banda Sea area. The area that is now Seram, and its equivalents along strike to the WNW-ESE, became a shelf-edge high that was remote from clastic sedimentation, resulting in the development of a 'Manusela' carbonate bank 40-50 km wide (Figure 5) and perhaps hundreds of km long. It is probable that several of these large carbonate banks were deposited along the shelf margin rimming the Banda Sea, such as the Bogal Limestone in Misool (Norvick 2003a/b). As the margin strikes east-west, it was possible to have carbonate banks, like Andross Island, over 1000's of km in the same climatic zone (for instance the Triassic Kuta Limestone was deposited coevally 1000 km to the east in Papua New Guinea). These banks may have been separated by lower areas through which clastic sediments were supplied to the deeper water offshore. There, deposition of 'Kanikeh' clastic detritus continued, sourced both from the east and through the gaps between carbonate banks.

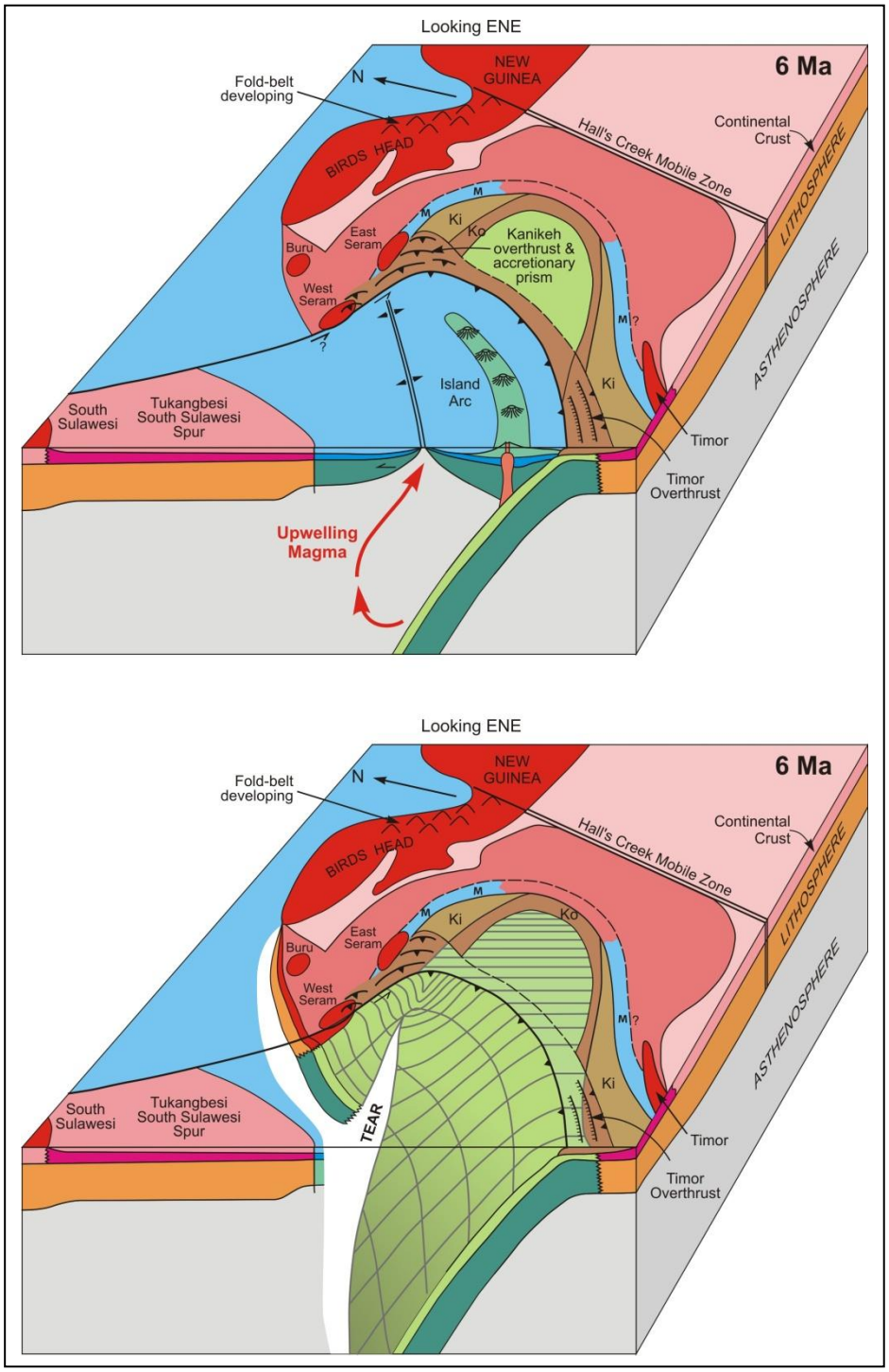


Figure 9. 3D visualisation of the inferred tectonic setting of the Banda Arc at 6 Ma, firstly with the overriding plate and then with the overriding plate removed to reveal the subducting slab.

Jurassic

Along Australia's NW Shelf and in New Guinea, Early Jurassic rifting led to Middle Jurassic (Callovian) break-up and Late Jurassic regional subsidence. The regional subsidence is clearly reflected in the sedimentary record in Seram, although it may have commenced earlier in the Jurassic. Carbonate deposition continued in the Early and Middle Jurassic in the area of Seram and along strike, adjacent to starved basins allowing deposition of excellent oil source rocks in the Saman Saman Formation (Figure 5). To the southwest, clastic deposition continued in the Early Jurassic, sourced from the east, but gradually dwindled due to continued subsidence and flooding, again facilitating deposition of source rocks.

In the Middle Jurassic, it is proposed that sands were shed from the emergent Bird's Head basement and were deposited in a rim around the Kemum High (e.g. Hill et al. 2002). These sands were also deposited in the northern Bintuni Basin forming the reservoir for the giant Tangguh Complex gas fields. It is interpreted that such sands prograded across the shallow water basin between the Misool-Onin High and the Manusela carbonate bank. These regional sands were deposited over the southern margin of the carbonate bank, inhibiting its development. At this time the Manusela carbonate bank remained high and may have undergone karstification during times of sea level low.

In the Late Jurassic, the entire margin underwent regional subsidence, drowning the carbonate bank and starving the area of sediments throughout the Late Jurassic and the Cretaceous, allowing deposition of a condensed sequence of Kola Shale and Lower Nief Beds (Figure 5).

Cretaceous

The Seram and Banda Sea area was in deep water throughout the Cretaceous and starved of sediment. The area between the Misool-Onin High and southern Seram was probably in a few hundred metres of water, but the thinned continental crust to the south subsided to water depths of a few kms and the Permian oceanic crust probably subsided to depths of ~5 kms. Lower Nief deep-water limestone and chert condensed sequences were deposited regionally.

Paleogene

In the latest Cretaceous to Paleogene, eastern and possibly northern New Guinea, including part of the Bird's Head, were uplifted due to rifting (Hill & Hall 2003). Western New Guinea underwent continued subsidence allowing deposition of the New Guinea Limestone mainly in very shallow water, but with deep-water limestones and shales on the deeper part of the shelf. Thick New Guinea Limestone was deposited on the Misool-Onin Arch, which became a regional depocentre, although always in shallow water. The high carbonate productivity, combined with shale derived from the Paleocene uplift, allowed deposition of deep-water to shelfal carbonate and shale (Upper Nief Beds) along the Seram margin between the Misool-Onin High and the southern limit of Seram (Figure 5).

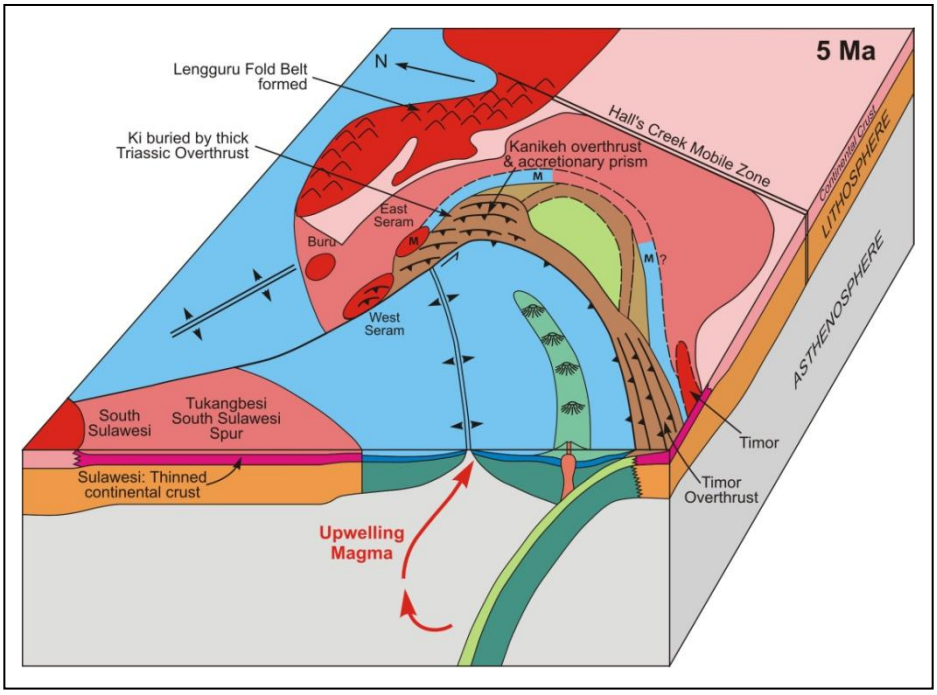


Figure 10. 3D visualisation of the inferred tectonic setting of the Banda Arc at 5 Ma.

Miocene

Carbonate productivity and regional deposition of New Guinea Limestone accelerated along the entire northern margin of the Australian Plate, producing prograding thick shallow water reefs and shelf carbonates from Queensland through New Guinea and along Australia's Northwest Shelf. In the Seram area this resulted in thick Openta and Kais Limestone on the Misool-Onin 'High' that prograded south into the basin towards Seram depositing the Upper Nief Beds as shelfal carbonates. Water depths decreased in the Seram area as thick Upper Nief beds were deposited across a basin up to 150 km wide. Locally, water depths reached the photic zone allowing deposition of reefal carbonates similar to the Kais Limestone in the Salawati Basin. (Figure 5). These may have been located above sites of local inversion associated with the onset of compression in New Guinea towards the end of the Middle Miocene (14-12 Ma), continuing through the Late Miocene. Kais reefs may be anticipated above the Manusela shelf edge as a long-lived structural high. These would now lie in the Upper Nief Imbricates along the north coast of Seram.

Late Miocene to Present

The compressional deformation of the Banda Arc, focussed on Seram, is shown on a series of block diagrams (Figures 3 and 7-12) and on schematic sections trending to 040^0 that passes through the Oseil-1 well in Seram (Figure 6).

9 Ma (Figure 7)

Fold and thrust deformation in the Fold Belt had just commenced in mainland New Guinea, but had not yet affected the Seram area, except perhaps for local inversion. The subduction zone beneath the Indonesian archipelago had reached the tip of the Bird's Head microcontinent and the subduction zone jumped southward (Hall 2002) to the limit of old, cold and dense Permian oceanic crust that was more dense that the underlying mantle and therefore ready to sink. The oceanic crust captured in the overriding plate may have been Permian in age. It became a forearc and now lies beneath the Weber Deep.

At this time the Banda Sea comprised four main zones arranged in a

horseshoe around the sea (Figure 7). In the middle was Permian oceanic crust overlain by a relatively thin sequence of Triassic to Miocene pelagic sediments. Around this was a belt of Kanikeh (Ko) shallow to deep-water sediments and Jurassic to Miocene pelagic sediments overlying Permian oceanic crust, ringed by the Continent-Ocean-Boundary (COB). The next belt comprised thick Kanikeh (Ki) sediments and thin Jurassic to Miocene deep-water sediments, in moderate water depths, overlying thinned and stretched (intermediate) continental crust. This zone is interpreted to have been bound by a fundamental crustal boundary from thin to thicker continental crust marked by major normal faults and a long-lived shelf-edge, coincident with the southern limit of Seram. The shelf edge was marked by thick Manusela carbonates on regional highs or horsts and a thick Upper Nief sequence in relatively shallow water (Figure 6). At this time, West and East Seram may have been separate (Hall 2002) at least within the cover sequences.

7.5 Ma (Figure 8)

The old, cold and dense Permian oceanic crust had started sinking of its own accord pulling the subduction zone into the Banda Sea area in an arcuate shape. As the overriding plate moved towards the east the Tukangbesi (South Sulawesi) Spur of thin continental crust moved with it (Hall 2002). As the oceanic crust was subducted beneath the overriding plate adjacent to the Seram margin, the Kanikeh (Ko) beds were scraped off to form a very wide and thick accretionary prism. Along the Seram margin, motion of the overriding plate relative to the subducting plate was of a left-lateral strike-slip nature (Figure 8). Compressional thrusting within the accretionary prism along this strike-slip zone was oblique to the wrenching, with faults striking ~ 330-350^0. The accretionary prism was thrust over the relatively deep-water Kanikeh (Ki) sediments overlying thinned continental crust. As the down-going Permian oceanic slab was subducted in a horseshoe shape it was stretched with increasing depth and a tear formed along the axis close to the Seram margin (Figure 8).

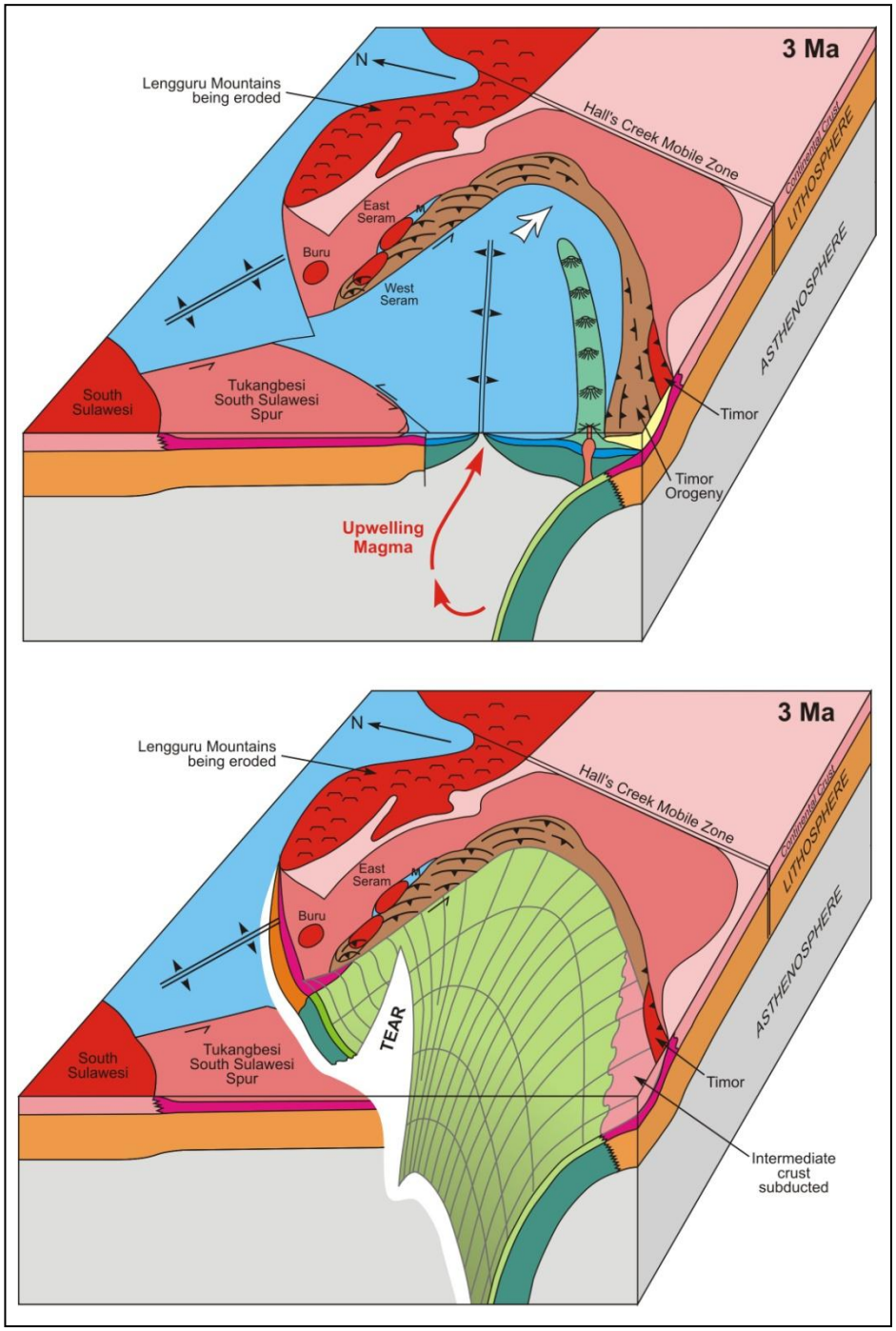


Figure 11. 3D visualisation of the inferred tectonic setting of the Banda Arc at 3 Ma, firstly with the overriding plate and then with the overriding plate removed to reveal the subducting slab.

At this time compressional deformation continued in the northeastern Lengguru Fold Belt, and minor compressional deformation and regional inversion and erosion occurred on the Misool-Onin High.

6 Ma (Figure 9).

Subduction of the Permian oceanic crust continued along a curved subduction zone that advanced across the Banda Sea. The tear in the downgoing slab propagated to the east and widened. This allowed upwelling of underlying magma, creating a spreading ridge behind the volcanic arc, which developed a back-arc basin (Figure 9). The northeast end of this buoyant spreading ridge migrated east along the Seram margin subjecting the margin to sinistral transpressional forces.

By 6 Ma, the eastward verging accretionary prism ahead of the subduction zone had been thrust over the thick Kanikeh sequence lying on thinned continental crust immediately south of eastern Seram. This involved relative shortening of up to 100 km

and is similar to the overthrusting of the Liguride accretionary prism in the Late Miocene to Pliocene in the Apennines, Italy (e.g. Hill & Hayward, 1987). As the thick Kanikeh sequence had previously been in deep water, it is likely that the overthrust accretionary prism remained below sea level or just emergent (Figure 6). It is unlikely that a significant thickness of Kanikeh was thrust up the shelf-edge and over the Manusela carbonates at this time.

To the south, the subduction zone had reached the outer limits of the Timor margin generating a thick and wide accretionary prism that had started to thrust over the extended continental margin. If the model of Keep et al (2003) is correct the Timor collision may have started earlier due to the subduction zone reaching a large promontory to the west of Timor incorporating the island of Sumba, which was uplifted at ~8 Ma.

5 Ma (Figure 10).

The same processes continued from 6 to 5 Ma, but the subduction zone swept past the southern margin of eastern Seram and the spreading ridge was directly offshore from eastern Seram, maintaining a transpressional ENE to NE-directed stress. West Seram started moving sinistrally to join east Seram according to Hall (2002). To the south the accretionary prism had been thrust over Timor and true arc-continent collision commenced (Figure 10). In the Bird's Head the Lengguru Fold Belt had formed with mountains at least 1 km higher than today.

3 Ma (Figure 11).

By the Late Pliocene almost all of the Permian oceanic crust in the Banda Sea had been subducted and the Timor orogeny was well underway, locking up subduction to the south. Compression in the Lengguru fold belt was waning and it was being eroded. The entire rim of the Banda Sea was placed into compression, more or less radially around the arc. This was probably the start of compression within continental crust in Seram, probably towards 035^0, resulting in structures striking to ~305^0. West and East Seram had joined and compression occurred within the thick Kanikeh sequence overlying thinned continental crust to the south of the main shelf-edge fault (the southern margin of Seram). From 3 to ~1 Ma, the Kanikeh sequence was shortened as a duplex and the overlying Kanikeh accretionary prism was thrust to the NE over the Manusela sequence on the shelf. The accretionary prism acted as a bulldozer pushing and deforming the Upper Nief sequence in front of it, initially without deforming the strong, underlying Manusela carbonates. An imbricate fault zone formed, of varying thickness, incorporating underlying Upper Nief beds and overlying Kanikeh accretionary prism beds. During this thrusting, the Manusela carbonates were probably buried to depths of several km for the first time (Figure 6). In the Late Pliocene the Kanikeh accretionary prism was eroded supplying sediment to the uppermost Nief Beds for the first time.

The tear in the downgoing oceanic slab widened and propagated towards east Seram. This allowed yet more upwelling of buoyant magma and backarc spreading, perhaps also driving compression around the periphery of the Banda Arc. Propagation of the tear towards the east end of Seram means that strike-slip motion was facilitated along the tear, allowing varying deformation in Seram compared to the area to the southeast, e.g. more compression in Seram.

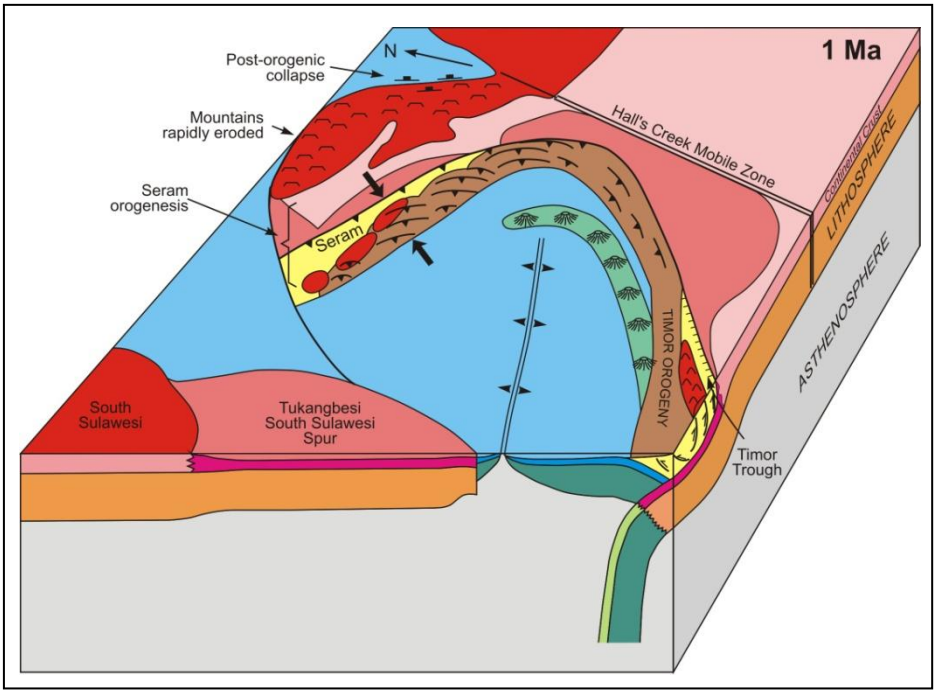


Figure 12. 3D visualisation of the inferred tectonic setting of the Banda Arc at 1 Ma.

1 Ma (Figure 12)

Around 2 Ma, extensional collapse commenced in the northeastern Lengguru Mountains indicating the removal of compressional forces along the NE margin of the Birds Head. To the south, the compressional orogeny in Timor dwindled and renewed subduction commenced towards the southwest. Compression continued from the direction of the Banda Sea towards the northeast due to the locking up of subduction and continued spreading associated with steepening of the subduction zone and widening of the tear within it. Hall (2002) infers that the Birds Head moved ~100 km to the NE along the Hall's Creek Mobile Zone. From 1 Ma to the Present compression increased along the northern margin of the Banda Sea, perhaps associated with movement back to the southeast of the Birds Head (Hall 2002) and due to sinistral movement along the Tarera-Aiduna Fault Zone.

The intensified compression occurred towards 040^0, resulting in structures striking 130-310^0 in Seram and cross-cutting (tear) faults striking 040-220^0. This compression was manifested in a duplex in the Manusela carbonates with a roof thrust at the base of the overlying Kanikeh accretionary prism sequence, passing northeast into the base of the Upper Nief sequence. Consequently, there was simultaneous

thrusting of the Manusela carbonates and the Upper Nief sequence to the northeast, within the Seram Trough. Compression was particularly focussed in the Oseil area forming a highly fractured antiformal stack in the Manusela carbonates. The location of this may be related to the offshore tear in the subducting slab and/or to an extra wide sequence of Manusela carbonates. During formation of the Manusela duplex, the adjacent oil source rocks were deeply buried for the first time and generated and expelled hydrocarbons, which continues to the Present.

0 Ma – Present Day (Figure 3)
The compressional regime present at 1 Ma continued with thrusting towards 040^{0}. The thrusted Manusela and Upper Nief beds placed a considerable load on the margin of the Birds Head micro-continent causing it to subside, creating the Seram Trough. The bottom of the trough is the front of the fold and thrust belt within the Upper Nief sequence. The relief between the shoreline and the bottom of the Trough has allowed minor extensional collapse within the Upper Nief thrust sequence resulting in some Recent toe-thrusts.

DISCUSSION

The tectonic model and cross sections that have been presented indicate that the Seram margin has been subjected to over 100 km of shortening with overall shortening of the order of 50%. As the section is roughly perpendicular to the margin and the compression is inferred to have been highly oblique (sinistral transpression) the true shortening may be considerably greater. Much of the shortening is inferred to have been taken up by overthrusting of the accretionary prism, but there was also substantial shortening of the continental margin sediments, as indicated by the antiformal stack in the Manusela Beds and the thrusting of the Upper Nief beds to the northeast of Seram.

In the Oseil and East Nief area, the Manusela carbonate reservoir porosity dominantly occurs in fractures. The structural-tectonic model indicates two different directions of thrusting, which will have a bearing on the orientation of fractures within the Manusela carbonates. The Early Pliocene thrusting was towards 070^{O}+/-10^{O} and open fractures at that time are likely to have been parallel to this direction. Late Pliocene to Present thrusting was towards 040^{O} including in the Manusela carbonates, and open fractures are likely to be parallel in the same orientation. However, a full evaluation of the stress field through time is needed to predict the full range, intensity and width of fractures.

The Oseil and Bula oilfields, and the prolific seeps along Nief Gorge, which trends 040^{O}, demonstrate the Late Triassic to Early Jurassic source system. The structural model suggests rapid Pleistocene burial and heating by overthrusting, so that the system is active today. In terms of hydrocarbons, it is possible that there are more Manusela carbonate plays, but there may also be reef plays in the Upper Nief duplexes and structural-stratigraphic traps in the inferred Middle Jurassic sandstone reservoir.

Comparing Seram to Timor, whilst there are broad tectonic similarities due to their positions around the Banda Arc, there are structural and stratigraphic differences. As Seram lay along the northern margin of the proto-Banda Sea, it is likely that it received more Triassic sediment than the Timor margin due to Early to Mid Triassic uplift and erosion in New Guinea. In the model presented here, this would have led to a large accretionary prism to overthrust Seram, but less so for Timor. In addition, the collision in Seram was highly oblique, whilst that in Timor was more orthogonal. This may have caused more fracturing in Seram, but potential carbonate plays in Timor may have been less buried.

A clear problem with all the models and hypotheses presented above is the general paucity of data in the Banda Arc region with which to test the ideas. Hopefully, ongoing exploration will help to rectify this.

ACKNOWLEDGEMENTS

This study was supported by Kufpec Indonesia Limited, with particular thanks to Al Stawicki, Rob Barraclough and Nara Nilandaroe. The work was carried out as part of the former 3d-geo partnership. Prof Robert Hall is thanked for supplying maps from his regional tectonic reconstructions that could be edited to accommodate new data. Whilst this work was carried out in collaboration with Kufpec, the views expressed here are solely those of the author.

REFERENCES

Charlton, T.R., 2001a. Permo-Triassic evolution of Gondwanan eastern Indonesia, and the final Mesozoic separation of SE Asia from Australia. J. Asian Earth Sciences, 19 (5), 595-617.

Hall R. 2002. Cenozoic geological and plate tectonic evolution of SE Asia and the SW Pacific: computer-based reconstructions, model and animations. J. Asian Earth Sciences 20, 353-434.

Hill K.C. & Hall R. 2003. Mesozoic-Tertiary Evolution of Australia's New Guinea Margin in a West Pacific Context. In Hillis R.R. & Muller R.D. (eds) *Evolution and Dynamics of the Australian Plate*. pp. 265-290. Geological Society of Australia Special Publication **22** and Geological Society of America Special paper **372**.

Hill K.C. & Hayward A.B. 1987. Structural constraints on the Plate Tectonic evolution of Italy. Marine and Petroleum Geology. *Marine and Petroleum Geology* **5**, 2-16.

Hill K.C. & Hoffman N. 2004. Restoration of a deepwater profile from the Browse Basin: implications for structural-stratigraphic evolution. Abstract, Australian Geological Congress, Hobart, Feb 2004.

Hill K.C., Hoffman N., Lunt P. & Paul R. 2002. Structure and Hydrocarbons in the Sareba block, "Bird's Neck", West Papua. Proceedings of the Indonesian Petroleum Association. P. 227-249.

Hoffman N. & Hill K.C., 2004. Structural-stratigraphic evolution and hydrocarbon prospectivity of

the deep-water Browse Basin, North West Shelf, Australia. In Ellis G.K., Baillie P.W. & Munson T.J. (ed), Timor Sea Petroleum Geoscience. Proceedings of the Timor Sea Symposium, Darwin, Northern Territory, 19-20 June 2003, p. 393-409.

Keep M., Longley I. & Jones R. 2003. Sumba and its effect on Australia's northwestern margin. In Hillis R.R. & Muller R.D. (eds) *Evolution and Dynamics of the Australian Plate*. pp. 309-318. Geological Society of Australia Special Publication **22** and Geological Society of America Special paper **372**.

Kemp G. & Mogg W. 1992. A re-appraisal of the geology, tectonics and prospectivity of Seram Island, Eastern Indonesia. Proceedings of the 21st IPA Convention, p. 521-552.

Kendrick R.D. & Hill K.C. 2002. Hydrocarbon play concepts for the Irian Jaya Fold Belt. Proceedings of the Indonesian Petroleum Association. P. 353-368.

Kendrick R.D., Hill K.C., McFall S.W., Meizarwin, Duncan A., Syafron E., & Harahap B.H., 2003. The East Arguni Block: Hydrocarbon prospectivity in the Northern Lengguru Foldbelt, West Papua. Proceedings of the Indonesian Petroleum Association. P. 467-484.

Kendrick R.D., Hill K.C., O'Sullivan P.B., Lumbanbatu K., & Saefudin I., 1997. Mesozoic to Recent thermal history and basement tectonics of the Irian Jaya Fold Belt and Arafura Platform, Irian Jaya, Indonesia. In, *Petroleum Systems of S.E. Asia and Australasia*. IPA conference, Jakarta, May 1997, p. 301-306.

Kendrick, R.D., Hill, K.C., Parris, K., Saefudin, I., and O'Sullivan, P.B., 1995. Timing and style of Neogene regional deformation in the Irian Jaya Fold Belt, Indonesia Proceedings 24th Annual Convention, Indonesian Petroleum Association, Jakarta, 1995 p. 249-262.

Linthout K, Helmers Henk, Wijbrans J.R. & Van Wees J.D.A.M., 1996. 40Ar/39Ar constraints on obduction of the Seram ultramafic complex: consequences for the evolution of the southern Banda Sea in Hall R. (ed) *Tectonic Evolution of SE Asia*. Geological Society of London Special Publication No. 106, 455-464.

Metcalfe, I., 1996. Pre-Cretaceous evolution of SE Asian terranes. In: Hall, R., & Blundell, D., (Eds). Tectonic evolution of southeast Asia. Geol. Soc. London Spec. Pub., 106, 97-122.

Metcalfe, I., 2002. Permian tectonic framework and palaeogeography of SE Asia. J. Asian Earth Sciences, 20, 551-566.

Norvick M.S., 2003a. Chronostratigraphic Sections of The Northern Margins of The Australian Plate, unpublished.

Norvick M.S., 2003b. Palaeogeographic Maps of The Northern Margins of The Australian Plate, unpublished.

Pairault A.A., Hall R., Elders C.F., 2003a. Structural styles and tectonic evolution of the Seram Trough, Indonesia. Marine and Petroleum Geology, 20, 1141-1160.

Pairault A.A., Hall R., Elders C.F., 2003b. Tectonic evolution of the Seram Trough, Indonesia. Proceedings of the 29th IPA Convention. P. 355-370.

Perkins T.W. & Livsey A.R. 1993. Geology of the Jurassic gas discoveries in Bintuni Bay, western Irian Jaya; Proceedings 22nd IPA convention, p. 229-261.

Sayers, J., Symonds, P.A., Direen, N.G. & Bernadel, G., 2001. Nature of the continent-ocean transition on the non-volcanic rifted margin of the central Great Australian Bight. In Wilson, R.C.L., Whitmarsh, R.B., Taylor, B. & Froitzheim, N. (Eds) *Non-volcanic rifting of continental margins: a comparison of evidence from land and sea. Geological Society of London Special Publication* 187, 51-76.

Snyder D.B., Milsom J. & Prasetyo H., 1996. Geophyscial evidence for local indentor tectonics in the Banda arc east of Timor, in Hall R. (ed) *Tectonic Evolution of SE Asia*. Geological Society of London Special Publication No. 106, 61-73.

Struckmeyer H.I.M., Blevin J.E., Sayers J., Totterdell J.M., Baxter K. & Cathro D.L. 1998. Structural evolution of the Browse Basin, North West Shelf: new concepts from deep-seismic data. In Purcell P.G. & R.R. (eds) The Sedimentary Basins of Western Australia 2: Proceedings of Petroleum Exploration Society of Australia Symposium, Perth, WA, 1998. p. 345-368.