Berita Sedimentologi

Indonesian Journal of Sedimentary Geology

Number 23
03/2012

ISBN 0853-9413

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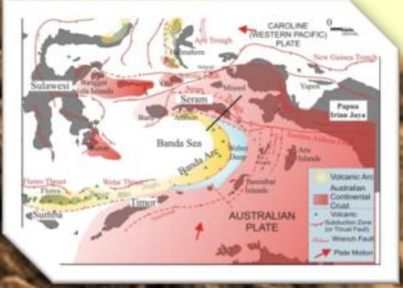

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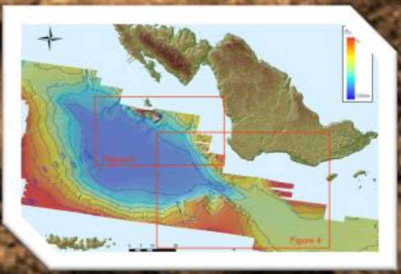

HALMAHERA, SERAM & BANDA

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

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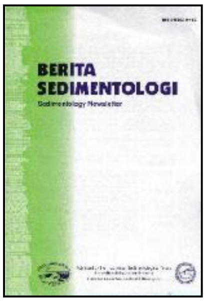
Cover Photograph:

Bedded Cordierite-Bearing Dacites (Ambonites), Ambon Island.

Taken from Watkinson et. al. (BS#23, page 21)

Berita Sedimentologi
Indonesian Journal of Sedimentary Geology

- Published 3 times a year in March, July and November by the **Indonesian Sedimentologists Forum** (Forum Sedimentologiwan Indonesia, **FOSI**), a commission of the **Indonesian Association of Geologists** (Ikatan Ahli Geologi Indonesia, **IAGI**).
- Cover topics related to sedimentary geology, including their depositional processes, deformation, minerals, basin fill, etc.



Berita Sedimentologi

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

From the Editor

Berita Sedimentologi No. 23/2012 will cover Halmahera, Seram, Banda Arc and the northern portion of western Papua. The far eastern part of Indonesia has had more research activities recently due to the involvement of both Indonesian and foreign researchers; and also contributions from the oil and gas industry, who acquired exploration acreages offered by the government of Indonesia through several licensing rounds a few years ago.

The March edition of BS contains three articles on the Banda Arc and Seram Sea region and two articles on the northern part of western Papua. Kevin Hill will discuss the tectonic and regional structures of the Seram and Banda Arc, while Herman Darman and Paul Reemst wrote their observations on seismic expression of the geological features in the Seram Sea. The third article on Banda Arc is written by Awang Satyana, where he discusses the origin of the Banda Sea.

On western Papua, Claudia Bertoni and Juan Álvarez will discuss the interplay between tectonic activity and submarine depositional processes in the Biak Basin; and J.T. van Gorsel discusses nearly-forgotten papers where previous researchers documented their discoveries of Middle Jurassic Ammonites on the coast of the Cendrawasih Bay. The presence of Ammonites within Middle Jurassic black shales in the Cendrawasih Bay can have an impact to how explorationists see the paleogeographic reconstruction of the region while searching for Middle Jurassic reservoirs. We also include an article on new insights of the geological evolution of eastern Indonesia based on recent research undertaken by SE Asia Research Group of the Royal Holloway University of London.

We would like to welcome Dr. Tom Reijers, who joined us as an International Reviewer. Dr. Reiders is a consultant with special interest in carbonate and deltaic sedimentology and stratigraphy. Together with Prof. Harry Doust and Dr. Han van Gorsel, Tom will play a role in ensuring articles published in Berita Sedimentologi to be of high scientific standard.

As of March 2012, FOSI have had more than 410 members who joined our group through LinkedIn. The statistics of our members is provided in the next page. We hope that our articles will be useful to all of you, our readers, and in the next issue, we will still continue with a thematic issue on Timor and Arafura Sea. If you would like to contribute to BS No. 24, please get in touch with us.

Best Regards,

Minarwan
Deputy Chief Editor

INSIDE THIS ISSUE

About FOSI

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

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

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

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

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

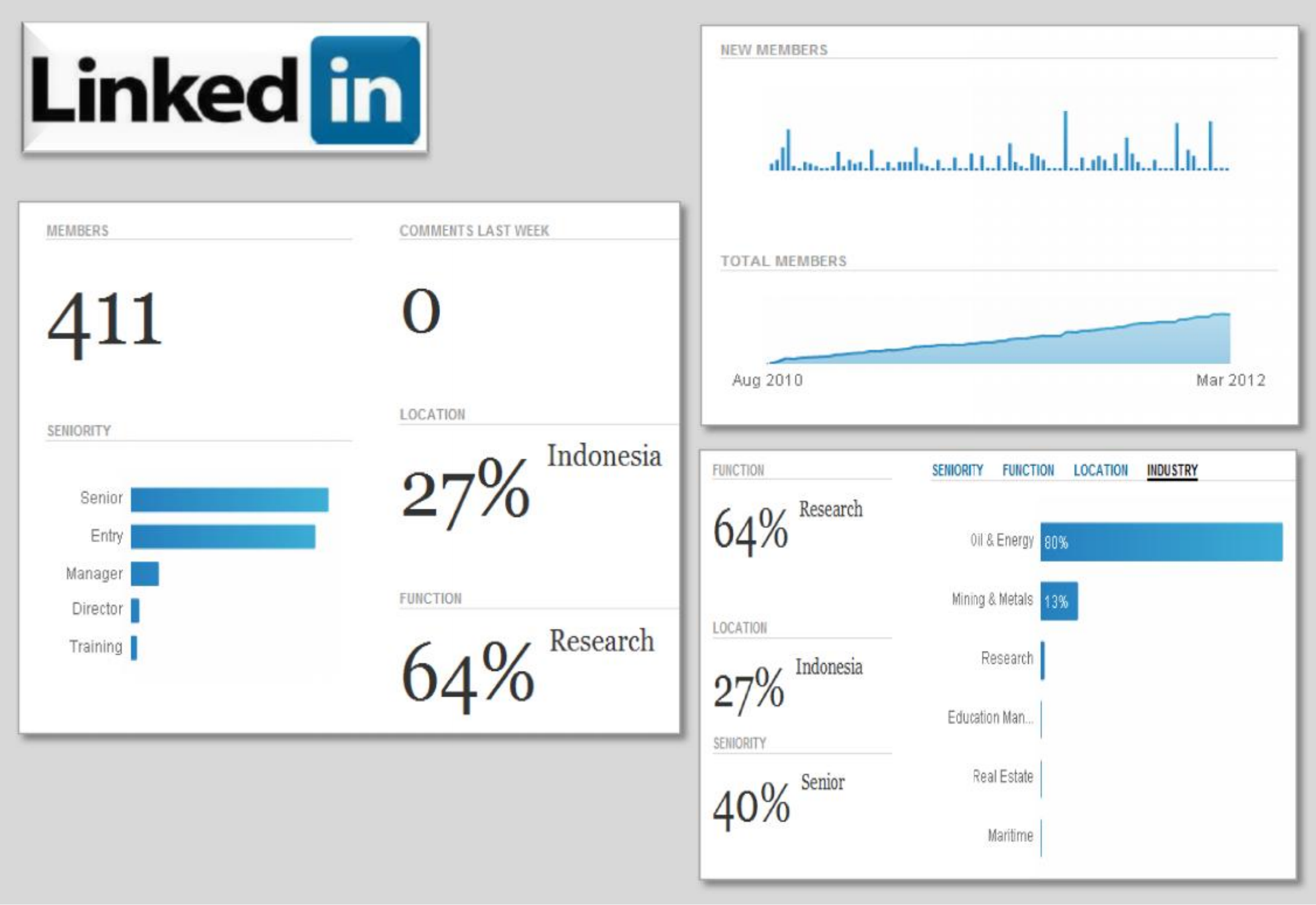
The official website of FOSI is:

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

FOSI Membership

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

Total registered members : 411 as of March 2012



Tectonic and Regional Structure of Seram and the Banda Arc

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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.

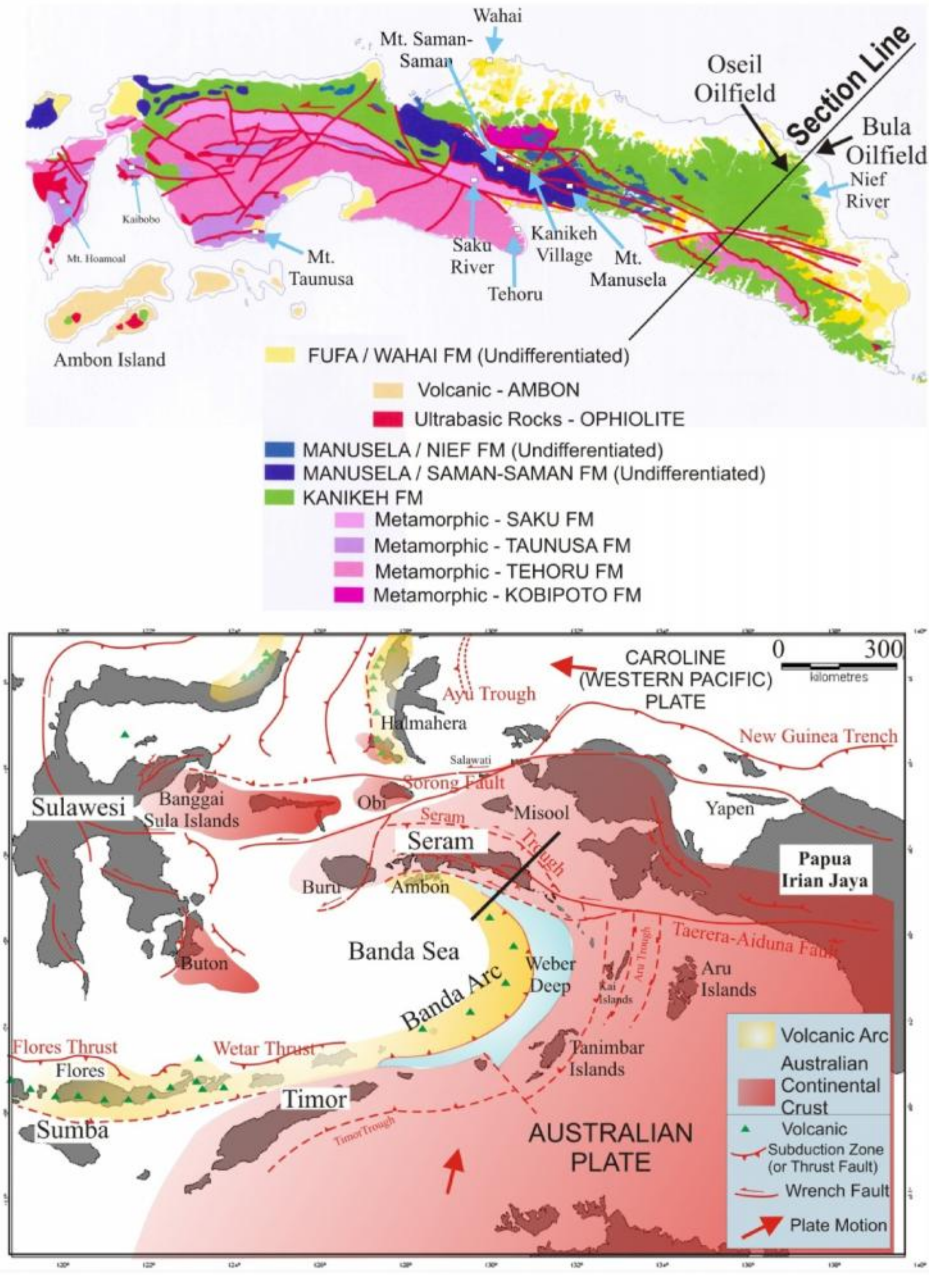

Figure 1. **Tectonic setting of the Banda Arc and simplified geology map of Seram, courtesy of Kufpec (Indonesia) Limited, showing the location of the regional cross section.**

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.

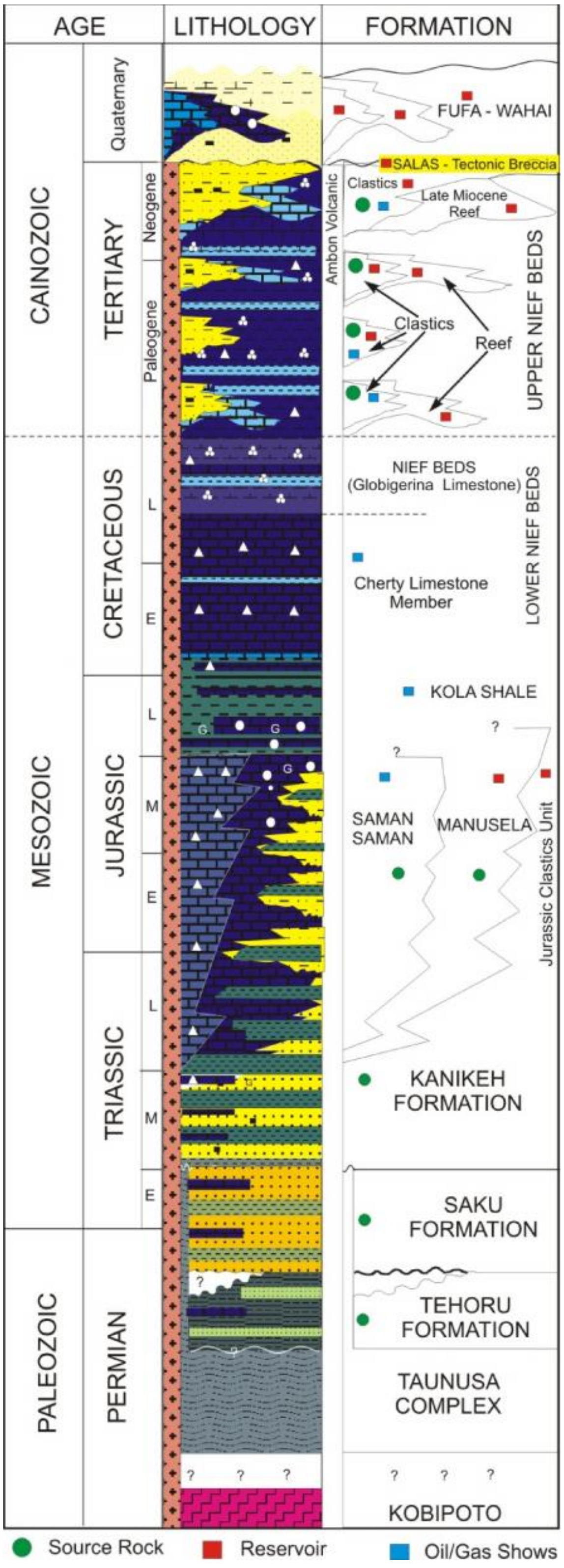

Figure 2. **Simplified stratigraphy for Seram courtesy of Kufpec (Indonesia) Limited.**

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 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.

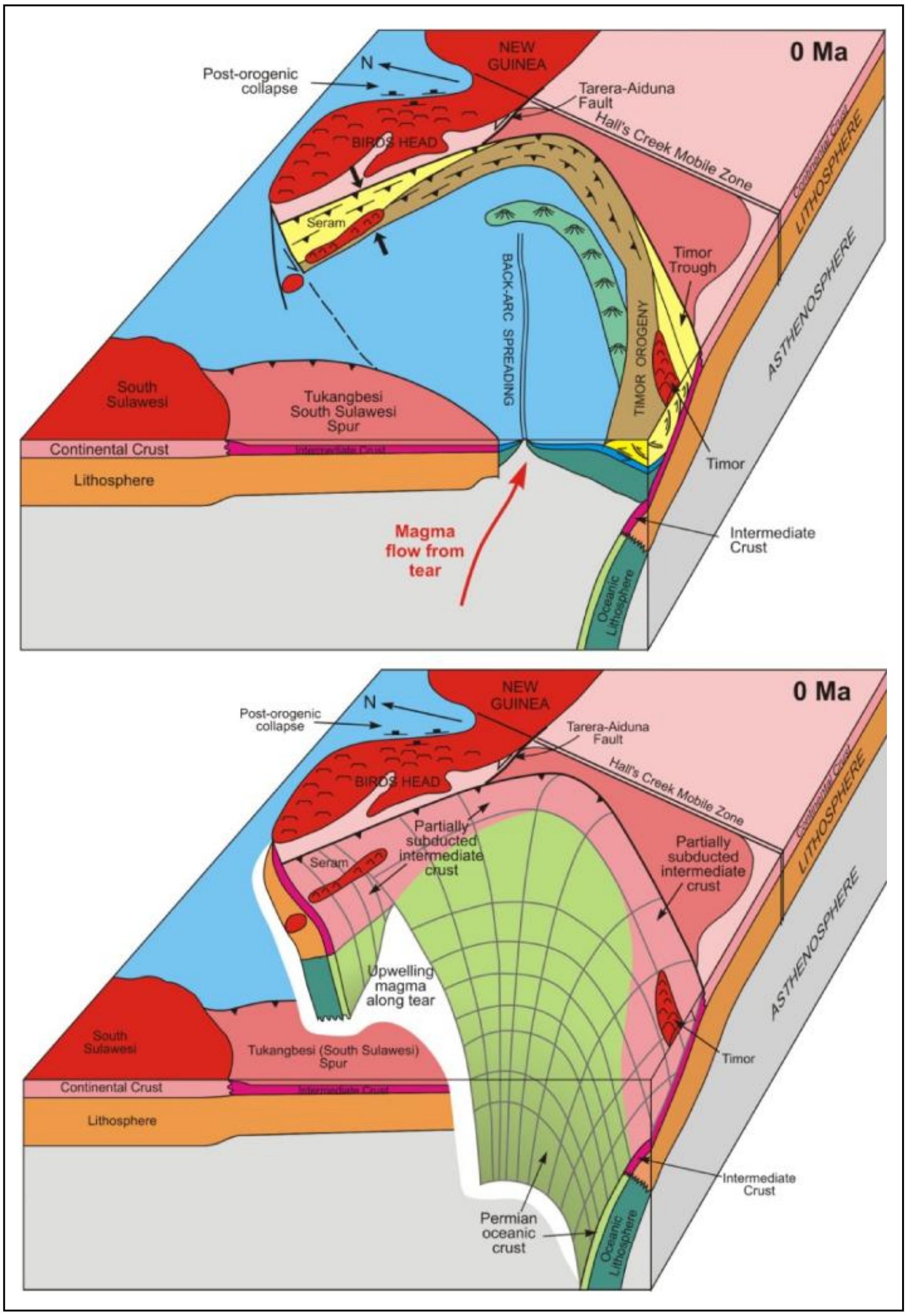

Figure 3. **3D visualisation of the present tectonic setting of the Banda Arc, firstly with the overriding plate and then with the overriding plate removed to reveal the subducting slab.**

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.

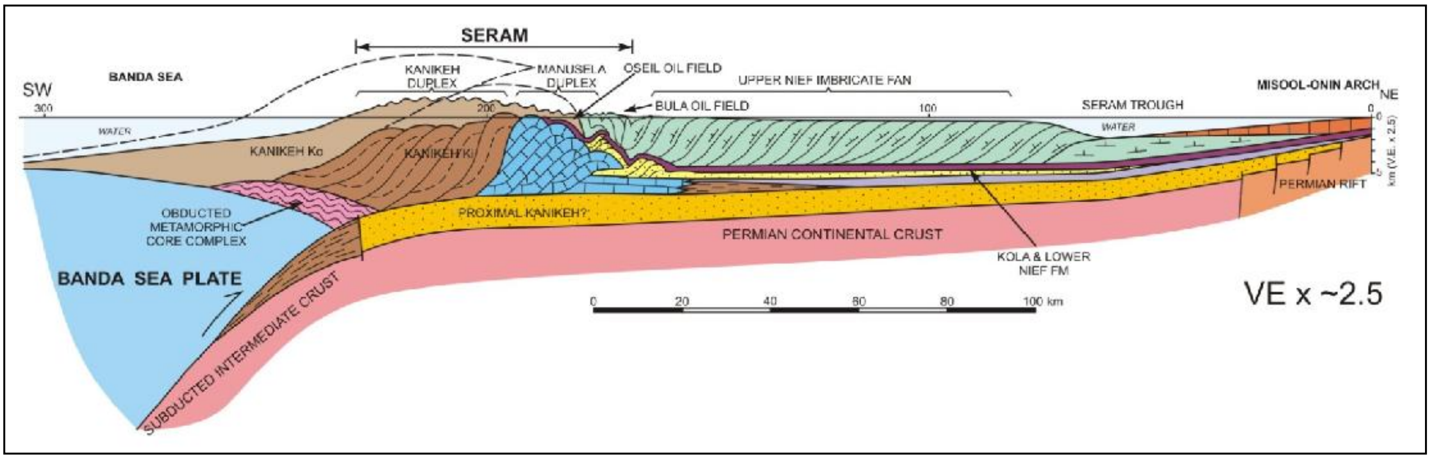

Figure 4. **Schematic regional cross-section across Seram, with a vertical exaggeration of x ~2.5. See Figure 1 for location.**

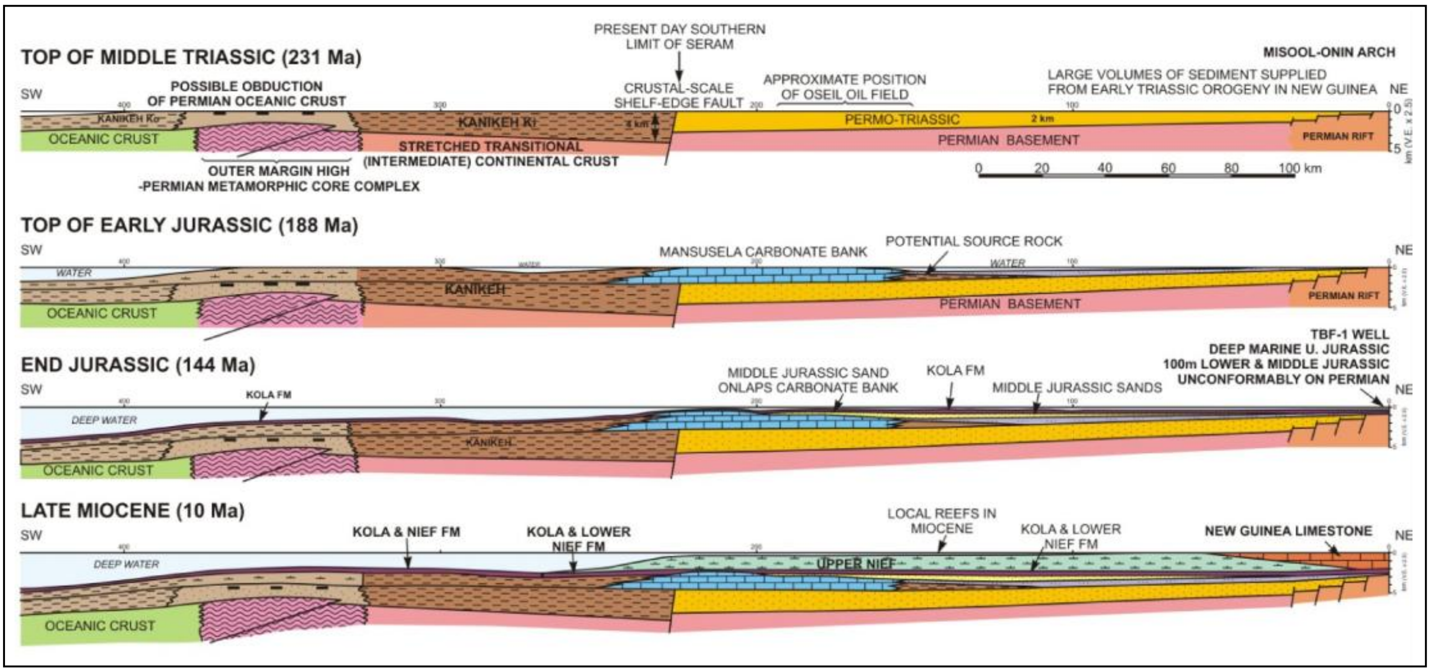

Figure 5. **Schematic cross sections of the Triassic to Miocene evolution of the Seram margin (VE x 2.5).**

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

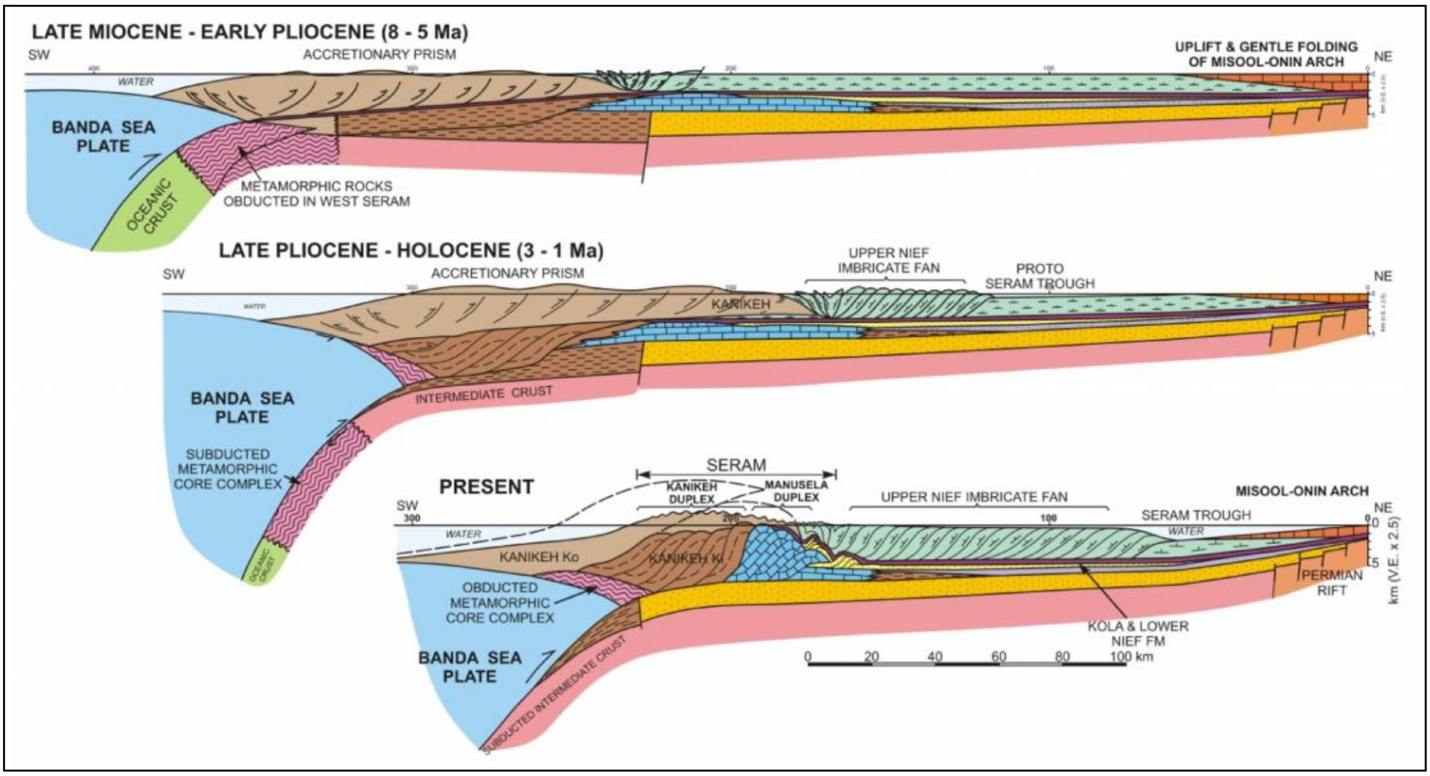

Figure 6. **Schematic cross sections of the Late Miocene to Present evolution of the Seram margin (VE x 2.5)**

REGIONAL CROSS SECTION

The section trends 040-220°, 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.

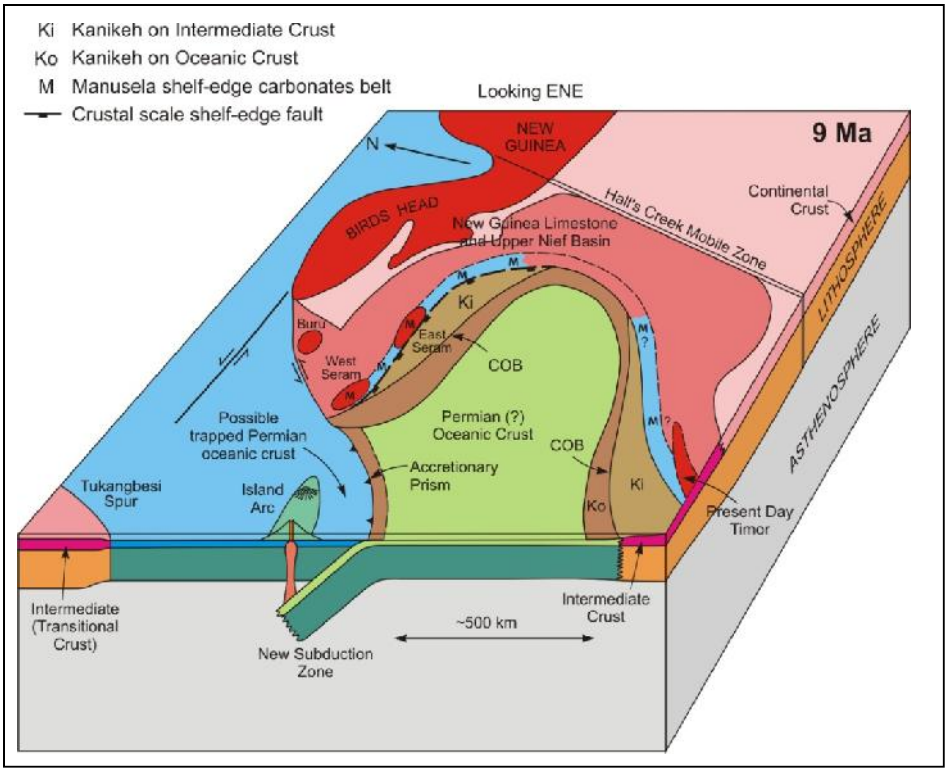

Figure 7. **3D visualisation of the inferred tectonic setting of the Banda Arc at 9 Ma.**

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.

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).

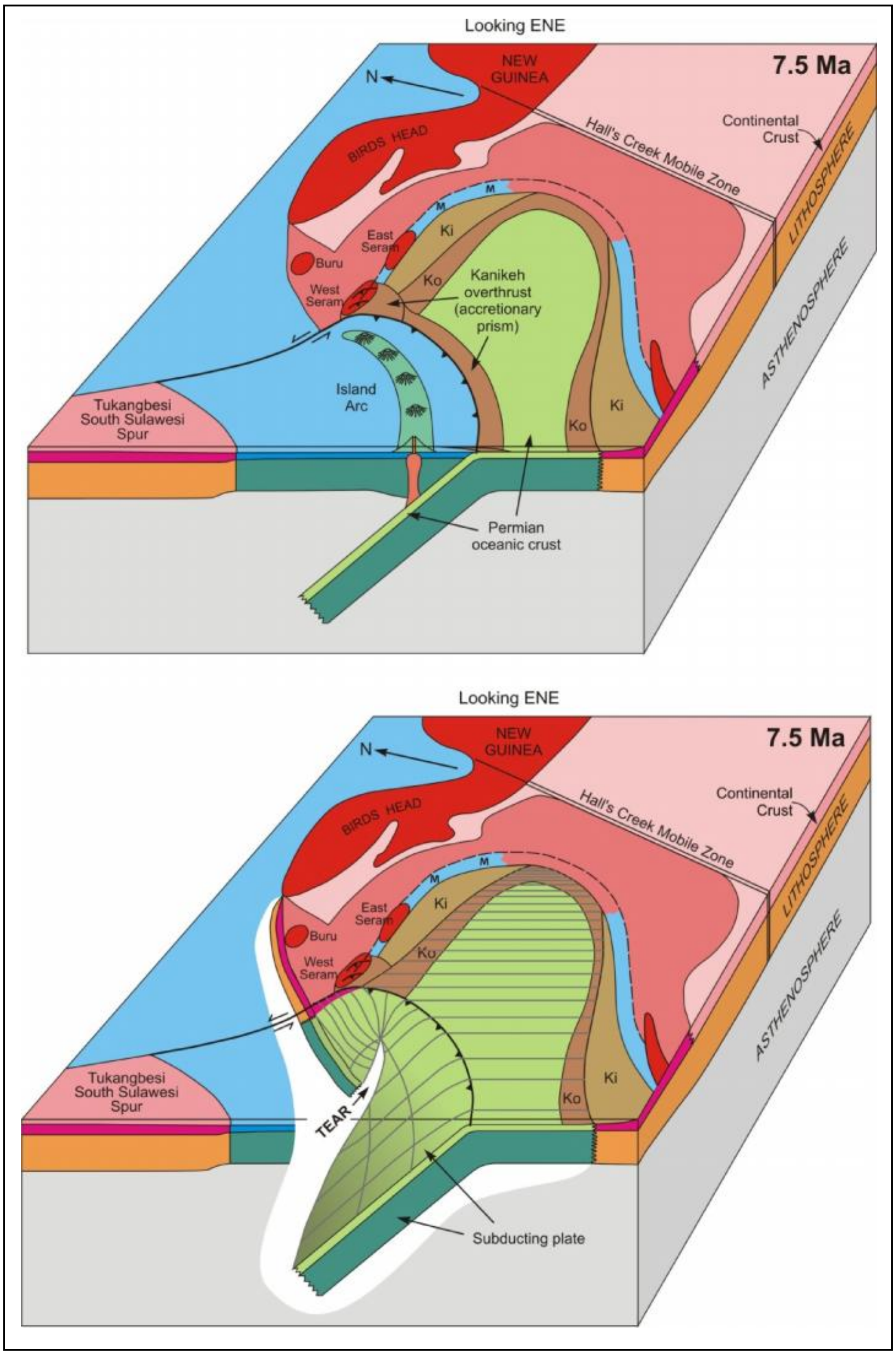

Figure 8. **3D visualisation of the inferred tectonic setting of the Banda Arc at 7.5 Ma, firstly with the overriding plate and then with the overriding plate removed to reveal the subducting slab.**

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.

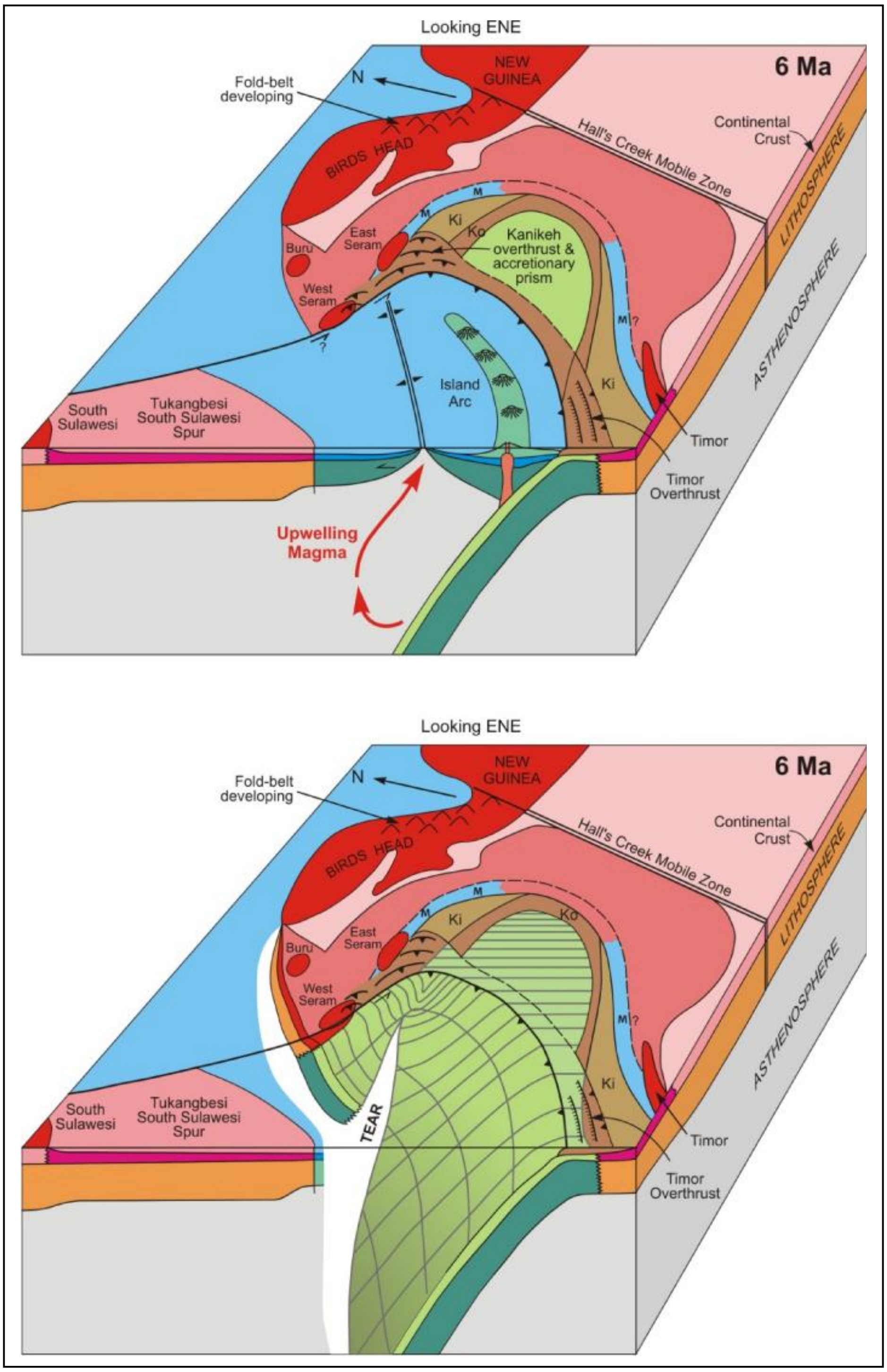

Figure 9. **3D visualisation of the inferred tectonic setting of the Banda Arc at 6 Ma, firstly with the overriding plate and then with the overriding plate removed to reveal the subducting slab.**

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.

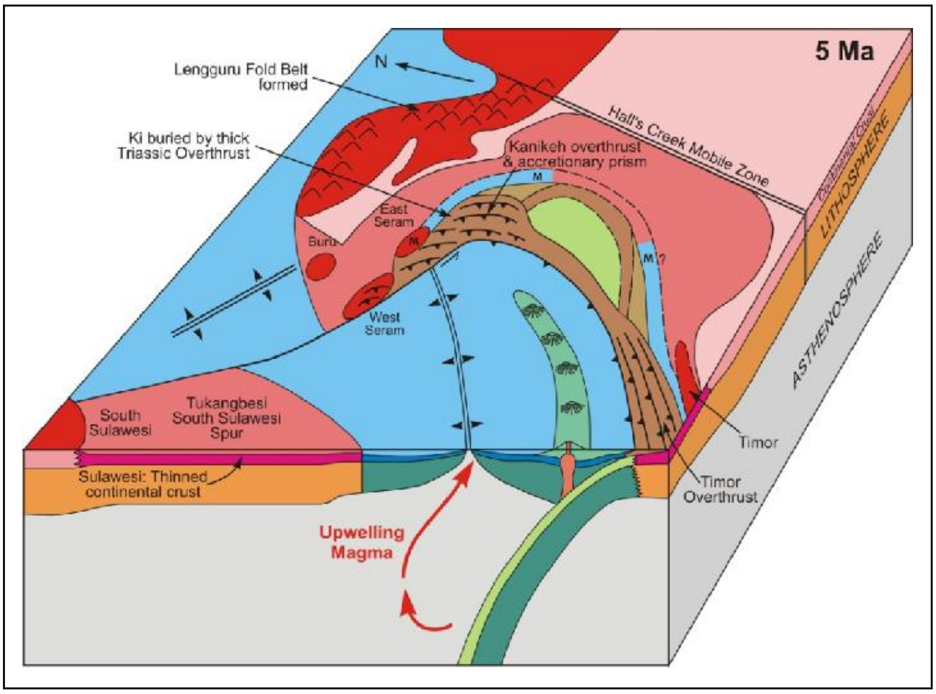

Figure 10. **3D visualisation of the inferred tectonic setting of the Banda Arc at 5 Ma.**

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).

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°. 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).

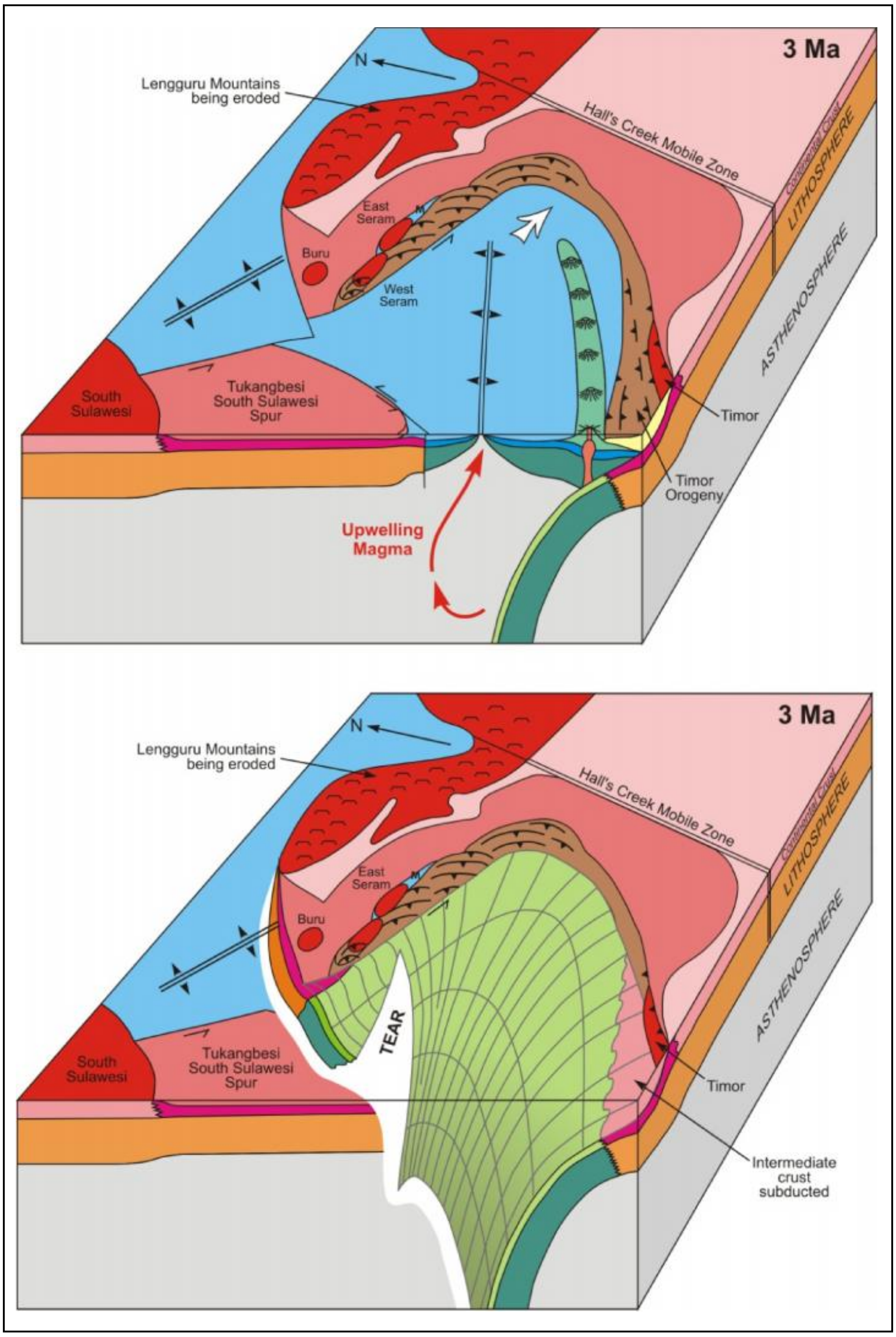

Figure 11. **3D visualisation of the inferred tectonic setting of the Banda Arc at 3 Ma, firstly with the overriding plate and then with the overriding plate removed to reveal the subducting slab.**

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.

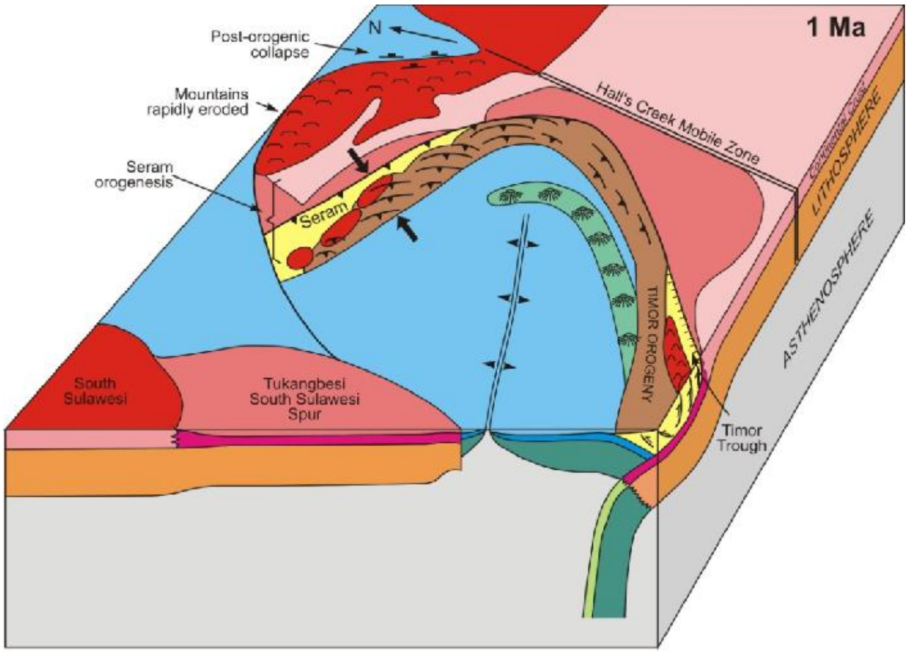

Figure 12. **3D visualisation of the inferred tectonic setting of the Banda Arc at 1 Ma.**

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 $\sim 305^0$. 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.

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 $130\text{-}310^0$ in Seram and cross-cutting (tear) faults striking $040\text{-}220^0$. 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°. 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°+/-10° and open fractures at that time are likely to have been parallel to this direction. Late Pliocene to Present thrusting was towards 040° 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°, 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.

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Origins of the Banda Arcs Collisional Orogen and the Banda Sea

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Many of the best examples of young arc-continent collision are found in eastern Indonesia, where the northern margin of Australia has been in collision throughout the Neogene with a succession of island arc systems (Charlton, 1991) (*Figure 1*). The Banda Arc is the youngest of these collision zones and forms the present plate boundary in this region. Behind the Banda Arcs, is the Banda Sea oceanic crust with its debatable origin.

Origin of the Banda Arcs Collisional Orogen

The origin of Timor Island and its collisional orogen have been matters of debates. Most authors describe the region as an arc–continent collision zone in which the Banda volcanic arc collided with Australia. Barber (1981) drew attention to the presence of Asian continental crust within the arc. Richardson (1993) proposed that a collision between a microcontinent, forming part of an extended passive margin and an Asian arc preceded collision of the volcanic arc and the Australian margin. Linthout *et al.* (1997) proposed that several microcontinental fragments collided with the Australian margin before the very young arc–continent collision. (Audley – Charles, 2011).

Hamilton (1979) regarded the island as a chaotic mélange. Barber (1981) interpreted Timor as collision result of Lolotoi microcontinent with Australian continent in Pliocene resulting in southward overthrusts over the Australian continental margin, or as upthrusts of Australian continental basement. Three main structural models, resulting mainly from near-surface observations, have been proposed for Timor:

(1) the Imbricate Model (Hamilton, 1979; Audley- Charles, 2011) : Timor is interpreted as an accumulation of chaotic material imbricated against the hanging wall of a subduction trench, the Timor trough, and essentially forms a large accretionary prism,
(2) the Overthrust Model (Carter *et al.*, 1976): Timor is interpreted in terms of Alpine-style thrust sheets where allochthonous units of Timor overthrust the parautochthonous units of the Australian continent.
(3) The Rebound Model (Chamalaun and Grady, 1978): the Australian continental margin entered a subduction zone in the vicinity of the Wetar Strait. Subsequently, the oceanic lithosphere detached from the continental part, resulting in the uplift of Timor by isostatic rebound on steep faults.
(4) Audley- Charles (2011) saw the Banda Trench gradually converted into a Tectonic Collision Zone progressively filled by two highly deformed Australian continental upper crust mega-sequences that were uplifted and raised Timor 3 km above sea level.

Combinations of these models have also been proposed (e.g. Charlton, 1989 and Harris, 1992) in which the parautochthon is divided into two parts, reflecting the step-wise nature of the collision. The main part, the 'underplated parautochthon', is thought to have accreted in the early stages of collision by the sequential addition by underplating of imbricate thrust slices of the outermost Australian continental margin to the base of the forearc complex. A second phase of collision is thought to have commenced in the early Pliocene with the addition to southern Timor of younger parts of the Australian continental margin, the 'frontally accreted' parautochthon. (See also Audey Charles 2011, Figure 6, 7, 8).

A particular controversy has also been the position of the suture (Hall and Wilson, 2000). Audley-Charles (1986a, 1988, and 2011) has advocated that there was a south-dipping suture in the Wetar Strait. Cases can be made for all these suggestions. The base of the Banda allochthon is the boundary between the former Asian Plate and underlying deposits of the former Australian passive margin. The base of the parautochthon is the deformation front and represents the boundary between completely autochthonous deposits of the Australian margin and those that have been displaced. The thrust north of Wetar can be interpreted as the new boundary between the Asian and Australian plates formed after subduction ceased south of Timor, and perhaps in response to slab break-off. Audley-Charles (1986a, 2011) summarised in diagrammatic form the contrast between the principal models. Harris (1991) suggested that each of the different models may be appropriate for different sections through the developing orogen, and each may apply at different stages in the collision process.

Timor has undergone young and severe tectonic activity. Mid-Pliocene limestones are the youngest rock formation to be folded. The deduced mid-Pliocene tectonic event has been interpreted as the collision of the northern margin of Australia with the subduction zone and volcanic arc (Barber, 1981). Sediments as young as early Miocene show some evidence of multiple deformation. In contrast, the Pliocene sediments are simply folded with horizontal fold axes.

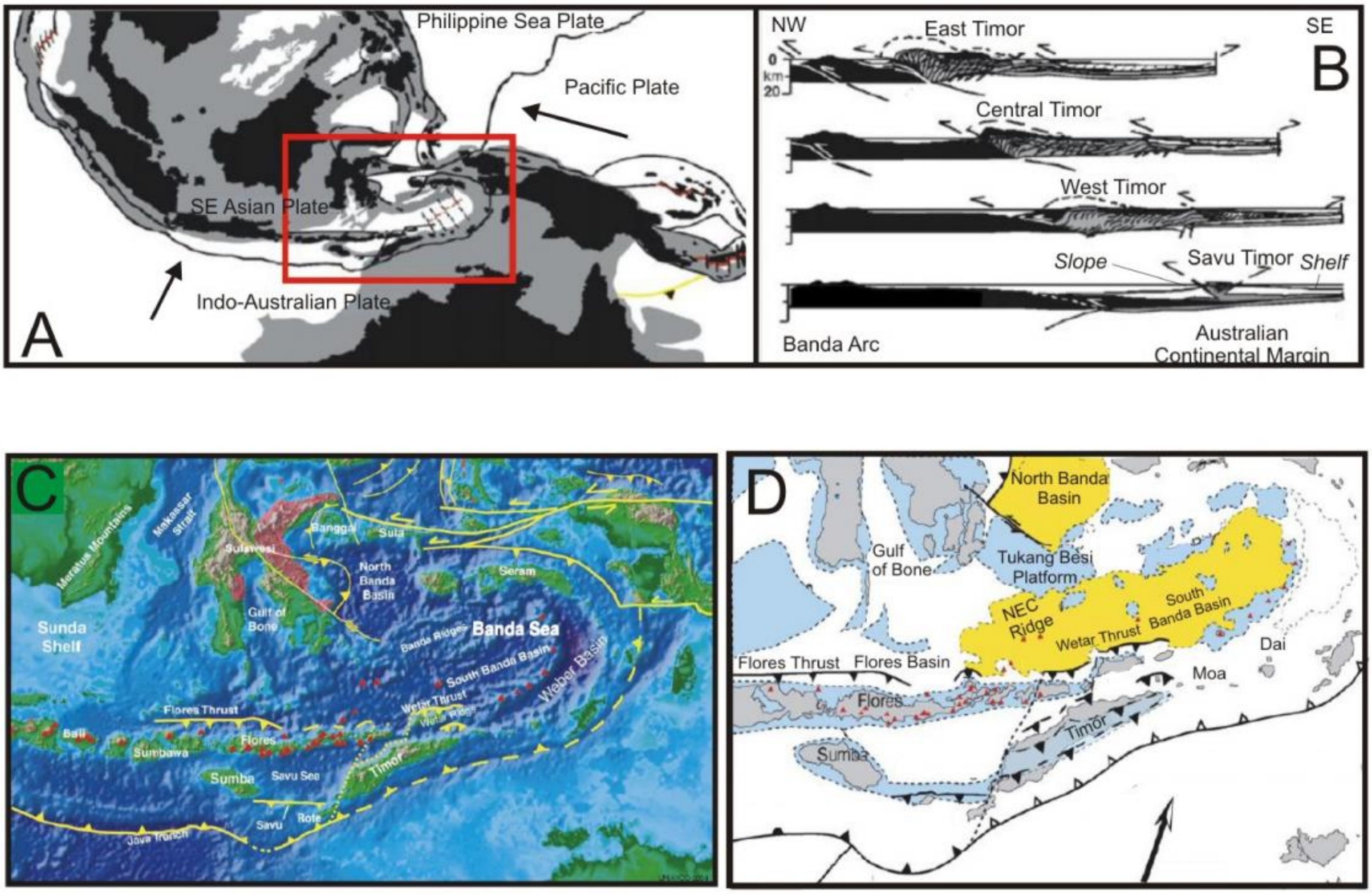

Figure 1. **Maps and serial sections of the Banda Arc region. A) Northern Australasian region. Grey is continental crust and white is oceanic crust. Rectangle is area of map 1C. B) Serial cross-sections through the western Banda Arc from Savu to East Timor. C) Digital elevation model of the Banda Arc region showing active faults (yellow lines), active volcanoes (red triangles), the Sulawesi ophiolite (pink area), and the many fragments embedded in oceanic crust of the Banda Sea floor. D) Location map of distribution of continental and arc fragments (blue),**

Based on deep seismic reflection profiles across the zone of convergence between Australia and the Banda arc east of Timor, Richardson and Blundell (1996) (see Figure 2) reveal the structures formed during lithosphere deformation in response to continental collision. Australian continental crust is bent down to the north to form the lower lithospheric plate. The immediately overlying upper plate is made up of a former outlier of the Australian continental shelf, now squeezed between the Australian continent to the south and the Banda arc to the north. The outlier began to accrete to the upper plate in the late Miocene. Near the Timor Trough, at the junction between the two plates, the upper plate to be cut by north-dipping structures interpreted as thrusts in an accretionary prism formed since the arrival of the Australian continental shelf at the collision zone at about 2.5 Ma.

The northern part of the collision zone is dominated by structures dipping southwards, antithetic to subduction, which penetrate the lithosphere to depths of at least 50 km, dividing the upper plate into imbricate slices. The oldest thrusts are presumably the more southerly ones. Since then the locus of activity has propagated northwards in a normal fashion until it has reached the backarc region where thrusts are active at the present day. Uplift is currently continuing as evidenced by several hundred meters of elevation of Pliocene coral reef of terraces on Alor, Atauro and Wetar and Sumba. In this collision, both oceanic and continental material is being shortened, thickened and uplifted. The overall, large-scale character of the collision zone is dominated by two sets of divergent structures. The southern set is related to the subducting (lower) plate and dips in the same direction as subduction. The northern set, in the upper plate, is antithetic to this.

Origin of the Banda Sea

The Banda Sea (South Banda Basin) is an oceanic crust. The origin and age of the Banda Sea has long been debated. Both low heat flow values and depth of basement greater than 4500 meters are in agreement with a creation of the oceanic crust during Mesozoic or Early Cenozoic time now trapped by the volcanic and non-volcanic arcs (Lapouille *et al.*, 1985). The hypothesis of a trapped Mesozoic origin for the Banda Sea is uncertain because there are controversies on ages determined from magnetic lineaments. The 'old' Banda Sea floor hypothesis was challenged by Honthaas *et al.* (1998) who recovered 9.4–7.3 Ma backarc basalt from fault scarp exposures of the basement of the North Banda Basin. They also recovered pelitic metamorphic rocks from the Sinta and Tukang Besi Ridges, and Lower Miocene limestone from the Rama Ridge further to the south. Other

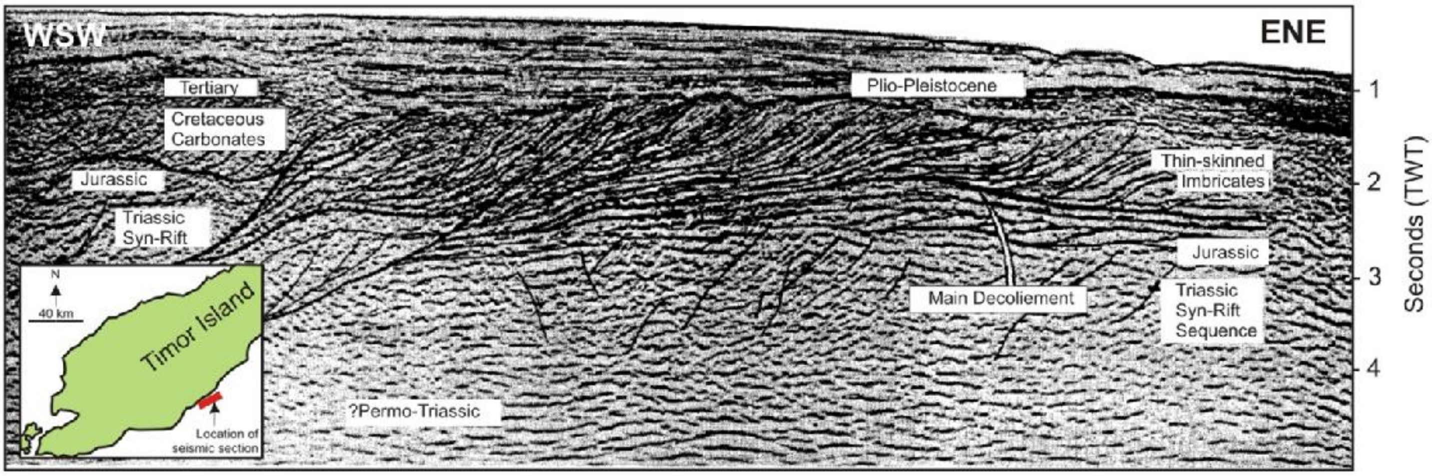

Figure 2. **Migrated seismic line from offshore south of the Kolbano fold and thrust belt shows thin-skinned thrust imbricates overlying a gently deformed stratigraphic sequence (Sani et al., 1995).**

dredged samples from the Lucipara and Nieuwerkerk Emperor of China ridges, and volcanic islands within the South Banda Basin, include Late Miocene to Early Pliocene backarc basalt, and cordierite-and sillimanite-bearing andesite. The occurrence of cordierite and sillimanite xenocrysts, and high Sr and low Nd ratios of samples throughout the region require that volcanic units are mounted on, and erupted up through continental crust with similar mineral assemblages to the Banda Terrane metamorphic basement.

These results led Honthaas *et al.* (1998) to also interpret the Banda Ridges as foundered continental crust pulled from the edge of Sulawesi by intra-arc spreading. The arc complex is mounted on the southern edge of the detached continental fragment, which was repeatedly pulled apart by diffuse spreading and the opening of intra-arc basins. According to this model, the eastern Sunda and western Banda Arc islands from Pantar to Damar are volcanic constructs mounted on a continental fragment that was rifted from the Tukang–Besi platform and Banda Ridges during the Late Miocene to Early Pliocene opening of the South Banda Basin. The Wetar segment and the Lucipara Ridge at the south and north of the South Banda Sea, respectively represented a single volcanic arc at 8-7 Ma resulted from high dip subduction of the Indian oceanic lithosphere beneath continental blocks originated from New Guinea. The rifting of the South Banda Basin at about 6 Ma separated the Wetar and the Lucipara volcanic arc, and intra-arc opening processes occurred from about 6.5 to 3.5 Ma (Late Miocene-Early Pliocene) forming the present Banda Sea. The spreading ceased at about 3 Ma due to the arc-continent collision occurred to the south and north of Wetar and Lucipara arc. The young age of the South Banda Sea Basin is contradictory with its great depth. Hinschberger *et al.* (2001) offered three mechanisms causing this great depth : rapid thermal subsidence due to a heat loss in the small basin, induced tectonic subsidence due to compressive tectonic setting, and increased tectonic subsidence due to drag stress of two downgoing slabs (Banda and Seram slabs) converging at depth.

A recent paper by Harris (2006) considered that the Banda Sea was initially related to subduction rollback of the old oceanic lithosphere of the Australian/Indian Plate. The upper plate was forced to extend, which resulted in suprasubduction zone seafloor spreading to form the Banda Sea basin. Trench retreat eventually brought the southernmost rifted ridge of Banda Terrane into collision with the Australian continental margin. As the cover sequences of the Australian slope and rise stacked up in the collision zone the Banda collisional terrane was folded, detached, and uplifted, during accretion to the edge of Australia. Now the southernmost part of the Banda Terrane forms an allochthonous thrust sheet that acts as the structural lid of the Timor fold and thrust belt. As the collision progressed it widened and the plate boundary localized in the thermally weakened backarc where the southern Banda Sea Basin underthrusts the Banda Arc. Closing of the Banda Sea basins puts the allochthonous part of the Banda Terrane on a collision course with autochthonous Banda Terrane fragments imbedded in the Banda Sea floor, and eventually with Sulawesi, where most of these fragments started their journey over 50 Ma.***

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New Insights Into the Geological Evolution of Eastern Indonesia From Recent Research Projects by the SE Asia Research Group

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Introduction

Eastern Indonesia has a prolonged, complex tectonic history. It is where the Eurasian, Indo-Australian, Caroline and Philippine Sea plates converge, and where processes such as subduction, obduction, slab rollback, rifting, supracrustal extension, lower crustal flow and exhumation are very young or still active (e.g. Hamilton, 1979; Silver et al., 1983; Hall, 1996; Bock et al., 2003; Spencer, 2011; Spakman & Hall, 2010; Hall, 2011).

For these reasons, the SE Asia Research Group (SEARG) at Royal Holloway, University of London, has made Eastern Indonesia one of its major research themes in recent years. The SEARG has been conducting geological research in SE Asia since 1982. Work has been undertaken in Indonesia, Malaysia, Thailand, the Philippines, Vietnam and the South China Sea. In 2012 the SEARG is directed by Professor Robert Hall, and involves 12 postgraduate students, 2 postdoctoral researchers, a large number of academic staff, research associates and collaborators in the UK and overseas. The group is funded by a consortium of oil companies.

Here we summarise recent and ongoing SEARG projects in Eastern Indonesia (Figure 1). Most of the projects are field-based, but they all also employ new data and techniques, such as 40Ar-39Ar, U-Pb dating (SHRIMP and LA-ICP-MS), Hf isotope dating (LA-MC-ICP-MS), U-Th/He dating, multibeam bathymetry, high quality seismic and remote sensing data.

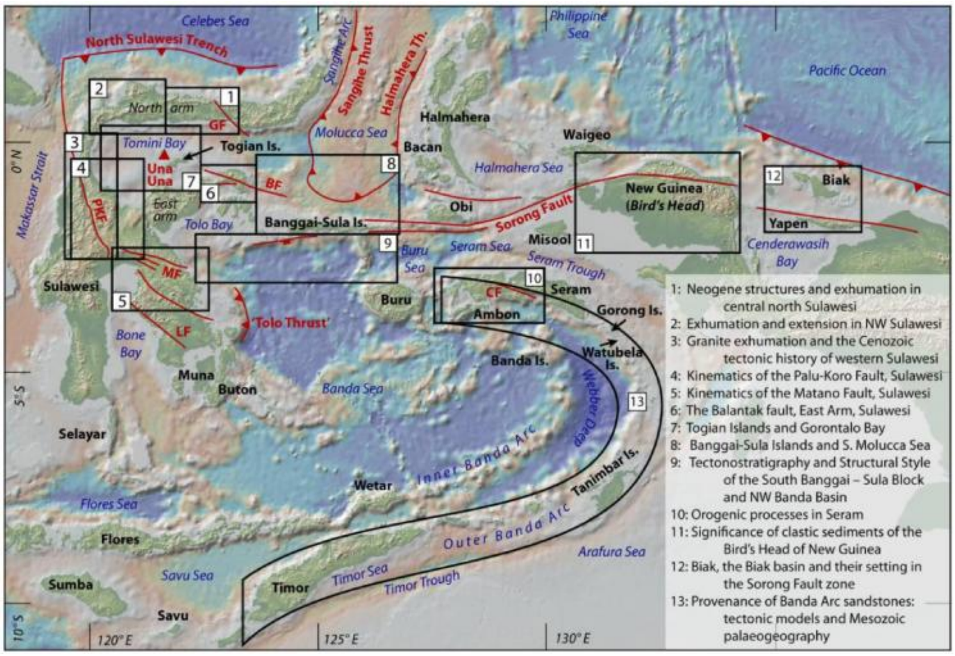

Figure 1. **Overview map of Eastern Indonesia showing geographical features, structural elements and ongoing SEARG projects (numbered). PKF: Palu-Koro Fault; MF: Matano Fault; LF: Lawanopo Fault; GF: Gorontalo Fault; BF: Balantak Fault; CF: Central fault zone of Seram.**

Sulawesi

The SEARG is involved in several studies aimed at understanding the evolution of Sulawesi in the context of Eastern Indonesia.

West, central and SE Sulawesi

In west, central and SE Sulawesi, metamorphic rocks (e.g. Egeler, 1947), are partly overlain by volcanic-sedimentary rocks and intruded by granitoids as young as Pliocene (e.g. Sukamto, 1973; Sukido et al., 1993; Elburg et al., 2003; van Leeuwen & Muhardjo, 2005). Widespread uplift has formed >3km high mountains, associated with deep intermontaine basins.

The sinistral Palu-Koro Fault (PKF) (Figure 2) bisects central Sulawesi and links to the North Sulawesi Trench (e.g. Silver et al., 1983; Bellier et al., 2001). Many workers also link it via the Matano/Lawanopo faults to the Tolo thrust or 'East Sulawesi Trench' in the southeast, forming a continuous structure that bounds a rotating Sula Block (e.g. Hamilton 1979; Silver et al., 1983; Bellier et al., 2006). Others link the Matano Fault (MF) to a Sorong fault strand that passes south of the Banggai-Sula Islands (e.g. Katili, 1975; Socquet et al., 2006).

SEARG studies of the PKF show that strike-slip diminishes to the south, and the fault terminates at the northern end of Bone Bay. Similarly, the MF terminates in the west where it is

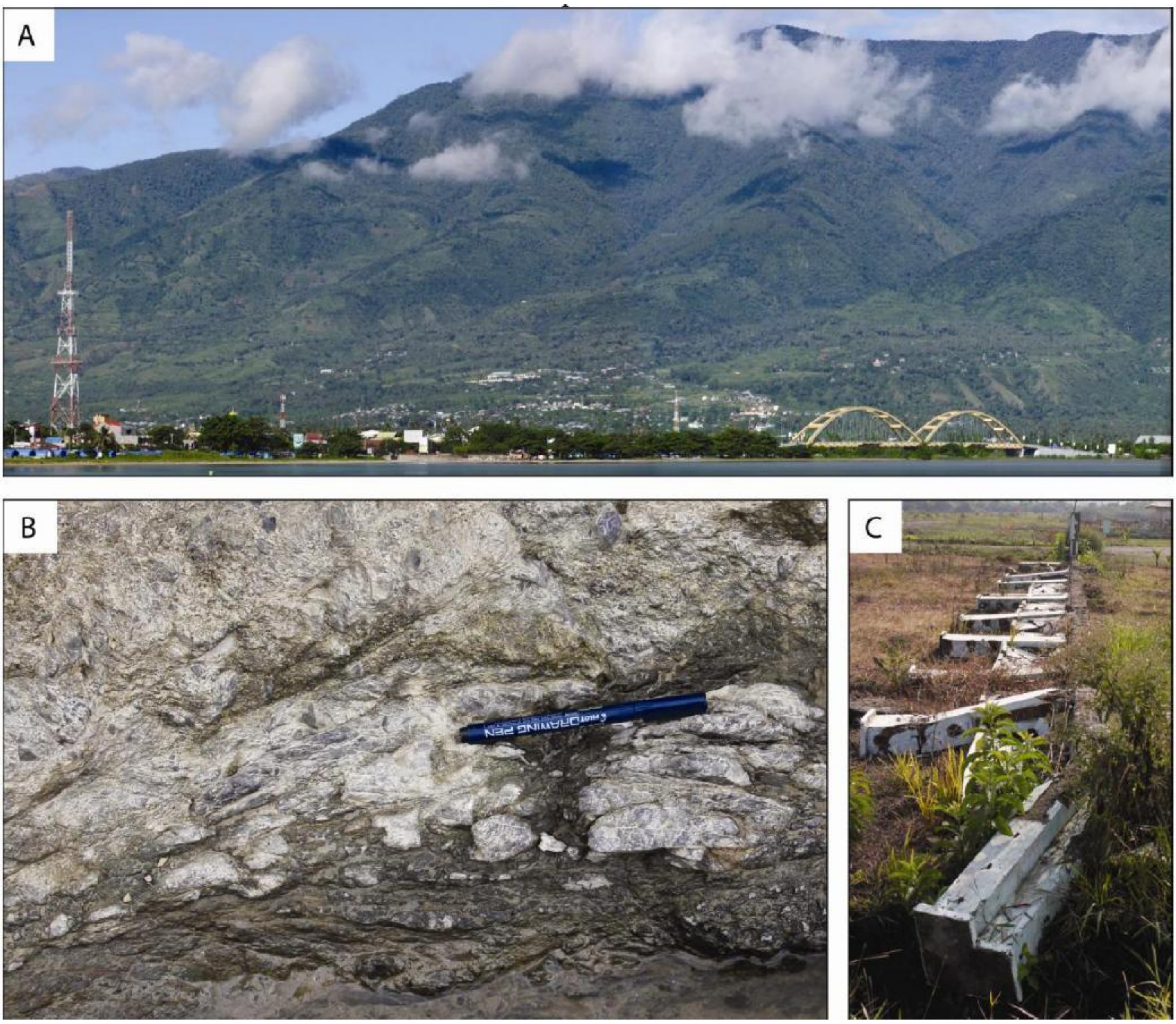

Figure 2. **(A) View west across Palu Bay to mountains adjacent to the Palu-Koro Fault. (B) Sinistral Reidel shears in fault breccia of a major Palu-Koro Fault strand south of Gimpu. (C) Damage caused by the 15-02-11 Mw 6.1 Matano Fault earthquake at Mahalona.**

propagating towards, but does not yet connect to the PKF (Watkinson, in prep.). Such a strain distribution is inconsistent with the fault bounding a rotating block. Instead, we suggest that the PKF forms the western transform boundary of a zone of lithospheric extension, and the MF is a transtensional structure at the southern margin of extension.

At the eastern end of the MF, recent work by the SEARG, utilising high resolution multibeam and seismic data, suggests that the Tolo thrust is a gravity-driven feature (Rudyawan, 2011), and not a tectonic structure that could terminate a strike-slip fault. These data also show that strands of the Sorong fault barely reach the Banggai-Sula Islands from the east (Ferdian et al., 2010; Rudyawan, 2011), and certainly do not link to strike-slip faults onshore Sulawesi (Rudyawan, 2011).

Metamorphic massifs in central Sulawesi characterised by NNW-trending corrugations may have been formed during exhumation of a metamorphic core complex (MCC) (Spencer, 2011). Recent SEARG fieldwork in central Sulawesi tentatively supports an interpretation of MCC exhumation during top-to-the-north shear, representing considerable lithospheric extension (Watkinson et al., in prep.).

In west and central Sulawesi, Cenozoic magmatic rocks include older calc-alkaline/tholeiitic intrusions and younger (including Pliocene) mafic-felsic magmas (Elburg et al., 2003). A current SEARG project aims to determine when and how granitoids in west and central Sulawesi were exhumed, by using low-temperature U-Th/He and 40Ar-39Ar thermochronology on apatites and micas. Of particular interest are the relationships between granitoid emplacement, cooling and uplift, to extension and exhumation of the metamorphics and strike-slip along the PKF.

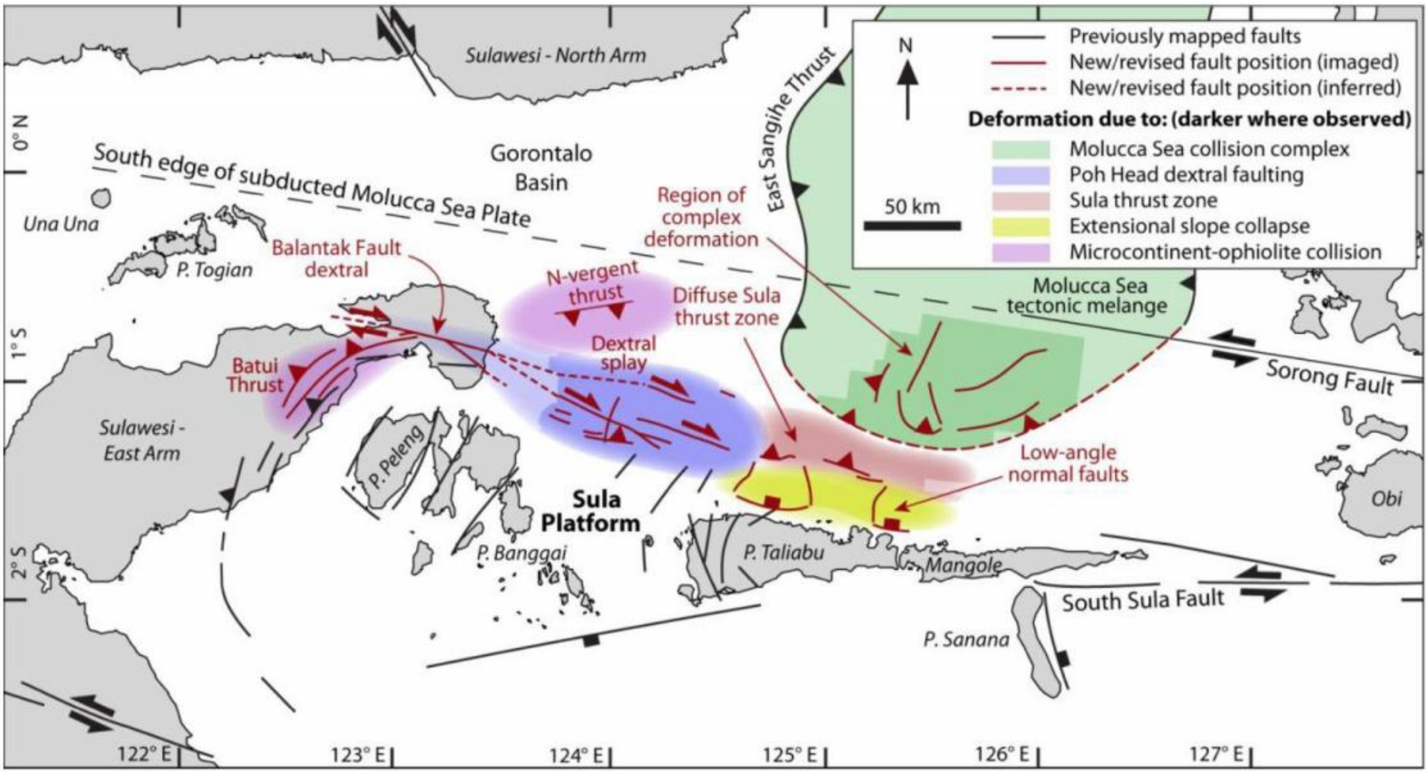

Figure 3. **Map showing newly imaged faults and their deformation mechanisms. Note the absence of a through-going Sula Thrust, the Sorong Fault as a plate boundary which does not reach the surface, and the Balantak Fault and region of dextral transpression west of the east arm. Sources of deformation in the region are indicated by regions of colour. From Watkinson et al. (2011).**

Tomini Bay

The Gorontalo Basin of Tomini Bay is a deep, enigmatic basin, containing up to 5 km of sediment (Hamilton, 1979). New field, geochemical and geophysical studies by the SEARG are revealing more about the basin. Cottam et al. (2011) presented a new stratigraphy for the Togian Islands, in the centre of Tomini Bay, and interpreted the age, character and evolution of the basin. The western end is underlain by continental crust, the central part by Eocene to Miocene oceanic and arc rocks, with the possibility of Banggai-Sula microcontinental crust south of the Togian Islands. Field relationships indicate a latest Miocene to Pliocene age for inception of the basin. Volcanism in the Togian Islands is not a result of Celebes Sea subduction. Instead, it is the result of extension in the Pliocene and Pleistocene. Modern volcanism at Una Una may be the result of the same process (Cottam et al., 2011).

Sulawesi's North Arm

In the western north arm, the Malino Metamorphic Complex (MMC) contains gneisses and schists with a greenschist carapace, and may be a MCC (Kavalieris et al., 1992; van Leeuwen et al., 2007). The SEARG is undertaking detailed field and thermochronological investigations to determine whether the MMC is indeed a MCC similar to those of central Sulawesi, and whether it formed/is forming during the same phase of extension. A related project on the Neogene tectonics of the central north arm aims to understand relationships between the Gorontalo Fault, intermontaine basins and uplift east of the MMC. Igneous rocks, including an unexpectedly large quantity of felsic material, will be used to determine emplacement ages and uplift rates.

Banggai-Sula Islands

The Banggai-Sula microcontinent has long been considered to have been sliced from New Guinea and travelled west along strands of the Sorong Fault (e.g. Visser & Hermes, 1962; Hamilton, 1979; Silver & Smith, 1983). Collision of the microcontinent with the east arm of Sulawesi has been thought to have caused deformation throughout Sulawesi (e.g. Bergman et al., 1996; Simandjuntak & Barber, 1996; Calvert, 2000; McClay et al., 2000).

Recent SEARG projects utilising new seismic and multibeam data from north and south of the islands show that major continuous faults previously interpreted to bound the microcontinent, including strands of the Sorong Fault, do not exist (Ferdian et al., 2010; Rudyawan, 2011; Watkinson et al., 2011) (Figure 3). Gently dipping strata of the Banggai-Sula microcontinent margin can be traced north beneath younger rocks, and are not truncated by a major fault. The strike-slip Balantak Fault passes from the east arm of Sulawesi and terminates in a zone of dextral transpression close to the Banggai-Sula Islands. There is no evidence that the Banggai-Sula microcontinent was translated along through-going structures, or that compressional deformation related to its suturing to Sulawesi was widespread (Cottam et al., 2011; Watkinson et al., 2011).

Seram

Controversies surround the geological evolution of Seram. These include the possibility of subduction at the Seram

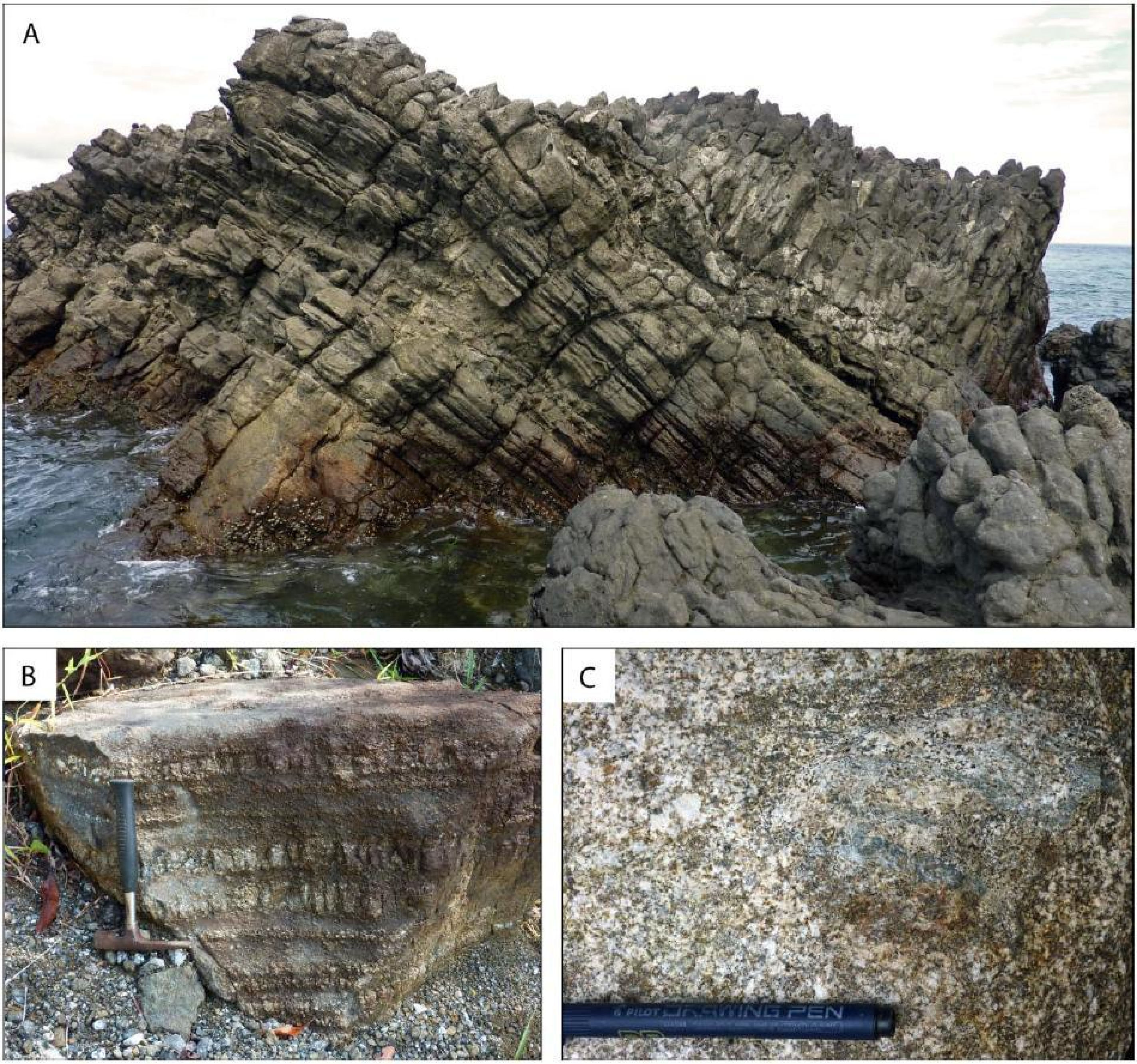

Figure 4. **(A) Bedded cordierite-bearing dacites (ambonites), Ambon Island. (B) Layered peridotite, closely associated with cordierite-bearing granite. (C) Large cordierite + spinel + sillimanite restite in granite, Ambon.**

trough (e.g. Hamilton, 1979; Karig et al., 1987); thrust sheet emplacement and ophiolite obduction (e.g. Audley-Charles et al., 1979; Linthout & Helmers, 1994); and the causes of anatexis and cordierite-rich volcanism (Linthout & Helmers, 1994; Honthaas et al., 1999).

Recent SEARG studies in Seram are aimed at resolving these uncertainties. Peridotites crop out throughout Seram, particularly in the west, in the SE, and in the Gorong and Watubela islands to the east. Peridotites are not associated with other typical ophiolitic components. Granites (SHRIMP U-Pb zircon age: 3 Ma, J. Decker, pers. comm., 2011) characterised by abundant cordierite and garnet, and numerous cordierite + spinel + sillimanite restites, are in contact with the peridotites. Eruptive cordierite + garnet dacites ('ambonites') are widespread on nearby Ambon (Figure 4) and have a similar ~3 Ma age (J. Decker, pers. comm., 2011).

There are many examples where peridotite appears to intrude the granites. Peridotites and granites seem to comprise a single tectonic unit exhumed along low-angle NNE-dipping detachments, not obducted by SSW-dipping thrusts as previously thought. Seram's central fault zone incorporates thin slivers of peridotite and may have been active at a similar time. North of the central fault zone in the Kobipoto Complex, cordierite-granites as well as (ultra-) high temperature granulites, with identical mineralogy to the granite-hosted restites, are found with peridotites and were probably exhumed in a similar manner to those of west Seram (Pownall et al., 2012).

West Papua

The Bird's Head of New Guinea is underlain by Australian continental crust and is considered to represent a coherent and little deformed domain of

Australian affinity with a relatively complete Palaeozoic to Recent stratigraphy (e.g. Dow et al., 1988; Audley–Charles, 1991).

An ongoing SEARG study is focused on the clastic sedimentation of the Bird's Head. Heavy mineral analysis and zircon dating is revealing the composition and provenance of these sediments. The Mesozoic Tipuma Formation includes material from local source rocks north of the formation and material from the North Australian craton (Gunawan et al., In Press) (Figure 5). Sediments from the Tipuma Formation indicate that this region experienced volcanic activity during the Triassic (Gunawan et al., In Press). This project has also shown that the Bird's Head has a more complicated tectonic history than previous models suggest.

The Biak basin, between Biak and Yapen islands, is a frontier region whose structural and sedimentary evolution and hydrocarbon potential is poorly known. The relationship between the Sorong Fault, subsidence of the Biak basin and uplift of the islands is the focus of a new SEARG project that will integrate detailed field studies, offshore seismic and multibeam data.

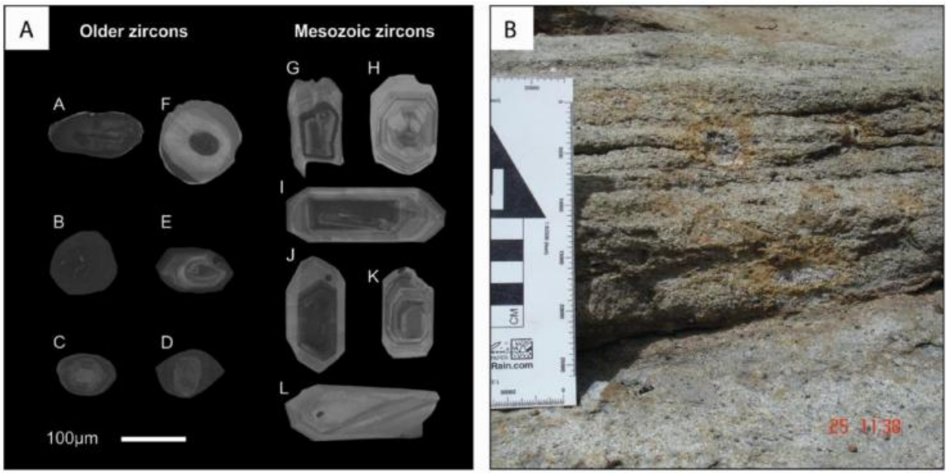

Figure 5. **(A) CL image showing older (Precambrian ages) and Mesozoic zircons from the Tipuma Formation in the Bird's Head. (B) Bedded sandstones of the Tipuma Formation, Bird's Head. After Gunawan et al., In Press. Watkinson et al. SEARG research in Eastern Indonesia 7.**

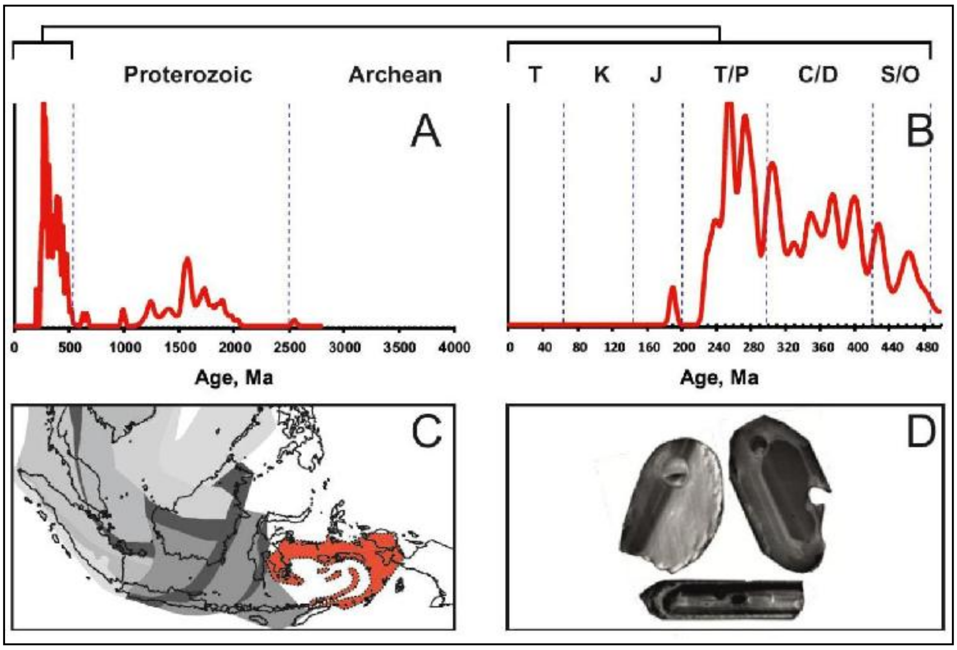

Figure 6. **(A&B) Schematic probability density plot of detrital zircon U-Pb ages from the Banda Arc. (C) Cartoon showing location of Australian basement fragments (After Hall et al., in prep.) from which these zircons were analysed. (D) Examples of zircon CL-images. Watkinson et al. SEARG research in Eastern Indonesia 8.**

Banda Arc

The geodynamic evolution of the Banda Arc is a subject of great interest (e.g. Cardwell et al., 1978; McCaffrey et al., 1989; Hall, 2002). Recent work combining seismic tomography and plate tectonic reconstructions (Spakman & Hall, 2010) has shown that Jurassic oceanic crust of the Banda embayment was subducted from 15 Ma. Eastwards slab rollback continued up to 2 Ma, and was associated with extensional break-up of the Sula Spur – an arm of Australian crust extending around the north of the Banda Arc. Slab rollback and associated delamination of the continental crust explains many of the enigmatic features of the Banda Arc, such as the synformal geometry of the subducted plate in the mantle, deep marine troughs, and the distribution of fragments of Australian crust in Eastern Indonesia (Spakman & Hall, 2010).

An ongoing SEARG study aims to provide a detailed regional provenance fingerprint of zircons in SE Asia by compiling a database of existing U-Pb and Hf isotope analyses and acquiring new data (e.g. samples recently collected from Timor). Preliminary results suggest that detrital zircons in the Banda Arc (Seram), including recently discovered Permian-Triassic population (Figure 6), were derived from the Sula Spur. This confirms the existence of an acid volcanic Permian-Triassic source in or near the Sula Spur, similar to that recognised for the Bird's Head area (Sevastjanova et al., 2012).

Conclusions

Recent research by the SEARG and its collaborators shows that many long-held assumptions about the structural, magmatic, metamorphic and sedimentary evolution of Eastern Indonesia require revision. Previously it was assumed that continuous lithospheric faults bounded continental fragments, and deformation was predominantly related to collision and extrusion tectonics. Models for the development of sedimentary basins built around these ideas have been proven to be incorrect, and blocks are generally not bounded by continuous faults. The SEARG's research shows that collision (e.g. India – Asia collision, Banggai-Sula – Sulawesi collision) is not as important in controlling intraplate deformation as subduction initiation, slab rollback, lithospheric delamination and lower crustal flow.

Acknowledgements

The SE Asia Research group is funded by a consortium of oil companies. Too many individuals and organisations have contributed to our research to list here, but a few include: Marnie Forster, Gordon Lister, Benyamin Sapiie and students at Institut Teknologi Bandung, Wim Spakman, Theo van Leeuwen, TGS-NOPEC, Fugro (FMCS) and Searcher Seismic.

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Seismic Expression of Geological Features in Seram Sea: Seram Trough, Misool-Onin Ridge and Sedimentary Basin

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Shell International E & P, The Haque, Netherlands

Introduction

The Seram Sea (Figure 1) is located between Seram Island and the Bird's Head of Papua, Eastern Indonesia. This sea extends to the east towards Bintuni Bay. Some part of the sea, between Seram and Misool are deeper than 2000 m. The Seram Island is mountainous with altitudes reaching 3000 m above sea level at the center of the island.

Several seismic surveys have been conducted to understand the geology of this region. The first seismic sections were published by Hamilton in 1979. These seismic sections were acquired by Western Geophysical for Phillips Petroleum. In 2000, Schlumberger published some seismic lines acquired in 1997 with an improved resolution improvement (Blunden, 2000). More higher quality seismic lines were acquired as part of non-exclusive and multi-client projects in the late 1990's which provide a better geological understanding of the region and lead to several petroleum exploration opportunities.

This article discusses the seismic expression of several geological features in the Seram Sea vicinity based on published seismic sections. The offshore seismic sections cover part of the imbricated complex in the north of Seram Island, the Seram Trough, the Misool-Onin High and the sedimentary basins the east of the Misool-Onin Ridge, such as the Tamaloi-Malagot Basin, the Semai-Berau Basin and the Bintuni Basin (Figure 1).

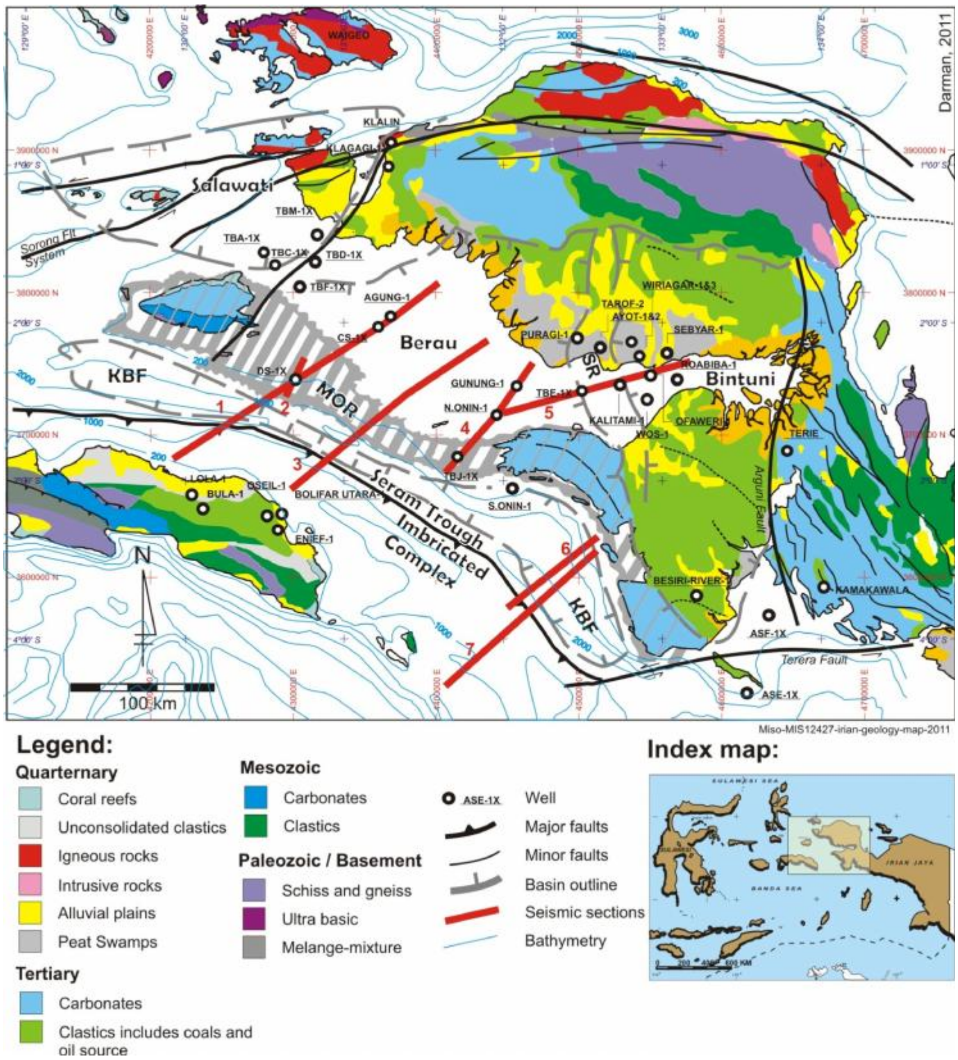

Figure 1. **Regional Geological map of Seram Sea and vicinity, showing the structural elements in this area, outcrops and major faults. Seismic sections discussed in this article is shown in red. Main wells are also displayed as reference. SR = Sekak Ridge; MOR = Misool-Onin Ridge; KBF = Kepala Burung Foreland Basin.**

Misool-Onin Ridge

The Missol-Onin Ridge is a structural high located in the Seram Sea between the island of Seram and the Bird's Head of Papua. This feature is exposed above the sea as the Misool Island in the northwest and the Onin Peninsula in the southeast. This high is truncated by the large Sula-Sorong Fault System in the north and the Terera Fault in the south. Both faults are interpreted as sinistral lateral faults (Figure 1). At present the southern flank of this high forms a steep sea bottom relief towards the Seram Trough but the northern flank has been covered by younger sediments and does not show a significant bathymetric expression.

Several wells have been drilled on the Misool-Onin Ridge. Daram Selatan-1 penetrated the northern part of the Misool-Onin High and TBJ-1X was drilled in the south. Daram Selatan-1 tested a section of more than 1000 m of Triassic age dominated by limestones section (Wongsosantiko & Mertosono, 1996) and TBJ-1X encountered an interval of almost 200 m of Permian clastic and carbonate interval (Fraser et al, 1993).

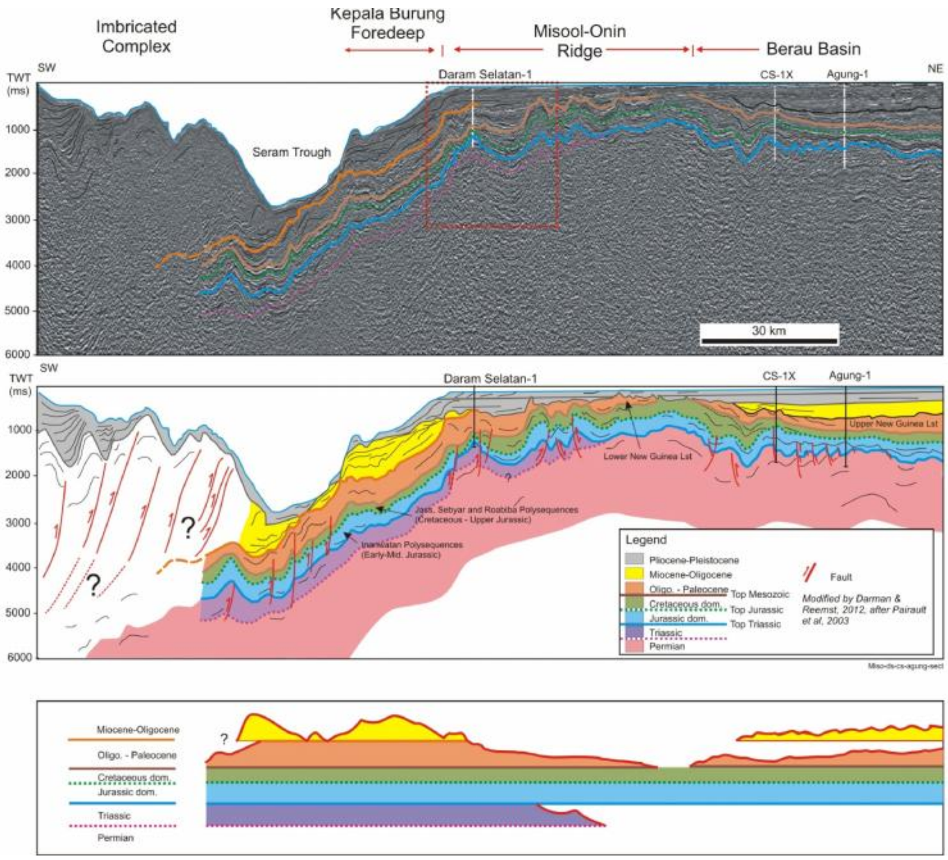

Figure 2. **Section 1 across Seram Sea showing the seismic expression of the imbricated comples, Seram Trough, Kepala Burung Foredeep Basin, Misool-Onin Ridge and Bintuni Basin. CS-1X and Agung-1 well control occur in the north of the section. This section is modified after Pairault et al, 2003.**

Seismic section 1 (Figure 2) located in the western part of the Seram Sea extends from the SW to the NE, and shows the Seram Imbricated Complex, the Seram Trough, the Kepala Burung Foredeep, the Misool Onin Ridge and the Berau Basin. The western part of the Misool-Onin Ridge has been penetrated by the Daram Selatan-1 well. Figure 3 shows a seismic section acquired for Amoseas and processed by Texaco in 1991 (Wongsosantiko and Mertosono, 1996). The structure and stratigraphy is very complex in this area and the seismic is very difficult to interpret as a result of relatively poor data quality. The two sections in figure 3 show the seismic interpretation prior to drilling of well Daram-Selatan-1 and the geological interpretation based on well data such as lithologies and stratigraphic data. The Top Triassic marker was interpreted significantly shallower and the structures are more complex than those in previous interpretations.

The northern part of the Misool-Onin Ridge has been uplifted as indicated by the missing Paleocene-Miocene stratigraphic section . Pliocene-Pleistocene interval covered the whole area. The eastern uplift is also indicated in Section 3 (Figure 4) at the center part of the ridge. Section 1 and 4 (Figure 5) clearly show an unconformity that cuts through the Paleocene – Miocene interval. Section 3 (Figure 4; Blunden, 2000), however, does not show any indication of erosion.

Based on stratigraphic reconstruction of Section 1 and 4 we identify at least two major uplift events in the Misool-Onin High area. The first one is a post Triassic age and is followed by a second event of post Cretaceous to Pleistocene time. Both uplift events mainly took place in the northern part of the ridge (Figure 2 and 4).

Imbricate Complex at North of Seram Island

The Imbricated Complex north of Seram Island and south of Misool-Onin Ridge is characterized by a highly complex fault system that generates poorly image seismic section. Some of the trust faults have been interpreted by Pairault et al. (2003) in Section 1, 3, 6 and 7 (Figure 2, 4 and 7). Steeply dipping thrust faults can be seen on Section 6 and 7. The fault system generated a rough sea bottom and as a result mini basins developed between fault blocks that accommodate Pleistocene-Pliocene sediments (Figure 2)

Blunden (2000) published a detail seismic section of the imbricated complex (Figure 4). Unfortunately the quality of the seismic is poor. Figure 8 shows a higher quality seismic published by Searcher. The reflectors which cross the structures and almost parallel to the sea bottom indicate potential hydrate layers in this area.

Seram Trough

The northwest part of the Seram Trough is relatively narrow compared to the southeast. The deepest part of this trough can reach >2000 m water depth. Recent sediment supply is mainly accommodated the southeastern part of the trough, indicated by flat sea bottom as shown in Figure 7 and 8. Bright amplitude in the northern part of section 6 (Figure 8) is interpreted as a slope failure deposit from the Kepala Burung Foreland in the north.

Differences in thickness of recent sediments deposited in the Seram Trough show that the locus of depocentres changed through time (Figure 8). In some areas in the south sediments are thicker than the north. This suggests active tectonism and rapid deposition in the area.

Kepala Burung Foreland

A foreland basin developed between the Seram Trough and the Misool-Onin Ridge. Generally this tectonic unit covers an area with water depths of about 200 to 2000 meters. Section 1 (Figure 2) shows a structural high in west part of the foreland (Figure 2). Further east, Section 3 shows a simple dipping foreland. Section 6 (Figure 7.A) shows 3 anticlinal features which developed locally. Just south of this section the anticlines disappear and the largest anticline is faulted (Figure7.B).

The structural map in Figure 1 also shows that Section 3 is located in the narrowest foreland area. The foreland developed well in the south of Onin Peninsula.

Berau Basin

The Berau Basin is located north of the Misool-Onin Ridge. Section 1, 3, 4 and 5 dissect this basin. All these sections show a significant unconformity as a result of a major uplift in the south towards the Misool-Onin Ridge and the north. Another major unconformity is shown in Section 1, below the Oligocene-Paleocene unit. This unconformity mainly occurs in the south, close to the Misool-Onin Ridge.

Wells Agung-1 and CS-1X along Section 1 penetrated Tertiary to Permian sedimentary formations deposited in the northern part of the Berau Basin. In the south of the basin, wells North Onin-1 and Gunung-1 encountered a mainly Cenozoic unit but Gunung-1 also went through Permian clastics and carbonates section at the bottom of the hole (Fraser et al, 1993).

Sekak Ridge

The Sekak Ridge is a large anticlinal feature which separates the Berau Basin from the Bintuni Basin. Section 5 (Figure6) shows a seismic profile of this ridge. The ridge has several minor highs, that are penetrated by well TBE-1X and Kalitami-1X. Fraser et al. (1993) called the minor highs Inanwatan and Puragi ridge. Both wells penetrated a Jurassic interval at their deepest levels.TBE-1X found some sandstones with coal fragments and reddish color shale indicating low terrestrial influence (Fraser et al, 1993). Kalitami-1 encountered more sands of a similar depositional setting in a Jurassic interval. The Cretaceous interval of both wells are very shally, deposited in an open marine environment.

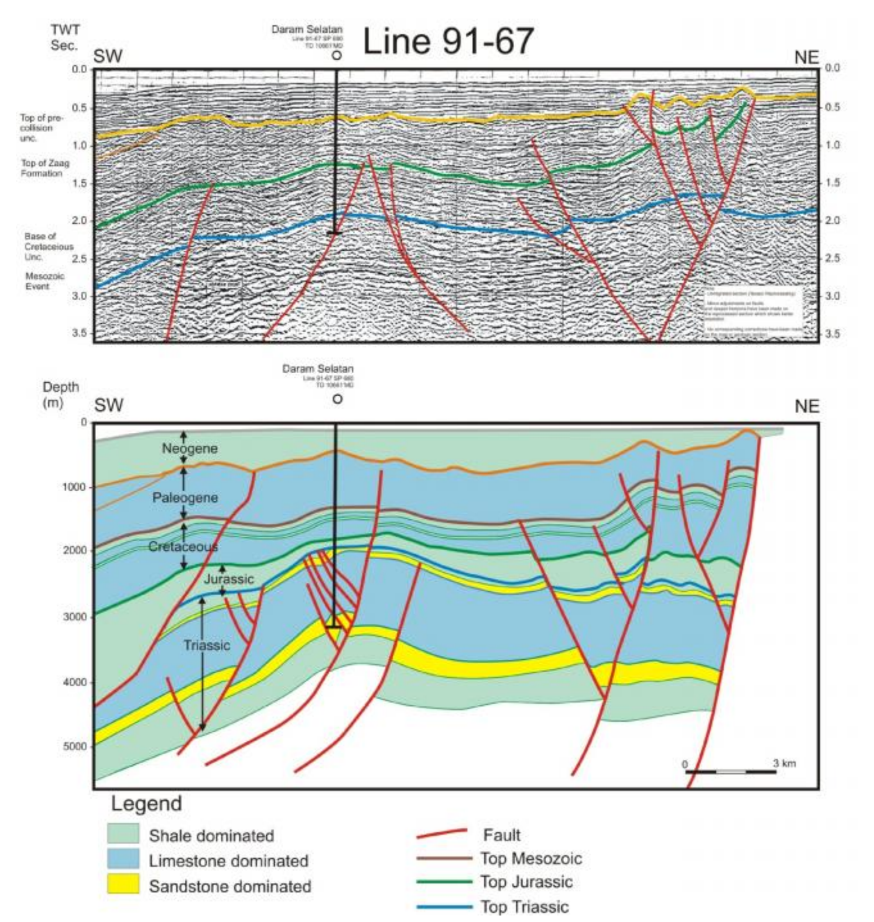

Figure 3. **A detail seismic section across Daram Selatan-1 well acquired by Amoseas. Two interpretations are displayed: A) prior to the drilling result and B) after the drilling result. Note the changes of stratigraphic and structures interpretation (after Wongsosantiko & Mertosono, 1996).**

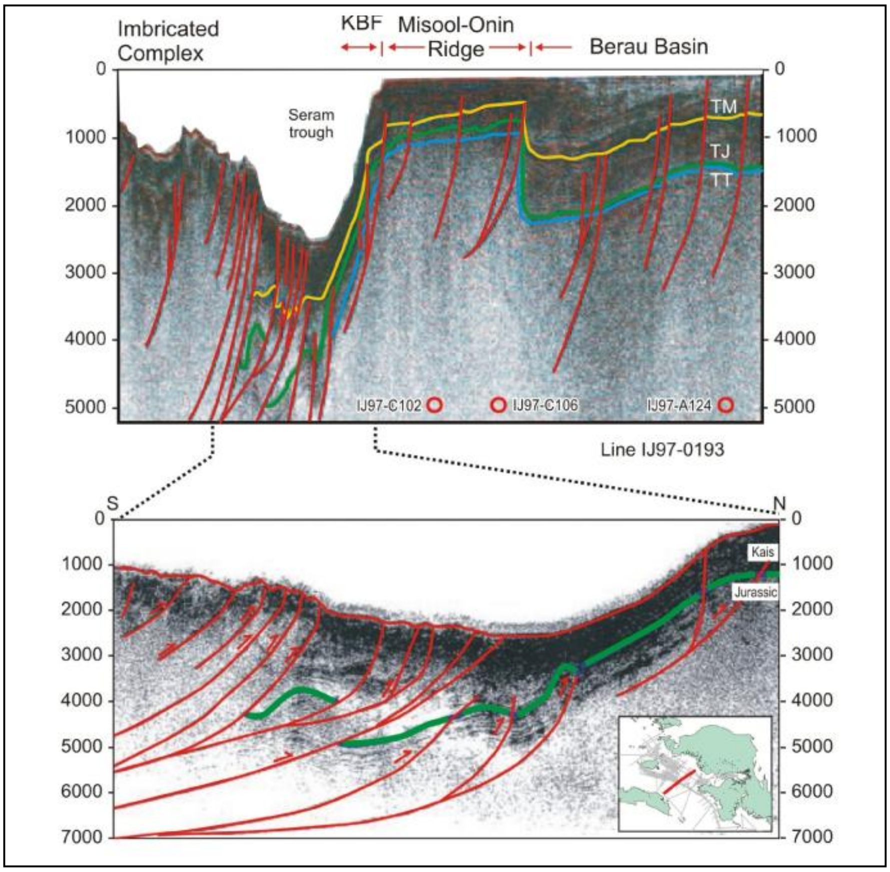

Figure 4. **Seismic section at the center of Misool-Onin Ridge acquired by Schlumberger Geco-Prakla in cooperation with the government of Indonesia in 1997 (after Blunden, 2000)**

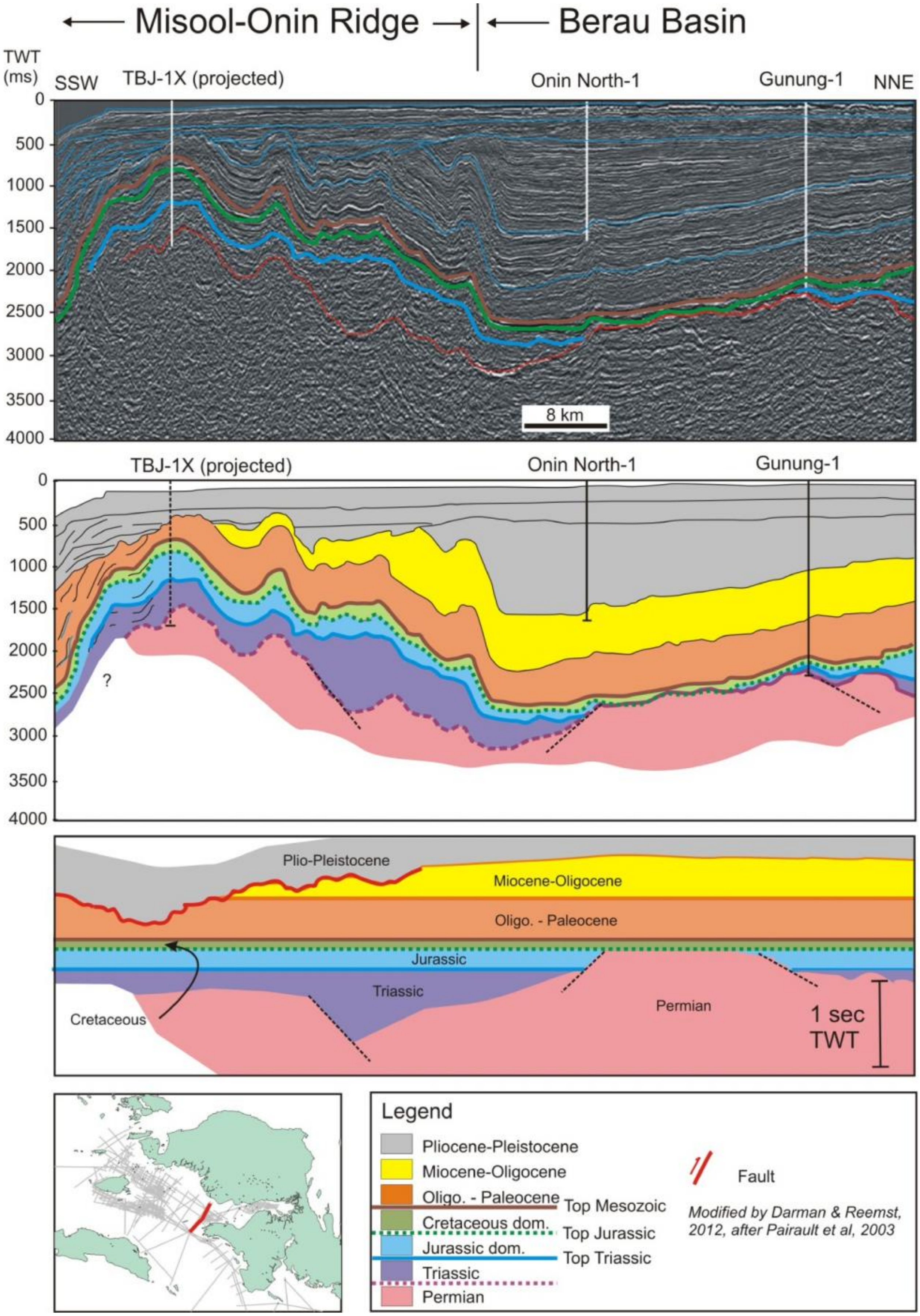

Figure 5. **Section 4, modified after Pairault et al. (2003). The stratigraphic reconstruction shows a Permian paleo high and a tectonic uplift in the Misool-Onin High which caused the erosion of Tertiary section shown as unconformity in the south of the section.**

The northern onshore extension of the Sekak Ridge was penetrated by wells Puragi-1, Tarof-2 and Ayot-1&2. Tarof-2 and Ayot-2 wells also encountered Permian clastics. The Mesozoic interval of Tarof-2 well is dominated by shale, but Ayot-2 well found some limestone. All wells reported the presence of a thick Miocene Kais limestone formation at shallower level.

Bintuni Basin

The sedimentary basin east of the Sekak Ridge is called the Bintuni Basin. This basin contains significant petroleum accumulation as discovered in the Vorwata, Wiriagar, Roabiba and Ofaweri fields. Towards the east, the Bintuni Basin is bounded by the north-south trending Arguni Fault.

Section 5 (Figure 6) shows a seismic section across the western part of the Bintuni Basin. Several structures developed during the Mesozoic but do not continue into the Cenozoic part of the section.

Kepala Burung Foredeep Basin

A foredeep basin developed between the Misool-Onin High and the Seram Trough. This structural unit is shown in Section 1, 3, 6 and 7. Section 1 (Figure 2) in the north of this unit indicates a Miocene-Oligocene remnant but it is not calibrated by any well. Section 3 (Figure 4) shows a relatively steeply dipping Mesozoic interval towards the Seram Trough. Several structures developed in the southern part of this foredeep basin as shown in Section 6 and 7 (Figure 7). Limestone build ups are potentially developed in the Upper Jurassic interval and generated discontinuous strong seismic reflectors. Tertiary deposits in this area have thin and continuous reflectors typical for distal marine deposits that are usually dominated by fine grained clastics (Figure 8). Hydrate layers can also be recognized from the detailed seismic section and indicated low (< 0°C) temperature, which is typical for deep water deposits.

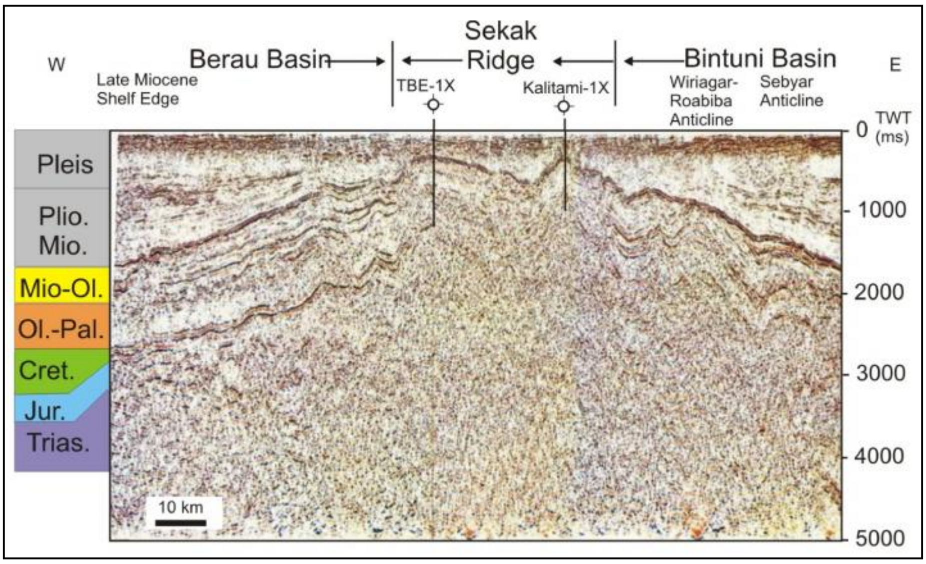

Figure 6. **Section 5 across Berau Basin, Sekak Ridge and Bintuni Basin. TBE-1X is located on Inanwatan Ridge and Kalitami-1X on Puragi Ridge. These ridges are part of larger Sekak Ridge.**

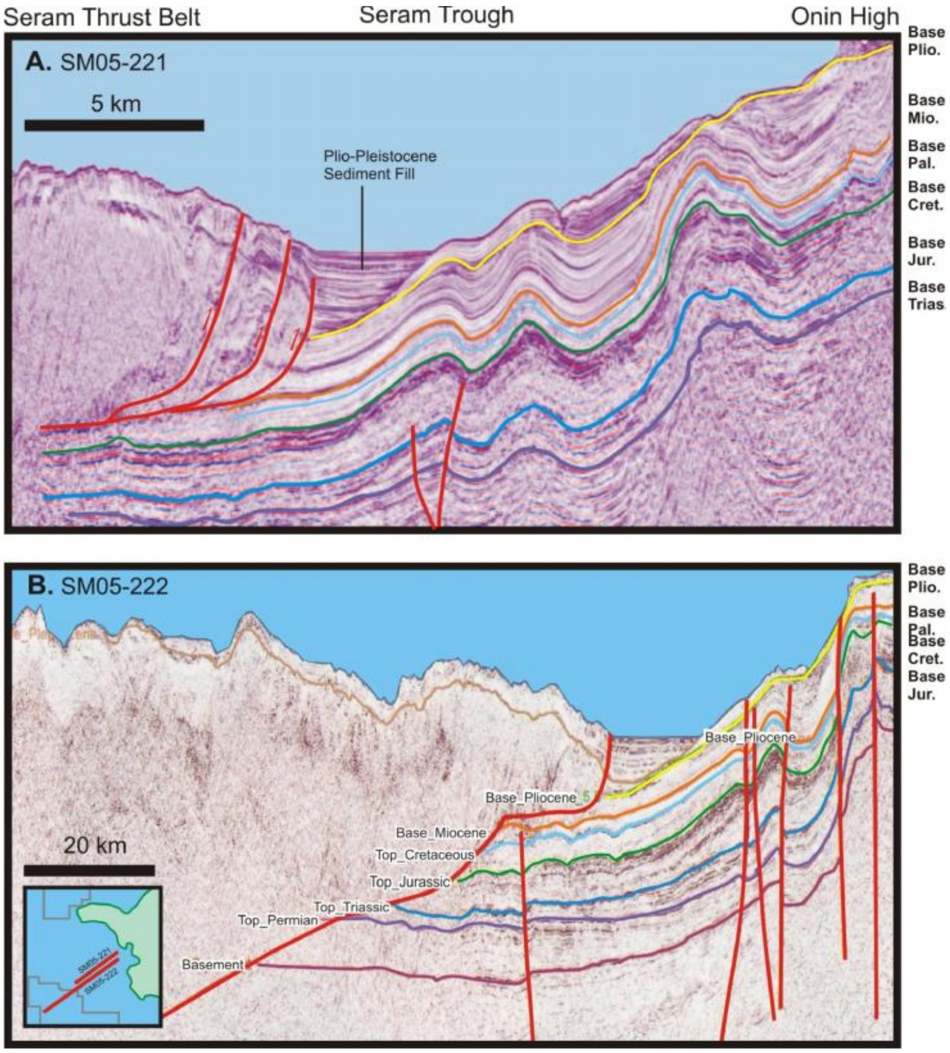

Figure 7. **Two seismic sections acquired by Fugro in the south of Misool-Onin Ridge, covering Kepala Burung Foldbelt system, Seram Trough and the imbricated complex in sourth. Both sections are SW-NE trends. A) SM05-221 section shows 3 large anticlines in the complex. B) SM05-222 covers a larger area of imbricated complex.**

Well South Onin-1 drilled in this basin and reported Upper Cretaceous limestones at bottom hole with minor shale interbeds (Fraser et al, 1993). Slightly shallower the well encountered >500 m thick Paleogene limestone. Although there are some gas shows, the well is unfortunately considered as a dry well.

Seram Trough

A deep flat sea bottom characterizes the southern part of the Seram Trough (Figure 7) indicating a recent sediment fill. In the north, Section 1 (Figure 2) and Section 3 (Figure 4) show a narrow trough with limited recent sediment fill. A strong amplitude anomaly in the north of Section 6 (Figure 8) is an indication of slope failure debris flow deposits came from the north slope of the Kepala Burung Foredeep basin. This section also shows a shift of depocentres as some sediment packages are thicker in the south and some are in the north.

Imbricate Complex at South of Study Area

The Imbricate Complex in the south of the study area is generally seismically poorly imaged due to intensive faulting as shown in Figure 2, 4, 7 and 8. The thrust faults are dipping to the south and some of them are seen on the seismic sections, especially at the front end of this structural unit. Figure 4 and 8 show the detail of the faults.

Small depositional centers developed between fault blocks in the southern part, capturing recent sediments supplied from Seram Island (Figure 2). At the sea bottom the active faults generate a rough bathymetry as seen in Figure 4a and Figure 7. Tighter anticlinal features occur as drag folds as a result of the faulting. This implies that the faults are currently still active.

A potential hydrate layer occurs in this area (Figure 8) as can be interpreted from a reflector parallel to the sea bottom imaged in the south of the section. Several petroleum discoveries were made onshore Seram Island, with the Manusela Jurassic oolithic limestone unit as primary target (see K. Hill article in this volume).

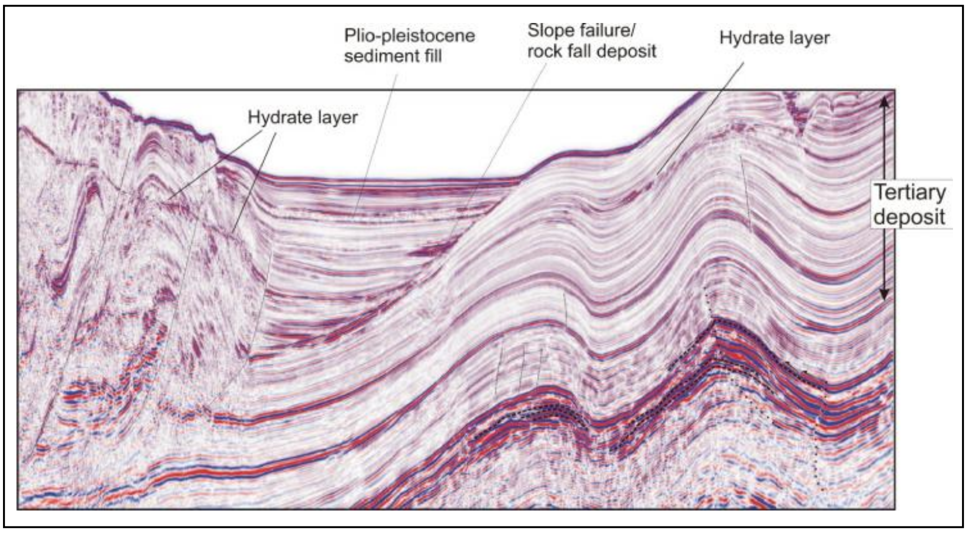

Figure 8. **A detailed section of Figure 7B showing the potential hydrate layer on the left of the section and the two major anticlines on the right. Potentially some limestone developed in the north of the area as shown on this figure.**

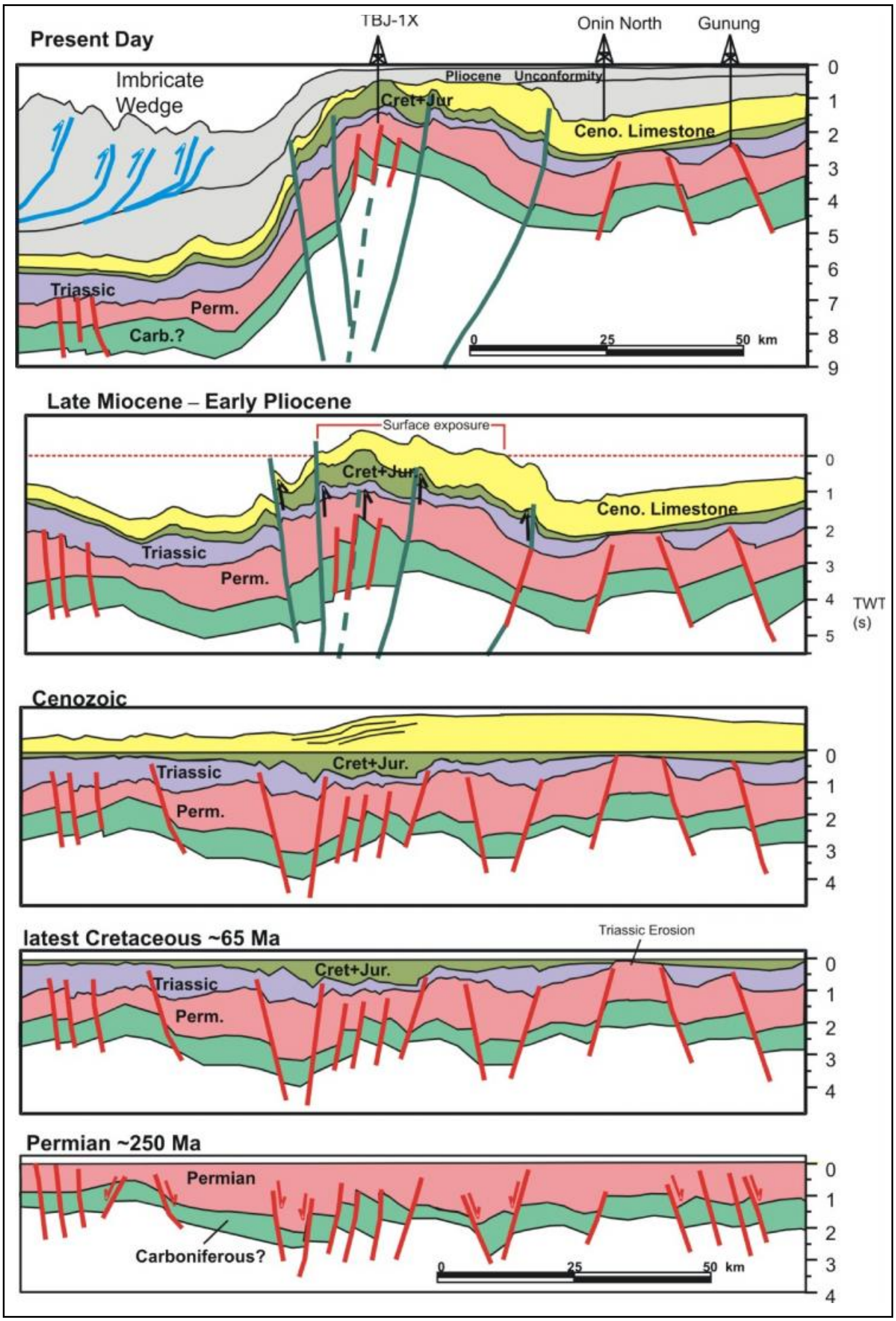

Figure 9. **Structural and depositional reconstruction of Misool-Onin Ridge. Faults are red for normal faults, green for inverted faults and blue for reverse faults. See Figure 5 for location of this section.**

Conclusion

The seismic sections reveal a complex tectono-stratigraphic history of the Seram Sea. Based on the interpretation of several key seismic lines, we propose the following sequence of events:

- Rift related faulting took place over an extensive area during the Permian, followed by partial uplift in the Triassic.
- During the Cenozoic, Paleogene and Miocene limestones developed extensively during this period of time.
- An inversion phase in Late Miocene – Early Pliocene indicated by transpression and folding, and reactivation of older extensional faults. Erosional process developed at the Misool-Onin Ridge during this stage.
- Emplacement of the Imbricate Wedge during Pliocene to Quaternary times.

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Middle Jurassic Ammonites from the Cendrawasih Bay Coast and North Lengguru Fold-Belt, West Papua: Implications of a 'forgotten' 1913 Paper

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ABSTRACT

Occurrences of Middle Jurassic bathyal shales with typical ammonite faunas were reported from the 'Birds Neck', West Papua, in 1913 and 1927 publications but these appear to be largely forgotten. They signify an eastern limit for the gas-productive Middle Jurassic sands of Bintuni Bay and thus have significant negative implications for the potential of Mesozoic hydrocarbon plays in Cenderawasih Bay.

Introduction

Almost 100 years ago, in 1913, German paleontologist Georg Boehm from the University of Freiburg, published a paper on Middle Jurassic ammonites from locations along the coast of Cenderawasih Bay in West Papua's 'Bird's Neck' and from nearby locations in the North Lengguru foldbelt. It is entitled 'Unteres Callovien und Coronaten-Schichten zwischen MacCluer Golf und Geelvink-Bai' (translated: 'Lower Callovian and Coronatus beds between MacCluer Gulf and Geelvink Bay' (MacCluer Gulf= west Bintuni Bay, Geelvink Bay = Cenderawasih Bay). There is no record in the literature that these outcrops have ever been revisited, except probably by NNGPM geologists around the 1950's (Visser and Hermes 1962; Loc. 16 on Encl. 6).

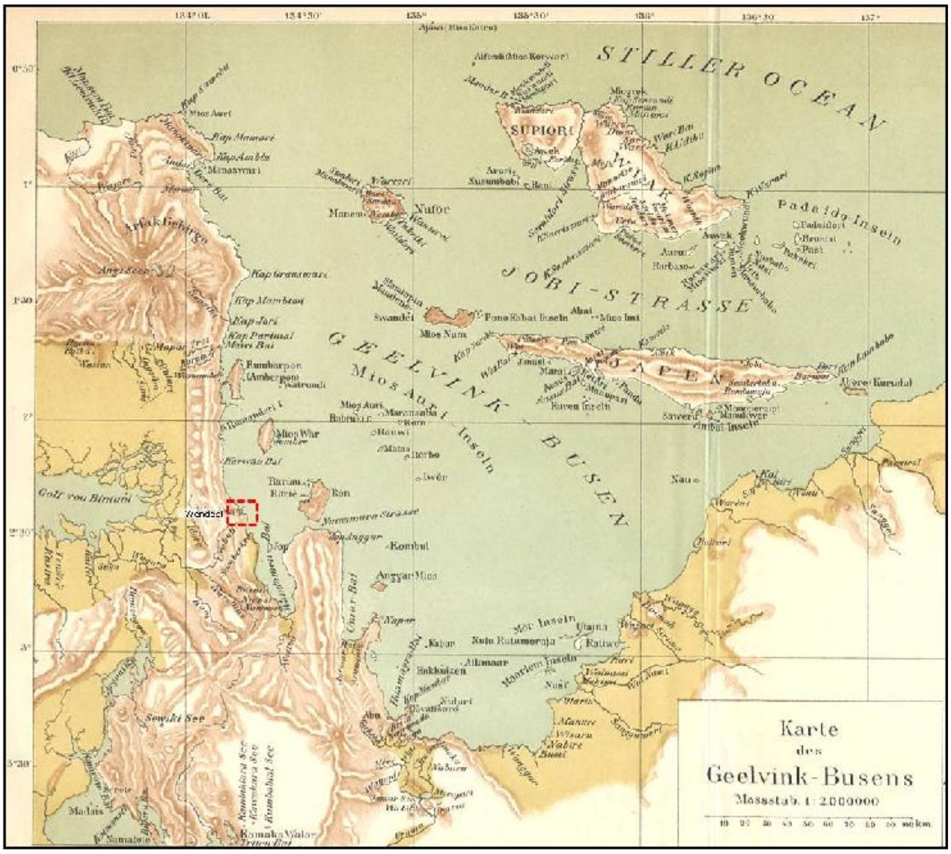


Figure 1. **Overview map of Cenderawasih Bay (then called Geelvink Bay; Wichmann, 1917).**

Most of the ammonites described by Boehm were collected during the 1903 'Dutch scientific expedition to New Guinea in 1903', a 9-month journey along the northern coastal regions of West Papua, led by Arthur Wichmann, professor of geology and geography at the University of Utrecht, Netherlands. Additional, similar Middle Jurassic ammonite material was available from material collected by BPM geologist, Hirschi, around 1906 from localities farther inland, west of the main divide of the northern outliers of the Lengguru foldbelt. All fossil material ended up in the collections of the University of Utrecht.

Boehm (1913) claimed that this paper was the first record of ammonites from New Guinea Island that could be reliably dated, although Etheridge (1889) had already reported similar ammonite finds at the Strickland River of Papua New Guinea. Similar ammonite faunas were also known from Taliabu and Mangoli in the Sula islands of eastern Indonesia (Boehm 1912).

A later paper by Gerth (1927) entitled 'A new occurrence of the bathyal cephalopod facies of the Middle Jurassic in Netherlands New Guinea' largely confirms the Boehm results. It describes a collection of Middle Jurassic ammonites collected by a Dutch government official from Fakfak. Unfortunately, location information is very poor, only described as Wairor River and its Weriangki tributary, supposedly near Fak Fak. Ammonites are from geodes in hard black limestone, and species are similar to those from Cenderawasih Bay and the Sula islands.

The Boehm (1913) paper now appears to be largely forgotten, but the presence of Middle Jurassic open marine black shales is an important control point in paleogeographic reconstructions of the region, and may be particularly relevant to the distribution and provenance of the presumably age-equivalent gas reservoir sandstones of the Tangguh complex of Bintuni Bay.

Localities

Several localities were mentioned by Boehm (1913), but not described in great detail. More details can be found in the lengthy report of the 1903 North New Guinea expedition by Wichmann (1917). There are some inconsistencies between the Boehm (1913) and Wichmann (1917) maps of the Wendesi area. We assume the Wichmann maps are the more accurate ones (Figures 1, 2).

The richest ammonite assemblages were collected along the Mamapiri and Papararo and creeks, SE of the coastal village of Wendesi (Figure 2). The Mamapiri Creek assemblages are particularly rich, probably belonging to multiple horizons, and include up to 30 cm large specimens of *Phylloceras mamapiricum* n.sp. Most of the ammonite material was not collected in situ, but as float in the riverbeds. Wichmann described the few small outcrops in Mamapiri creek as steeply dipping dark shales (Wichmann 1917, p. 343).

Rocks are described as black, very fine-grained, hard calcareous marl at Mamapiri and as non-calcareous, slightly metamorphic shaly claystone at Papararo. Most of the ammonites are in non-calcareous black geodes. At Mamapiri the ammonites are typically undeformed, only a few are clearly squeezed. At Papararo creek almost all ammonites are more or less deformed.

Similar Jurassic ammonite material was collected farther inland by BPM geologist Hirschi, around 1906, west of the main divide of the northern outliers of the Lengguru foldbelt. The locality is named Aramasa and was described as steeply dipping dark shales from 'the western foot of the Wiwi Mountains, specifically from a right tributary of the upper Aramasa called Urubate' (Figure 3). This locality description is rather vague and it will probably be difficult to re-locate the site, but it does suggest that Middle Jurassic open marine shaly facies are present inland near the Northern termination of the Lengguru foldbelt as well.

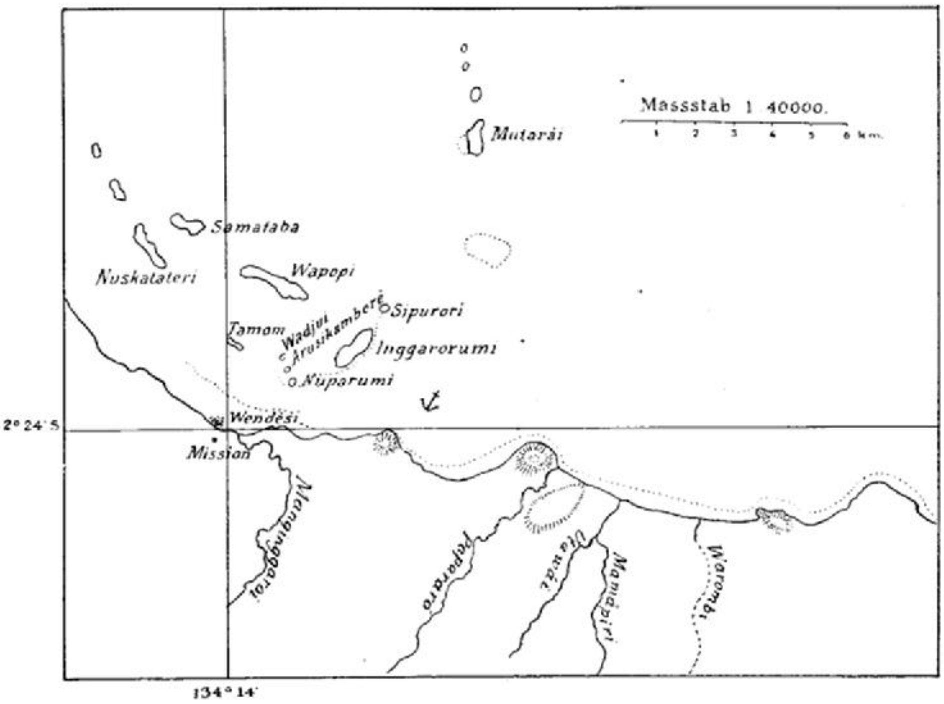


Figure 2. **Map of Wendesi area, showing Mamapiri and Paporaro creeks (Wichmann, 1917).**

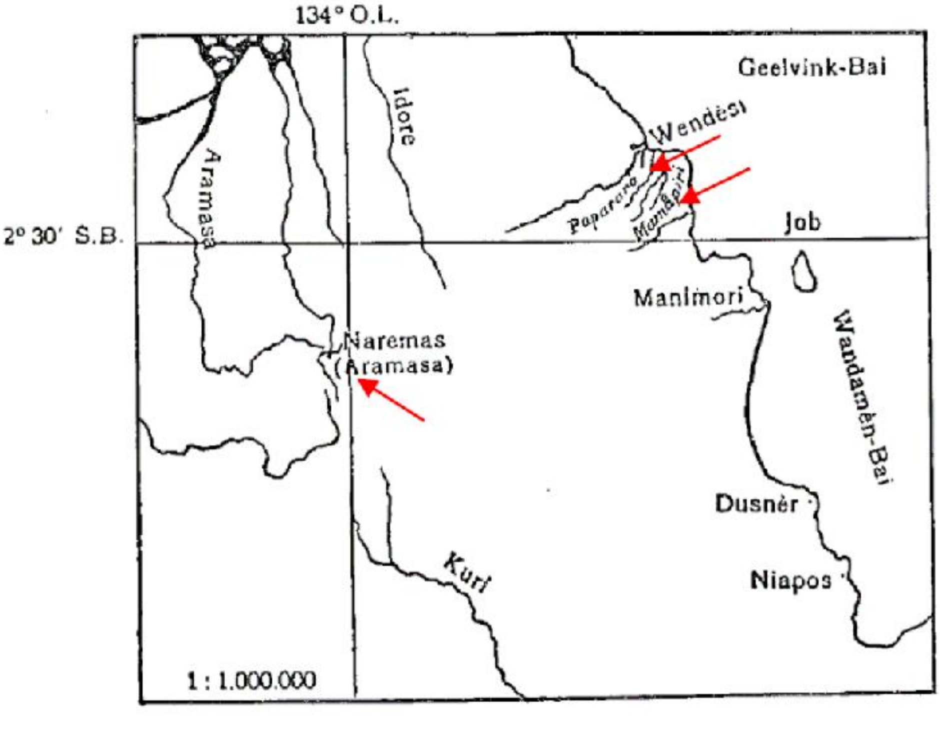


Figure 3. **Locality map of Boehm (1913), showing Wendesi area localities of Wichmann and upper Aramasa area, where Hirschi collected Middle Jurassic ammonites.**

Faunas

The macrofaunas are composed mainly of ammonites (Figures 4, 5), some quite large (30 cm). They are associated with rare and poorly preserved canaliculate belemnites, brachiopods (*Rhynchonella* aff. *moluccana*) and bivalve mollusks.

Ammonite assemblages are dominated by species of the subfamily Macrocephalitinae and the older, but morphologically similar subfamily Sphaeroceratinae. Dominant species are *Macrocephalites keeuwensis* and *Phylloceras mamapiricum*.

Boehm grouped many of the *Macrocephalites* species in informally named varieties of *M. keeuwensis*, a species he first described from the Sula Islands in 1912. Taxonomy of this group is somewhat difficult; genus and species names have been revised multiple times (see e.g. Kruizinga 1926, Westermann and Getty 1970, Westermann and Callomon 1990).

Westermann and Callomon (1990) described a new genus and species of Sphaeroceratidae, named *Satoceras satoi*, which is quite abundant at the Mamapiri locality (= *Macrocephalites keeuwensis* B of Boehm 1913?)

Age

Boehm (1913) recognized the Cenderawasih Bay/ N Lengguru ammonites as Middle Jurassic species, assigning them to the Lower Callovian and 'Coronatenschichten' (an old German term for Bajocian). Westermann and Getty (1970) in their description of ammonite assemblages from the West Papua Central Range, revised some of the genus/ species names of Boehm (1913), but essentially concurred with Boehm's Bajocian to Early-Middle Callovian age assignments (Fig. 6).

The ammonite faunas described by Gerth (1927) from the Werianki River (Fakfak District?) contain *Macrocephalites keeuwensis*, *Sphaeroceras* cf. *bullatum* and *Peltoceras*, suggesting an Early Callovian age. From the Wairori River two *Stephonoceras* species indicate a probable Bajocian age

Other localities on New Guinea and depositional/ paleotectonic position

Since the Boehm (1913) and Gerth (1927) papers, additional occurrences of similar Middle Jurassic ammonite assemblages were reported from the Birds Neck/ Cenderawasih region by Donovan (in Visser and Hermes, 1962; Roemberpon Island and South Cenderawasih Bay/SE Lengguru).

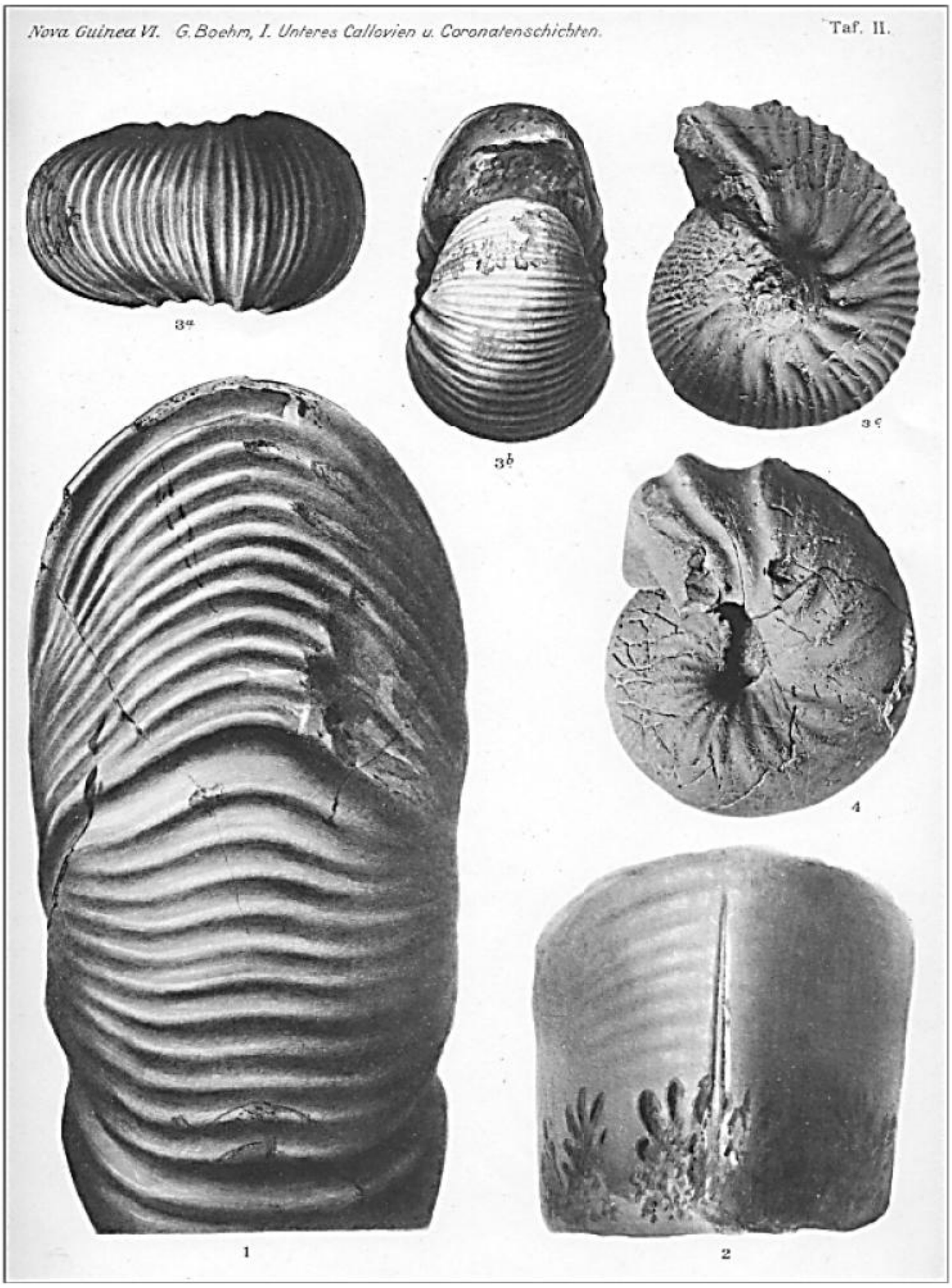


Figure 4. **Plate 2 of Boehm (1913), showing '*Phylloceras mamapiricum* n.sp.' (figs. 1-2; re-assigned to *Holcophylloceras indicum* by Westermann and Callomon 1990) and '*Sphaerocers cf submicrostomata* (figs. 3-4; re-assigned to *Sphaeroceras boehmi* by Westermann 1956).**

Similar Middle Jurassic ammonite faunas have subsequently been reported from the Central Range of New Guinea, in both in West Papua (Gerth 1965, Westermann and Getty 1970, Helmcke et al. 1978, Westermann and Callomon 1990) and in Papua New Guinea (Etheridge 1889) (Fig. 7). I also observed these in river float North of Wamena/ Tiom. Like at the Cenderawasih Bay locations, the ammonites are found in nodules in black shales and are generally well preserved.

Depositional/ paleotectonic setting

Observations made on the Middle Jurassic *Macrocephalites* shales of the 'Lower Kembelangan Formation' in the Papua Central Range foldbelt include:

1. The outcrops are limited to the northernmost part of the foldbelt, well north of the topographic divide, and immediately south of the Miocene collisional suture zone between the Australian- New Guinea continental plate (south) and the belts of metamorphics, ophiolites and Pacific oceanic and arc terranes (north);

2. These black shales are clearly bathyal marine facies;
3. Age range shows these are a distal facies equivalent of the widespread Middle Jurassic 'Plover'/Tangguh reservoir sandstones. Whether they were deposited on a distal passive margin or within a deepening marine rift setting that subsequently became a passive margin after oceanic break-up, is not clear;
4. The ammonite shales are invariably steeply dipping and highly deformed. They also become gradually more metamorphic to the north, towards the ophiolite belt and much of the metamorphic rock is probably metamorphosed Kembelangan Formation sediment (Visser and Hermes 1962, Cloos et al. 2005, personal observation during Pertamina-Esso 1991 joint study fieldwork). They therefore represent the outer margin of the New Guinea sector of the Australian continental margin prior to Miocene collision with the N-dipping subduction zone of a Pacific volcanic arc system. The collision then caused the accretionary prism-style deformation of sediments and the 'metamorphic sole' below obducted ophiolite.

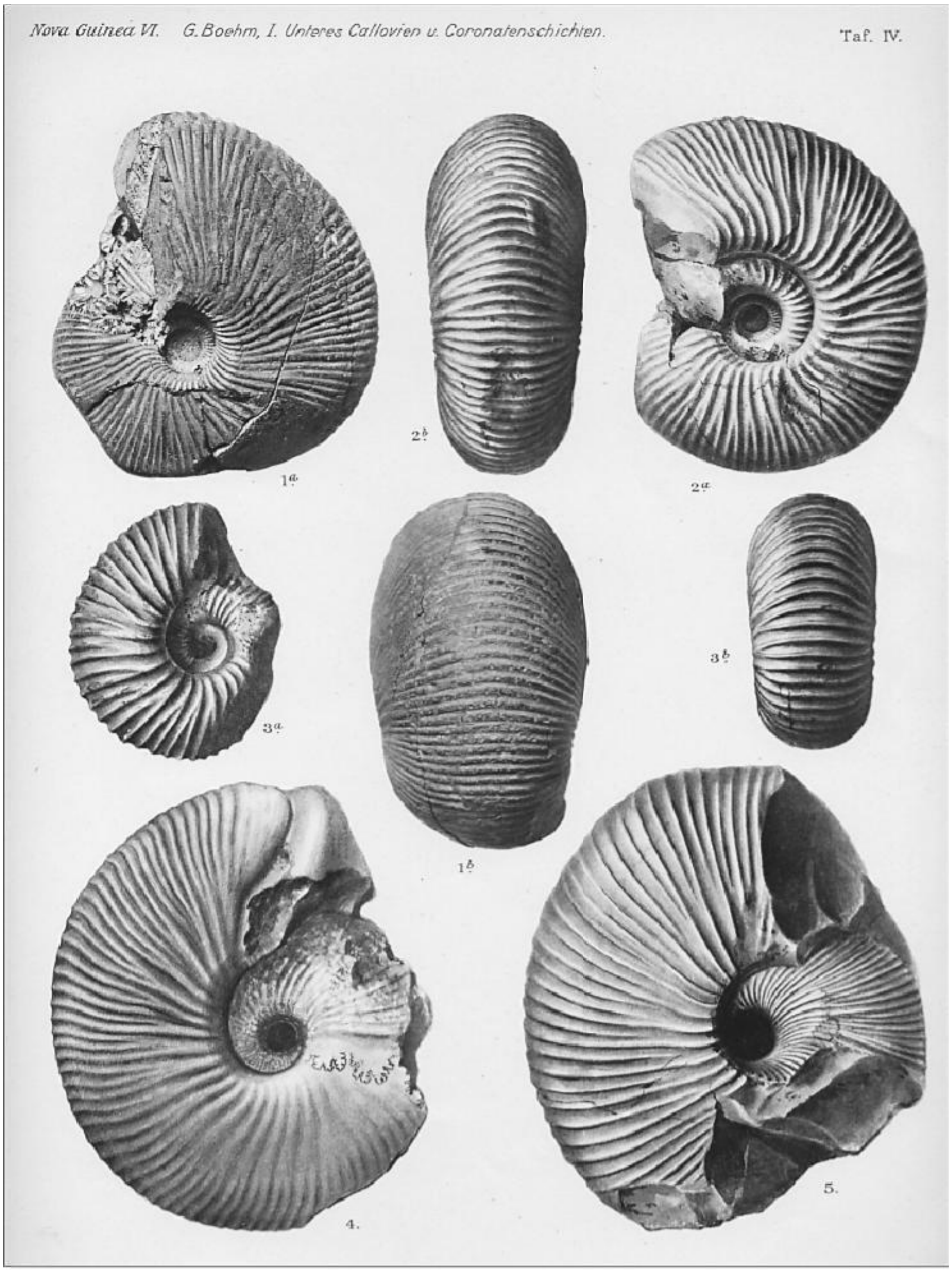


Figure 5. **Plate IV of Boehm (1913), showing his *Macrocephalites keeuwensis* varieties y (figs. 1-3) and B (figs. 4-5), species characteristic of 'North Gondwana' Early Callovian. *M. keeuwensis* variety B was renamed *Satoceras satoi* by Westermann and Callomon (1990).**

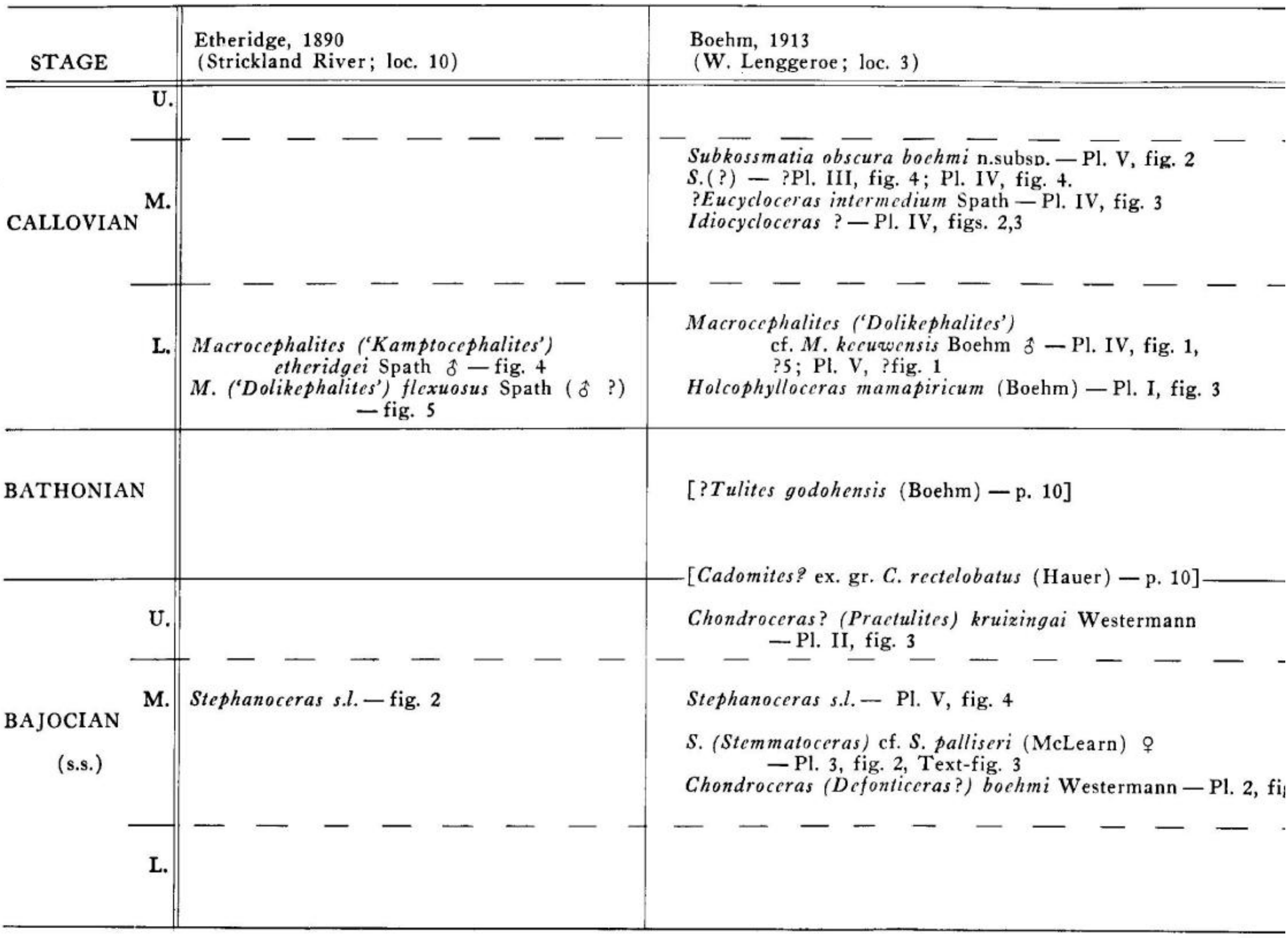
Distribution of 'Macrocephalites fauna' outside New Guinea and biogeographic significance

The classic Middle Jurassic *Macrocephalites*-dominated ammonite assemblages from New Guinea and Sula islands are of relatively low diversity and are very similar across the area. Several genera *(Satoceras, Irianites)* and species of this fauna are endemic to East Indonesia- New Guinea. This typical ammonite fauna differs from Middle Jurassic ammonite assemblages from low-latitude Tethys regions like the Mediterranean. Westermann and Callomon (1990) suggested they were a group that flourished in temperate, southern latitudes, perhaps around 35°-40°S or between ~30°-60° S as shown on the restoration in Westermann (2000).

The '*Macrocephalites* fauna' characterizes a distinct biogeographic province, variously named 'Gondwanan-Tethyan', 'Austral- Indo-Pacific', 'Indo-SW Pacific', 'Himalayan', etc. This province can be traced from Nepal/ Tibet in the Himalayas through East Indonesia- New Guinea and possibly east to New Zealand (Uhlig 1911, Enay and Cariou 1997, 1999, Westermann 2000, etc.). On a Middle Jurassic restored map all these occurrences elegantly line up along the northern/ eastern margin of Gondwana, from the North India margin in the west, around the NW Australia- New Guinea margin and farther East (Fig. 8).

Occurrences of '*Macrocephalites* fauna' in Eastern Indonesia outside New Guinea include:

1. Taliabu and Mangoli, Sula Islands (Boehm 1912, Kruizinga 1925)
2. Obi (*Phylloceras, Stephanoceras, Macrocephalites* from concretions in phyllitic shales on SW Obi Besar, indicating Bajocian–Early Callovian; Brouwer 1924)
3. Rote (Roti, Rotti): rare *Macrocephalites compressus* and *Stephanoceras* from a mud volcano in NE Rote. (Boehm in Verbeek 1908, Krumbeck 1922) (some authors argued that this may be part of an allochtonous block, not necessarily part of the present-day Australia NW Shelf margin).



STAGE		Etheridge, 1890 (Strickland River; loc. 10)	Boehm, 1913 (W. Lenggeroe; loc. 3)
CALLOVIAN	U.		
	M.		*Subkossmatia obscura boehmi* n.subsp. — Pl. V, fig. 2 *S.*(?) — ?Pl. III, fig. 4; Pl. IV, fig. 4. ?*Eucycloceras intermedium* Spath — Pl. IV, fig. 3 *Idiocycloceras* ? — Pl. IV, figs. 2,3
	L.	*Macrocephalites* (*'Kamptocephalites'*) *etheridgei* Spath ♂ — fig. 4 *M.* (*'Dolikephalites'*) *flexuosus* Spath (♂ ?) — fig. 5	*Macrocephalites* (*'Dolikephalites'*) cf. *M. keeuwensis* Boehm ♂ — Pl. IV, fig. 1, ?5; Pl. V, ?fig. 1 *Holcophylloceras mamapiricum* (Boehm) — Pl. I, fig. 3
BATHONIAN			[?*Tulites godohensis* (Boehm) — p. 10] [*Cadomites?* ex. gr. *C. rectelobatus* (Hauer) — p. 10]
BAJOCIAN (s.s.)	U.		*Chondroceras?* (*Praetulites*) *kruizingai* Westermann — Pl. II, fig. 3
	M.	*Stephanoceras s.l.* — fig. 2	*Stephanoceras s.l.* — Pl. V, fig. 4 *S.* (*Stemmatoceras*) cf. *S. palliseri* (McLearn) ♀ — Pl. 3, fig. 2, Text-fig. 3 *Chondroceras* (*Defonticeras?*) *boehmi* Westermann — Pl. 2, fi
	L.		

Figure 6. **Taxonomic revision of species described by Boehm (1913) with age interpretation by Westermann and Getty (1970). Specimens from Mamapiri placed here in *Subkossmattia boehmi* were originally described by Boehm (1913) as *Macrocephalites keeuwensis var. y.*, then renamed *Satoceras boehmi* by Westermann and Callomon (1990).**

4. Babar Island: *Macrocephalites* fauna ammonites from outcrop and mud volcano material, dominated by *Satoceras satoi* (Callomon and Rose 2000) (also subject to the allochtonous-autochtonous debate).

Macrocephalites faunas have never been reported from West Indonesia (Sumatra, NW Kalimantan) or the Indochina/Malay Peninsula area (e.g. Sato 1975). Marine Middle Jurassic deposits are present in these places, but whether the absence of *Macrocephalites* fauna reflects different paleogeographic positions (more equatorial) or whether these deposits are not of exactly the right age and facies, remains to be determined.

Macrocephalites faunas have also not been reported from other East Indonesia islands with Jurassic sediments. Misool and Timor do have Middle Jurassic marine sediments, but probably not in the right facies (too shallow?). Buton, Buru and Seram have marine Early and Late Jurassic sediments, but Middle Jurassic sediments appear to be very thin or absent, which was interpreted as the expression of a 'breakup unformity' by Pigram and Panggabean (1984)

Conclusions/ implications of the Boehm (1913) paper

1. Distal continental margin setting?
The Middle Jurassic ammonite-rich black shales described above from the Birds Neck/Cenderawasih Bay clearly represent a relatively distal, deep and open marine facies. They are very similar in lithology, fauna and deformational history to the ammonite-bearing 'Kembelangan Formation' black shales in the northernmost part of the Central Range fold-thrust belt and are also situated adjacent to a belt of young metamorphic rocks (Wandamen Metamorphic complex). It is very tempting to also interpret the Cenderawasih- North Lengguru localities as part of the outermost zone of sediments along the Jurassic Australian-New Guinea passive margin, which became the frontal collision zone in the Neogene.

2. Nature of Cenderawasih Bay basement
If the Cenderawasih/North Lengguru bathyal Middle Jurassic ammonite shales do indeed represent distal Australia-New Guinea continental margin clastics, it is unlikely that there is much, or any, Australian continental crust outboard of this (Cenderawasih Bay). The traditional view that Cenderawasih Bay is underlain by North New Guinea-equivalent volcanic arc and oceanic terranes that originated in the Pacific realm, perhaps with a fringe of metamorphics and ophiolites (e.g. Dow and Hartono, 1982), appears more likely than a floor of continental crust, as argued in some recent papers

(e.g. Sapiie et al., 2010). Sula-like microcontinental blocks that rifted off the New Guinea margin in Jurassic or Cretaceous time may be present here, but no direct continuation of the Mesozoic 'Plover' hydrocarbon plays of Bintuni Bay/ Australia-New Guinea margin should be expected here.

3. Bintuni Bay- Birds Head Middle Jurassic sandstone distribution models

The Bajocian- Middle Callovian age range of the ammonite-bearing shales appears to be of the same that of the principal gas reservoir sandstones in the Tangguh field complex of Bintuni Bay (Roabiba Sand, etc.). These marginal marine- shallow marine, quartzose sandstones are compositionally and texturally mature and generally interpreted to be derived from a cratonic source (Australia-New Guinea). They may be compared to the widespread Middle Jurassic sandstones of the Australian NW Shelf, known as Plover Formation.

Decker et al (2009, Fig. 15) proposed a model for the Early-Middle Jurassic Tangguh reservoir sands in Bintuni Bay. It shows deposition confined within an extensive E-W trending 'incised valley', with Early–Middle Jurassic shallow marine-non marine sand systems backstepping towards a provenance area in the East. However, the Boehm (1913) and other papers document control points east of that 'valley' system, where Middle Jurassic is represented by distal marine shales. This shows that this part of the Birds Neck is not in the sand fairway that fed the Bintuni Bay Tangguh sands and that the Cenderawasih Bay-North Lengguru area was not part of the provenance area for these quartzose sediments in Jurassic time. Therefore, this Bintuni Bay sand distribution model can only be correct if some structural discontinuity (terrane boundary or a major transcurrent fault) is invoked between the Birds Head/Bintuni Bay block and the Cenderawasih Bay-North Lengguru area, as indeed suggested by Decker et al. (2009).

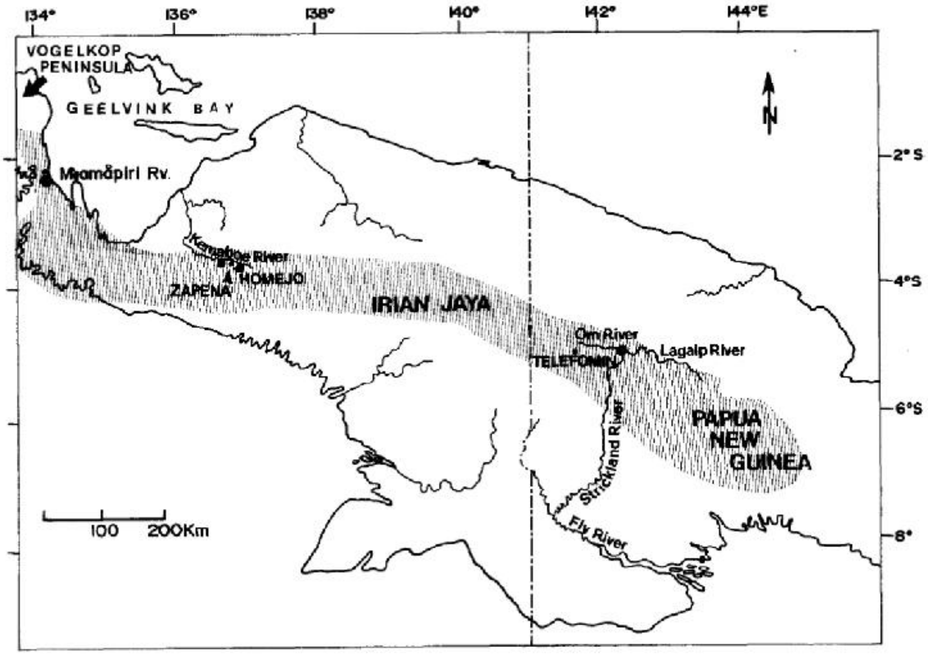


Figure 7. **Outcrop localities with Middle Jurassic ammonites, New Guinea island (Westermann and Callomon 1990) (not showing all known localities)**

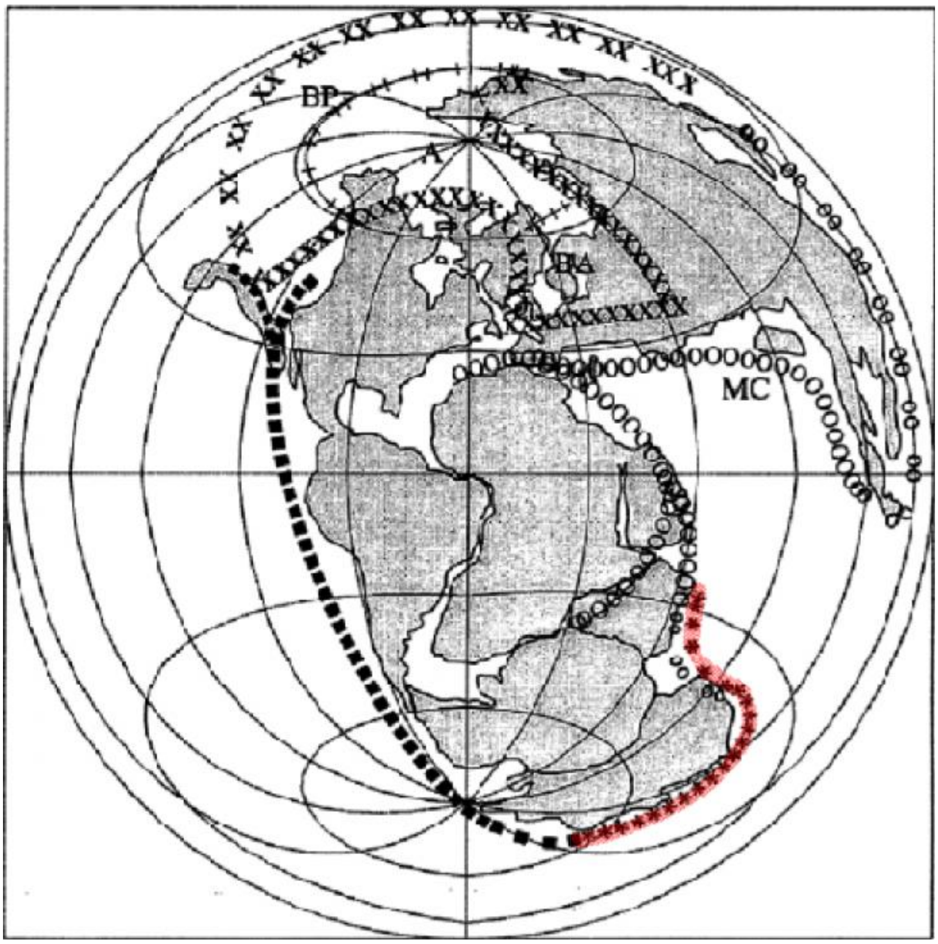


Figure 8. **Restoration at Bathonian time, showing Middle Jurassic ammonite paleogeographic realms (Westermann 2000). Highlighted in red is the belt of the *Macrocephalites*-dominated 'Austral-Indo Pacific Realm', which is known from Nepal, the NW Australia- New Guinea margin and possibly New Zealand, and which restores nicely as a continuous zone along the North/ East Gondwana margin, in temperate-latitudes.**

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Interplay between Submarine Depositional Processes and Recent Tectonics in the Biak Basin, Western Papua, Eastern Indonesia

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ABSTRACT

The offshore Biak Basin between Biak and Yapen Islands is a transtensional pull-apart basin. Deposition along basin margins is strongly influenced by active faulting. The bathymetric map of the basin shows submarine depositional processes occurred during relatively recent tectonic activity.

Introduction

The Biak Basin is located in Eastern Indonesia, Papua Province, between Biak and Yapen islands. The area is characterised by a complex tectonic history, being located in the oblique collision zone between the Australian and Pacific Plates. A major strike-slip system, the Sorong – Yapen Fault Zone, bounds the basin to the south (Figure 1).

The basin is a frontier area for oil and gas exploration and offshore data are very limited. As a consequence, the origin and evolution of this basin is still poorly known. Recently acquired offshore data can help constrain the history of this basin. In this study, we use suite of high-resolution bathymetric data acquired in the area by TGS (2007). These data allow detailed seabed imaging and thorough mapping of the various morpho-structural surface features observed in this tectonically active area (Figure 2).

On the seabed, fault lineaments and fold axes have been identified, together with submarine depositional features and their generating processes. The deformation is dominated by the presence of the Sorong-Yapen fault zone. Modern earthquake activity revealed by public domain data on focal mechanisms (Ekstrom, 2006) highlights remarkable consistency among earthquake mechanisms and some of the morpho-structural features mapped on the seafloor.

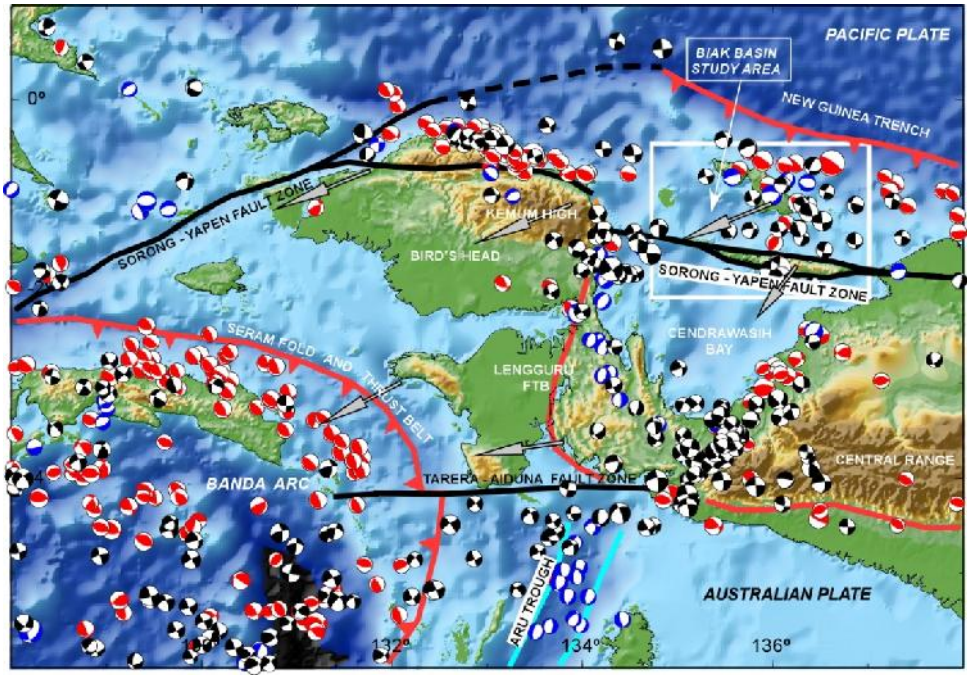

Figure 1. **Tectonic setting and structural elements of the West Papua area. Seabed and digital elevation model are from Gebco database (http://www.gebco.net/). Public domain data on earthquake focal mechanisms show recent seismic activity (from Ekstrom, 2006 http://www.globalcmt.org/). Color keys: black represents strike-slip, red and blue represent compressional and extensional mechanisms, respectively. The main fault zones are color-coded in the same way as the earthquakes focals. Grey arrows represent GPS motions relative to Australia (from Stevens *et. al*., 2002).**

Earthquake activity seems to be focused in the N and E flanks of the basin, where a series of fault scarps and associated deposits are observed. In other areas, where no earthquake activity has been registered (especially to the W and SW), deformation could be accommodated by plastic processes (e.g. seabed creeping). This allows us to draw conclusions on the general tectonic setting of the area, and eventually lead to a better understanding of the evolution of the Biak basin.

Submarine Depositional processes

The Biak basin is a semi-enclosed basin covering an area of *ca.* 4000 sq km in its central part, with water depth reaching over 1100m (Figure 2). The basin is connected to the Yapen Strait through a narrow corridor to the south-east and to the Pacific Ocean to the west, through a broader seaway, between the Biak and the Numfor Islands (Figure 1). The basin appears relatively sediment-starved with dominant deep water clastic deposition; carbonates develop on its margins and volcanic deposits are also locally observed and they outcrop on the nearby islands. The basin margin slopes are variable and range from few degrees in the W and SW, to relatively steep (5 to 15 degrees) on the NE and

E slopes. Sediment accumulation patterns in the basin vary and are normally associated with the different slope angles. The main deposits and processes observed are:

- Well-defined mounded bodies with lobular shape in plan view, either in isolated or coalescent configuration, located at abrupt decrease in gradient from the high angle slopes to the basin (Figures 3 and 4). The mounded bodies are interpreted as clastic lobes originated by re-sedimentation processes. Clastic lobes (Figure 3) are constructional depositional bodies developed downstream of points where laterally confined flows from the feeder channels expand (e.g. Stow *et al*., 1999). The shape and direction of the lobes suggest that they are fed from the north, where they are bounded by a series of semi-circular NW-SE scarps (Figure 3). The scarps represent major erosional features in the basin. Erosional activity is also documented by incisional episodes on top of the lobes and large blocks deposited in their most marginal parts (blue dashed lines in Figure 3).

  Figure 4 shows a belt of multiple adjacent lobes, forming a linear, slope-parallel apron, 20km long and between 3km (lateral) to 8 km (central) wide from scarp to base of slope. The described slope apron is directly associated with a series of parallel linear features observed on the seabed. These morphostructures are interpreted as terraced fault scarps and represent the likely linear source for the apron. The overlapping and coalescing series of lobes composing the apron suggest different phases of fault scarp activity that seems to be concentrated in the central part of the apron.

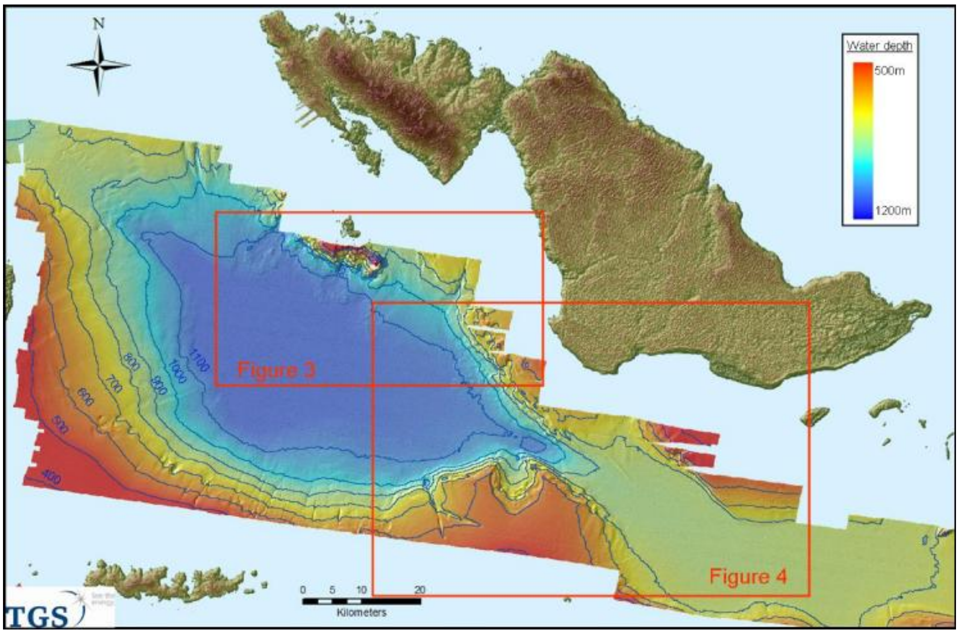

Figure 2. **Gridded multibeam data showing details of seabed morphology in the Biak Basin (data from TGS). Contour interval is 100m. Digital elevation model is from Aster Global Digital Elevation Model (GDEM) (http://www.gdem.aster.ersdac.or.jp/)**

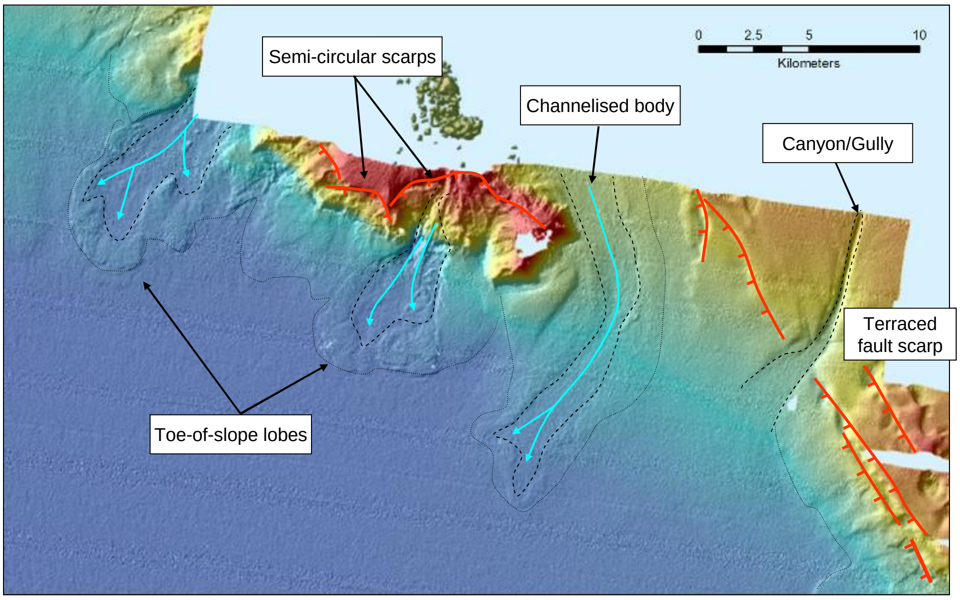

Figure 3. **Details of morphostructural interpretation of seabed in the northern part of Biak Basin (See Figure 2 for location). Note the presence of clastic lobes adjacent to semi-circular scarps, and toe-of-slope deposits developed at the end of a channelised**

- An aerially extensive circular crater-like structure (Figure 4) rimmed by an arcuate, crescent-moon shape feature, open to the N and bounded at the flank by small scale circular scarps. The maximum relief observed at the centre of this crater is *ca.* 300m, and diameter reaches nearly 10km. The typically concave-upwards subcircular shape and associated curved scarps resembles that of collapse structures (e.g. Stewart, 1999). Analogous arcuate-shaped escarpments interpreted as repeated slope failure episodes at the edge of a carbonate platform have been described by Ten Brink *et al.* (2006) offshore Puerto Rico. Possibly, this structure is associated with subcropping carbonate units and differential compaction of overlying deep-water sediments. Additionally, we observed a series of straight slope gullies, V-shaped in section, on the slope to the west of the circular collapse structure.

- A subtle wavy surface morphology is evident on the N-NW slope of the basin and is associated with low slope angles (Figure 2). This morphology is a typical expression of seabed sediment creep, i.e. a process of slow strain due to the downslope weight of sediment (Reading, 1999). Although creep might be a precursor to creep rupture and slope failure, normally it suggests the predominance of plastic deformation.

Tectonic Setting

West Papua represents an area where at least 3 major tectonic plates converge, with smaller terranes acting as buffers along the edges of the main plates (Figure 1).
The Biak Basin is located within the northern edge of the collision zone between the Australian and Pacific plates, in an area which can be interpreted as a crustal sliver bounded by the New Guinea Trench to the north and the Sorong-Yapen fault zone to the south. The crustal configuration of this area is the result of the collision and accretion of terranes of complex origin (volcanic arcs, rotated forearc terranes, submarine plateaus, etc.) that were dragged by a south facing subduction zone and collided against the Australian margin during Tertiary (Hill and Hall, 2003). This subduction seems to have ceased and relative plate motion is now oblique, as revealed by dominant strike-slip earthquake activity at Yapen Island along the left-lateral Sorong-Yapen Fault Zone (Figure 1).

To the west of the Biak Basin, in the Bird's Head area, present day seismicity together with GPS data suggest that this region is moving at the same pace as the Caroline Plate, at a rate of 7.5–8.0 cm/yr in the direction of 252° relative to northern Australia (Stevens *et al.*, 2002; Decker *et al.*, 2009). Considering these kinematic indicators, the Bird's Head area is interpreted to be a product of escape tectonics resulting from the oblique collision between the Australian plate and the remnants of volcanic belts and accreted terranes carried by the Pacific Plate (Pubellier and Ego, 2002). The escape movement is accommodated by two broad left lateral strike-slip fault zones, the Sorong-Yapen Fault Zone to the North, and the Tarera-Aiduna Fault Zone to the South (Figure 1).

Based on the above tectonic framework and interpretation of high resolution multibeam bathymetry, earthquake focal mechanisms and GPS data (Figure 5), we interpret the Biak Basin to be a transtensional pull-apart basin which developed in an oblique direction to the left-lateral Sorong-Yapen Fault Zone (Figure 6).

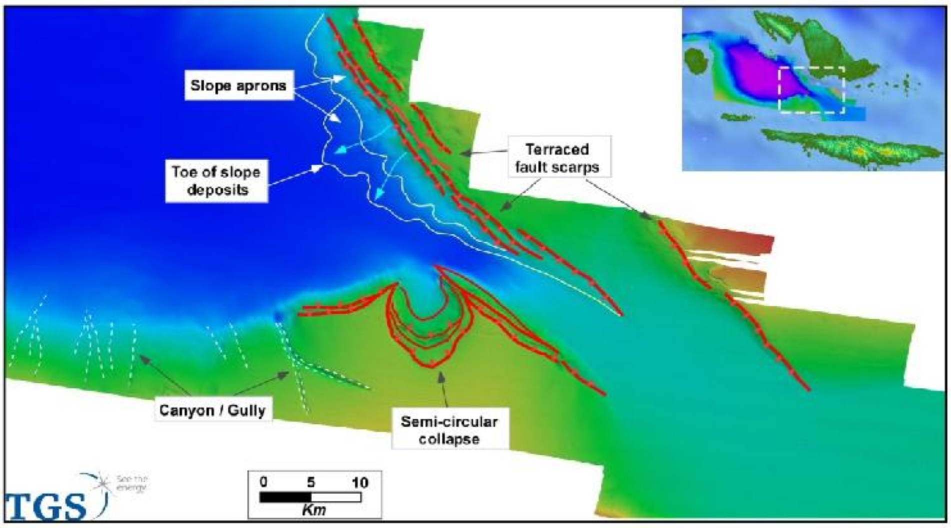

Figure 4. **Details of morphostructural interpretation of seabed in the eastern part of Biak Basin (see Figure 2 for location). Note the multi-episode slope aprons adjacent to terraced fault scarps.**

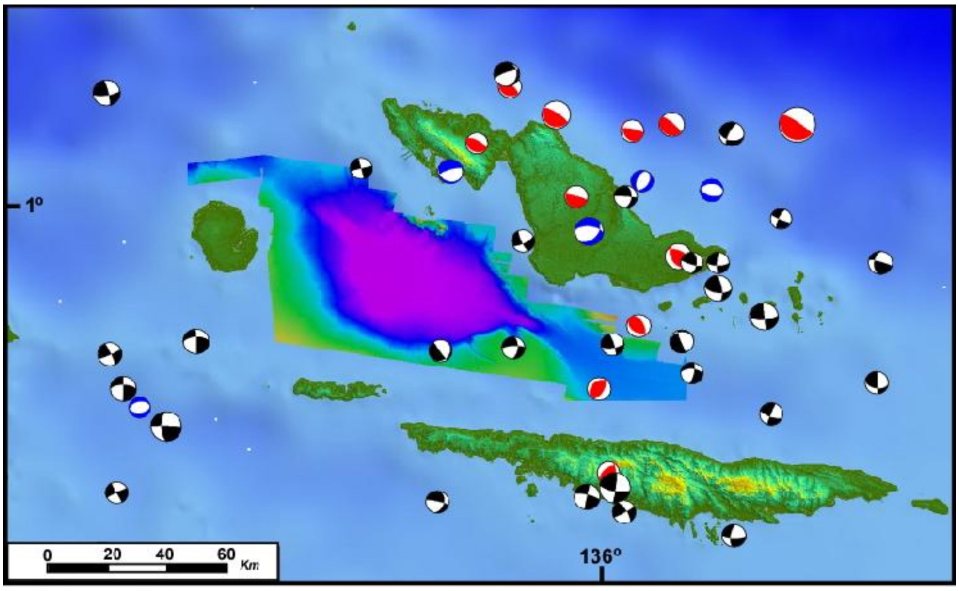

Figure 5. **Details of modern earthquake activity in the Biak Basin and surrounding areas, as shown by focal mechanism data (for key to symbols, see Figure 1). Bathymetry data s from TGS gridded multibeam merged with that of Gebco database. High resolution topography is from Aster GDEM database.**

The map view of the Biak Basin shows a sigmoidal to rhomboidal geometry oriented in NW-SE direction (Figure 5). Basin boundaries are analogous with terraced oblique-slip extensional sidewall fault systems, connecting laterally offset principal displacement zones (PDZ) of the main strike-slip faults. The basin floor is very flat and tends to be asymmetric where the sidewall faults join the PDZ. The sidewall faults show changes in kinematics from dominantly dip-slip extension in their central sections to oblique slip and strike slip at either end where they connect with the PDZ. Another characteristic feature for interpreting Biak Basin as a pull apart basin lies on the typical narrow ends of the basin, developing in-line horst and graben structures which broaden outward into the basin.

The overall geometry of the basin and its bounding structures seem to be compatible with a right-lateral strike-slip displacement (Figure 7; Dooley and McClay, 1997). Although left-lateral deformation is dominant in the Sorong-Yapen, right-lateral offsets have already been described in the Randaway Fault System (Charlton, 2010), which in fact, seems to be the southward continuation of the southeastern end of the Biak basin (Figure 6).

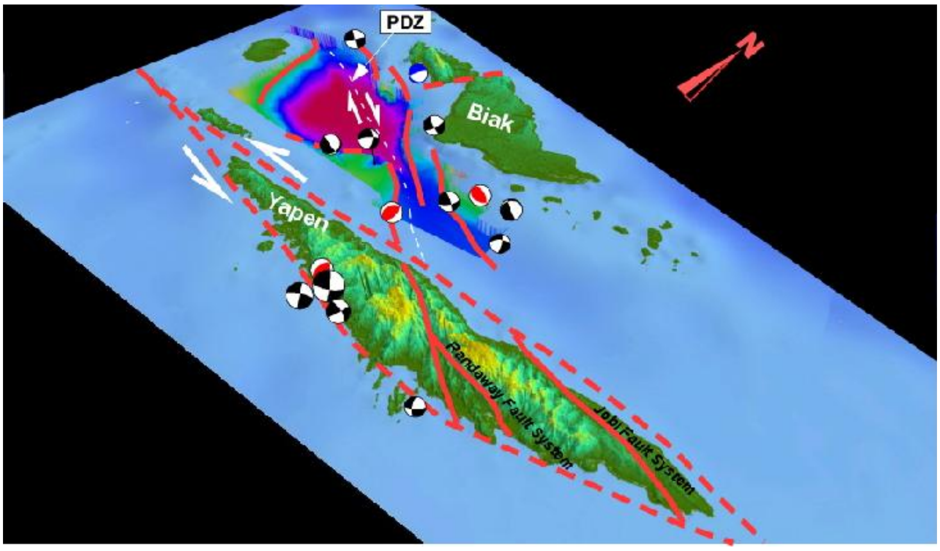

Figure 6. **3 D view of the integration of earthquake focal mechanisms with structural interpretation on the Biak Basin and surrounding areas. PDZ = Principal Displacement Zone (for key to symbols, see Figure 1)**

Analysis of computed focal mechanisms of earthquakes (Dziewonski *et al.*, 1981) shows that some of the sidewall fault systems bounding the Biak Basin are active at present day and are consistent with a strike-slip motion (Figures 6 and 7). This implies therefore that the submarine depositional processes previously described could be controlled by recent strike slip tectonics.

The earthquake data also point out that contractional deformation to the north of the Biak Island is partitioned into strike-slip deformation to the south, towards the Sorong-Yapen Fault system. In addition to the dominant strike-slip and contractional earthquake solutions, we also observed a few normal extensional earthquakes in the vicinity of Biak Island. This fact may be due to stress perturbations caused by pre-existing structures. As the crustal configuration of the area is composed of several fragments, fault block rotations and local extension may exist because changes of slip rates between different crustal blocks. These changes in slip rates could then explain the fact of having right-lateral structures coexisting with a dominantly left-lateral strain.

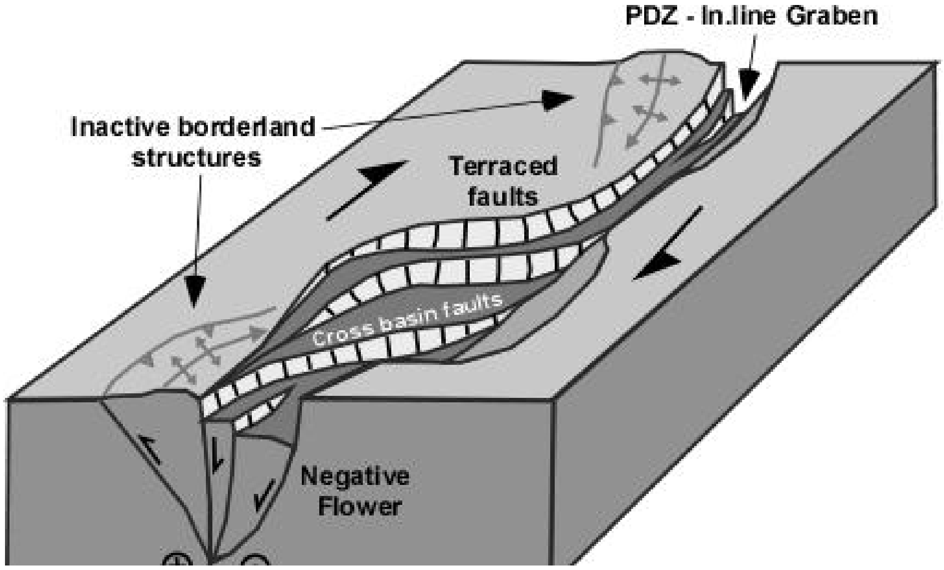

Figure 7. **Conceptual right-lateral pull apart basin (after Dooley and McClay, 1997).**

Summary and Conclusions

The observations made to date on the seabed depositional and tectonic processes suggest that current basinal depositional processes in the Biak Basin are significantly controlled by seismic activity in the region.

The interplay between recent seismic activity and deformation, erosional and depositional patterns of the Biak Basin is illustrated by the analysis of the circular shaped crater-like collapse located in the southern edge of the basin (Figure 4). This collapse is near a strike-slip focal mechanism solution and it allows us to speculate that the feature is controlled by recent fault activity. A second clear example of this interplay is how the fault scarps associated with base-of-slope depositional lobes are consistent in orientation and location with nearby strike-slip earthquake focal mechanisms (Figures 4 and 6).

Based on these indications, we infer that the seabed can be divided in two main zones, based on recent tectonic activity: seismic and aseismic zones. Seismic zones, where focal mechanisms are recorded, show steeper slope flanks and fault scarps with associated depositional lobes. Apron development is seen along one linear fault scarp. The composite character of the associated clastic lobes might indicate repeated scarp activities. It is well known that instability and re-sedimentation processes are favoured by high slope angles and repeated cyclical stress. We consider that this is more likely to be caused by the documented seismic activity, rather than high sediment supply, in this relatively starved basin. Conversely, the aseismic zones correspond to areas of absence of earthquake activity, and are located to the W and SW of the basin. These areas are associated with sediment creep, typical of slow-strain and plastic deformation, and the slopes are prone to erosion by gullies.

As a general conclusion, the uplift and bending recorded in the E part of the basin, and the scarps in the NE flank, are compatible with the basinal strike-slip tectonic setting proposed for the Biak Basin. The results presented here can therefore be used to support a basin evolution model and provide new insights on the regional tectonics of this highly complicated area.

Acknowledgements

The authors wish to thank Migas and TGS for granting permission to publish the data, and all colleagues from the Indonesia and New Venture teams in Repsol for discussions and their help in publishing this paper. We also are grateful to the editors of the Berita Sedimentologi for their support and suggestions for improving the manuscript.

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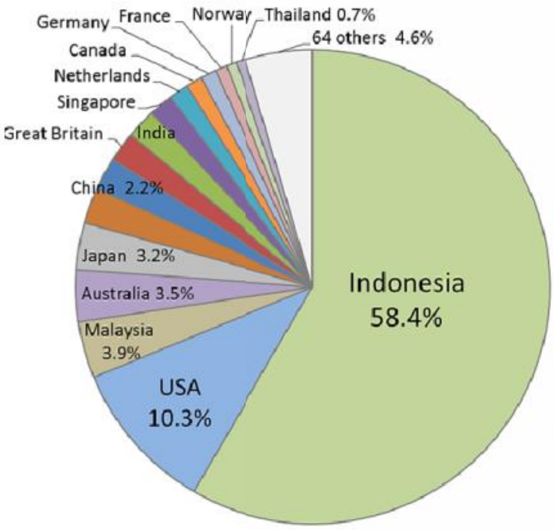

Seismic to Geological Modeling Workflow, an Integrated Approache to Determine the Reservoir Quality of a Fractured Limestone: Oseil Field Example

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CITIC Seram Energy Ltd., Indonesia

Summary

Natural fractured carbonate reservoir is extremely challenging in terms of reservoir characterization due to its high heterogeneity of reservoir property and also of its low oil recoveries. This paper will show how the integration of seismic data and well data had helped significantly for the well placement and also in the well completion stage.

The datasets that are available and being used in this process are 3D seismic, seismic Inversion, seismic attributes, conventional log and borehole image log. All these data are being utilized in an integrated way to characterize the fractures behavior of the reservoir.

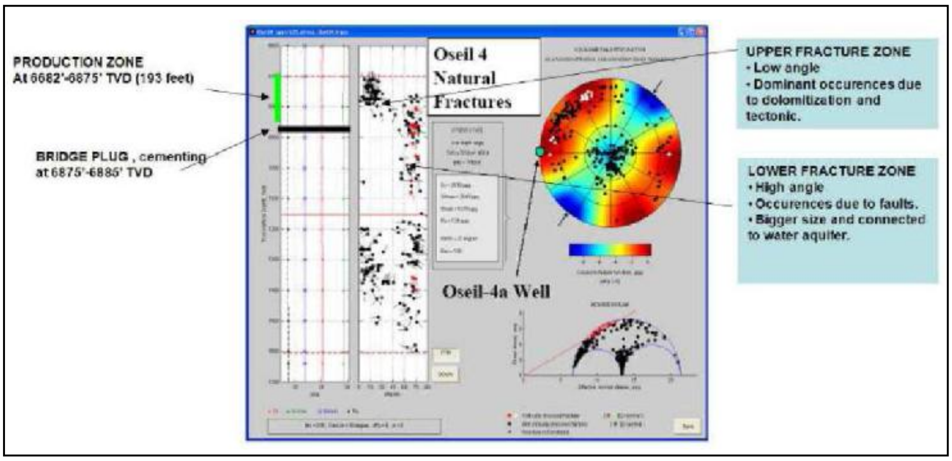


Figure 1. **Output screen from GMI*MohrFracs indicating the likelihood of slip on natural fractures seen in image data collected in the Oseil-4 well**

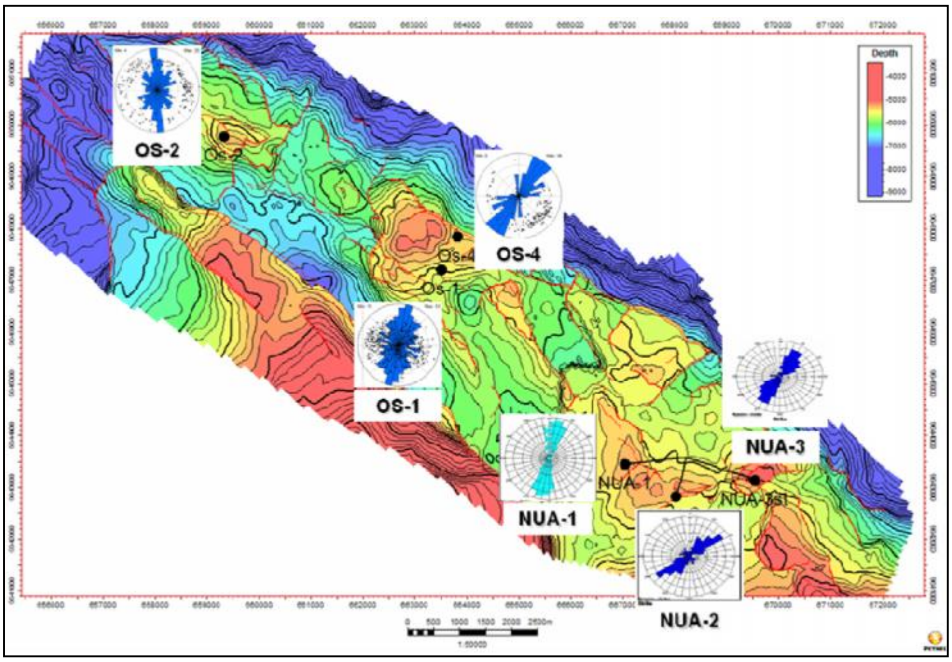


Figure 2. **Manusela Depth Structure Map showing the fracture orientation of the 6 exploration wells.**

Introduction

Oseil field is a naturally fractured carbonate heavy oil reservoir in folded thrust belts which presents extreme reservoir engineering and geological challenges and opportunities. These types of reservoirs are the extreme setting for large-scale high contrast and discontinuous reservoir properties. The presences of bottom water in conjunction with high viscosity oil result in low oil recoveries. Initial production stage experienced early water breakthrough, water cut rising and then stabilizing.

The reservoir in the Oseil field is the Jurassic Manusela Formation. Skeletal, oolitic limestones, deposited as a shallow water shoal, dominate the succession in the Oseil-1 and Oseil-4 area, and change to a muddier facies in the Oseil-2 area. In Oseil-1, Oseil-4 and East Nief- 1, the limestones were diagenetically altered to dolomite in discrete layers.Effective matrix porosity in all the Oseil wells is low. The Manusela Formation is however, extensively fractured on a macro and micro scale. The macro fractures provide both storage capacity and permeability. Intersection of macro fractures is required to achieve oil flow rates of hundreds of barrels per day.

The fracturing mechanism was related to tectonic and carbonates mineralization (dolomite). Manusela oolitic carbonate was developed during basin extension, and it was followed by uplifting, (Fraser et al, 1993) mineralization and then marine transgression of Kola shale.

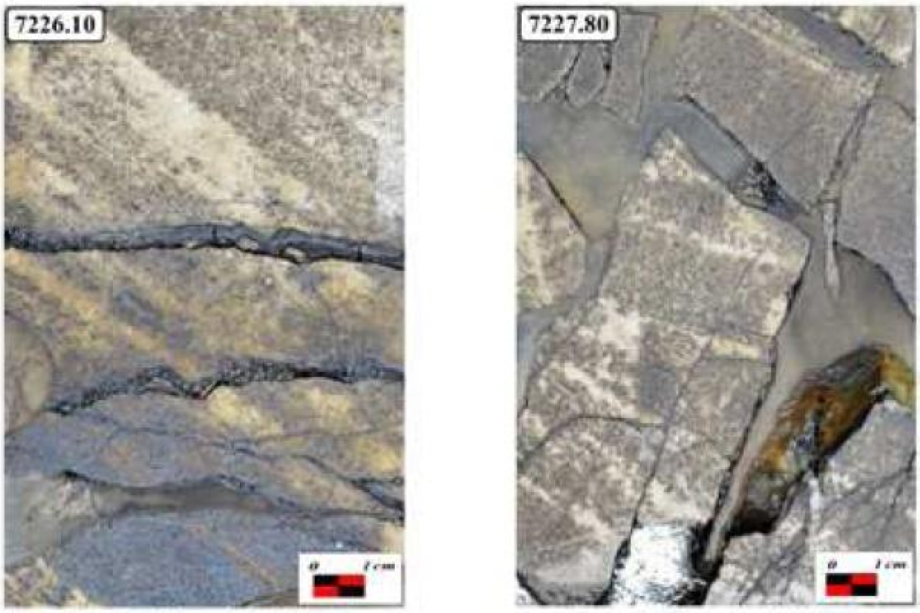
In the compression phase, stress generated were related to Australian movement which continue SW to NE direction starting in the age of late Miocene. As near surface of Manusela carbonate contains more dolomite mineral, which means easier to break compared with deeper carbonate, the near surface were fractures with low angle fracture as the rock were folded.

Extensional normal fault were dominated during development of Seram basin and extending to the end of Manusela sedimentation, high angle extensional fracture were developed. In compression phase basin inversion had happen and all normal faults reactivated to became reverse, create large high angle fractures and reopen existing fracture.

Two fracture systems were found in Oseil field, FMI log and dip meter data indicate distinct boundary (Fig 1 Oseil-4 dip meter). 100 feet upper part of Manusela carbonate zone is the zone dominated by low angle fracture and it is also the zone with high oil saturation. As they were low angle fracture, they created horizontal permeability and not connected to the aquifer. The deeper part is dominated by high angle fracture, which clearly found on logs and outcrops and this fracture having larger aperture, very high permeability and connects to the aquifer. As drilling the deeper part has high potential of hitting high angle fracture which are high risk of the well having high water cut, it is then recommended to drill the shallow part and avoiding the deeper part.

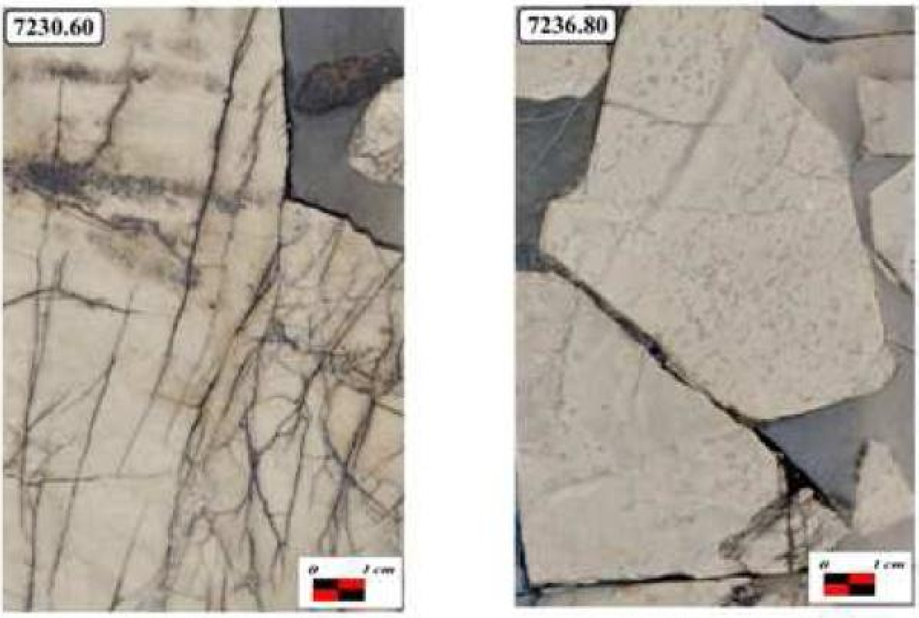
Background & Workflow

One of the main challenges of this field is the fact that the matrix porosity of Manusela carbonate is very low, hence the quality of the reservoir rely heavily on the presence of fractures. On the other hand the early water break-through that happened in several wells that was mainly derived by the fractures and faults.



Cross beds of oolitic and peloidal grainstone, porosity reduced by calcite cement. Oil stain [dark colour] on cross beds.

Cross beds of oolitic and peloidal grainstone porosity reduced by calcite cement. Oil stain [dark colour] on cross beds.



Cross beds limestone, oil stain [dark colour] with fractures.

Limestone with red algae & fractures.

Figure 3. **Close-up whole core photographs well NUA-3 of Manusela Formation Plate 2**

We need to characterize area where it have sufficient amount of fractures but must avoid those areas that have fractures connect to aquifers. By only utilizing well data, i.e conventional logs and borehole images, we are limited by a small localized area. Since the heterogeneity of this reservoir is very high, then a more regional approach to define the fractures characteristic distribution is required.

To have a more regional understanding of the fault, we have utilized our 3D seismic data by applying a Pre-Stack Anisotropy Inversion to detect the distribution of the fracture in this field. The next step is to utilize the information from this seismic data to simulate the dynamic behavior of the reservoir. A dual porosity permeability model was built by generating a Discrete Fracture Network (DFN) base on the combination of well data (mainly image interpretation) and the result of the Pre-Stack Seismic Anisotropy.

The result of the seismic anisotropy, 3D model building & simulation then was used to place new infill wells. During the testing & completion mode of the new drilled wells, all the well & seismic data are continuously being used to monitor the performance of the well. One of the very useful is the Ant-Tracking Attribute that was derived from the original 3D seismic data.

Well Based Fracture Analysis

There are 6 wells that have complete image data of this field. Base on the image interpretation, it can be seen that to the east the main orientation of the fractures is NNE-SSW while to the west it's tends to orient more to the NE-SW to E-W direction (Figure 2).

Core data are also available, and base on core, the apertures of the fractures was measured. From two wells, the aperture width of the fractures falls within range 0.00 mm – 5,5mm. While based on image data, the range of aperture width is between 0,00 to 0.57mm (Figure 3).

From the borehole image, there are several types of fractures/faults that can be classified (figure 4).

Below are the different types of fractures:

1. Conductive Continues Fracture (CCF),
2. Conductive Discontinues Fracture (CDF),
3. Conductive Micro Fracture (CMF),
4. Conductive Vuggy Discontinues Fracture,
5. Stylolites,
6. Vuggy Stylolites,
7. Faults.

Pre-stack Seismic Anisotropy for Fracture Detection

Studied on reservoir fractures intensity in Oseil field using pre stack 3D seismic data are based on P-wave reflection amplitude. P-wave seismic amplitude exhibiting variable attenuation with difference fracture orientation have an anisotropy orientation, which is captured by the seismic anisotropy as a result of this process Fractures especially vertical one will generate seismic anisotropy. By analyzing the seismic anisotropy we can detect the most possible area where high intensity fracture occurs. The end result of this process is a Fracture Intensity cube.

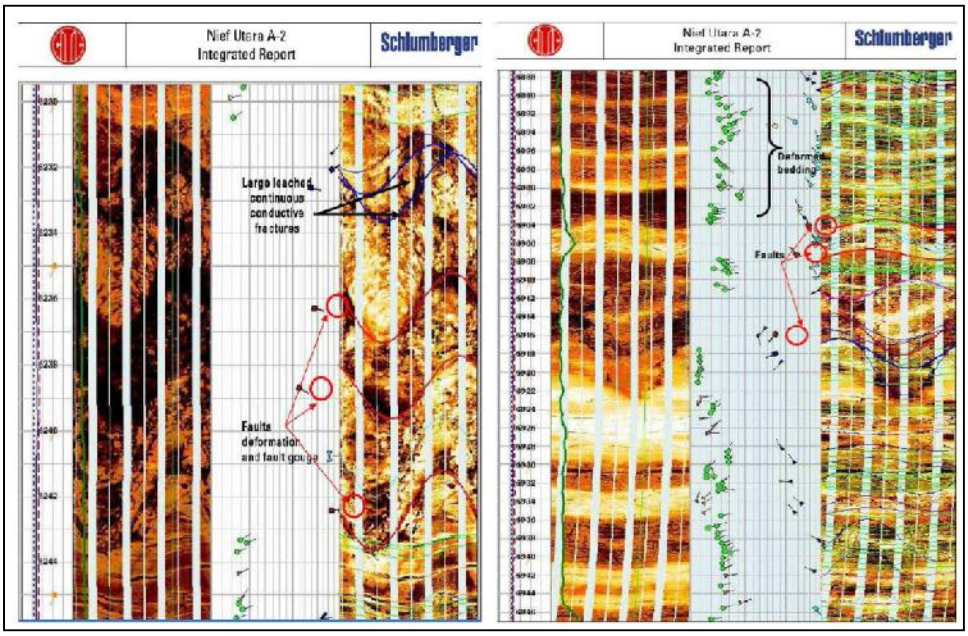


Figure 4. **An example image log from NUA-2 wells showing different type of fractures.**

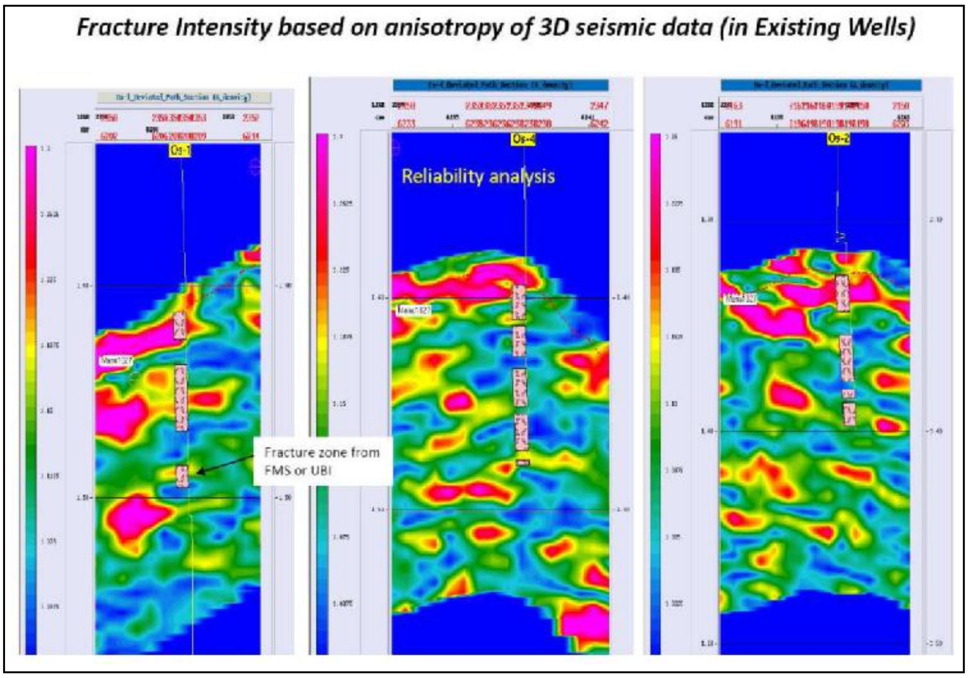


Figure 5. **Fracture intensity correlation between wells and seismic relatively match.**

There are several steps were used to generate fracture intensity cube from well and 3D seismic data. First performed reserved amplitude processing, well and seismic correlation, rockphysical modeling of fractured reservoir based on rock physical studies were built to model seismic anisotropy.

Then four azimuth seismic data sets were achieved by selecting and combining seismic data set in the range of 0-2000 meters offset and 0-180 degree azimuth; and calculated different azimuth amplitudes and analyzed their azimuth variations.

The next step is the spatial distribution of amplitude azimuth ellipse that represents amplitude decay along different direction. This anisotropy curvature attribute then finally converted to fracture intensity cube.

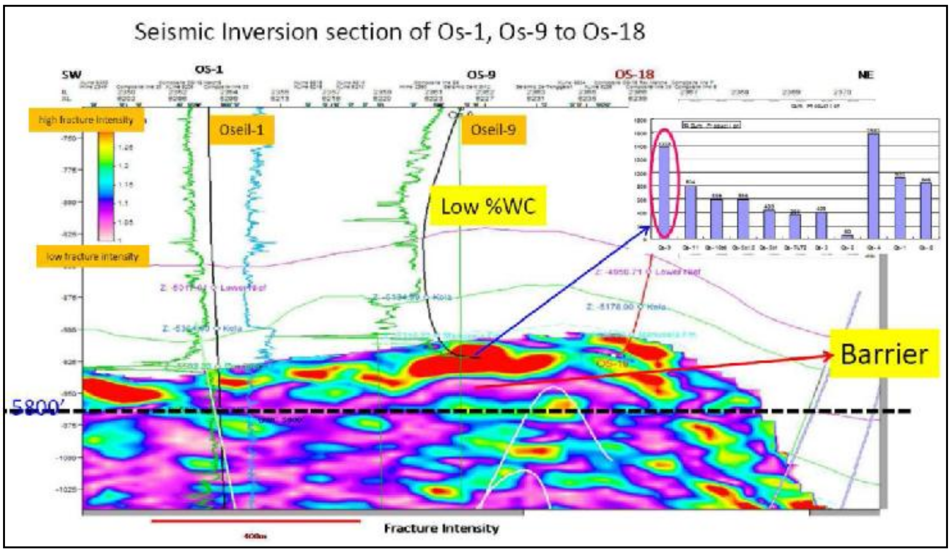


Figure 6. **A seismic section of the fracture intensity cube along Os-1, Os-9 to Os-18, showing wells penetrating high intensity fracture zone.**

Geological Modeling

3D geological modeling is an integrated reservoir study combining seismic data, well data, geological information and reservoir data. This model will be used later for in-place hydrocarbon volume estimation of the field and also upscaled for simulation purposes.

For a fractured reservoir, there is additional step required in order to generate a dual porosity permeability model. A discrete fracture network (DFN) was built to create simulation properties to predict the reservoir dynamic behavior.

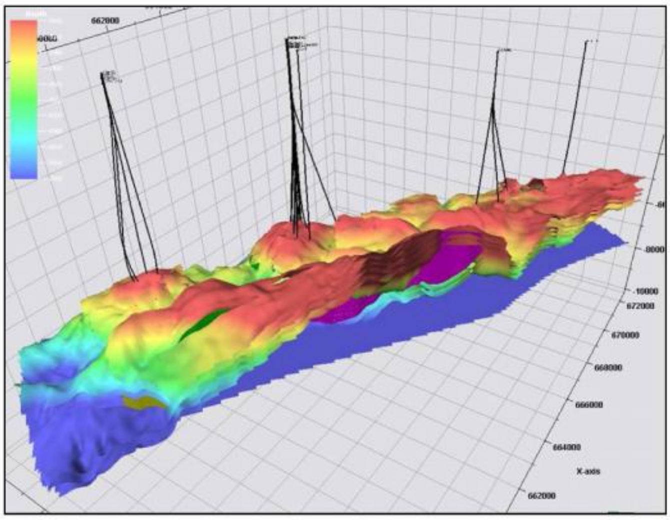


Figure 7. **Modeled Reservoir Top Horizons in Oseil field showing the structural faremwork.**

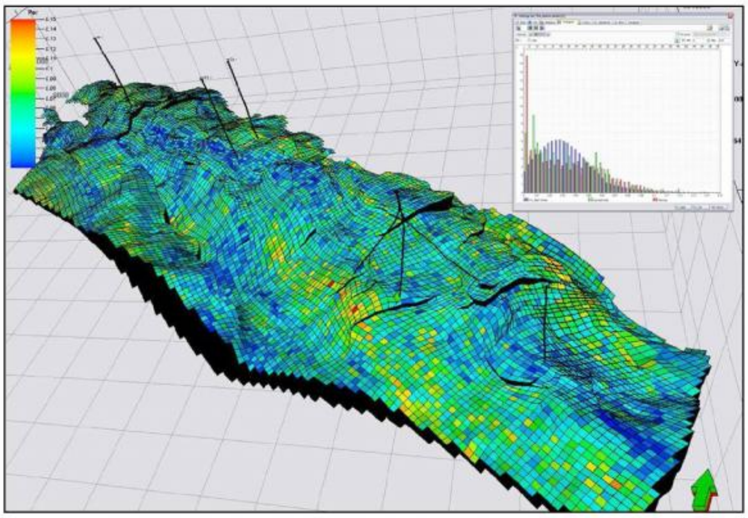


Figure 8. **The matrix porosity model of the Manusela Reservoir.**

A 3D fine scale geological model was developed integrating all available data. The faults from seismic were modeled in 3D after defining their interrelations. The depth converted seismic horizons were incorporated into the 3D model, and together with the already existing fault then were used to construct the structural framework of the 3D model. (Figure 7).

The structural framework then was populated by petrophyscial properties to define the matrix property of the reservoir. They are the porosity matrix porosity, matrix permeability and water saturation. (Figure 8).

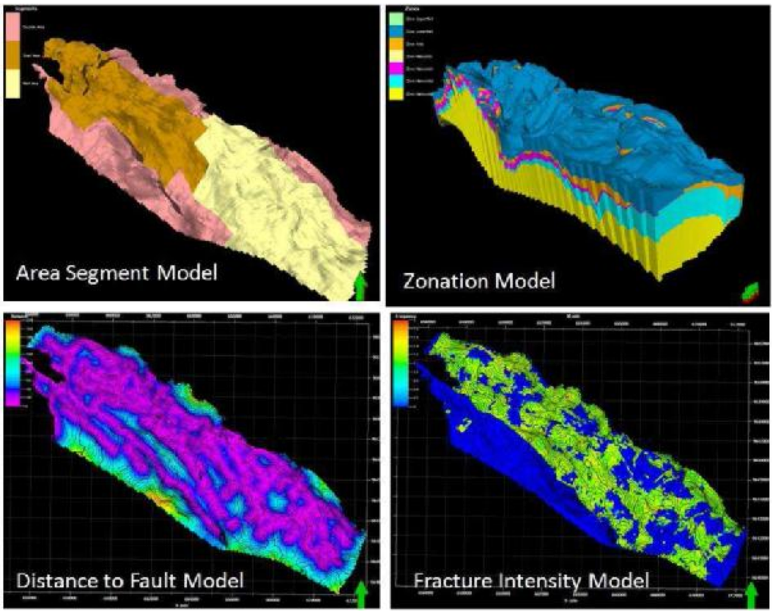


Figure 9. **Several fracture drivers base on different parameters.**

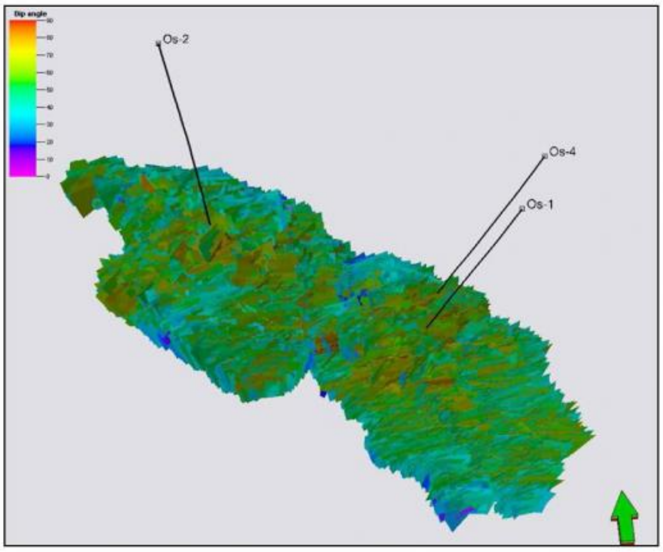


Figure 10. **DFN result of Oseil field using the fracture intensity cube as the distribution control.**

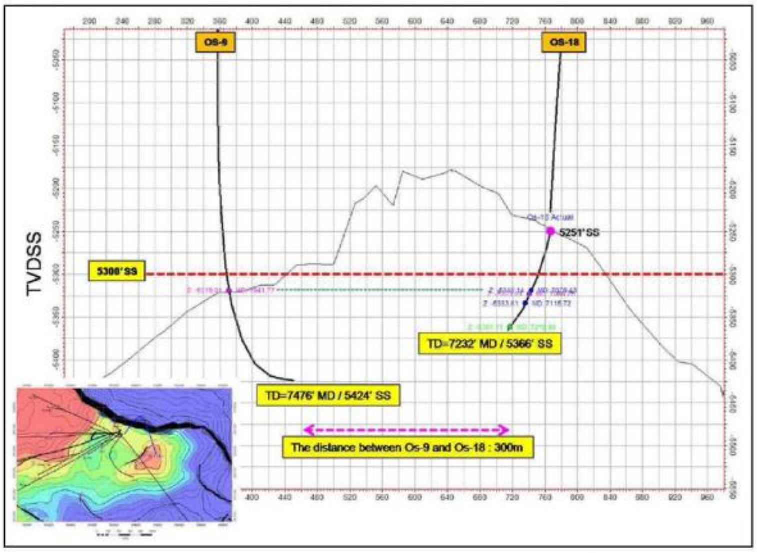


Figure 11. **Section of Manusela Depth structure from Oseil-9 to Oseil-18.**

Prior the discrete network building, model parameters need to be defined since they are the object that will control the intensity of the fracture. This is called the fracture drivers.

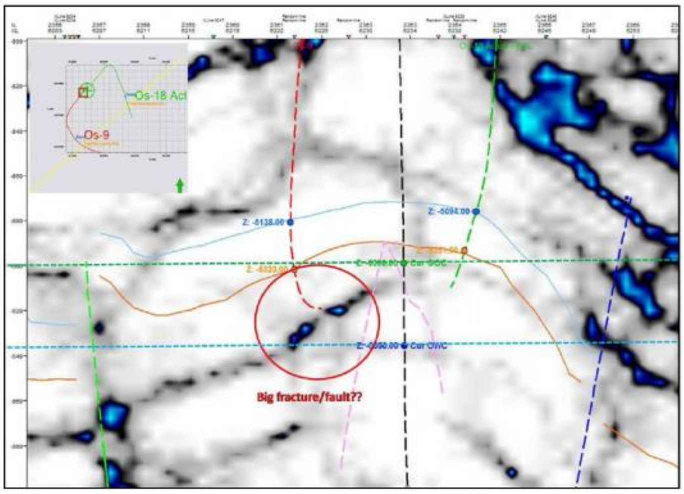


Figure 12. **Section of An-Track cube showing that Os-18 might possibly hit a major fracture at the bottom of the well.**

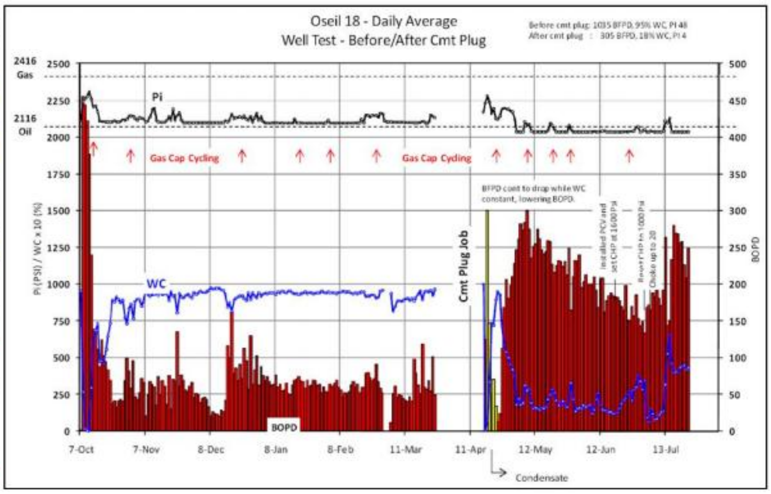


Figure 13. **Oseil-18 Daily Average Well Test – Before/After Cement Plug.**

Generally fracture drivers are made base on assumption. For instance fractures are more intense along the fault zone, hence the distance to fault model is built. In our case, we already have the Fracture Intensity cube from the Pre-Stack Seismic Anisotropy. By integrating the fracture intensity cube in the 3D model, we can have a more reliable distribution of the fractures (Figure 9).

Discrete Fracture Network Generation

A discrete fracture network (DFN) was built to create simulation properties to predict the reservoir behavior. There are 6 wells with image interpretation. The fracture interpretation based on image log is the main input for the DFN parameter setting. In addition to the image interpretation, the fracture intensity cube was used as a secondary variable to populate the density of the fracture. A linear relationship was taken from the intensity value from seismic and the density of fracture from wells to ensure that the distribution of fracture will honor the well data.

Well Placement

Base on this integrated study, three development wells were proposed and drilled in 2010-2011. The new wells produced oil with initial rate as much as 300-500 bopd. It was proven that the study had successfully characterized the quality of the reservoir by detecting the high intensity fracture.

However, one of the well (Oseil-18) experienced an early water break-trough. This is quite unexpected because the TD of this well is shallower 67 ft SS with the nearest well Oseil-9 with distance less than 300m (Figure 9).

We suspect there is sort of connection of Os-18 to aquifer which is not happening with nearby Os-9.

From the original seismic amplitude, no fault was interpreted so the other possibility is the existence of major fracture that connects Os-18 to bottom water.

Seismic Attribute (Ant-Tracking)

By applying the Ant-tracking workflow to the 3D seismic cube, we had successfully recognized the zone where a vertical fracture exist and act as a conduit for the water (Figure 10).

This zone then later was plugged by cement to prevent or minimize bottom water produced by the well. By this approach, the water cut was reduced from 95% up until 18 % (Figure 11).

Conclusion

The integration of well data and seismic data in the reservoir characterization of a fractured carbonate reservoir is beneficial especially to have a comprehensive understanding of the subsurface.

Maximizing information of each data source will enable reliable decision making and adding value to the data itself.

All the study results have been compared with the actual drilling & production result and have shown consistency between them.

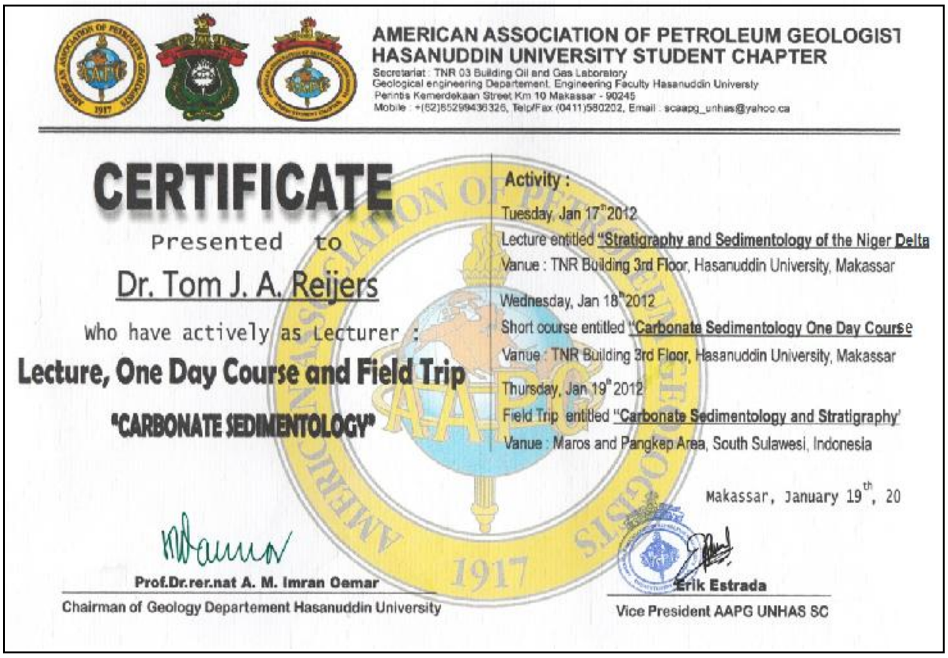
A Guest Lecture and An AAPG Course at Sultan Hasanuddin University, Makassar, Indonesia

Reviewed by
Tom J.A. Reijers
Geo-Training & Travel, Anderen, The Netherlands
E-mail : **tjareijers@hetnet.nl**

Mr Herman Darman (Shell, The Netherlands) asked me to contribute a paper for a special edition of IAGI 2010 (the Bulletin of the Indonesian Geological Society) at the occasion of the celebration of 50 years of existence. This triggered a series of follow-up activities that are summarised here.

The paper on 'Indonesian Geotourisme and Geoparks' was duly published (Berita IAGI 2010, p. 12-15), but the author felt that the courtesy of being invited for a paper needed reciprocal action and discussed possibilities with Mr. Darman. Thus the idea was born to present a recently published paper on the sedimentology and stratigraphy of the Niger Delta (Stratigraphy and sedimentology of the Niger Delta, Geologos, 2011, 17(3):133-162), and to give a short course on carbonates (syllabus in English by the author) at an Indonesian University during the author's vacation in that country (December 2011-January 2011).

In consultation with Mr Mohammad Syaiful (Secretary General Indonesian Geological Association) and Mr Geovani Christopher Kaeng (AAPG student chapter coordinator) the AAPG student chapter of the Sultan Hasanuddin University in Makassar was requested to organise the event. The effective organisation of Mr Eric Estrada (Vice President AAPG UNHAS SC) and in particular of professor Dr A. M. Imran Oemar (Chairman of the Geological Department of Hasanuddin University) who were so kind to formally invite me, resulted in a three day event with a lecture on the Niger Delta (Tuesday Jan 17th), a one-day course on Carbonate Sedimentology (Wednesday Jan 18) and a field trip on Carbonate Sedimentology in the Maros and Pangkep Area in South Sulawesi (Thursday Jan 19th) (Figure 1). It was a wonderful occasion with interested students who - after some hesitation to express themselves in English - asked many relevant questions and demonstrated their interest and know how. Apparently I was the first foreign visiting scientist at the 36 year old Geology Department of which the facilities are up to date, including a modern conference room. The interest for the event was great.



AMERICAN ASSOCIATION OF PETROLEUM GEOLOGIST
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CERTIFICATE
Presented to
Dr. Tom J. A. Reijers
Who have actively as Lecturer :
Lecture, One Day Course and Field Trip
"CARBONATE SEDIMENTOLOGY"

Activity :
Tuesday, Jan 17th 2012
Lecture entitled "Stratigraphy and Sedimentology of the Niger Delta
Vanue : TNR Building 3rd Floor, Hasanuddin University, Makassar
Wednesday, Jan 18th 2012
Short course entitled "Carbonate Sedimentology One Day Course
Vanue : TNR Building 3rd Floor, Hasanuddin University, Makassar
Thursday, Jan 19th 2012
Field Trip entitled "Carbonate Sedimentology and Stratigraphy'
Vanue : Maros and Pangkep Area, South Sulawesi, Indonesia

Makassar, January 19th, 20

Prof.Dr.rer.nat A. M. Imran Oemar
Chairman of Geology Departement Hasanuddin University

Erik Estrada
Vice President AAPG UNHAS SC

Figure 1. **Certificate of having given the lecture and the course. Similar certificates for attending the lecture, the course and participating in the fieldtrip were issued to students.**

Figure 2. **Pankep Maros karst, locally also known as 'petrified forest' with erosion notches at the base.**

Figure 3. **Negative handprints (left) and a deer 'pushed' (?) by negative hand prints (right) are fascinating remnants of early inhabitants of the Leang-Leang area in South Sulawesi.**

I benefitted personally from the invitation by participating in the fieldtrip to the 'hinterland' of Makassar, where wonderful karst scenery was already described by Russel Alfred Wallace (1869) in his travel book on the Malay Archipelago. This fascinating area is now the field area for students geology and geophysics of Hasanuddin University. We reached the Eocene-Miocene Tonassa limestone - now extensively quarried for cement for the new motorways - over picturesque country lanes through well laid out dessa's between fertile sawah's. Locally, erosion remnants of tower karst 'pinnacles' with tell-tale erosion notches at their base, triggered a discussion about their origin and the interpretation of their geomorphology. Clearly, eustatic sea level rises and/or movement of the South Sulawesi landmass have played a significant role.

The platform and slope facies of the Tonassa Limestones were studied in some outcrops where also inter fingering contacts were exposed with the underlying Malawa Formation, containing some lignite beds. The students geophysics were very interested in an explanation of a potential exploration strategy to investigate the areas for hydrocarbons and many questions were asked about hydrocarbon prospects in Sulawesi. Further courses on such matters are clearly required.

Figure 4. **Tower karst scenery around Bantimurung, South Sulawesi.**

Figure 5. **Colourful butterflies in the Bantimurung butterfly sanctuary, South Sulawesi.**

Very much in line with my own approach if I organise and guide geological fieldtrips, the AAPG student chapter also took care of including some touristically interesting sites. Some (of more than 60) caves around the dessa of Leang-Leang were visited. In many paintings of wild pigs, deer and negative handprints are present that have been dated by archeologists at 6.000-30.000 years. They are comparable to paintings in Papua and to aboriginal art in Australia, which opens fascinating speculations on the people that made this art.

Not far from Leang-Leang, the dessa Bantimurung was already in Wallace's time known for the enormous variety in colours and sizes of butterflies (Figure 5) that are diligently studied in an onsite laboratory next to the virgin forestation covering the tower karst karst cliffs (Figure 4) and that are covered over an extensive area by netting to keep the butterflies together.

This fascinating visit to Hasanuddin University clearly asks for repeats. Other geologists travelling in Indonesia should try also to contact local universities in their area of travel, to investigate possibilities to present a lecture or short courses.

I was invited to return in the future and will gladly do so, in particular if combinations are possible with some other universities to make the long voyage to and from Indonesia optimally beneficial. Let me now express my gratitude as follows:

"Saya berterima kasih untuk undangan untuk memberikan Kuliah dan kursus di Makassar. Saya berharap untuk mengunjungi Indonesia di tahun yang akan datang dan mungkin mengunjungi universitas lain dengan program yang sama."

Tom J.A. Reijers, The Netherland

Figure 6. **The core group that attended the course and the excursion.**

Book Review

The SE Asian Gateway: History and Tectonic of the Australia-Asia Collision

Edited by
R. Hall, M. A. Cottam & M. E. J. Wilson

Geological Society, London, Special Publication, 355, 2011, 381 pp. ISBN 978-1-86239-329-5.

Reviewed by
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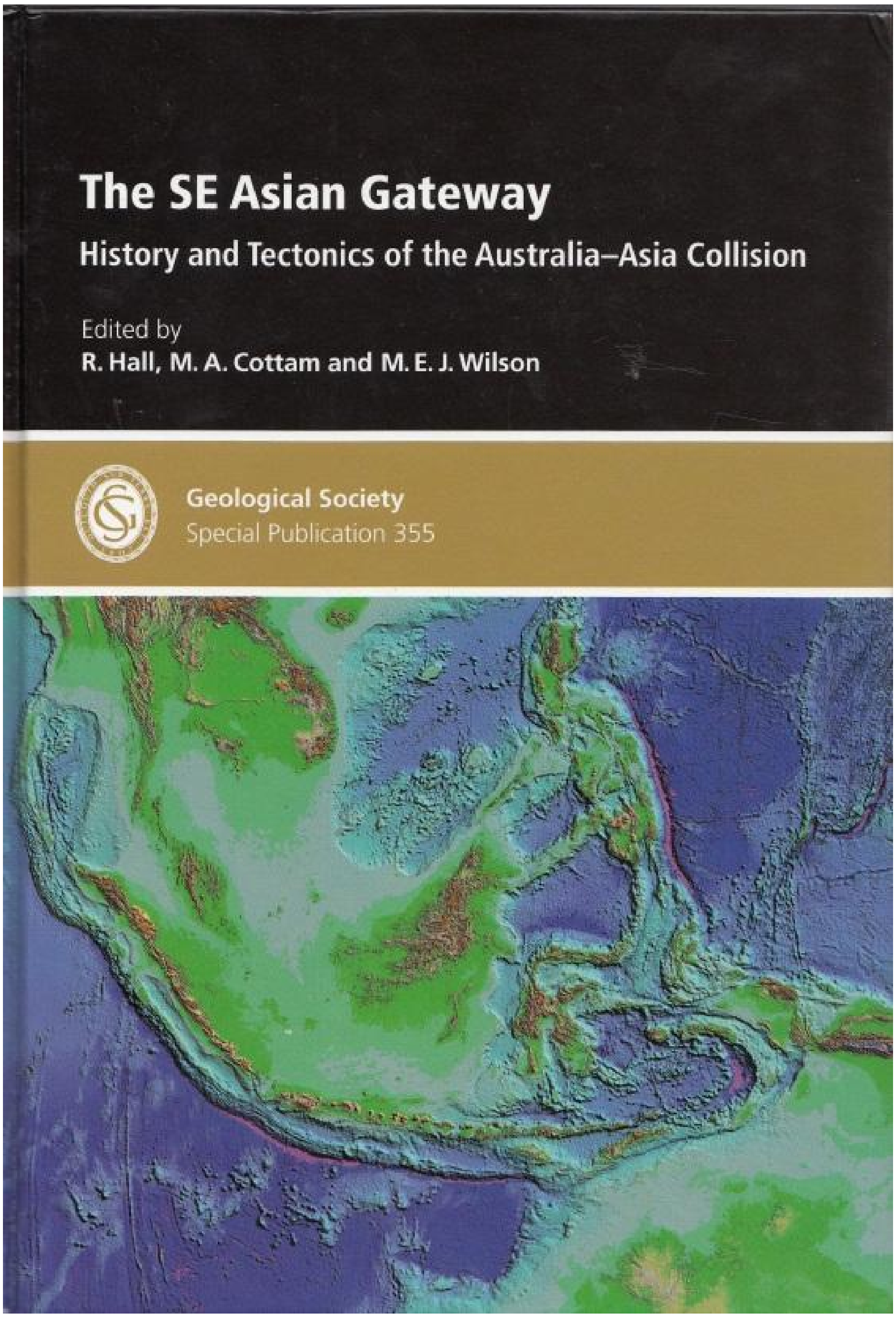

The 18 papers collected here are the result of a conference organised by the Geological Society of London in September 2009 on the connections between geology and biodiversity within 'The Indonesia Through flow Area', where currents from the Pacific Ocean flow to the Indian Ocean. They have been arranged to first explain and discuss the Palaeozoic and Mesozoic geological development of the region, and then its Cenozoic history which provides the background to understand the present Indonesia.

The fragmentation of Gondwana and the assembly of these fragments in SE Asia accompany the gradual closure of the Paleo-, the Meso- and the Ceno-Tethys Oceans. **Metcalfe**'s review highlights a new understanding of the SE Asia basement structures composed of terranes by the South China-, the Indo-China-East Malayan, the Sibumasu- and the west- and the east Borneo blocks and their sutures. The SW Borneo and/or East Java-West Sulawesi blocks are the missing 'Argoland' that separated from NW Australia in the Jurassic and accreted to SE Sundaland in the Cretaceous. **Clements et al** discuss a widespread regional unconformity suggesting topography at the end of the subduction period, due to which the Upper Cretaceous-Paleocene rocks are almost completely absent throughout Sundaland. **Granath et al.** show an unexpectedly thick sedimentary section beneath the unconformity in the Java Sea, which was deposited while the basement block was still part of the Australian margin. **Hall** interprets the Neogene collision leading to the Cenozoic subduction beneath Indonesia being influenced by the rifted continental margin of Australia and by an oceanic embayment, leading to subduction rollback into that embayment. Such young deformation also results from lower crustal flow enhancing the effects of sediment loading and driving uplift of mountain ranges in northern Borneo and Sulawesi. **Kopp,** using new seismic sections, reviews subduction along the Java margin showing variations in an east-west direction. **Widiyantoro et al** show a 'hole' and a possible 'tear' in the subducting slab beneath East Java.

Sulawesi, close to the centre of Wallacea is composed of parts of pre-Neogene Sundaland and Australian crust, added from the Cretaceous onwards. The active strike-slip Palu Koro fault in West Sulawesi, with spectacular surface expression, seismicity and young deformation is a poorly understood hazard. **Watkinson** compares rocks on both sides and discusses the enigmatic wide Gorontalo (Tomini) Bay with a number of small islands including the Togian islands. The latter have recently been investigated by **Cottam et al** to understand the origin of the bay and its volcanic history. They revealed the collisional contact of the ophiolite with one of the micro continental fragments in Eastern Indonesia, possibly sliced of from New Guinea's 'Birds Head' and carried east along the Sorong-Fault zone. This interpretation is doubted by **Watkinson et al**, based on recent offshore multibeam and seismic data. Collectively these studies show that previous models for tectonic development of Sulawesi require substantial re-evaluation.

Studies on Timor and the Banda arc generated many ideas and controversies about arc origin, nature of the crust within the arc and the age of collision. The Savu basin north of the transition oceanic subduction to arc-continent collision, is discussed by **Rigg & Hall** with the aid of new seismic. The basin is underlain by Australian continental crust that was incorporated in the SE Asia margin in the Cretaceous. Subduction of part of the Australian continent resulted in uplift of Sumba and deformation of deep water deposits Audley-**Charles** summarises the results of Pliocene collision of the volcanic Banda Arc with the Australian margin. Detached parts of the Australian margin were stacked up beneath the leading edge of the fore-arc, as shown by the highest nappes of the Banda allochthon.

The last remaining equatorial gateway between the Pacific and Indian oceans is the 'Indonesian Trougflow'. **Tillinger** discusses the causes of this flow, the controls on shallow and deep flow and the variations in different passages. The relation between the monsoons and the El Niño-Southern Oscillation is reviewed and modelled in terms of restricting the through flow. The long-term history of the Indonesian Througflow, linked to global climate and to variations in sea surface temperatures, salinity and water mixing over the last 14ka, are studied by **Holbourn et al** with benthic and planktonic foraminifera. Termination of deep water flow restricted the Indonesian Gateway from the Early Miocene, which coincided with major changes in the global climate system, including rapid Late Oligocene warming followed by a brief pulse of glaciation. The long term development of the Indonesian Through flow is controlled by the geologic history of the region. **Von de Heydt & Dijkstra** discuss studies of control by the geological history and analyse the effect of increasing pressure of atmospheric greenhouse gasses and open tropical gateways.

Whether Pliocene plate tectonic changes such as the northward movement of New Guinea caused changes in temperature and salinity between the South and the North Pacific waters was earlier reviewed and is now further assessed by **Morley & Morley,** based on palynological studies from cores in exploration wells in the Makassar strait. They record vegetational and climate changes over the last 30 ka. **Lelono & Morley** use palynomorph assemblages to determine Oligocene climate changes in the East Java Sea. Finally **Wilson** reviews the very diverse shallow marine biota in the Indonesian waters of which a large proportion is related with coral reefs and associated habitats. Carbonates are valuable to trace environmental and climatic variations, but have in the Indonesian waters barely been studied. Wilson reviews changes on annual, decades, centennial and millions of year's timescales, and discusses the effects of terrestrial runoff, nutrient upwelling, tectonics, volcanism and human activity.

This publication offers a great variety of new processes, new views of the timing of large scale plate tectonic changes, the geological development of specific areas and a wealth of new ideas with which older models can be updated. The importance of the Indonesian Through flow and its impact on annual and longer-term regional and global climates are shown. The environmental history is unravelled from the biota in the rocks. In this special publication a genuine cross fertilisation takes place between the regions geological, oceanographically and climatic history. Strongly recommended to anybody interested in the latest development in geological and oceanographical thinking in SE Asia.

Book Review

Biodiversity, Biogeography and Nature Conservation in Wallacea and New Guinea
(Volume 1)

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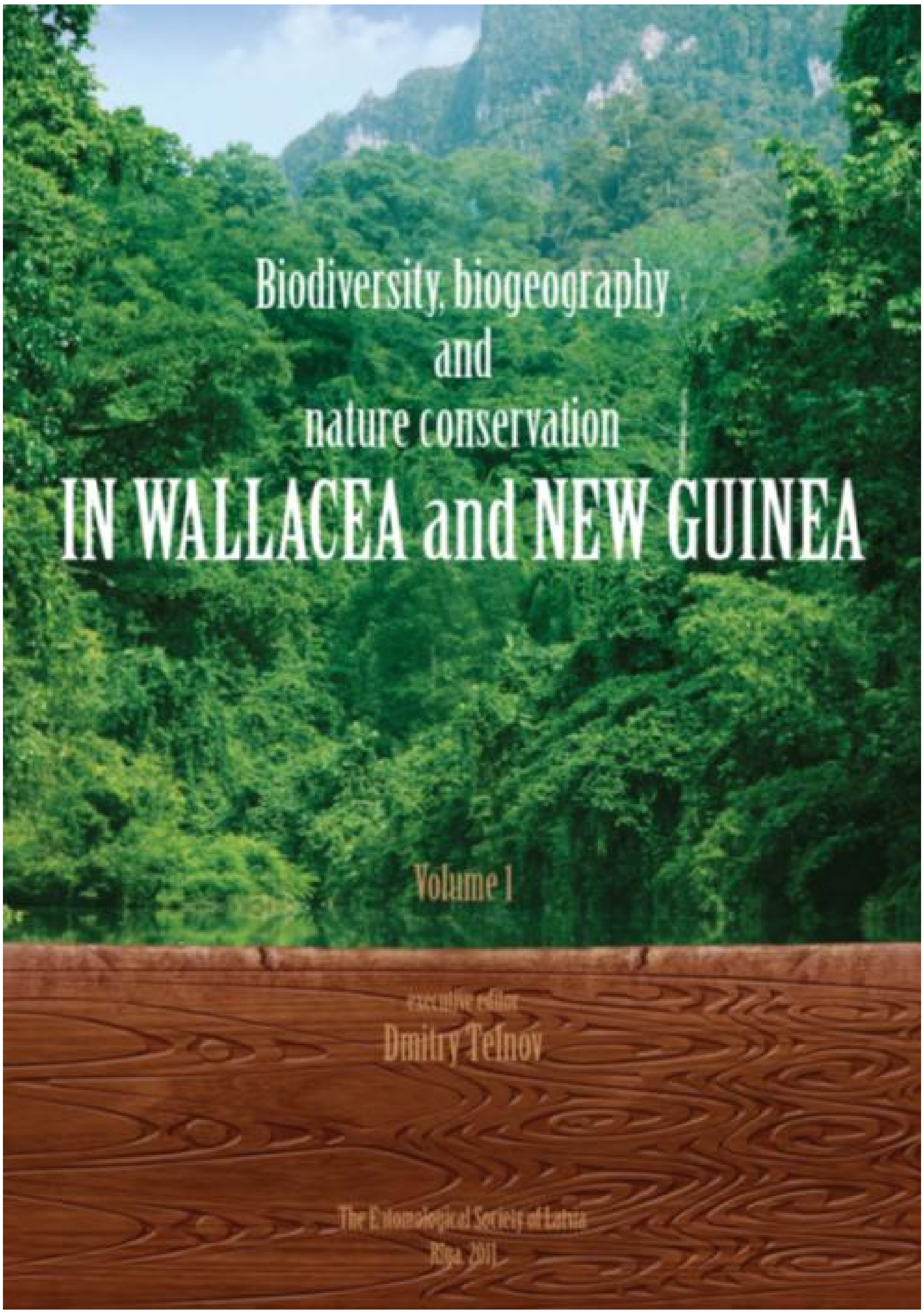
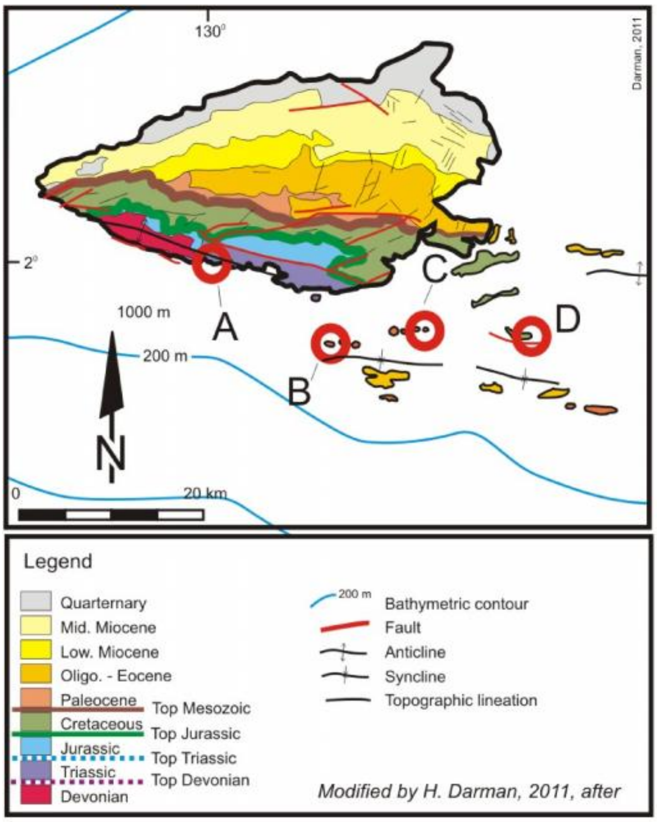
Outcrop Photos of Misool-Onin Ridge



Several outcrop photos are displayed on Google Map in the Misool-Onin Ridge area. Certainly ground-truth checking is necessary for accuracy but for remote sensing purposes, these pictures give an overview of the sedimentological and lithological information of the formation. These photos were taken by non-geoscientists. One of them is Dmitry Telnov.

Dmitry Telnov, PhD, is a coleopterist, working in taxonomy, biogeography, evolution and ecology of Anthicidae, a family of small beetles. For research purposes he visits Indonesia to work on taxonomy, biogeography, ecology and evolution of particular beetle families. Dmitry is the Chairman of Coleopterology of The Entomological Society of Latvia. He also has a great scientific interest to biogeography and speciation in the Indo-Australian transition zone, including 'classic' Wallacea, New Guinea and the Solomon Islands. For his work, Dmitry is travelling in areas less disturbed by human impact and he observes & photographs nature, particularly invertebrates and discovers local cultures. As a professional biologist, he has started to collaborate with UNIPAS, Universitas Negeri Papua in Manokwari, as also with Koleksi Serangga Papua in Jayapura. Previously he has visited Maluku Utara (Ternate, Moti, Halmahera), Maluku tengah (Seram, Saparua, Ambon), Raja Ampat (Misool) and Indonesian New Guinea (several regions, among them Bird's Neck, Bird's Head and Onin Peninsula). In February 2012 he visited Papua Barat again. Recently, he has published a new book titled **"Biodiversity, biogeography and nature conservation in Wallacea and New Guinea"**. During his journey to Eastern Indonesia, Dmitry took a number of pictures of sedimentary outcrops and published them in Google Maps by putting a coordinate of the outcrop location. These help geologists to get an initial idea about the geology of the area, prior to the field mapping. Although travelling in Eastern Indonesia is easier these days, in many cases it still takes a while to get there and it may be costly.



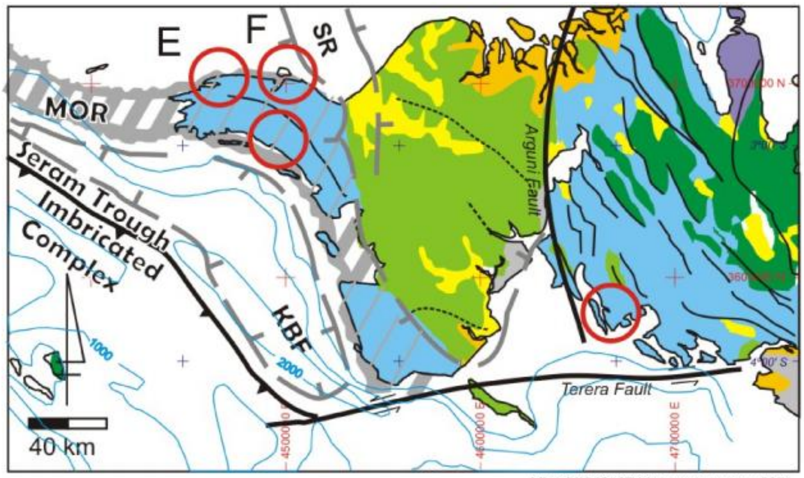
A. Small island in the south of Misool Island, composed of Triassic sediment. Photo by D. Telnov, 2009

Several photos were taken in the area and displayed on Google Map, showing Paleocene to Jurassic outcrops in the area. Paleocene limestone formed steep cliffs and exposed as series of islands in the south of Misool Island. Cretaceous and Jurassic outcrops here have more clastic components and easier to be eroded by sea waves.

B. Paleocene limestone cliff of Pulau Polee (Yefpolee) . Photo taken by D. Telnov, 2009

D. Cretaceous outcrop in the southeast of Misool Island which has been eroded by sea waves. . Photo taken by A. Muljadi, 2010

C. A lineation of islands in the south of Misool Island formed by Paleocene limestones. Photo by D. Telnov, 2009



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Some outcrop photos were taken from the Onin Peninsula and the south of the Lengguru Fold Belt. These outcrops belongs to an areas which generally identified as the Tertiary limestone unit. The three outcrop photos in the north of the Onin Peninsulla.

E. Thin layered sediments interval exposed in the north of Onin Peninsula. Each layer is about few centimeters thick, probably deposited in rather distal setting. Photo by Zoelchan,

F. A small island in the north of Onin Peninsula, with similar characteristics as Photo E. Photo by Zoelchan (Google Map)

G. Waterfall Wanita on River Sakarteman, in the southern part of Onin Peninsula. The rubbles at the foreground shows laminated sediments up to a couple of meters thick. Layered sediments also clearly seen behind the waterfall. Photo taken by D. Telnov, 2010

H. Limestone exposures on the southern part of the Lunguru Fold Belt. The cliffs are about few hundred meters high and very steep . Photo taken by D. Telnov, 2010


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