Permian-Jurassic Palaeogeography of the SE Banda Arc Region

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Abstract

Palaeogeographic maps covering the southern and eastern sectors of the Banda forearc (Savu to the Kei islands, also including Timor and the Tanimbar islands) and adjacent parts of the northwest Australian continental margin are presented for the Early Permian, Middle-Late Permian, Early-Middle Triassic, Late Triassic, and Early, Middle and Late Jurassic. A series of palaeotectonic reconstructions from the Devonian to the mid-Tertiary show an interpretation of the sequential phases of rifting that dismembered northeastern Gondwanaland through this period. Three major phases of rifting are documented for the core region of the future Banda forearc, commencing in the Early Permian, Late Triassic and Middle/Late Jurassic. Each rift event is characterised palaeogeographically by high facies diversity, which is a consequence of strong differential vertical crustal movements at that time. The three rift phases are separated by two quieter tectonic intervals characterised palaeogeographically by low facies diversity (widespread development of marine shales) during phases of post-rift thermal subsidence.

Introduction

The islands of the southern and eastern Banda non-volcanic arc (Savu, Roti, Timor, Babar, Tanimbar and Kei, with numerous smaller intervening islands: Figure 1) are situated in the Neogene zone of collision between the Banda island arc and the formerly passive northwestern continental margin of Australia. Although elements of both the overriding Banda/Eurasian plate and the underthrusting Australian plate are found in these islands and are exposed in the fold and thrust belt that comprises the collision complex, it is Australian tectonostratigraphic elements that overwhelmingly predominate. These thrusted Australian-affinity stratigraphic successions appear to represent the shortened outer edge of the underthrusting Australian continental margin – or at least there is no strong evidence for sudden discontinuities in lithological types and facies belts that would require the presence of allochthonous or 'suspect' Australian-affinity tectonostratigraphic elements and necessitate a tectonic model more complex than simple thrustbelt shortening (this refers only to the Australian-affinity successions: there is clearly also a true allochthon of Banda forearc material).

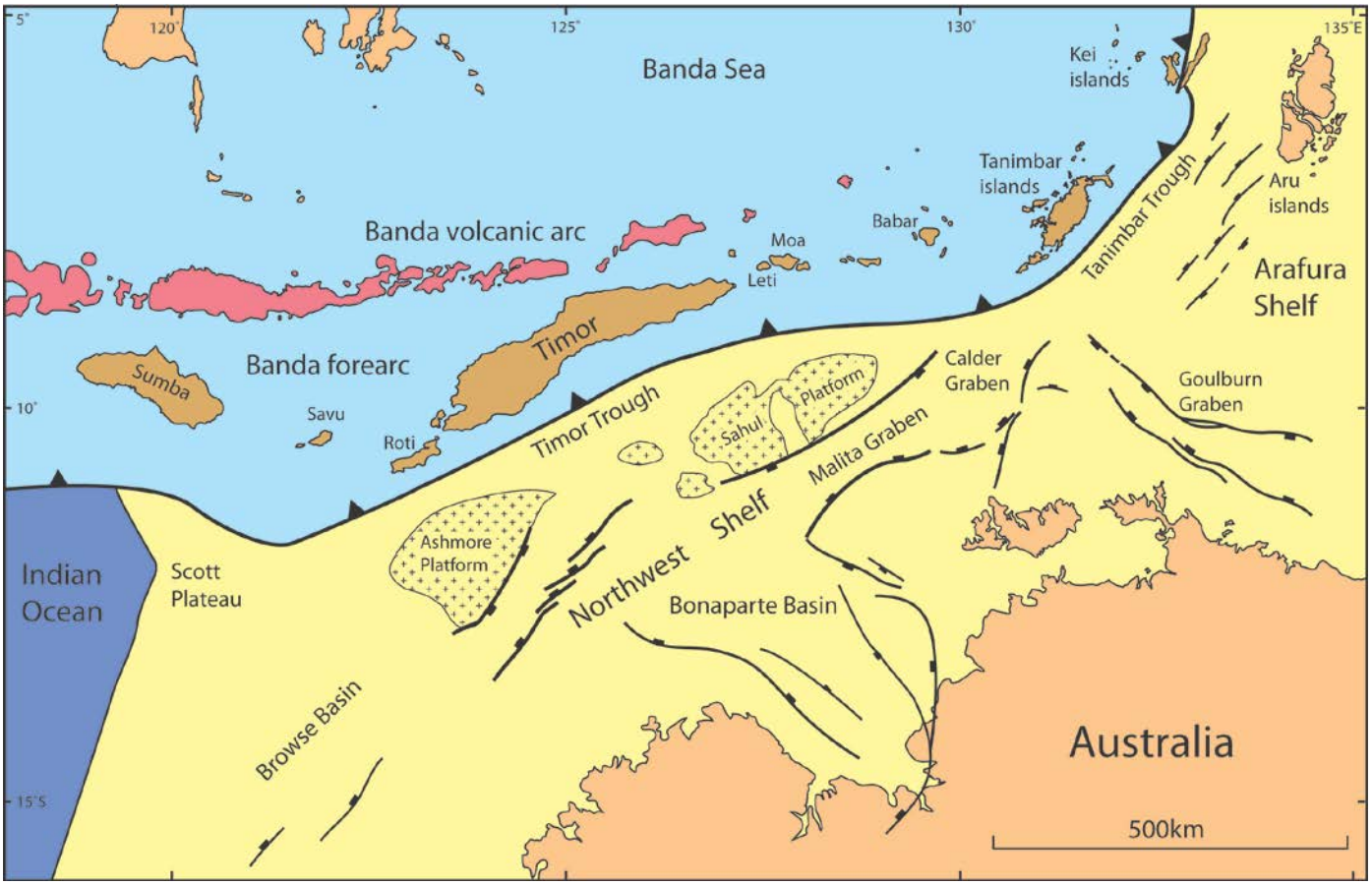


Figure 1. Tectonic setting of the southern and eastern Banda Arc

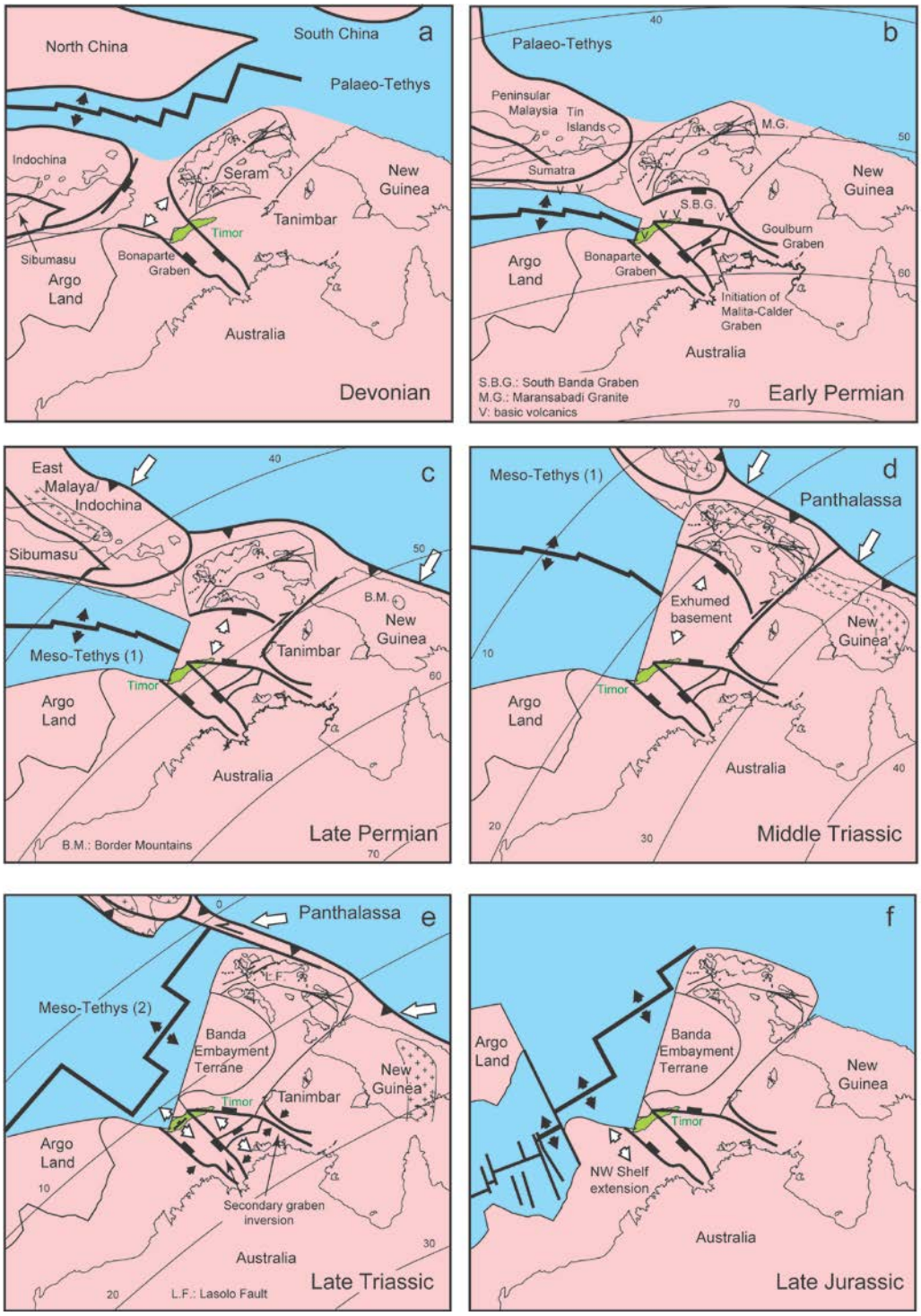


Figure 2. *Devonian–Jurassic evolution of northeastern Gondwanaland*

Palaeogeographic reconstructions of the Australian-affinity stratigraphic successions in the Banda forearc provide a valuable constraint for understanding the evolution of the northern margin of the Australian continent, complementing data gathered from the generally more proximal and much less deformed Australian 'passive' margin successions to the south and east of the Timor-Tanimbar Trough system (the deformation front of the Banda collision complex: Figure 1). For the Permian to Jurassic interval considered in the present study the reconstructions may be particularly significant for petroleum exploration as petroleum systems in both the Banda forearc and the northwestern Australian margin (Northwest Shelf to West Papua) are found primarily within rocks of this age range. An overview of the regional evolution through the Permian to Jurassic interval is presented here in the form of a series of regional tectonic cartoons (Figure 2) and more detailed palaeogeographic maps for seven time intervals (Figures 3-9).

Pre-Permian framework

Figure 2 illustrates the interpreted evolution of Gondwanan eastern Indonesia from the Palaeozoic through to the Jurassic. In Figure 2a the numerous continental fragments of present-day northern east Indonesia (eastern Sulawesi, Buton, Banggai-Sula, the Bird's Head, Buru, Seram, Misool, etc.) have been re-assembled into a coherent continental fragment, the Greater Sula Spur, and these are repositioned to the north of the present-day southern Banda Arc from Tanimbar to Timor (Charlton, 2000, 2001). The Greater Sula Spur represents just one of the marginal Gondwanan

terranes that were detached from present-day Australia in a series of Palaeozoic-Mesozoic continental rifting events. Other terranes reconstructed against the northern Gondwanan margin during the Early Palaeozoic include North and South China, Indochina and Sibumasu (Figure 2a).

The geological record for most of the Banda Arc region only extends back to the Permian, although there are unconfirmed reports of older Palaeozoic sedimentary rocks in Timor (Sousa Torres & Pires Soares, 1952). The pre-Permian history of the Banda Arc region can, therefore, only be inferred indirectly, particularly from the known Palaeozoic history of adjacent regions, and particularly from the Northwest Shelf and New Guinea Island. Prior to the Permian, the present-day Northwest Shelf formed an internal part of the Gondwanan supercontinent. In the Devonian a series of rift systems developed through this region, including the Bonaparte Graben which formed with a NW-SE orientation (present-day geographic coordinates) from the head of the Joseph Bonaparte Gulf on the NW coast of Australia towards present-day Timor (Lee & Gunn, 1988). This rift system appears to have been an entirely intracontinental aulacogen that never developed to a stage of oceanic rifting (O'Brien et al., 1993), although at the continental edge it probably connected with a continental margin rift system responsible for the separation of the North China block from the margin of Gondwanaland (Klootwijk, 1996). The Bonaparte Graben trend is interpreted in this study to have had a fundamental control on the evolution of particularly the Timor region, both in the pre-collisional phase and during Neogene arc-continent collision. This early differentiation into a relative structural high in what is now East Timor and a more basinal area in present-day West Timor (Figure 2a) is reflected in overall more basinal successions in West Timor compared to East Timor (see the individual palaeogeographic maps). This fundamental crustal differentiation between East and West Timor is also reflected by rather different structural styles in the present-day collision complexes in the two halves of the island (Charlton, 2004).

Permian

A further phase of rifting within Gondwanaland was initiated in latest Carboniferous or earliest Permian times (Figure 2b). The primary E-W strike of structures (present-day geographic coordinates) resulting from N-S extension during this structural phase was rather oblique to the previous trend in the Bonaparte Graben. This second extensional phase was probably associated with the detachment of the Sibumasu Terrane (present-day western Thailand, eastern Myanmar, western peninsular Malaysia and northern Sumatra) from Gondwanaland (e.g. Metcalfe, 1990, 1996; Charlton, 2001). An oceanic rift probably developed between Sibumasu and the Argo Land continental terrane located immediately west of Australia (Veevers et al., 1991). Further east, this oceanic rift is interpreted to have passed laterally into an intracontinental rift system along the line of the present-day southern Banda Arc (the South Banda Graben: Figures 2b, 3 & 4) and into the Goulburn Graben on the southern Arafura Shelf. Radiometric dating suggests that the Goulburn Graben was undergoing extension during the latest Carboniferous-earliest Permian (Bradshaw et al., 1990), while the lateral continuation of this rift system into Timor and other Banda forearc islands is indicated by abundant rift valley-type basaltic volcanism during the Early Permian, both in basinal clastic-dominated successions (Atahoc and Cribas formations in Timor), and particularly in the contemporaneous Maubisse Formation, which consists of basic volcanics, volcaniclastic sediments and shelf carbonates, and probably represents rift flank and intra-rift horst block successions. Directly comparable shallow marine carbonate and volcanic successions are also seen in Tanimbar (Selu Formation: unpublished field results), and similar successions are probably also present but less-well documented in the southwestern Maluku forearc islands (e.g. reddish Permo-Triassic limestones from Leti: Agustiyanto et al., 1994; crinoidal limestone from Babar: van Bemmelen, 1949). On the present Northwest Shelf to the south of this rift domain the shallow marine limestones of the Maubisse Formation can be correlated with Permian limestones encountered, for instance, in the Kelp Deep-1 well on the crest of the Sahul Platform (the Pearce and Dombey Formations/Members: Gorter, 1998; Charlton et al., 2002). Unlike the Tanimbar and Timor limestones, however, the Upper Permian limestones of the Australian Northwest Shelf are not known to be associated with volcanics.

Stratigraphic information from the Tanimbar islands is rather limited, but it is inferred, based on an integration of data from various geological intervals, that the successions accumulated in a graben setting. This Tanimbar Graben (as it will be described hereafter) probably began to develop during the Permian as an aulacogenic rift on the northern margin of the South Banda Graben, and formed a northern counterpart to the Calder-Malita Graben system which developed contemporaneously on the southern margin of the South Banda Graben.

Further north in Gondwanan eastern Indonesia (Banggai-Sula and northern New Guinea), granitoid plutonism commenced in the Carboniferous, and apparently continued throughout the Permian (summarised in Charlton, 2001).

Early-Middle Triassic

During the Permian and Triassic the Sibumasu Terrane drifted northward relative to Gondwanaland (Metcalfe, 1996). However, continuing stratigraphic links between Sibumasu and Gondwanan eastern Indonesia through this period suggest continuing connection between the two regions (Audley-Charles et al., 1988; Lunt & Djaafar, 1991). In Figure 2b-d it is suggested that this apparent paradox can be resolved by Gondwanan eastern Indonesia being displaced northward relative to Australia with Sibumasu through this period, with movement relative to Gondwanaland accommodated on a left lateral fault system along the western margin of the present-day Arafura Shelf. To the west of this, intracontinental extension involving delamination between upper and lower crust took place in the region between the present-day southern and the

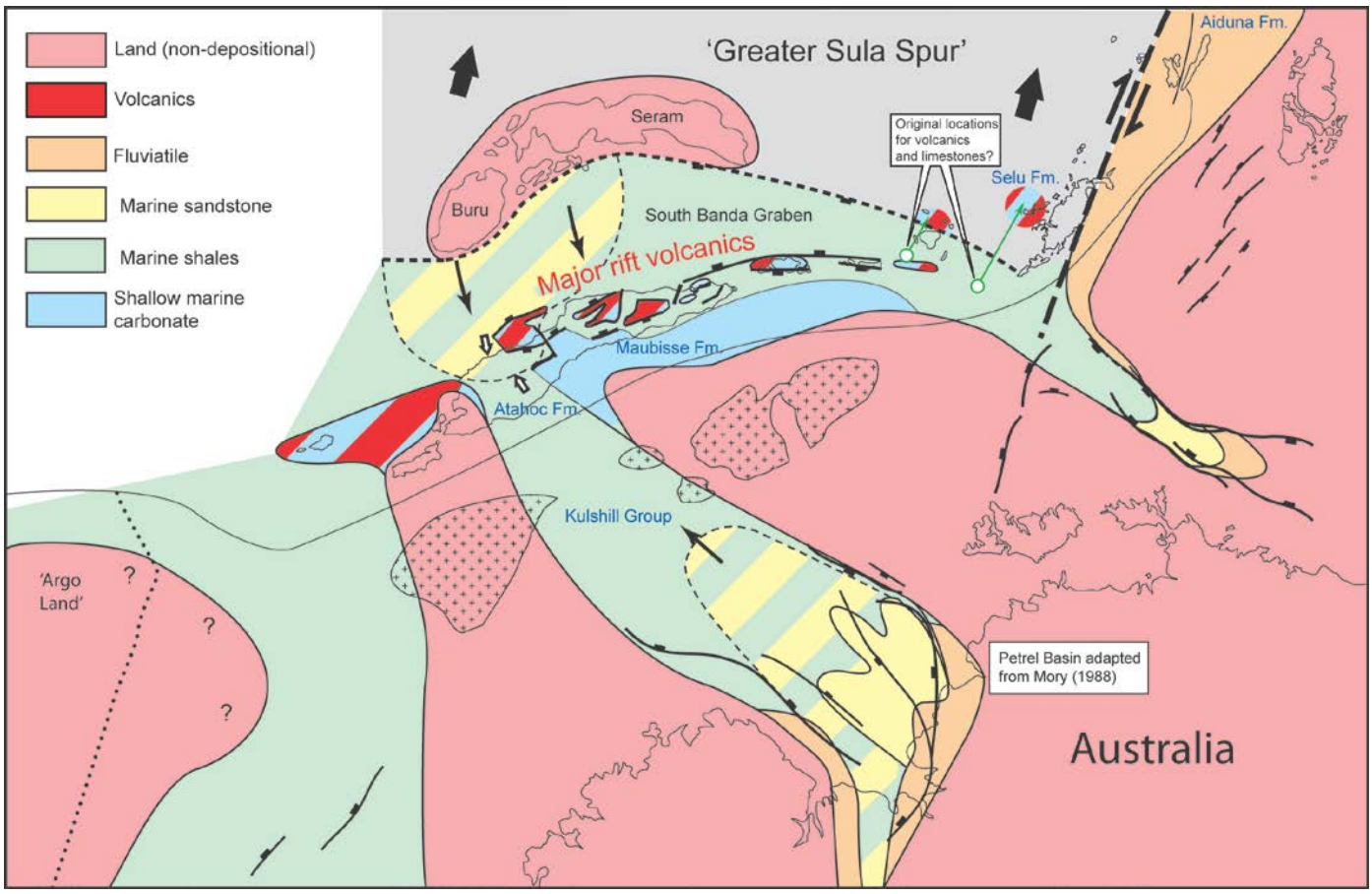


Figure 3. *Early Permian palaeogeography*

northern Banda forearc islands. The two opposing rift margins probably consisted of opposed upper-plate and lower-plate rifted margin pairs (cf. Lister et al., 1991), with what is now eastern Timor (upper-plate rifted margin) facing eastern Seram (lower-plate rifted margin), while western Timor (lower-plate rifted margin) faced western Seram and Buru (upper plate rifted margin). The switchover from upper- to lower-plate margin in Timor was probably associated with the graben-bounding faults along the pre-existing Bonaparte Rift trend (see Charlton, 2004 for further discussion).

From the Early Permian (Figure 3) through the Middle/Late Permian (Figure 4) and into the Early/Middle Triassic (Figure 5) extension was focused within the South Banda Graben. Through the Permian and Early/Middle Triassic the locus of rifting migrated sequentially northward away from the southern margin of the rift (Figure 2b-d), and this is marked in the regional geology of the present-day southern Banda forearc by a waning of rift volcanism; by a marked reduction in facies diversity as active rifting declined; and by a major transgression with an associated dominance of shaly clastic facies as post-rift tectonic subsidence set in. By the Early and Middle Triassic (Figure 5) shale successions dominate the Northwest Shelf (Mount Goodwin Formation) and Timor (Niof Formation). Contemporaneously in Timor condensed and highly fossiliferous *rosso ammonitico*-type limestone successions were accumulating on isolated structural highs formed during the extension (the Cephalopod Limestone facies: Charlton et al., 2009) In Tanimbar non-marine claystones were deposited in the far north of the island group (Maru island: unpublished field results).

In the Australian-affinity terranes of the present-day northern Banda Arc region (Seram, Buru, Misool; also Buton), a downward transition from non-metamorphic Middle Triassic turbidites into low-grade metamorphic rocks appears to be a characteristic feature (see Charlton, 2001 for a fuller discussion). The structure of the northern Banda Arc region at this time has been interpreted as a series of active half-grabens downthrowing away from a continental hinterland to the north and east (e.g. Price et al., 1987; Kemp & Mogg, 1992; Figure 2d).

In the northern part of Gondwanan eastern Indonesia granitoid intrusion continued through the Early and Middle Triassic in the Bird's Head, Banggai-Sula and possible eastern Sulawesi (Figure 2d; summarised in Charlton, 2001). Terrestrial and fluviatile successions equivalent to the Tipuma Formation of the Bird's Head also characterise the Triassic of Banggai-Sula and parts of southeastern Sulawesi, although these successions are generally not well dated.

Late Triassic

It has been suggested (Charlton, 2001) that although Sibumasu rifted away from the main body of Gondwanaland during the Early Permian (in accord with the interpretations of Metcalfe, 1996), Sibumasu did not finally separate from Gondwanan eastern Indonesia until the Carnian (early Late Triassic). At that time a new seafloor spreading régime was probably initiated to the north of Argo Land (Figure 2e), which had the effect of driving Sibumasu rapidly northward relative to Australia, and may also account for an important

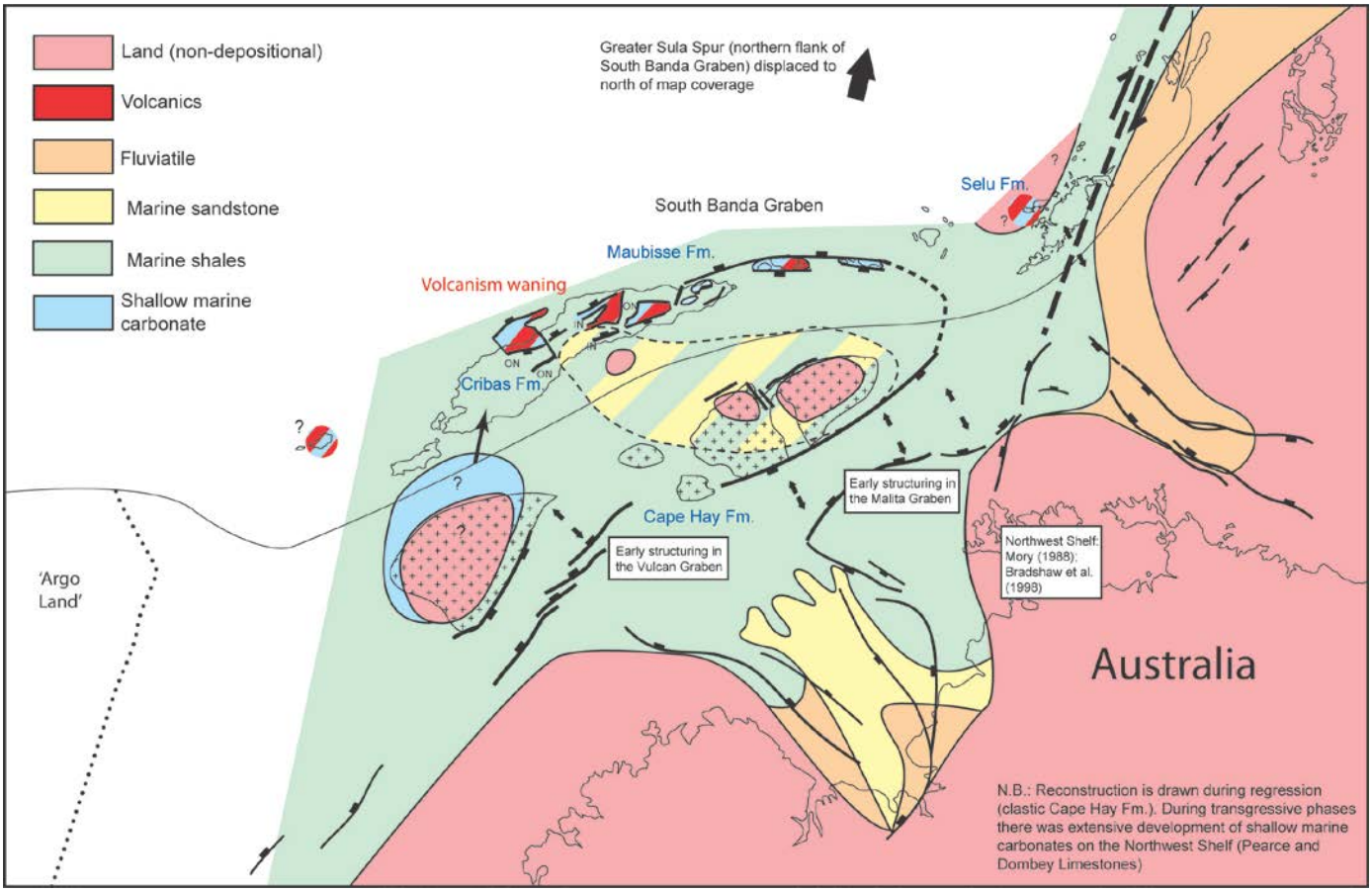


Figure 4. *Middle–Late Permian palaeogeography*

phase of Late Triassic fault reactivation in Timor (Audley-Charles, 1988) and the Northwest Shelf (Symonds et al., 1994).

Regional extension associated with this renewed seafloor spreading adjacent to the future southeast Banda region led once more to the type of facies diversity in the Late Triassic (Figure 6) that had been seen previously during the early stages of rifting in the Early Permian (Figure 3) – but in the Late Triassic without the presence of significant volcanism. The Late Triassic is the key interval for petroleum exploration in the Banda Arc region, with the development of restricted marine source rocks in the graben basins, and contemporaneous development of proven and potential reservoir sequences in shallow marine carbonates deposited primarily on isolated structural highs, and in siliciclastic successions shed into the basins from erosion of the rejuvenated Late Triassic landscape (Charlton, 2002a, b; 2004).

In Timor, Late Triassic reefal and other shallow marine carbonate buildups developed on active horst blocks (Fatu Limestone; 'Cablac' Limestone: see Haig et al. 2007, 2008 and later papers by these authors for discussion of the Mesozoic Cablac Limestone), while deeper, restricted marine sequences accumulated in adjacent grabens (the dominantly carbonate Aitutu Formation and the contemporaneous siliciclastic Babulu Formation). Towards the Australian continent more proximal sedimentary environments were established during the Late Triassic, represented by non-marine to shallow marine sandstones and subordinate shales of the Malita Formation. Somewhat more marine lateral equivalents of the Malita Formation have been encountered in the subsurface of southern West Timor in the Banli-1 exploration well (the Malita-equivalent: Sani et al., 1995).

Similar sedimentary environments and facies to those in Timor developed contemporaneously in Tanimbar, with reefal buildups (Wotar Formation) developed on local structural highs, and clastic sediments (Maru Formation) accumulating in adjacent basins (unpublished field results). Previously the present writer (Charlton et al., 1991) interpreted the Maru Formation as sourced from the Calder Graben to the south in a simple northward continuation of sedimentation within the Malita-Calder Graben system. However, further examination of palaeogeographic data for the Late Triassic of the Tanimbar islands suggests that the environmental polarity is wrong for a southern sedimentary source. The most proximal sandstone successions are found in the most northerly islands of Maru and Molu, where samples show a very strong terrestrial influence. Late Triassic sandstone-shale successions sampled from further south in the Tanimbar islands show only strong (as opposed to very strong) terrestrial influence, while the bivalve *Halobia*, which is found widely in the Late Triassic of Timor in low-energy, moderately deep shelf facies (see Charlton et al., 2009), has been recorded in the more southerly islands of the Tanimbar group (e.g. Weber, 1925). These palaeogeographic indications are more consistent with a northern sedimentary provenance within the Tanimbar Graben, as indicated in Figure 6.

The palaeogeographic setting of Savu during the Late Triassic was initially a relatively deep marine basin accumulating limestone-shale successions, into which more proximal, probably fluviodeltaic, sandstone-shale successions

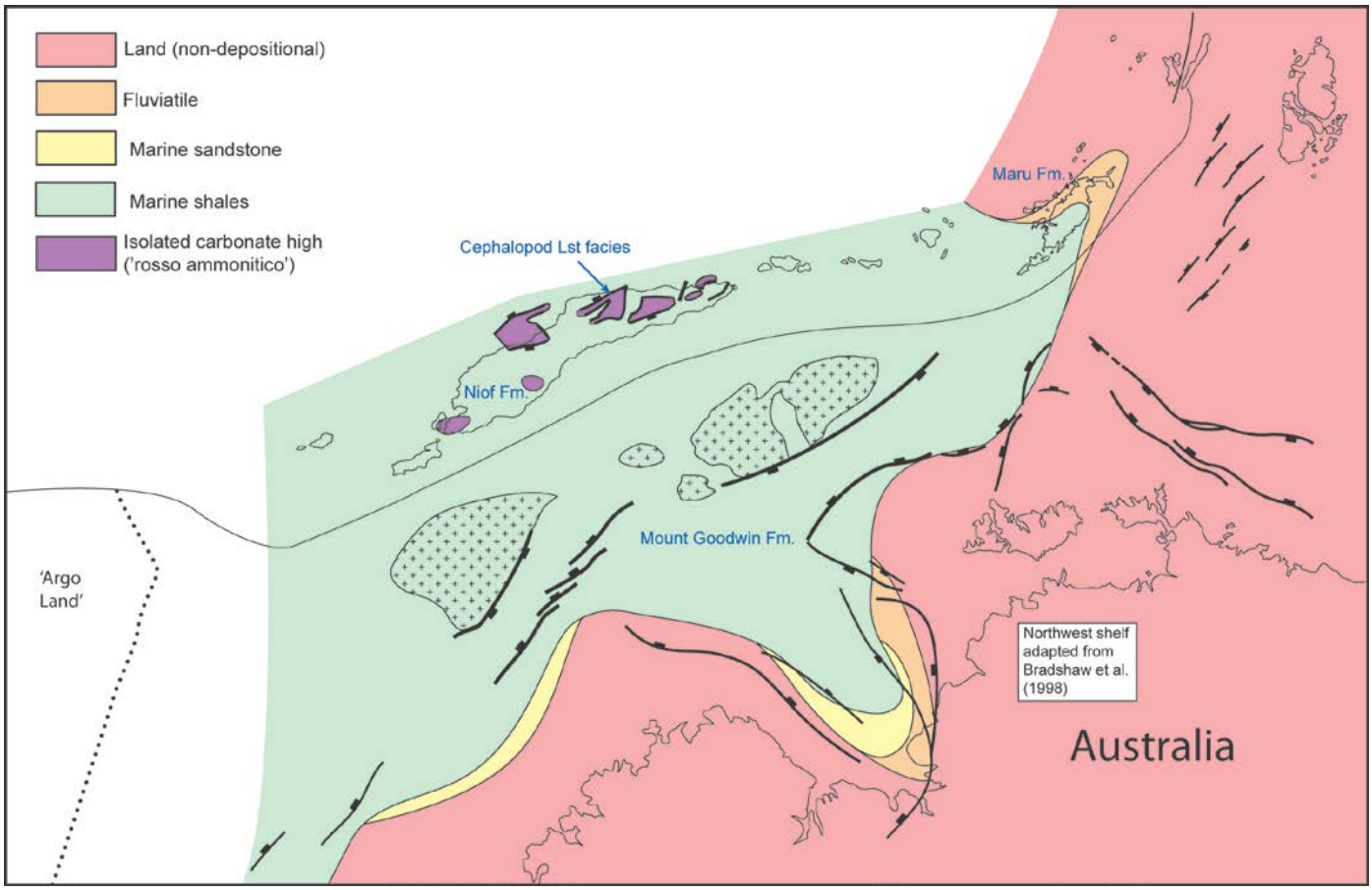


Figure 5. *Early–Middle Triassic palaeogeography*

were introduced. These relatively proximal sediments may have been sourced from an emergent landmass to the southwest of Savu, in the now-removed Argo Land marginal terrane.

In the northern Banda Arc and regionally, an important structural event is recognised in the mid-Carnian (Lunt & Djaafar, 1991), interpreted (Charlton, 2001) as marking the end of the main extensional phase in the northern Banda Arc province. In Misool, for instance, Lower Carnian and older turbiditic sediments of the Keskain Formation are folded and unconformably overlain by Lower Norian marls passing up into Middle and Upper Norian reef limestones (Wanner, 1931; Visser & Hermes, 1962).

Early-Middle Jurassic

The phase of active extension during the Late Triassic waned into the Early and Middle Jurassic as the spreading centre moved away from the immediate vicinity of the study area. Post-rift thermal relaxation is marked stratigraphically by the regional development of transgressive shale sequences (Figures 7 & 8). In Timor the main stratigraphic unit in the Early-Middle Jurassic is the Wai Luli Formation, which is a shale-dominated succession up to several hundred metres thick. In the Banli-1 well in the south of West Timor the Wai Luli shales of Middle Jurassic age succeed Early Jurassic sandstone-dominated successions described as the Plover-equivalent (Sani et al., 1995), after the Plover Formation which occurs extensively across the Northwest Shelf during the Early and Middle Jurassic.

In the Tanimbar islands Jurassic sections have not been recognised in normal outcrop, but Jurassic shales are identified from the ejecta of mud volcanoes. Palaeoenvironmental indicators from material erupted from mud volcanoes are consistent with regional transgression during the Early Jurassic. For instance, in samples from a short-lived mud volcano in Selat Yamdena to the west of Yamdena island (now eroded to below sea level) a Sinemurian-earliest Toarcian dolomitised ferroan nodule was deposited in a supralittoral environment, while a Pliensbachian-earliest Toarcian dolomite was deposited in a very shallow inner sublittoral environment; and marine shales are dated to the early Toarcian. This suggests marine transgression in about the Pliensbachian (mid Early Jurassic) at this locality, assuming that the mud volcanic material corresponds approximately to a disrupted original vertical stratigraphic succession. In other mud volcanoes in Tanimbar Early Jurassic ammonites have been collected (Wanner & Jaworski, 1931; Charlton et al., 1991), presumably originating from open marine, low energy sedimentary successions. As with Late Triassic samples, the environmental information from Tanimbar is more consistent with a northern sedimentary source, rather than sourcing from the Plover Formation sedimentary system of the Malita-Calder Graben system as previously interpreted (Charlton et al., 1991).

One additional interesting lithology from a Tanimbar mud volcano is a block of dolomite-replaced coral packstone dated to the Aalenien-earliest Bajocian. The present writer is unaware of other shallow marine limestones convincingly dated to the Middle Jurassic from anywhere else in the Banda Arc region (the Manusela Limestone in Seram,

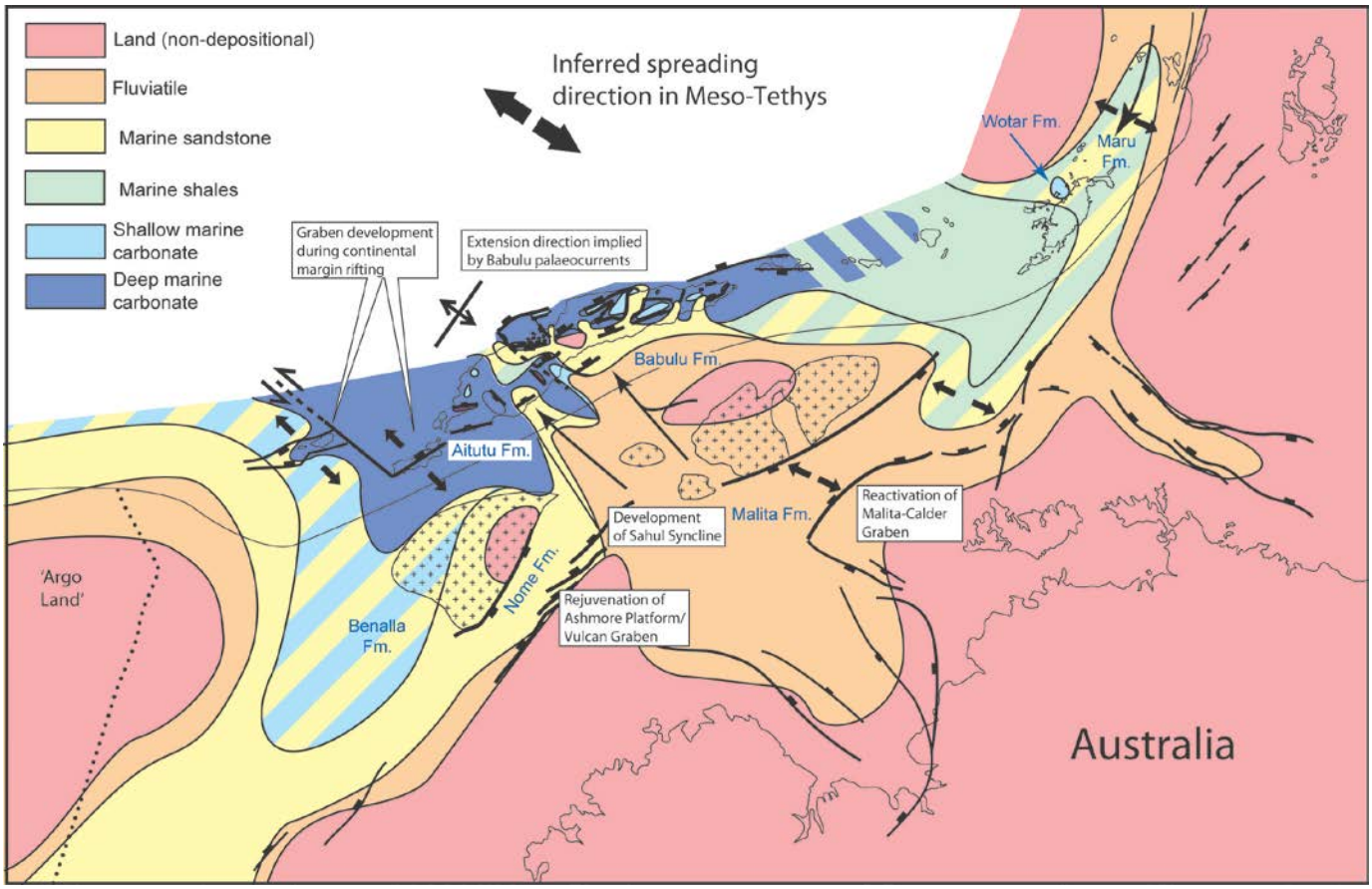


Figure 6. *Late Triassic palaeogeography*

interpreted by Kemp & Mogg (1992), as Middle Jurassic, appears to be dated only on long-ranging species, and seems more likely to be Early rather than Middle Jurassic in age).

In the Kei islands there is no known Jurassic outcrop, but the Kai Besar-1 well intersected a Lower Jurassic proximal open marine succession succeeded by Middle Jurassic (Aalenian-Bajocian) fluviodeltaic sediments. This broadly regressive succession contrasts with transgression in Timor, Tanimbar and the Northwest Shelf at this time.

In Savu equivalents of the Wai Luli Formation from Timor have been recognised on the basis of lithology, although these are not accurately dated (Harris et al., 2009). These clastic successions are associated with basic volcanics which these authors interpreted as probably Late Jurassic (and hence they are indicated on the Late Jurassic palaeogeographic map: Figure 9), but it is possible that they are Middle Jurassic in age and should be shown on Figure 8 together with Middle Jurassic volcanics known from the Barcoo Basin on the western margin of Australia to the south of Savu. These volcanics were a precursor to the Late Jurassic breakup event described in more detail in the following sub-section.

In the Leti-Babar sector of the Banda forearc the Early-Middle Jurassic appears to be developed primarily in Wai Luli-like shale facies. In Babar this facies is identified particularly through the occurrence of Jurassic ammonites in mud volcanic ejecta, including genera ranging in age from the Norian-Rhaetian (Late Triassic), through the entire Early and Middle Jurassic, and continuing possibly until the Oxfordian (early Late Jurassic) (Verbeek, 1908; Oyens, 1913). These ammonites were collected from ferruginous clay-marl geodes and marly limestone.

Late Jurassic

The Late Jurassic saw renewed vertical crustal movements across the Northwest Shelf and the future southeastern Banda forearc region. The boundary between the Middle and Late Jurassic on the Northwest Shelf is widely marked by the so-called Callovian unconformity, which is identified regionally as corresponding to the onset of rifting associated with the initiation of the Indian Ocean and the development of the present western continental margin of Australia (Figure 9). In the Argo Abyssal Plain, located in the NE corner of the Indian Ocean to the southwest of Savu, an initial phase of spreading is identified between magnetic anomalies M26-M15 (approximately Oxfordian to mid-Valanginian), with spreading oriented in a NNW-SSE direction relative to Australia (Veevers & Li, 1991; Figure 2f). In Timor a distinct stratigraphic package corresponding fairly precisely in age to this phase of Oxfordian to mid-Valanginian spreading can be characterised as a syn-rift or breakup succession. Below the Callovian unconformity, sea-level regression associated with the early stages of rifting is probably expressed stratigraphically in Timor by the upward passage within the Wai Luli Formation from predominant shales into more sandy facies (the Wai Luli Sandstone Member). There appears to be a distinct palaeontological hiatus within the Jurassic successions in West Timor that cuts out the Lower-Middle Oxfordian (earliest Late Jurassic), and the succeeding Oe Baat Formation, which consists primarily of turbiditic glauconitic sandstones, is the main

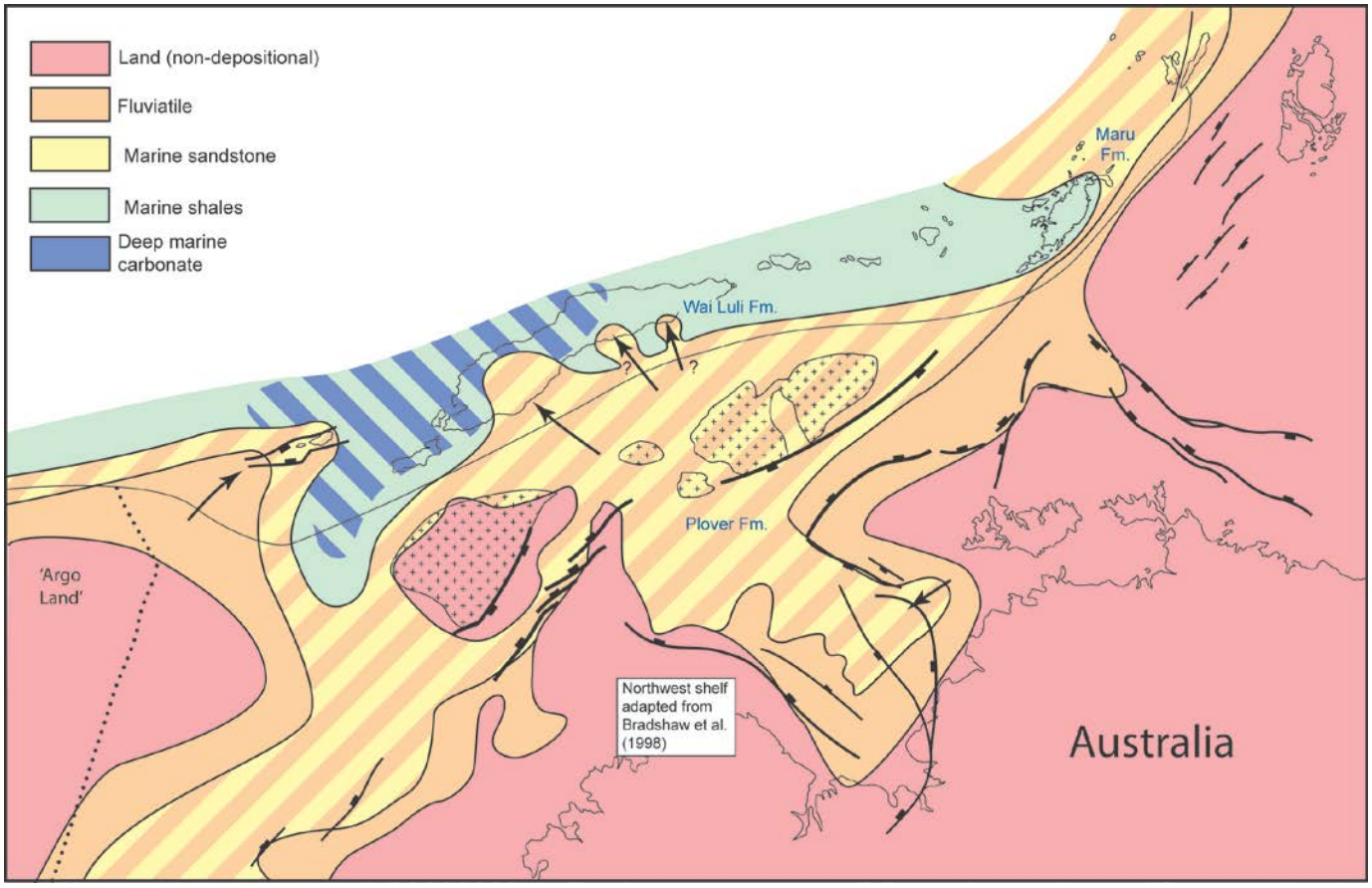


Figure 7. *Early Jurassic paleogeography*

element of the breakup megasequence (Charlton, 1987). Broadly contemporaneous sandstone successions encountered in the Banli-1 well are overlain by basic volcanics and volcaniclastics also inferred to be Late Jurassic in age (Sani et al., 1995).

In addition to the regional Callovian unconformity, interpreted as associated with the commencement of seafloor spreading during the Callovian/Oxfordian, there was also a marked change in spreading rate in the Kimmeridgian (Veevers & Li, 1991), and this also corresponds to a regionally important unconformity/disconformity. The Callovian unconformity appears to be more prominent in the extreme west of the Banda Arc-Northwest Shelf palaeogeographic region, for instance, in the Vulcan Graben of the Northwest Shelf (Pattillo & Nicholls, 1990); in western Timor (deposition of the high-energy Oe Baat Formation); and also in Buru in the northern Banda Arc (Oxfordian volcanics: Hummel, 1923). The intra-Kimmeridgian unconformity/disconformity, in contrast, appears be more prominent further east on the Northwest Shelf, e.g. in the Malita Graben which was probably reactivated in extension at this time (Anderson et al., 1993); and in the western part of the Joint Petroleum Development Area (JPDA) between Timor-Leste and Australia which is characterised by active block faulting at this time (Whittam et al., 1996). The Kimmeridgian phase of extension is also clearly marked in Seram, Misool and the Misool/Berau Shelf to the north of Seram. The intra-Kimmeridgian unconformity does not, however, appear to be of great stratigraphic significance in West Timor, for instance. It is possible that the trend of the Bonaparte rift acted as a barrier to the effective transmission of stresses associated with the earliest Callovian-Oxfordian rift phase, so that areas further to the east were less affected by this initial rifting event; but conversely the slightly later Kimmeridgian rifting had more effect to the east of the Bonaparte rift.

In Tanimbar the Late Jurassic is recognised through belemnites in the ejecta of mud volcanoes in the more southerly parts of the island group, and by perhaps more proximal red mudstone further north. There is also a major sandstone unit, the Ungar Formation (Charlton et al., 1991), which interdigitates in its upper part with radiolarian shales (Arumit Member: unpublished field results) of earliest Cretaceous, Berriasian-Valanginian age (Basir Jasin & Haile, 1996). The Ungar sandstones below the earliest Cretaceous radiolarian shales are not directly dated, but are likely to be Late Jurassic in age based on their significant thickness (several hundred metres) immediately below the dated earliest Cretaceous sediments.

In the Kei Besar-1 well the Late Jurassic is absent beneath an Early Cretaceous unconformity, and there is no known surface exposure of the Jurassic in the Kei islands. The Late Jurassic may also be absent in the Leti-Babar sector of the Banda forearc between Timor and Tanimbar, as no fossils from this interval have yet been reported, apart from relatively long-ranging ammonites from Babar that could be as young as Oxfordian. The Late Jurassic is also not definitively proven from Savu, where the youngest indication of the Jurassic is the dinocyst *Rigaudella aemula* (Harris et al., 2009), which is the zone fossil on the Northwest Shelf for the latest Callovian and earliest Oxfordian. As already mentioned, basic volcanics in Savu have been interpreted as

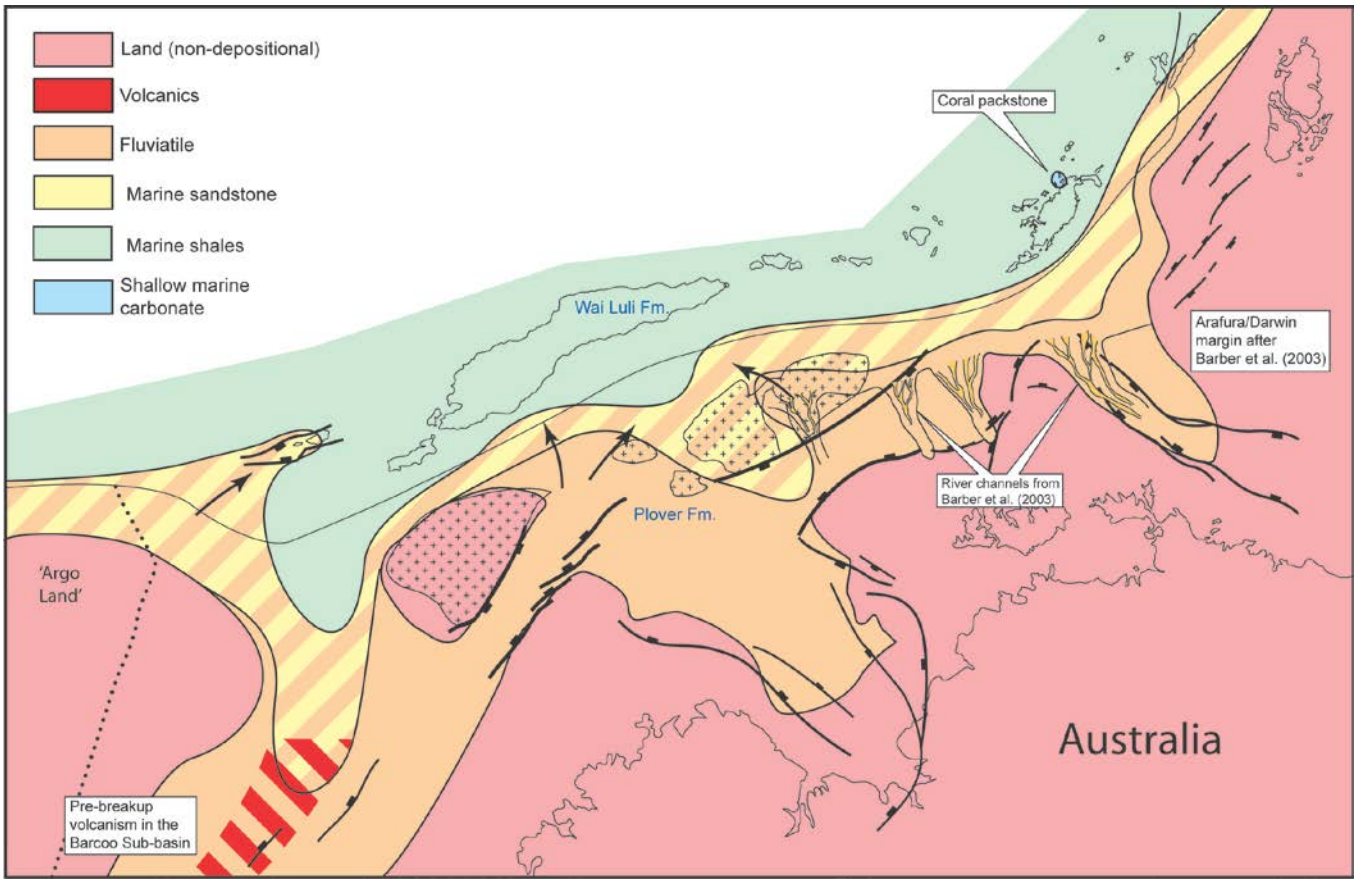


Figure 8. Middle Jurassic palaeogeography

Late Jurassic in age (Harris et al., 2009), but this is not established palaeontologically or radiometrically.

Cretaceous-Tertiary regional evolution

The extensional phase that commenced in the later Middle Jurassic continued into the Early Cretaceous. Based on seafloor spreading patterns from the Indian Ocean off the western margin of Australia, a significant reorganisation of spreading commenced in the mid-Valanginian, with a change from NNW-SSE spreading to spreading oriented WNW-ESE (Veevers & Li, 1991; Figure 10g). In this reconstruction it is speculated that the known spreading system off the western margin of Australia linked to a further spreading centre that initiated within what is now the Banda Embayment – i.e. within the continental crust of Gondwanan eastern Indonesia, detaching a microcontinental terrane (the Banda Embayment Terrane). It was speculated (Charlton, 2001) that the Banda Embayment Terrane was subsequently accreted to Southeast Asia as the West Burma Terrane which, according to Metcalfe (1990), consists of schist overlain by Triassic turbidites and Albian (mid-Cretaceous) shales and turbidites [the latter representing a post-breakup succession following the Early Cretaceous rifting?]. Metcalfe also considered the West Burma Terrane as a likely sedimentary provenance for the northerly-sourced Permian turbidites of Timor. An alternative is that part of the Banda Embayment Terrane was accreted to southeastern Sundaland as the East Java continental fragment (Smyth et al., 2007), although those authors preferred an origin for this allochthonous Gondwanan terrane further south on the western Australian margin.

In Timor the Early Cretaceous change in spreading direction coincided with dramatic deepening in the sedimentary environment, marking the boundary between a syn-rift megasequence deposited under neritic shelf water depths, and a post-rift megasequence deposited under bathyal and even abyssal water depths. Radiolarites and radiolarian shales in the Early Cretaceous Nakfunu Formation of West Timor and the equivalent Wai Bua Formation in East Timor are often lacking in carbonate fossil material, and it appears that these sediments were deposited at least in part below the carbonate compensation depth, at water depths of perhaps 4000m or more.

The earliest Cretaceous (Berriasian-Valanginian) of the eastern Northwest Shelf is also characterised by transgressive conditions, in contrast to global eustatic regression at that time, with widespread deposition of shale-dominated successions of the Flamingo and Echuca Shoals formations. Only limited Early Cretaceous age determinations have been made from Tanimbar, but these also seem to indicate generally transgressive conditions. The Arumit Member of the Ungar Formation, a succession of radiolarian claystones interdigitating with the Ungar sandstones, is dated as probably Berriasian-Valanginian (after Basir Jasin & Haile, 1996), while a shale sample from a mud volcano has been dated as Hauterivian (unpublished field results). The shale sample contains a palynoflora indicating a strong terrestrial influence, suggesting land nearby. Furthermore, although undated, shallow marine or possibly terrestrial sandstones immediately overlie the Arumit Member on Ungar island, suggesting regression perhaps from as early as the Hauterivian (while sea levels were rising globally).

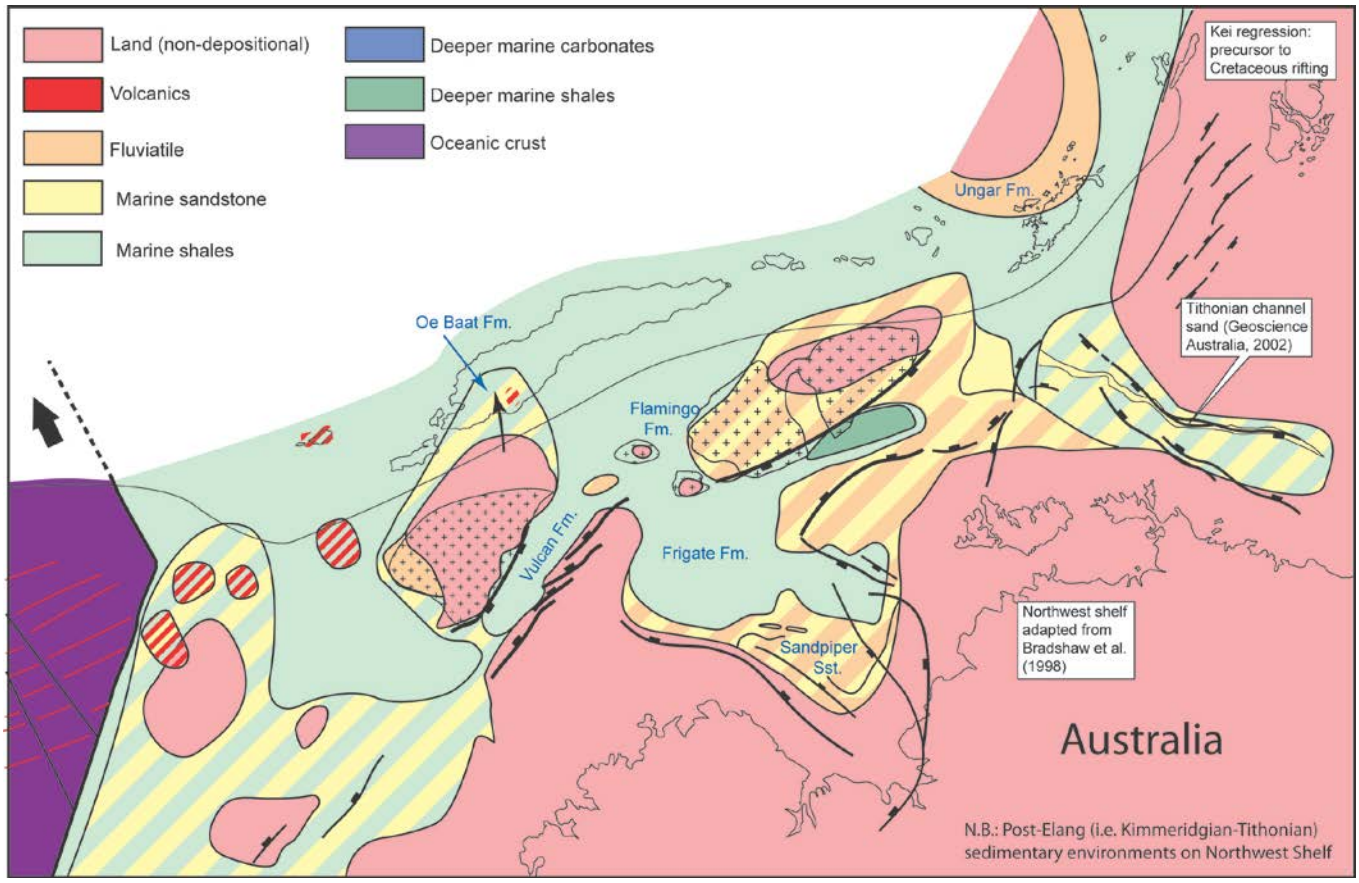


Figure 9. *Late Jurassic palaeogeography*

In Kai Besar-1 the Early Cretaceous is represented by a relatively thin (10-15m?) interval, details of which are not available to the present study. The Early Cretaceous has hardly been documented from the Leti-Babar sector of the Banda forearc, while in Savu the Cretaceous succession has not been studied in any detail, but appears broadly similar to that in Timor (Harris et al., 2009).

Following the Early Cretaceous rifting, it has been widely assumed that the outermost edge of the Australian continental margin in what is now the Banda forearc was tectonically quiescent, slowly subsiding and accumulating a prograding and shallowing-upward succession on the outermost edge of the Australian Northwest Shelf (e.g. Charlton, 1989). However, there are some indications that the region was not as 'passive' during the mid-Cretaceous and Paleogene as has been previously inferred. For instance, subsidence curves for petroleum exploration wells located near to the outer edge of the Australian continental margin external to the Banda Arc (Northwest Shelf, Arafura Shelf and Bird's Head block) show a characteristic pattern of relatively stable crust until a point in the mid-Cretaceous or Palaeogene when the rate of crustal subsidence increased sharply. The time of accelerated subsidence is generally concordant over a small sector of the margin, but shows considerable variability around the arc. The pattern is more complex than a simple progression in the onset of subsidence as might be expected if an oceanic spreading centre was sequentially migrating away from the Banda Embayment. For instance, the area of the Sahul Platform to the south of Timor began relatively rapid subsidence during the Albian, while the continental margin to the east and north (Calder Graben, Arafura Shelf, Berau Basin) began to subside slightly later in the Cretaceous, between about the Cenomanian and Santonian. To the west of the Sahul Platform in the Browse Basin-Ashmore Platform area rapid subsidence did not commence until the Maastrichtian (latest Cretaceous) or the Paleocene. The very delayed subsidence of particularly this western part of the Australian margin probably indicates a further phase of rifting (and subsequent post-rift subsidence) that is not apparent from the Indian Ocean seafloor spreading record.

A further possible indication of passive-margin tectonics continuing into the Late Cretaceous and Palaeogene is sedimentological-palaeontological evidence from the Kolbano Megasequence in Timor. The Kolbano Megasequence represents the very distal Australian continental margin succession that accumulated during the Cretaceous and Tertiary prior to arc-continent collision (Audley-Charles & Carter, 1972; Haig & McCartain, 2007), and is broadly a shallowing-up sequence that developed as the carbonate shelf of NW Australia prograded towards the distal continental margin (e.g. Charlton, 1989). A characteristic feature of the Kolbano succession identified particularly by micropalaeontologist David Carter, is the strong reworking of Cretaceous planktonic foraminiferal faunas into Lower Eocene and younger hemipelagic limestone turbidites (e.g. Audley-Charles & Carter, 1972; Carter, unpublished report to Timor Oil 1971). According to Carter (1971) 'It is possible that little if any sediment was accumulating on the slope of Timor in the late Senonian [Late Cretaceous] and that the material now found there accumulated up-slope, to slump down to its present position in the Lower Eocene. There is no direct evidence as to fall of the slope in the Cretaceous and Lower Eocene, but indirect

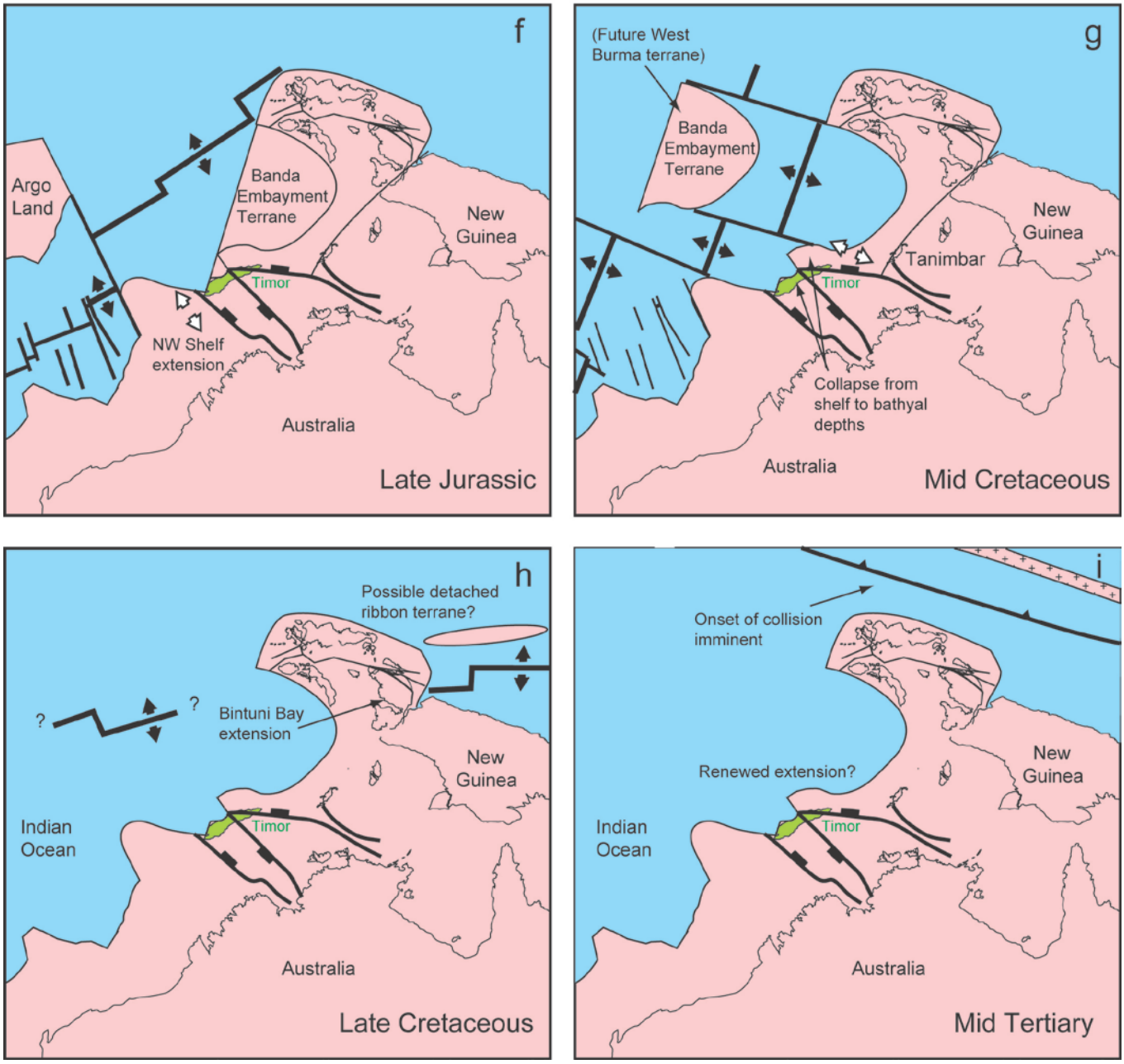


Figure 10. *Jurassic to Tertiary evolution of northeastern Gondwanaland*

evidence suggests that it was from north to south and that Timor lay directly behind the crest of the buckled, leading edge of the Australian plate.' This may suggest continuing vertical crustal movements (block faulting?) in Timor at least until the Eocene, and could indicate continuing seafloor spreading to the north of Australia more complex than is apparent from existing oceanic seafloor spreading patterns in the Indian Ocean (Figure 10h, i).

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