Permian to Lower Cretaceous plate tectonics and its impact on the tectono-stratigraphic development of the Western Australian margin

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PERMIAN TO LOWER CRETACEOUS PLATE TECTONICS AND ITS IMPACT ON THE TECTONO-STRATIGRAPHIC DEVELOPMENT OF THE WESTERN AUSTRALIAN MARGIN

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ABSTRACT

The post-Lower Permian succession of the Perth Basin and Westralian Superbasin can be directly related to the plate tectonic evolution of the Gondwanan Super-continent. In the Late Permian to Albian the northern edge of Gondwana continued to break into microplates that migrated to the north and were accreted into what is today the southeastern Asia (Burma–China) region. These separation events are recorded as a series of stratigraphically distinct transgressions (corresponding to the initial stretching of the asthenosphere and acceleration of subsidence rates) followed by rapid regressions (when new oceanic crust was emplaced in thinned continental crust causing uplifts of large continental masses). Because the events are synchronous across large regions, and may be identified from specific log and seismic signatures, the intensity of stratigraphically related transgressive/regressive cycles varies, depending on the distance from the break-up centres and these cycles allow the identification of regionally significant megasequences even in undrilled areas. The tectonic evolution and resulting stratigraphy can be described by eight plate tectonic events:

1. **Visean (Carboniferous) break-up of the southeastern Asia (Simao, Indochina and South China);**
2. **Kungurian (uppermost Early Permian) break-up of Qiangtang and Sibumasu;**
3. **Lowermost Norian uplift due to Bowen Orogeny in eastern Australia;**
4. **Hettangian break-up of Mangkalihat (northeastern Borneo);**
5. **Oxfordian break-up of Argo/West Burma, and Sikuleh (Western Sumatra);**
6. **Kimmeridgian break-up of the West Sulawesi microplate;**
7. **Tithonian break-up of Paternoster-Meratus (central Borneo); and**
8. **Valanginian break-up of Greater India/India.**

These events should be identifiable in all Australian Phanerozoic basins and beyond, potentially providing a template for a synchronisation of the Permian to Early Cretaceous stratigraphy.

KEYWORDS

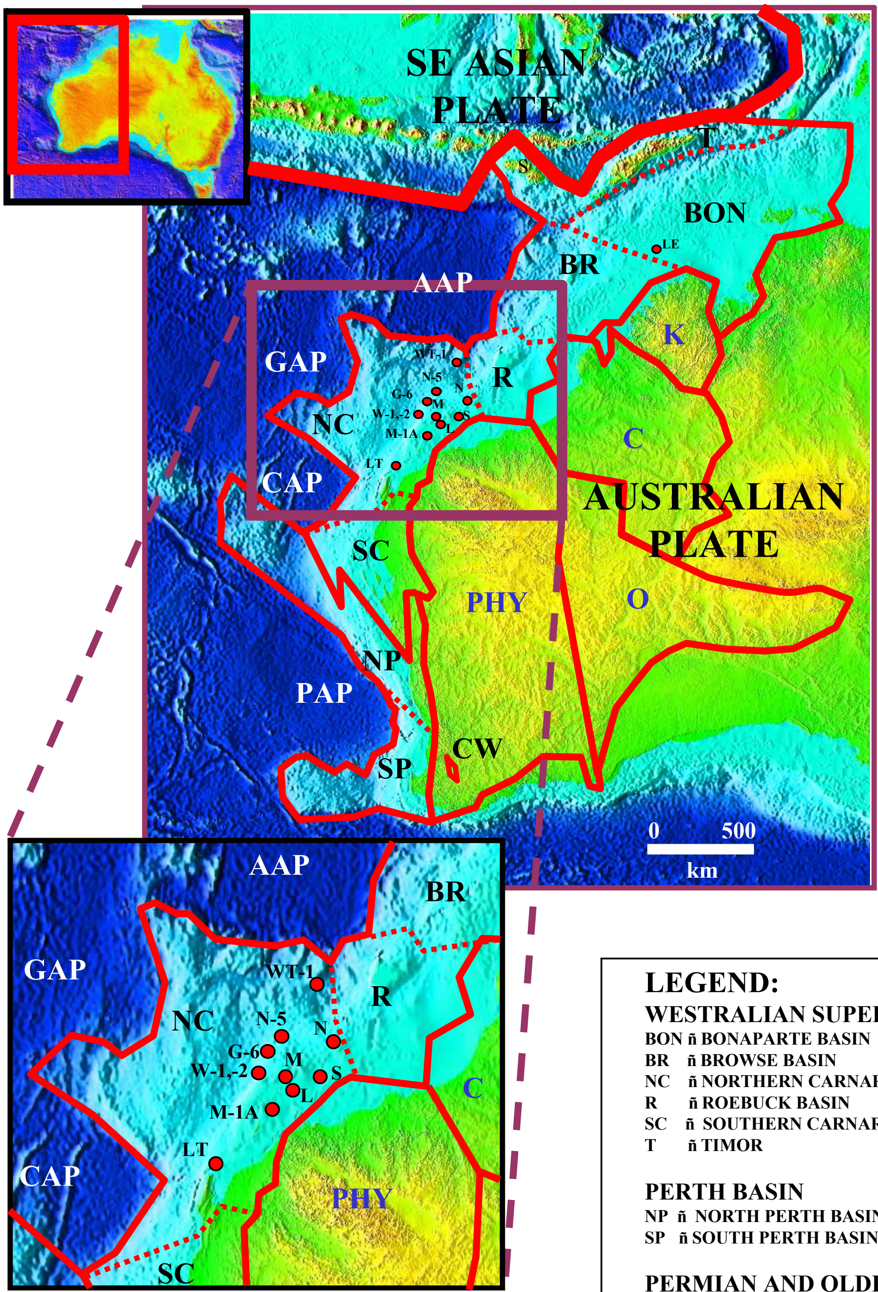
Plate tectonics, sequence stratigraphy, evolution of Gondwana.

INTRODUCTION

There have been numerous tectono-stratigraphic analyses and reviews of the Westralian Superbasin and the Perth Basin driven by the necessity of understanding stratigraphy and the influence of tectonic events in basin analysis. Plate tectonic history, regarded for years by many as of little immediate impact on the prospectivity of petroleum systems, is an integral part of basin analysis. The aim of this paper is to show how megascale tectonics (especially plate break-up and collisions) influenced facies distribution in the Permian to Lower Cretaceous of the Perth Basin, Westralian Superbasin and geologically adjacent areas. This study is the product of an in-house assessment of more than 100,000 line-kilometres of 2D and 3D seismic data, and almost all exploration wells in the Westralian Superbasin (730) and the Perth Basin (220) using sequence stratigraphic techniques. The east African margin, east Indian basins, southeast Asian region, Papua New Guinea (PNG) and onshore Australian basins have also been included in the analysis. A revised rifting mechanism for continental break-up is proposed to explain the origin and timing of regionally significant stratigraphic boundaries. A historical analysis of previous models shows how various misconceptions developed and became accepted by the petroleum community.

Tectonic setting

The Westralian Superbasin and Perth Basin stretch from the southern-most edge of Western Australia to a submerged portion of the Bonaparte Basin colliding with the southeast Asian plate (Fig. 1). Papua New Guinea (PNG) and the Arafura Basin could also be included in the Westralian Superbasin, as both regions share the same tectono-stratigraphic history. The Westralian Superbasin and the Perth Basin acted as a single structural entity influenced by progressive micro-plate break-ups and occasional collisions. There are some marked differences in structural orientation and facies development, but despite the predominantly north–south orientation of the Perth Basin compared to the northeast–southwest Westralian Superbasin, both regions produced relatively similar structures. Despite most facies in the Perth Basin being proximal and deposited at high palaeolatitudes, both regions record the same set of tectono-stratigraphic events.



LEGEND:

WESTRALIAN SUPERBASIN
BON ñ BONAPARTE BASIN
BR ñ BROWSE BASIN
NC ñ NORTHERN CARNARVON BASIN
R ñ ROEBUCK BASIN
SC ñ SOUTHERN CARNARVON BASIN
T ñ TIMOR

PERTH BASIN
NP ñ NORTH PERTH BASIN
SP ñ SOUTH PERTH BASIN

PERMIAN AND OLDER
ONC ñ ONSHORE CANNING BASIN
CV - COLLIE/WILGA BASINS
PHY ñ PILBARA, HAMERSLEY &YILGARN BLOCKS
O ñ OFFICER BASIN
K ñ KIMBERLY BLOCK

OCEANIC CRUST
APP ñ AGRO ABYSSAL PLAIN
GAP ñ GASCOYNE ABYSSAL PLAIN
CAP ñ CUVIER ABYSSAL PLAIN
PAP ñ PERTH ABYSSAL PLAIN

WELLS
G-6 - GOODWYN-6
L - LAUCHIE-1
LE - LEEWIN-1
LT - LEATHERBACK-1
M - MADELEINE-1
M-1A - MAWBY-1A
N - NEBO-1
NR-5 - NORTH RANKIN-5
S - SABLE-1
W-1,-2 - WILCOX-1 & -2
WT-1 - WHITETAIL-1

Figure 1. Locality map.

These megatectonic events formed composite unconformities on the basin margins where later erosion has often removed or amalgamated them (a process that also applies to marine transgressions). Although tectonic intensity varies depending on the location relative to plate break-up or collision zones, these events imply synchronisation of stratigraphies between basins. This is indicated by stratigraphic similarities of Western Australian basins to east India, east Africa, southeast Asia, PNG and onshore Australian basins. The Westralian Superbasin is composed of a northeast–southwest oriented series of basins, with the Southern and Northern Carnarvon Basins in the south, the Roebuck, and Browse Basins in the middle, and the Bonaparte Basin and Timor Orogen in the north. All basins, with the exception of the Roebuck Basin, contain aborted en-echelon Triassic to Late Jurassic rifts and most of Western Australia's hydrocarbon discoveries. The northwestern edge of the Westralian Superbasin is still debated, particularly in relation to Simba Island (Keep et al, 2002; Longley et al, 2002; Rutherford et al, 2001; Lytwyn et al, 2001). Plate tectonic reconstructions discussed in this paper assume Simba to be part of the Australian plate, following Keep et al (2002) and Longley et al (2002).

The Perth Basin, south of the Westralian Superbasin, is almost similar in size and contains similar aged rifts. A Lower Cretaceous rifting stage, however, left an imposing structural overprint in the Perth Basin that is not as well developed in the Westralian Superbasin.

Brief historical background

The Westralian Superbasin and Perth Basin have been the focus of structural and stratigraphic studies since the 1950s when the first wells were drilled. In the early 1970s the scale of regional unpublished studies by the major permit holders, WAPET and Woodside, was driven by the then vast size of permits and the geographical separation of the first exploration wells. These wells were usually well sampled and most surprisingly cheap to drill by modern standards. Seismic data quality in the main area of interest was poor, especially the Barrow and Dampier Sub-basins, so hydrocarbon discovery rates were low and prognoses poor. For example, the Triassic to Lower Jurassic reservoir of the North Rankin giant gas field was unexpectedly discovered below the main target, an interpreted reef in the Cretaceous Toolonga Calcilutite (Kopsen pers. comm., 2004). Despite poor seismic data and the sparseness of wells, remarkably accurate stratigraphic and tectonic predictions were made that set solid tectono-stratigraphic foundations for future exploration.

With gradual improvements in 2D seismic data quality during the late 1970s and early 1980s, seismic stratigraphic studies became more detailed although often limited to individual seismic projects. Control of projects was wrestled from geologists and a number of seismic interpretations, often ignoring well data and over-emphasising seismic geometries, generated hot debates among explorationists. For example, Veenstra, one of the more controversial and imaginative seismic interpreters, who joined Woodside in the early 1980s, created a rift between geologists and geophysicists with his paper summarising the tectonic development of the Dampier Sub-basin (Veenstra, 1985). He favoured rapid subsidence and deposition of deepwater (more than 2 km deep) sediments in the Late Jurassic as opposed to Crostella and Barter (1980) who in their synthesis of the Northern Carnarvon Basin advocated deposition in shallower environments. Palynological studies have not been able to resolve this impasse, although Apthorpe's (1994) foraminiferal studies supported the shallow water deposition model, particularly during the Early to Middle Jurassic. The stand-off was finally resolved in the early 1990s when conventional cores from Wanaea were analysed and placed the answer between two earlier models (Di Toro, 1994; Bint, 1991).

Meanwhile, the North Rankin stratigraphy has been examined in unprecedented detail, thanks to almost 500 m of continuous conventional core recovered from North Rankin–5, although no serious attempts were made to correlate events between separate fault blocks (Fig. 1; Beston, 1986). This was caused by the difficulty with detailed palynological subdivision in high energy fluvio-deltaic sediments, an entrenched lithostratigraphic approach, the complexity of Triassic stratigraphy, and organisational structures that hindered communication between teams within the operating company. Lithostratigraphic principles, whilst often adequate at the field scale, did not adequately account for complex depositional systems as demonstrated by Wilcox–1 and Wilcox–2 in the Carnarvon Basin (Fig. 1) (Vincent and Tilbury, 1988).

The first Woodside sequence stratigraphic intra-horst correlations were made in the early 1990s aided by a growing database derived from conventional cores, high-resolution palynological studies and a new generation of explorationists skilled in sequence stratigraphy. For the first time increasing availability of workstations allowed the interpretation of large volumes of 3D and 2D seismic, and open file well data at a basinal scale indicating a far more complex picture of stratigraphy (Taylor et al, 1998; Whittam et al, 1996; AGSO, 1994; Barber, 1994a, 1994b; Wulff, 1992).

Although sequence stratigraphy allowed a more realistic interpretation of the sub-surface, there were still some attempts to predict facies in areas where current or subsequent drilling did not confirm the models. This was often attributed to inaccurate seismic interpretation rather than the model's validity. For example, Barber (1994a and 1994b) illustrates fans of the *W. digitata* to *R. aemula* Zones, shed from the upthrown side of the Rosemary Fault System. This, however, does not take into account the large channel incisions and up to 500 m of section missing in places on the upthrown side of the Rosemary Fault System and Enderby Trend. Stein (1994) explained the process of erosion through footwall uplift of the Rankin Trend. Jablonski (1997) illustrated a number of wells in the Northern Carnarvon Basin as examples of Oxfordian erosion, which he attributed to tectonic uplift associated with continental break-up of the Argo land (West Burma) after a short but rapid period of subsidence—a conclusion that did not correspond to the widely accepted view of Callovian break-up proposed by Veevers (1988).

When Late Jurassic water depths were hotly debated, no one challenged Veevers' (1988) Callovian timing of continental break-up. This was understandable in the middle 1980s, as almost no deep sea floor drilling results were available (von Stackelberg et al, 1980). At this time the industry probably viewed such interpretations as largely academic with little relevance to the understanding of petroleum systems (Colwell et al, 1994; Exon and Colwell, 1994; Exon and von Rad, 1994; Dumont, 1992; Exon and Buffler, 1992; von Rad et al, 1992; Haq et al, 1992; Gorur et al, 1992). With the recognition of clay-dominated synrift wedges (Jablonski, 1997; Mawby–1A, Fig.1), the Perseus giant gas discovery partially sealed by synrift claystones (Thompson et al, 1998) and Callovian oil discovery in Nebo–1 (Osborne, 1994; Fig. 1), attention became increasingly focussed on nature of main megatectonic events and hence rifting processes. These were helped by the acquisition of new high resolution regional seismic surveys that extend across the continental shelf to the oceanic crust (Ostby, 1994). For the first time deep sea drilling results were integrated with the new and reprocessed regional seismic (Smith et al, 1999, Struckmeyer et al, 1998; AGSO, 1994; Colwell and Stagg, 1994; Stagg and Colwell, 1994; Symonds et al, 1994) and intra-basinal studies flourished (Archbold, 1998; Apak and Backhouse, 1998; Backhouse, 1998; Bradshaw et al, 1998, 1994 and 1988; Baillie et al, 1994). New predictive models were developed that often described multi-plate dispersal histories (Stampfli and Boral, 2002; Borel and Stampli, 2002; Muller et al, 2002; Norvick, 2002; Muller et al, 1998; Mihut et al, 1998). Whilst these studies are examples of originality and audacious regional thinking, no attempts were made to correlate major stratigraphic boundaries (with the exception in the Callovian/Oxfordian) with the plate tectonic history, as pre-Oxfordian tectonic plates had been destroyed through subduction, leaving only fused remnants of micro-plates that once were part of the Australian plate.

While basinal and intra-basinal studies will continue to be presented in more detail (e.g. Hull et al, 2002), a new generation of regional papers are presented at the intra-continental scale (Archbold, 2002; Dore and Steward, 2002). Veevers (2001, 2000), a long advocate of a mega-regional scale, has reconstructed a billion year Australian plate and its neighbours' history with unprecedented detail providing a bridge between Australia, Africa, India and southeast Asia. Further work to resolve plate dispersion history relies on the integration of Western Australian, central Asia and southeast Asia regional geology. Metcalfe (2002); Charlton et al, (2002); Fontain (2002); Metcalfe (2001); Barber (2000); Metcalfe (1999); summarising the pre-Cretaceous southeast Asian geology, propose a number of different plate dispersion scenarios with evolutionary implications for the Australian plate. This paper draws on the conclusions of Veevers (2001, 2000), workers of southeast Asia, our east African margin knowledge with its predecessors (Alconsult, 1997; McGillivray and Hussein, 1992; Murris, 1980), together with the most recent work published on the east Indian Gondwanan basins (Biswas, 2003; Ramamohanarao et al, 2003; Sengupta, 2003; Vijaya, 2003) and recently published studies dealing with the geology of the eastern Australia basins (Fielding et al, 2001; Lang et al, 2001; Nakanishi et al, 2001; Norvick and Smith, 2001; Norvick et al, 2001; Totterdell et al, 2000).

Previous rifting models vs proposed break-up tectonic model

A continental break-up tectonic model was developed to explain tectono-stratigraphic inconsistencies, first noticed in the Callovian and Oxfordian section, between previous work and our sequence stratigraphic analysis of almost 1,000 wells and more than 100,000 line-kilometers of seismic.

Firstly, sands predicted in synrift wedges, as a result of footwall uplift in the Callovian, are absent (Jablonski, 1997). Synrift wedges are clay-prone even on down-thrown locations close to synrift faults. Secondly, the proposed timing of continental break-up varied from Callovian to Oxfordian. The Callovian timing was mostly based on absolute age estimates of the oldest magnetic oceanic floor anomaly, loosely correlated to the pre-Helby (1987) biostratigraphic zonation. In quoting two ages, Callovian and Oxfordian, for the same continental break-up event, Veevers (1988) caused some confusion, but the idea of the Callovian break-up unconformity survived and is now applied routinely by almost everyone in the industry.

Rifting models developed by Falvey (1974), McKenzie (1978), Leeder (1983), Gunn (1988), Veevers (1988) and others usually assume the development of a break-up arch and an angular erosional unconformity followed by gradual flooding in areas of active rifting. The regional angular unconformity on the Rankin Trend and Exmouth Plateau overlain by Lower Cretaceous marine strata seemed to confirm these models. Even the Barrow and Dampier Sub-basins were thought to contain a break-up unconformity that was assumed to correspond to a small time break in the middle of the Upper Jurassic depocentre. This time break cannot, however, be readily identified as most key wells contain sections with continuous deposition throughout the Callovian and Oxfordian. In fact, important younger unconformities of Kimmeridgian to Tithonian age were found (e.g. Lauchie–1 in the Carnarvon Basin, Fig. 1). Only in Madeleine–1 (Fig. 1) is there a short Early Oxfordian time break, as the upper portion of the *W. digitata* Zone and the *R. aemula* Zone are missing. This, however, did not change the idea of Callovian break-up, but merely introduced a local unconformity (JO) that had no bearing on the mechanism and timing of rifting.

In the Bonaparte Basin, the break-up unconformity was placed between the *W. indotata* and *W. digitata* Zones (Arditto, 1996). The significance and timing of this event has not been challenged, despite conventional cores from Laminaria showing no such gap, but rather deeper water conditions across the zonal boundary. Similarly, core from the same stratigraphic interval in Perseus wells indicates flooding, rather than exposure (Thompson et al, 1998).

Independent high-resolution stratigraphic analyses of both fields show that flooding was coeval, despite Laminaria being located relatively closer to an area of active sediment input in the Oxfordian–Callovian. Such coincidence is unlikely, as the two fields are more than 2,000 km apart.

Deep sea drilling and radiometric dating also indicates that the oldest oceanic crust associated with the break-up of Argo Land is Oxfordian (Veevers, 2001; Symonds et al, 1998; Muller et al, 1998; Exon and Colwell, 1994). Similarly, on the eastern edge of the African continent (offshore Kenya) a pocket of Oxfordian oceanic crust is preserved, implying that the continental break-up at this time was widespread.

These observations can be readily explained in terms of various stages of continental break-up. These, however, are contrary to existing rift models in which doming (erosion) is followed by graben collapse and flooding. Traditional rifting models in Western Australian basins incorporate the following assumptions:

- Callovian transgression and Oxfordian regression are not separate events;
- break-up (Callovian Unconformity) is followed by Oxfordian flooding; and
- break-up is Callovian rather than Oxfordian (which ignores the lack of an angular component on the Callovian unconformity).

Sequence stratigraphic analysis of the Permian and Triassic also reveals inconsistencies in existing tectonic models. Therefore, a new rifting model is proposed that invokes the following phases of rifting:

- pre-rift phase—uniform subsidence (Fig. 2a);
- synrift phase—initial stretching of the asthenosphere and associated flooding (Fig. 2b);
- break-up phase—basin margin uplift of the active and passive rift arms as a result of oceanic crust extrusion and footwall uplift (Fig. 2c); deposition of basin floor fan sands delivered by lowstand deltas in the basin proper;
- post-rift transgression phase—basin margin flooding of exposed areas with transgressive (usually sandy) sediments (Fig. 2d); basin proper flooding of lowstand deltas and basin floor fans with clays; and
- post-rift thermal subsidence phase—finally flooding by widespread clays when oceanic crust has drifted sufficiently away to allow thermal decay of rifted area (Fig. 2d).

This mechanism has been repeated as microplates north of the Westralian Superbasin progressively separated and drifted north to form part of present central and southeastern Asia. The model can be applied at plate-wide and local scales, predicts specific criteria in wells and seismic associated with each of these phases, and simplifies geological history without the need for special cases. Furthermore, any megatectonic event is identifiable in the other basins allowing broader stratigraphic correlations (Figs 3–5).

Correlation and definitions of megatectonic events

Previous stratigraphic works were initially used to establish main boundaries (usually related to second order relative sea level variations) and to tie the new sequence stratigraphic framework to existing lithostratigraphic names (e.g. Mory and Iasky, 1996; Hocking; 1994; Hocking et al, 1987). Sequence stratigraphic terminology is based on Jablonski (1997), Thompson et al (1998) and Longley et al (2002). The plate tectonic evolution is principally based on Sampfli and Borel (2002); Metcalfe (2002), Veevers (2001) and Charlton (2001). Whilst Permian lithospheric terrain history is well documented and relatively well understood, the Triassic to Jurassic evolution is more speculative (Nicoll, 2002; Nicoll and Foster, 1998) as it is hampered by Cenozoic collision-subduction processes of the rifted Australian plates in southeast Asia. This paper presents a Triassic–Cretaceous plate tectonic history as indicated by the Westralian and Perth Basins stratigraphies and some aspects may change as more work becomes available on preserved Mesozoic terrains in southeast Asia. The following summary of megatectonic events tied to the plate tectonic evolution and various stages of continental break-up is often significantly different to previous interpretations (Figs 3–5 and Table 1).

VISEAN SEQUENCE BOUNDARY (CV; BREAK-UP OF SOUTHEAST ASIA I.E. SIMAO, INDOCHINA AND SOUTH CHINA)

Definition

The CV (Carboniferous Visean) event is a composite sequence boundary within the *G. maculosa* Zone (Redfern and Williams, 2002), which on basin margins is marked by a significant time break associated with the break-up of southeast Asian microplates. In the Canning Basin it is marked by an angular unconformity, which is interpreted to correspond to the formation of Carboniferous oceanic crust. In wells, CV corresponds to a sequence boundary, which has been equated with the Alice Spring Orogeny (Hocking, 1994), separating non-glacial facies below from the glacial Grant Group above (Jonasson and Reiser, 2002; Eyles et al, 2001; Kennard et al, 1994; Fig. 3b). In the Petrel Sub-basin the event forms the boundary between the Carboniferous Point Spring Sandstone and the overlying glacial Kuriyippi Formation (Mory, 1988; Fig. 3b). In the Perth Basin exposure continued until the late Visean when glacial deposits of the Nangetty Formation were deposited (Mory, pers. comm., 2003; Fig. 3b). The glacially influenced Grant Group, Kuriyippi Formation, Lyons Group and the Nangetty Formation of the Westralian Superbasin and Perth Basin are interpreted as a post-rift transgression phase following the Alice Spring Orogeny.

Similarly to the Perth Basin, this unconformity is also present in Madagascar, Arabia, along the east African margin, India, Irian Jaya, Timor and southeast Asia (Sibumasu)

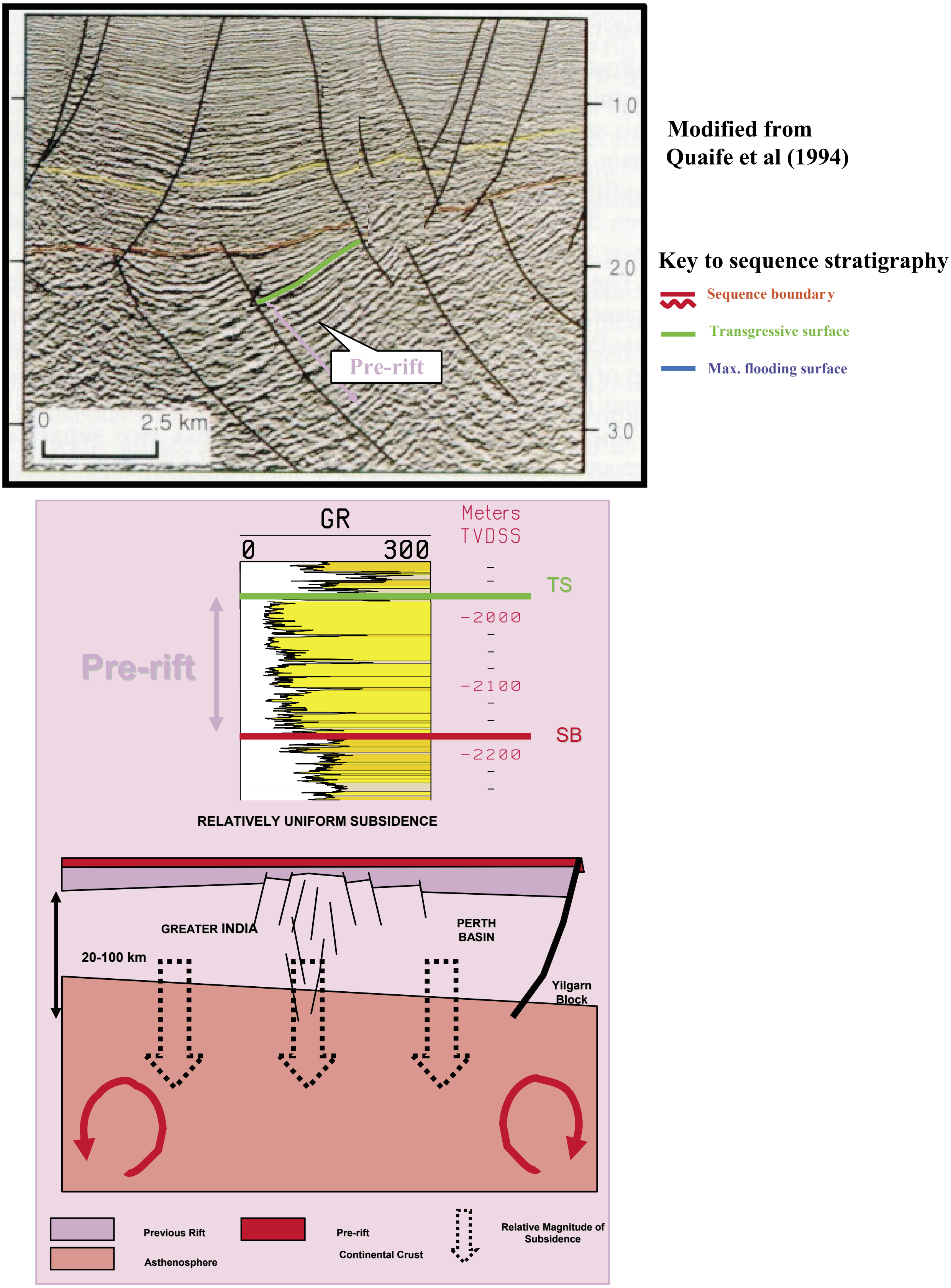


Figure 2a. Pre-rift phase.

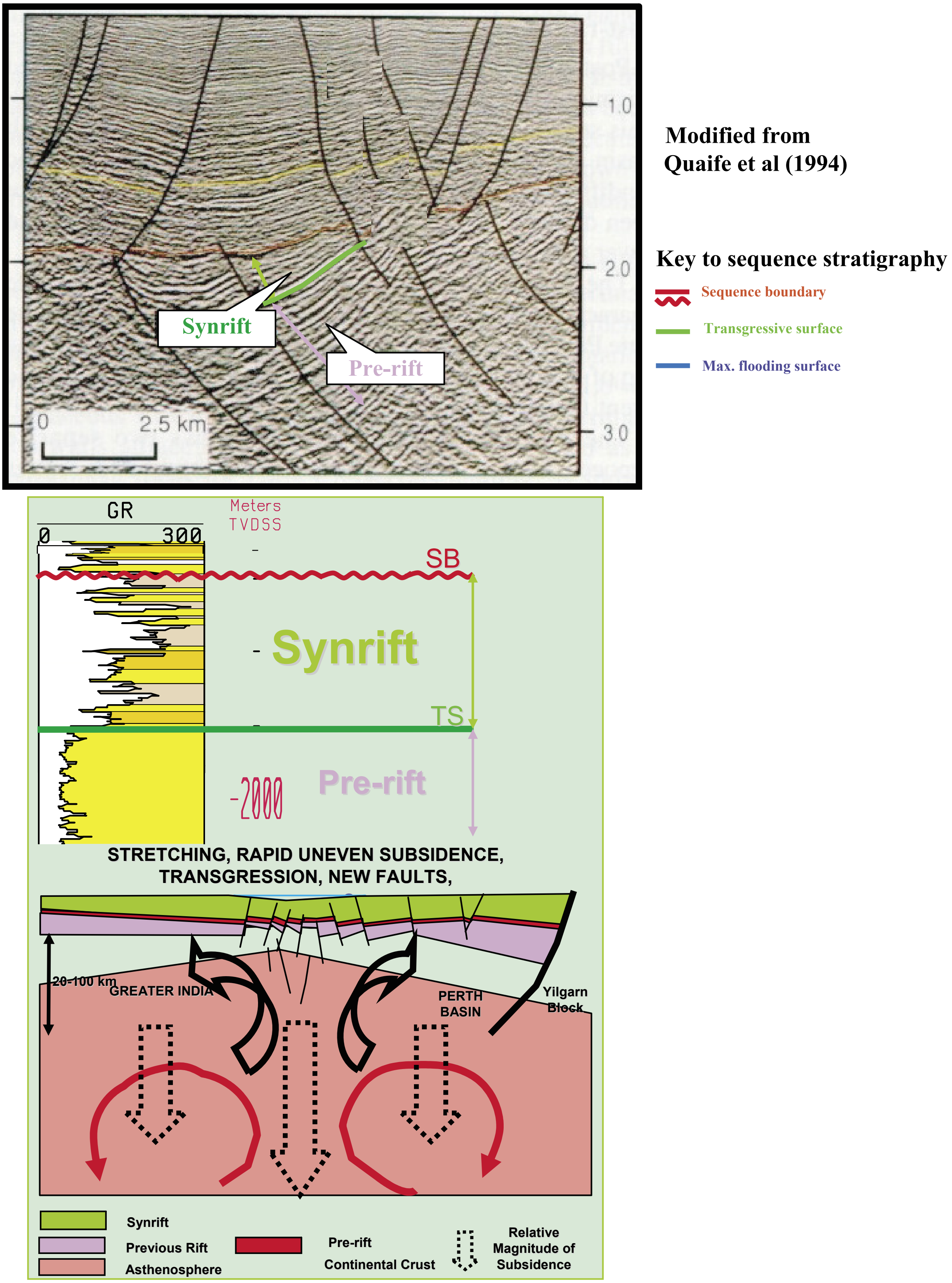


Figure 2b. Synrift phase.

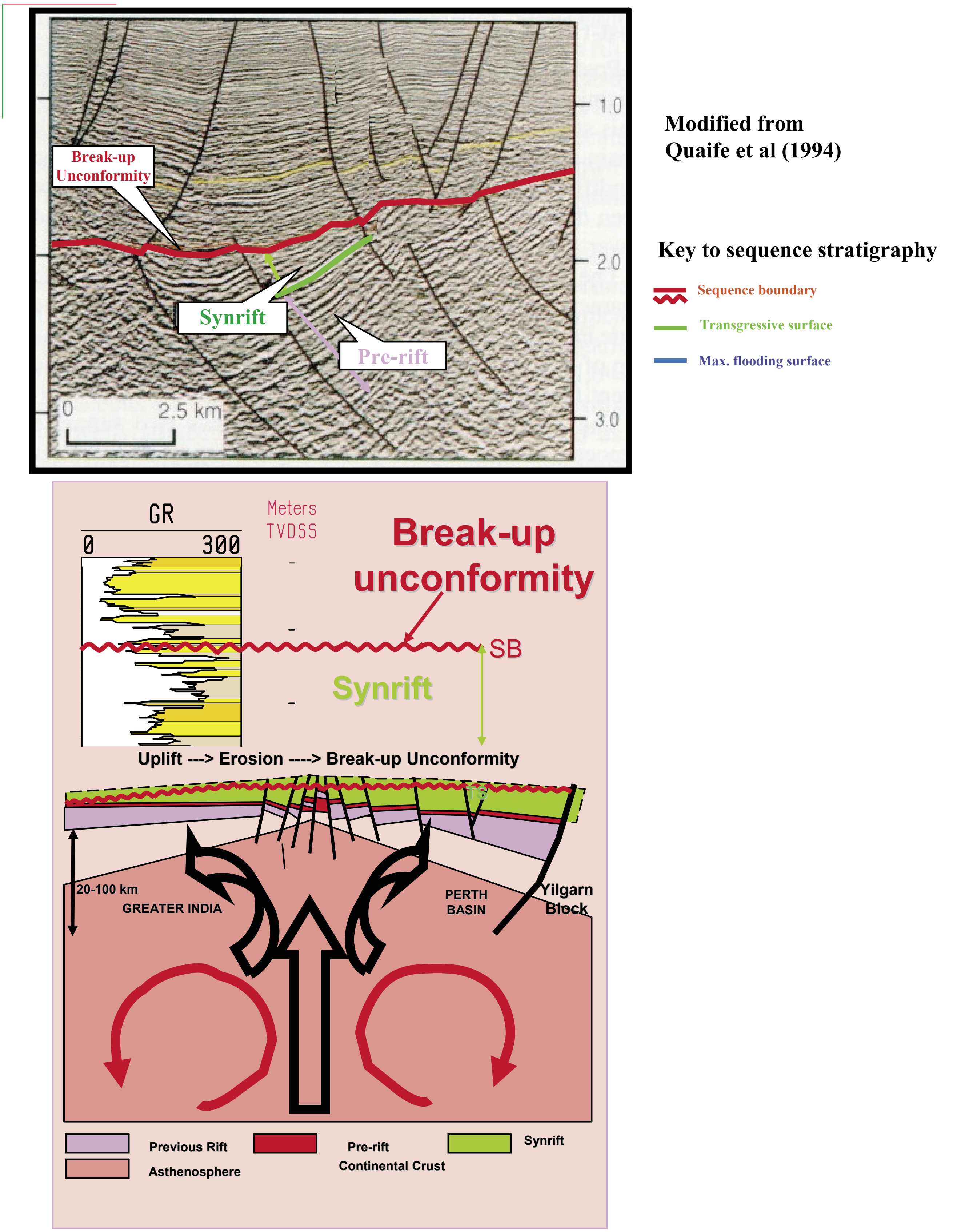


Figure 2c. Break-up unconformity phase.

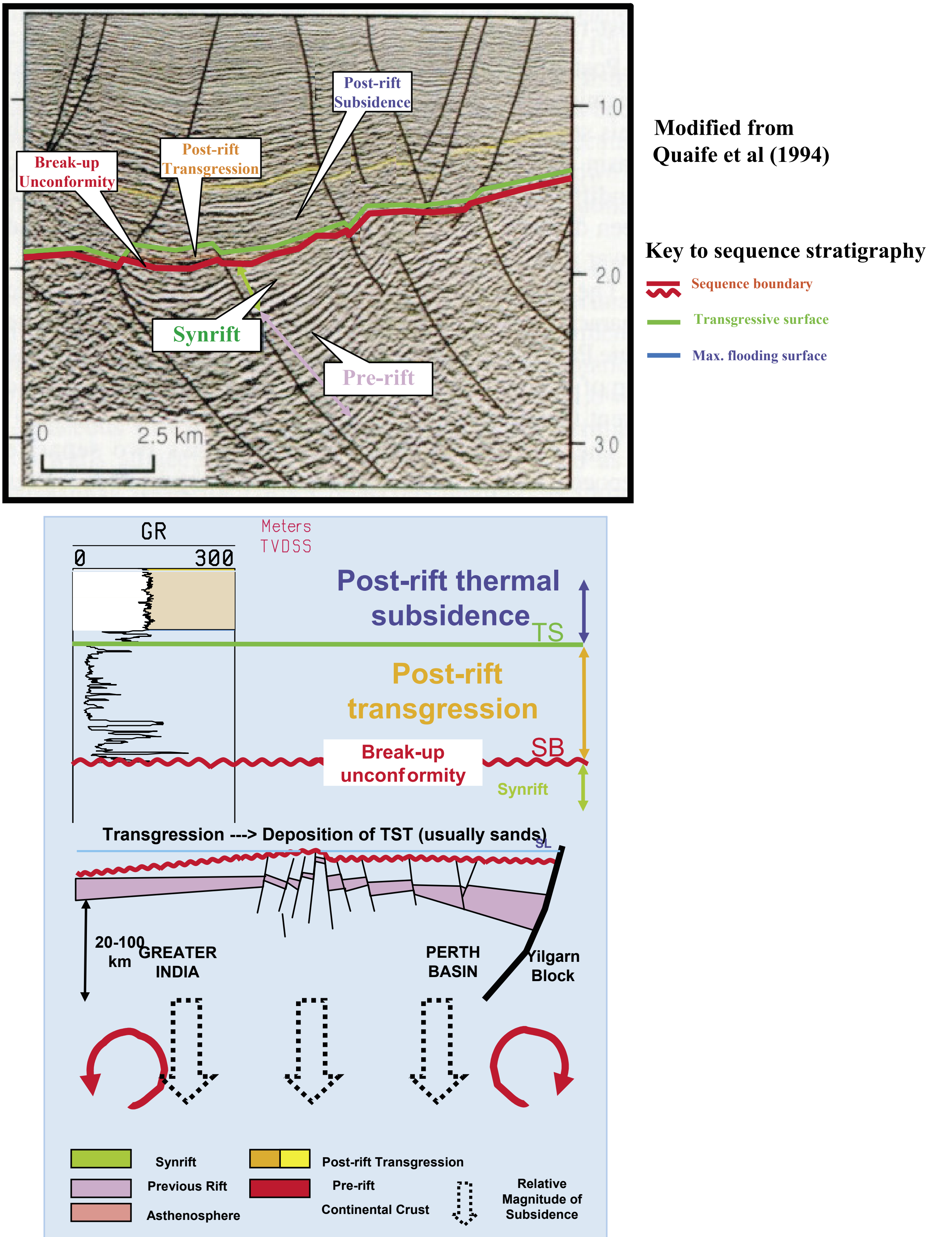


Figure 2d. Post-rift transgression and post-rift thermal subsidence phases.

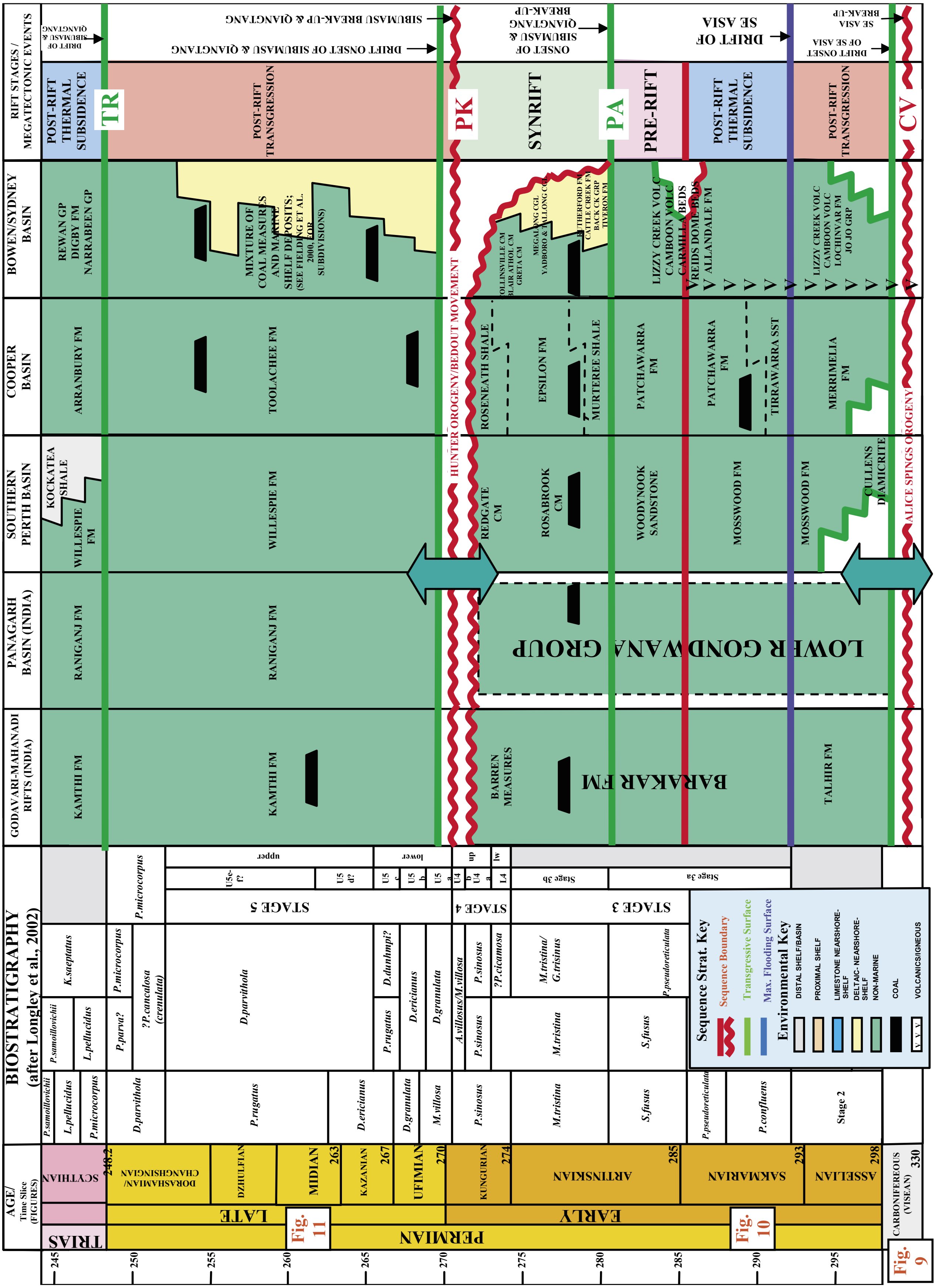


Figure 3a. Generalised Permian stratigraphy of high palaeolatitude Gondwana Basins.

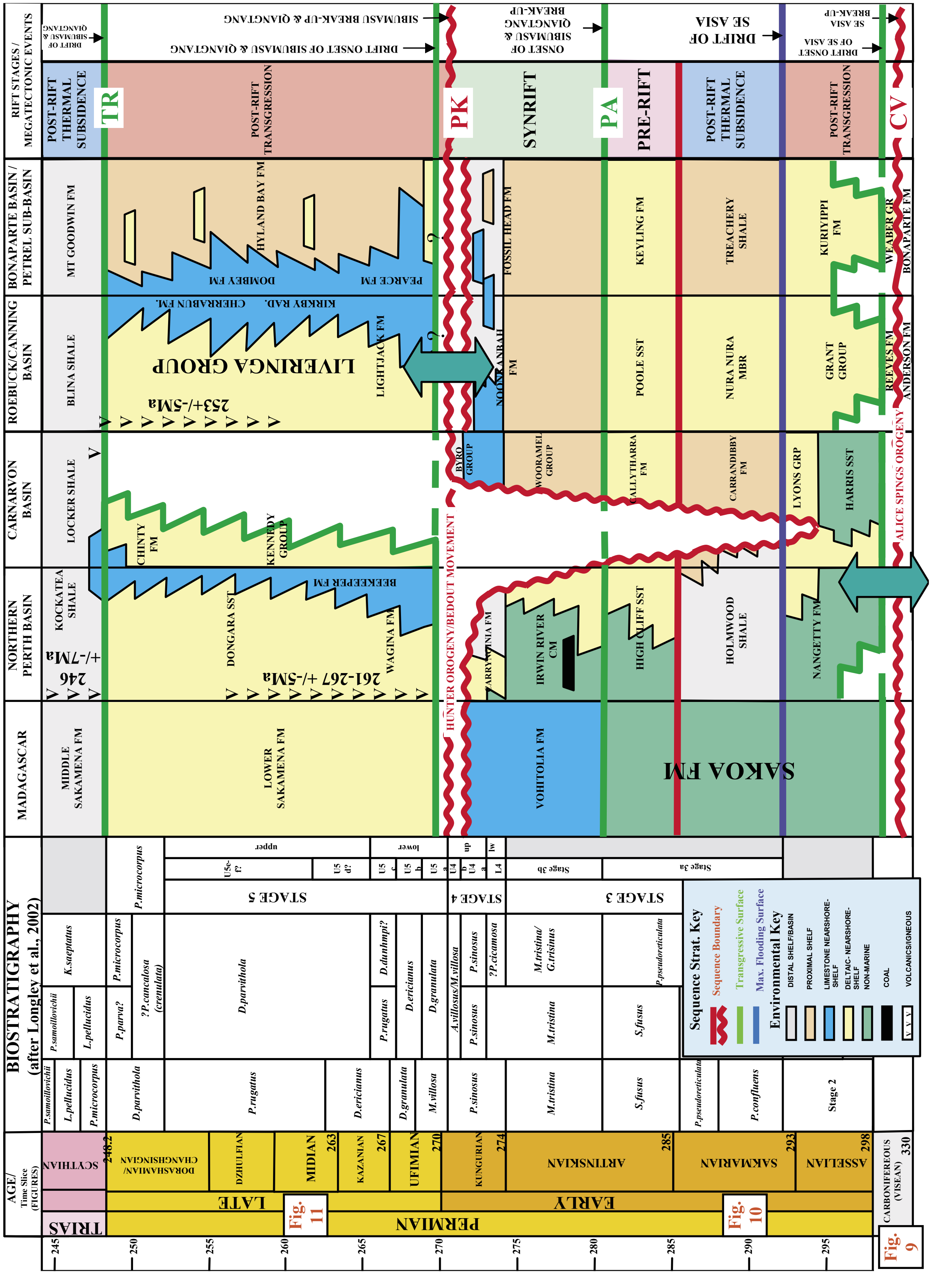


Figure 3b . Generalised Permian stratigraphy of middle palaeolatitude Gondwana Basins.

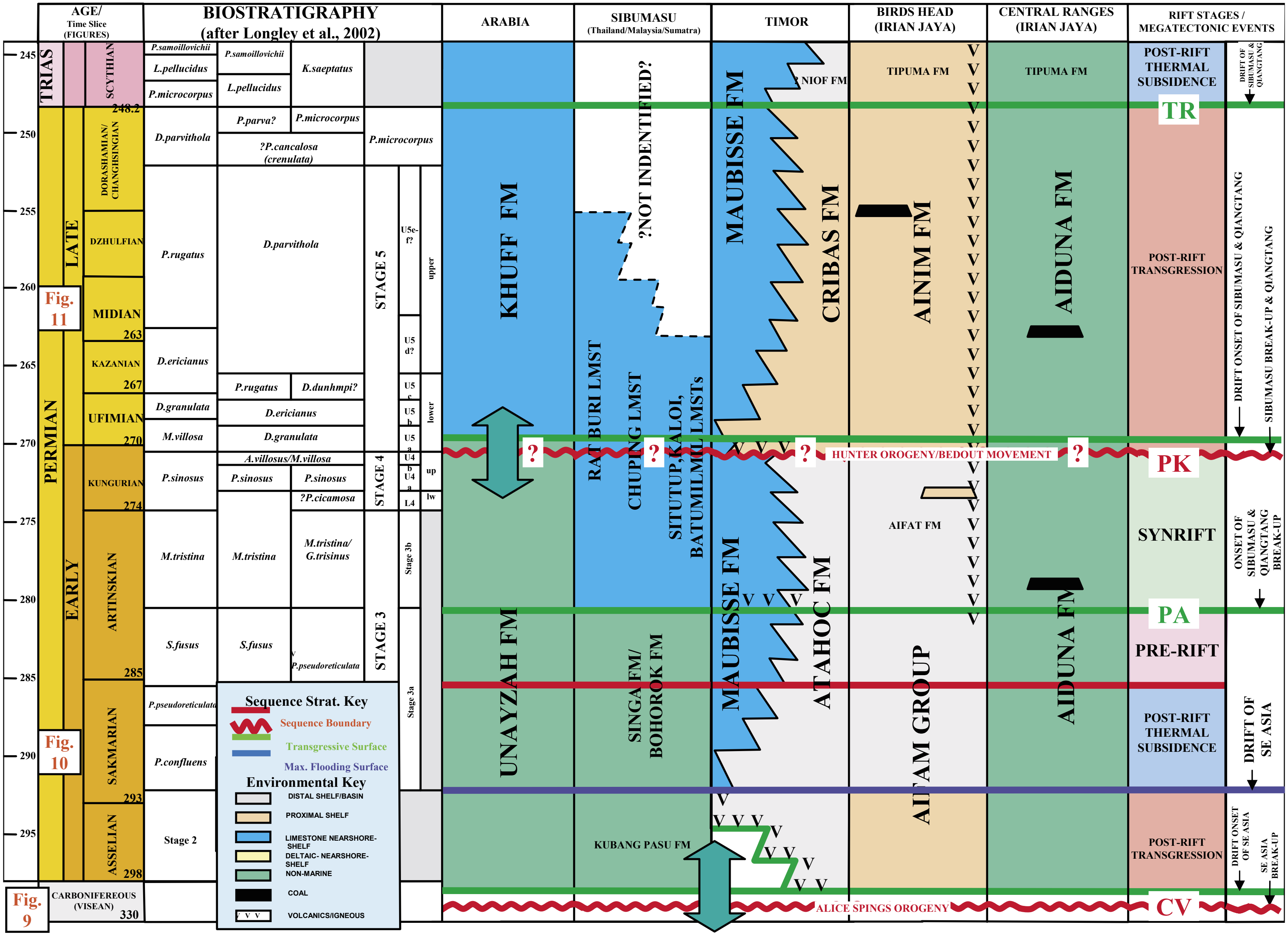


Figure 3c. Generalised Permian stratigraphy of low palaeolatitude Gondwana Basins.

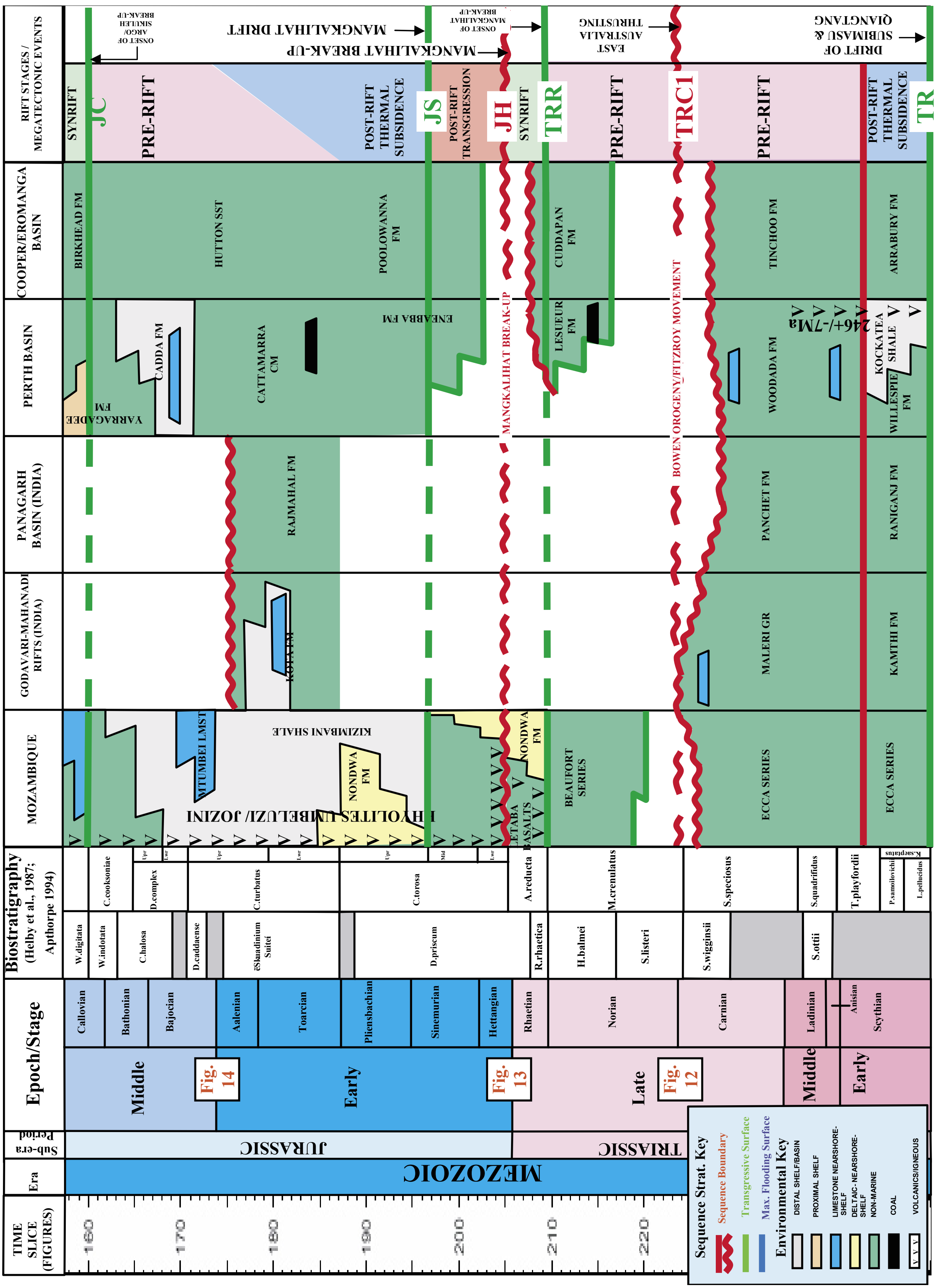


Figure 4a. Generalised Triassic to Middle Jurassic stratigraphy of high palaeolatitude Gondwana Basins.

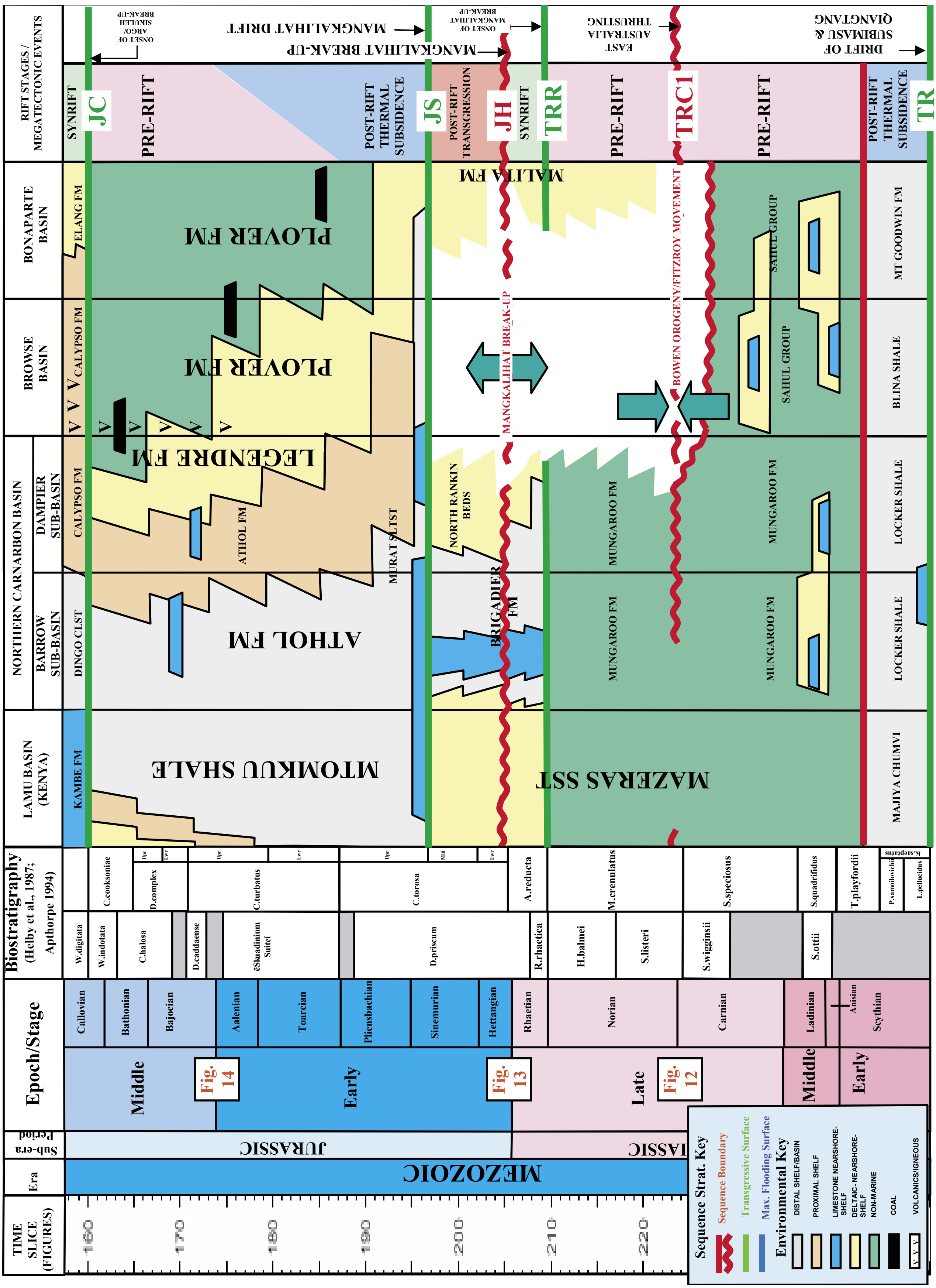


Figure 4b. Generalised Triassic to Middle Jurassic stratigraphy of middle palaeolatitude Gondwana Basins.

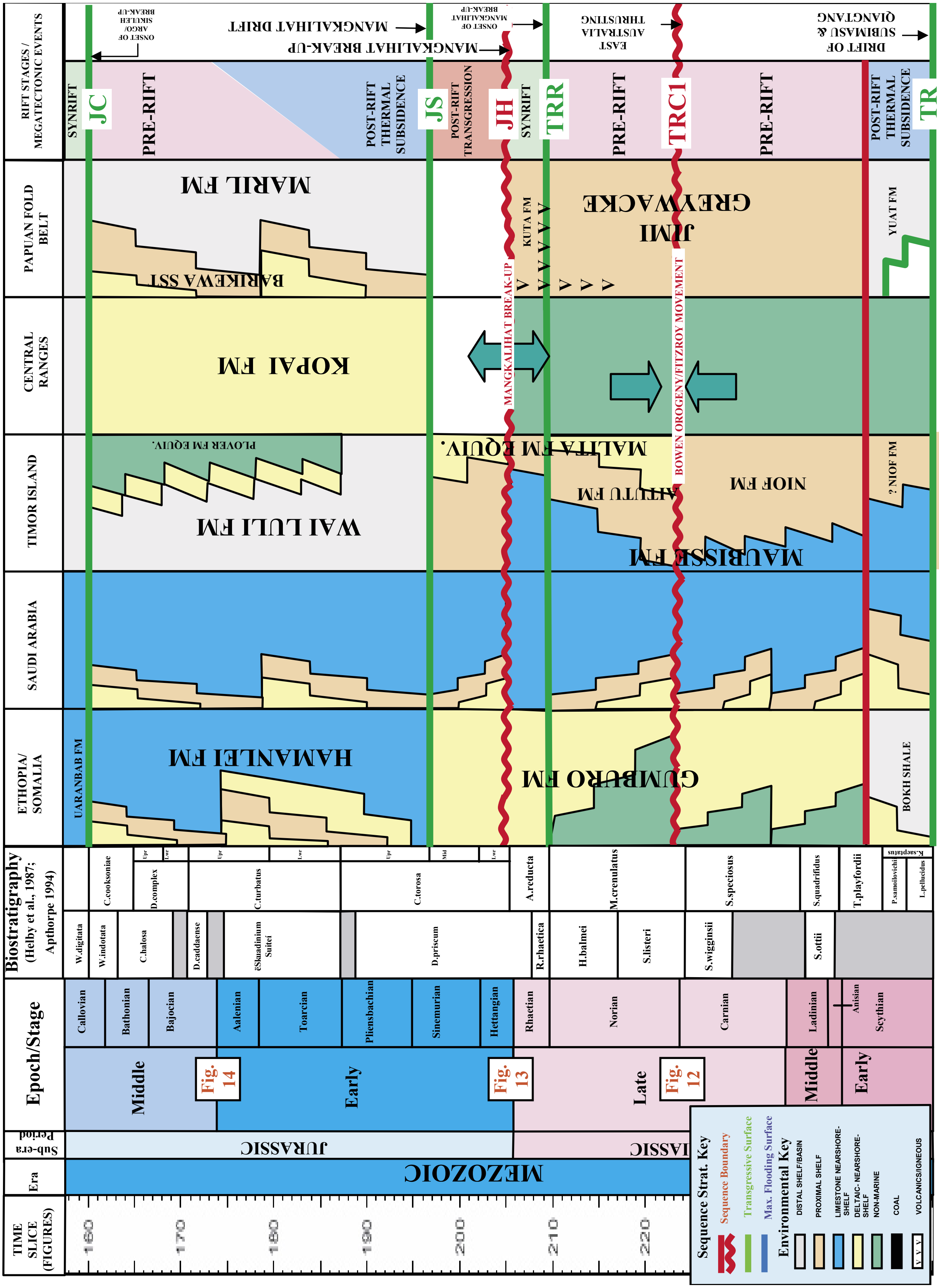


Figure 4c. Generalised Triassic to Middle Jurassic stratigraphy of low palaeolatitude Gondwana Basins.

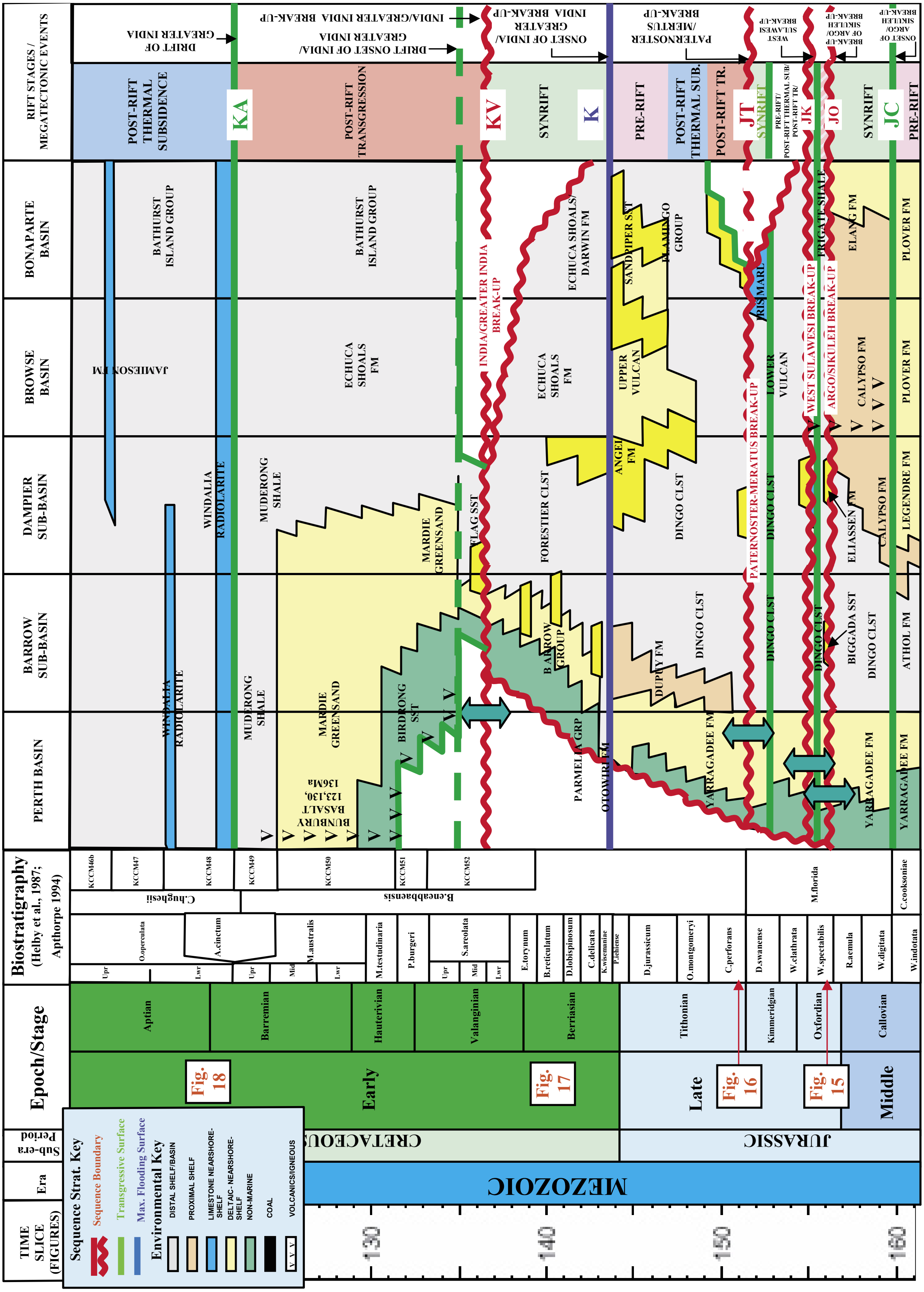


Figure 5. Generalised Callovian to Albian stratigraphy of Perth Basin and Westralian Superbasin.

Table 1. Summary of tectono-stratigraphic events in Westralian Superbasin and Perth Basin.

Event	Seq. strat. type	Seq. strat. order	Stratigraphic age	Origin	Well recognition criteria	Suggested seismic recognition criteria	Examples
KA	TS	2nd	lower *O.operculata*	Rapid sea level rise (open oceanic circulation). Post-rift thermal subsidence	First occurrence of lmst	Mostly good regional reflector, base downlaps, apparent onlaps, no truncations below	Most wells in Westralian Superbasin.
KV	SB	2nd	middle *S.areolata*	Relative sea level fall due to India/ Greater India break-up	Usually small time break and conformable	Usually conformable in Westralian Superbasin. In Perth Basin—angular unconformity	Figure 8
K M	FS	2nd	lowermost *K.wisemaniae*	Sea level rise due to increased subsidence; associated with stretching of asthenosphere prior to India/Greater India break-up	Where preserved max. development of claystone bed	Where preserved base downlaps, apparent onlaps, no truncations below	Wells located in failed arms (Barrow-Dampier & Vulcan Sub-basins)
JT	SB	2nd	base *D.jurassicum*/top *C.perforans*	Relative sea level fall due to Paternoster/Meratus break-up	If preserved small time break	Where preserved should be conformable with possibly minor angularity	Gorter and Kirk, 1995
JK	SB	2nd	base *W.clathrata* /top *W.spectabilis*	Relative sea level fall due to West Sulawesi break-up	If preserved small time break	Where preserved should be conformable with possibly minor angularity	Madeleine–1
JO	SB	2nd	lower *W.spectabilis*	Major sea level fall (about 200 m in places—basin margin). Break-up of Argo-West Burma/Sikuleh blocks	Basin margin —unconformity/Basin proper—base of turbidites or lowstand delta	1. Where continous deposition (Base downlaps, apparent onlaps, no truncations below 2. Where erosion (truncation, base transgressive sands, onlap of variable age reflecting uneven palaeotopography)	Figure 7
JC	TS	2nd	lower *W.digitata*	Relative sea level rise associated with stretching of Argo-West Burma/Sikuleh blocks	Top blocky non-marine sands	Base apparent onlaps, no truncations below	Figure 7
JS	TS	2nd	middle *C.torosa*	Relative sea level rise associated with thermal subsidence following Mangkalihat break-up	Base blocky non-marine sands	Located on top of TRC1 angular unconformity. Reflects 1st flooding of the basin after TRC1 exposure	Figure 5 in D.Jablonski (1997)
JH	SB	2nd	base lower *C.torosa*	Relative sea level fall associated with Mangkalihat break-up	Stratigraphic time break (difficult to isolate as normally no time missing or combined with TRC1)	Since little or no stratigraphic time mising, difficult to map. May correspond to top of faults	North Rankin -3, -6, -5
TRR	TS	2nd	*M.crenulatus–R.rhaetica* boundary	Relative sea level rise associated with stretching of Mangkalihat	Boundary between more proximal sediments below and more distal above	Base of synrift geometries	Bauer et al, 1994
TRC1	SB	2nd	Lowermost lower *M.crenulatus*	Relative sea level fall due to Bowen Orogeny	Unconformity	Angularity below, uplift features. May correspond to top of faults	Fig. 9 in Gorter et al, 1998
TR	TS	2nd	Base Triassic (*L.pellucidus*)	Relative sea level rise associated with thermal subsidence following Subimasu/Qiangtang break-up	Base of regional seal, on basin margin corresponds to PK unconformity	Regionally should display angularity, but in distal areas is conformable, good seismic marker	Figure 6
PK	SB	2nd	Upper Permian (*Stage 4b/M.villosa*)	Relative sea level fall associated with Subimasu/Qiangtang break-up	Unconformity, some time may be missing	Top of Lower Permian Synrift wedges, unconformity, may correspond to top of faults	Figure 6
PA	TS	2nd	Lower Permian (*Stage 3a/S.fusus*)	Relative sea level rise associated with Subimasu/Qiangtang stretching	Transgression. Section below more proximal than above	Onset of synrift wedges, no truncation below	Perth Basin and Onshore Canning wells - deeper facies (coal measures and limestone) on top of usually non-marine sediments
CV	SB	2nd	Uppermost Carboniferous (*G.maculosa*)	Sea level fall due to break-up of SE Asia	Significant unconformity with glacial sediments on top. Usually basement overlain by Permian deposits.	Displays angularity	Onshore Canning wells, Perth Wells - basement with Permian deposits on top

SB - Sequence Boundary TS - Transgressive Surface MFS - Maximum Flooding Surface marking the boundary between Precambrian to Proterozoic basement and overlaying Lower Permian glacinogenic sediments (Figs 3a–3c).

UPPER PERMIAN TRANSGRESSIVE SURFACE (PA; ONSET OF SIBUMASU AND QIANGTANG SYNRIFT)

Definition

The PA (Permian Artinskian) transgressive surface corresponds to an onset of crustal stretching in northern Gondwana associated with break-up of Sibumasu and Qiangtang, and initiation of the northeast-southwest and north–south tectonic frameworks in the Westralian Superbasin and the Perth Basin respectively. On seismic, the event corresponds to the base of Permian synrift wedges (Fig. 6). In wells, it is usually evident as flooding and a shift to more marine facies (often marking onset of carbonate deposition in more tropical regions) towards the basin margin during the Stage 3a/*S. fusus* Zone (Figs 3a—3c).

UPPER PERMIAN SEQUENCE BOUNDARY (PK; BREAK-UP OF SIBUMASU AND QIANGTANG/BEDOUT MOVEMENT/ HUNTER OROGENY)

Definition

This event is marked by a break-up unconformity/ sequence boundary in Upper Stage 4b/M. villosa Zone (PK—Permian Kungurian) due to crustal uplift and break-up of the Sibumasu and Qiangtang microplates. This unconformity is particularly obvious in the northern, offshore Perth Basin where it is expressed as a gentle angular unconformity on seismic (Fig. 6). Onshore, the unconformity occurs between the marine Carynginia Formation and the overlying transgressive Wagina Formation and the Dongara Sandstone (Mory and Iasky, 1996) and spans the *D. granulata* Zone thereby indicating an uppermost Kungurian to lowermost Ufimian age (Figs 3a—3b).

On the basin margin the event merges with younger and/or older sequence boundaries. In the eastern part of the Carnarvon Basin it is marked by strata unconformably overlying Pre-cambrian basement. In western areas and the Bonaparte Basin where the Permian is preserved, the PK sequence boundary corresponds to the base of a limestone dominated interval (Gorter and Davies, 1999; Gorter, 1998; Fig. 3b). In the Roebuck Basin the event is associated with a major episode of volcanism which is equated to the Bedout Movement (Gorter and Deighton, 2002; Smith et al, 1999; AGSO, 1994). In eastern Australia Veevers (2001) recognised this event as the Hunter Orogeny. This event is often confused (marked) with the base Triassic Unconformity.

In India this unconformity has also been recognised by Biswas (2003), Vijaya (2003) and Sengupta (2003; Fig. 3a). Presence of an equivalent stratigraphic time break in areas located in the lower palaeolatitudes is less obvious although an increase in volcanic activity has been recorded in Timor (Charlton et al, 2002; Fig. 3c).

BASE TRIASSIC TRANSGRESSIVE SURFACE (TR; ONSET OF POST-RIFT THERMAL SUBSIDENCE)

Definition

The TR (Triassic) transgressive surface corresponds to an onset of thermal subsidence of the northern portion of Gondwana at the base of Triassic (*L. pellucidus* Zone) (Figs 3a–3c). In the areas where sedimentation continued uninterrupted, the event corresponds to the base of widespread marine claystones. On basin margins TR onlaps older events including Pre-cambrian basement. This event is often confused with the base Triassic Unconformity (TR).

LOWERMOST NORIAN SEQUENCE BOUNDARY (TRC1; BOWEN OROGENY/FITZROY MOVEMENT)

Definition

The TRC1 (Triassic Carnian) event is an unconformity/ sequence boundary within the lowermost *M. crenulatus* Zone formed as a result of thrusting that affected Eastern Australia with folding (Figs 4a–4c; Fig. 13 in Davidson, 1995), low grade metamorphism and localised pluton intrusions (Veevers, 2001). This caused severe uplift, formation of new faults, and rotation and erosion of the eastern part of the Westralian Superbasin and Perth Basin (Fig. 9 in Gorter et al, 1998; Figs 6–8 in Struckmeyer et al, 1998; Symonds et al, 1994; p.69 in AGSO, 1994). In the western areas, where sedimentation continued uninterrupted, the event is marked as the base of massive sandstones in Goodwyn–6 (Bint and Helby, 1988; Fig 1), deposited as a result of eastern margin erosion of the Westralian Superbasin and Perth Basin (Gorter, 1994).

In the literature, this event has been recognised as the Fitzroy Movement (Smith et al, 1999; Etheridge et al, 1994) and the Bowen Orogeny (Veevers, 2001), but the Bonaparte Basin is commonly designated as the base Jurassic unconformity (Young et al, 1995). Charlton (2001) suggesting that this event marks the final separation of the Sibumasu/Qiangtang plates from Australia. This conclusion, however, is not supported by seismic and well data from the Westralian Superbasin, as no synrift geometries with more marine intervals are associated with this unconformity.

RHAETIAN TRANSGRESSIVE SURFACE (TRR; ONSET OF MANGKALIHAT SYNRIFT)

Definition

The TRR (Triassic Rhaetian) transgressive surface corresponds to an onset of northern Gondwana crustal stretching associated with break-up of the Mangkalihat

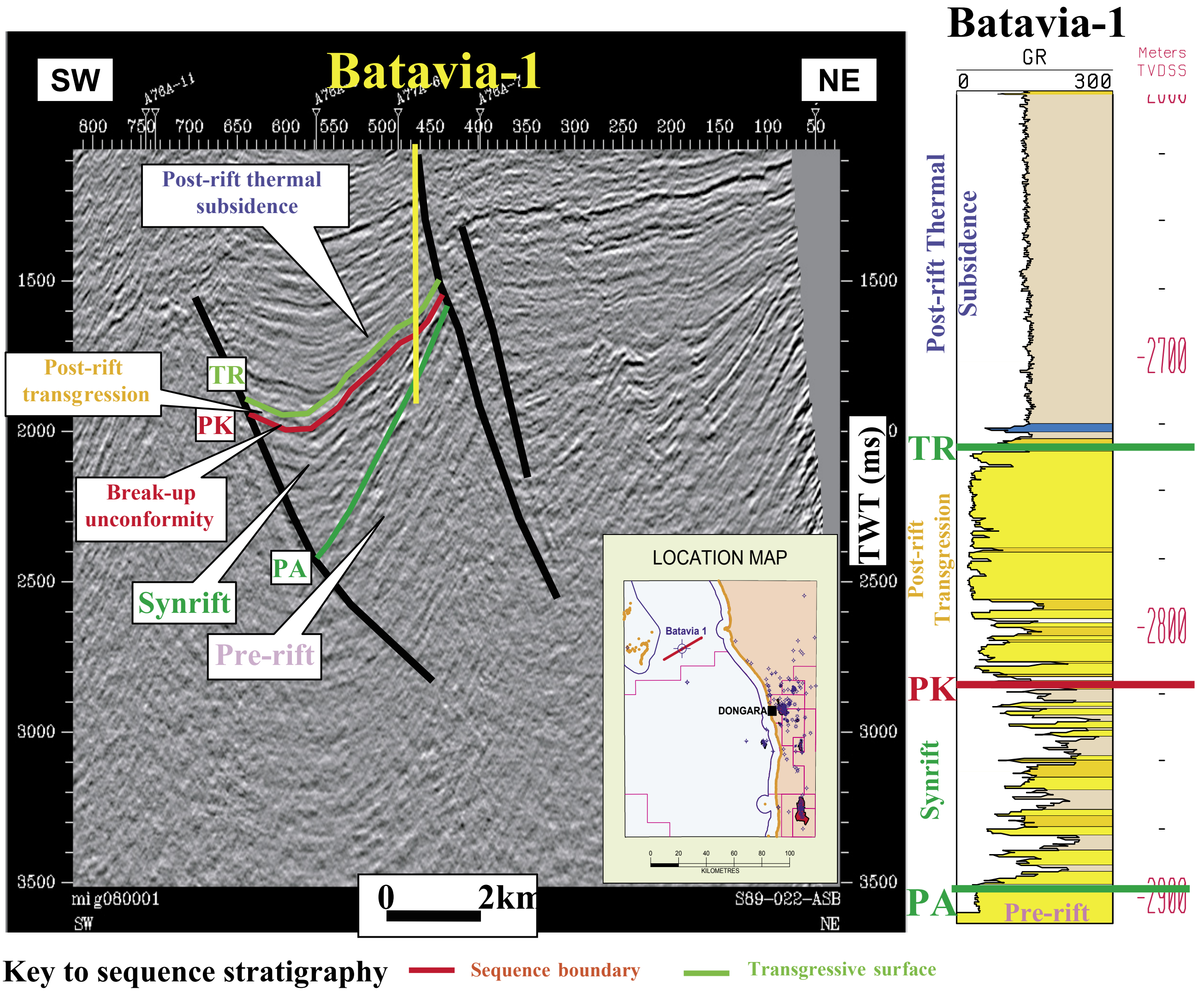


Figure 6. Perth Basin—Permian rifting in Batavia–1.

microplate (northeastern Borneo). On seismic data the event marks the base of Rhaetian synrift wedges. In wells it usually corresponds to flooding and shift of more marine facies towards basin margins at the base of *R. rhaetica* Zone (Figs 4a–4c; Bauer et al, 1994). This event is often confused with the base Jurassic unconformity in the Exmouth and southern part of the Barrow Sub-basin because some areas there display strong onlap geometries (Fig. 10 in Ostby and Johnson, 1994).

HETTANGIAN SEQUENCE BOUNDARY (JH; BREAK-UP OF MANGKALIHAT)

Definition

The JH (Jurassic Hettangian) event is defined as a sequence boundary marking break-up of the Mangkalihat microplate at the base of the *C. torosa* Zone (Figs 4a–4c). Significant dinoflagellate extinction, reported by Backhouse et al (2002), near the boundary between the *R. rhaetica* and *C. torosa* Zones was probably caused by a rapid change in the oceanic water chemistry when Hettangian oceanic crust reached the ocean floor. Red bed sandstones are routinely reported at this level indicating exposure in arid conditions (Sable-1, Fig. 1). This event also corresponds to a basinward shift of less marine facies. No significant stratigraphic time break is recorded at this level probably reflecting the relatively distal location of the Westralian Superbasin and Perth Basin relative to the active rift arm break-up at this time. On the eastern edge of the Westralian Superbasin, JH merges with the TRC1 unconformity. This event is recognised as the base Jurassic unconformity, but often confused with the Carnian unconformity (TRC1).

SINEMURIAN TRANSGRESSIVE SURFACE (JS; ONSET OF THERMAL SUBSIDENCE)

Definition

The JS (Jurassic Sinemurian) transgressive surface corresponds to thermal subsidence of the northern portion of Gondwana, and was previously described as the JP1 transgressive surface within the Pliensbachian (Longley et al, 2002; Kingsley et al, 1988; Jablonski, 1997). Whilst the palynological dating of this transgression remains the same (boundary between the lower and middle *C. torosa* subzones), revised correlations of the Australian biostratigraphic zonation to European stage names now place JS within the Sinemurian (Marshall pers. comm., 2003; Longley et al, 2002; Figs 4a–4c).

As with JH, this event is often confused with the base Jurassic unconformity particularly on the Exmouth Plateau where it can be mapped at the base of stratigraphically younger Legendre Delta progrades.

CALLOVIAN TRANSGRESSIVE SURFACE (JC; ONSET OF ARGO– WEST BURMA AND SIKULEH BREAK-UP)

Definition

The JC (Jurassic Callovian) transgressive surface corresponds to an onset of crustal stretching between the Australia, Argo Land–West Burma and Sikuleh plates. On seismic data the event marks the base of Callovian synrift wedges (Fig. 7). In wells it corresponds to the flooding and shift of more marine facies towards the basin margin at the base of lower *W. digitata* Zone (Jablonski, 1997; Fig. 5). This event is often described as the Callovian unconformity.

OXFORDIAN SEQUENCE BOUNDARY (JO; BREAK-UP OF ARGO– WEST BURMA AND SIKULEH)

Definition

The JO (Jurassic Oxfordian) event of lower *W. spectabilis* age is a break-up unconformity/composite sequence boundary associated with significant uplift along margins of active and failed rift arms (Fig. 5). The event corresponds to the formation of the first Oxfordian oceanic crust (M25 anomaly). In the areas adjacent to active and failed rift arms it is marked by a significant angular unconformity and channel incisions. In Upper Jurassic depocentres, where sedimentation continued uninterrupted, the event marks the base of basin floor fan sands and lowstand deltas (Fig. 7).

Possibly up to three triple junctions that controlled separation of the Australia, Argo West Burma and Sikuleh plates, developed at this time. The Barrow, Lewis and Cossigny Troughs formed the southern-most failed rift arm connecting to the Argo/West Burma triple junction. The middle triple junction was most likely located north of the Timor Island area, with the Heywood Graben, Vulcan Graben and Cartier Trough acting as a failed arm rift system. The northern-most triple junction was likely located in the Banda Arc region undergoing subduction. Similar to JC, the JO sequence boundary has been erroneously referred to as the Callovian unconformity in some published literature.

KIMMERIDGIAN SEQUENCE BOUNDARY (JK; BREAK-UP OF WEST SULAWESI)

Definition

The JK (Jurassic Kimmeridgian) unconformity/sequence boundary is possibly associated with break-up of the West Sulawesi microplate in the lower *W. clathrata* Zone (Madeleine–1, Figs 1 and 5). This unconformity is often merged with younger erosional events and its exact timing cannot be easily established. Distal sandy facies in Madeleine–1 indicate erosion of the basin margins at the onset of the Kimmeridgian. The lack of stratigraphically equivalent strata along the Legendre Trend indicates a significant basinward shift into more proximal facies. Despite some uncertainty in the age of the onset of this event, the magnitude and presence of more marine facies in Leewin–1 (Fig.1) indicates that it is probably related to rifting rather than eustacy or sediment input variation.

TITHONIAN SEQUENCE BOUNDARY (JT; BREAK-UP OF PATERNOSTER-MERATUS)

Definition

The JT (Jurassic Tithonian) unconformity/sequence boundary is associated with break-up of the Paternoster–Meratus microplate in the lower C. perforans Zone (Madeleine-1, Figs 1 and 5). This unconformity is best illustrated in the Timor Sea where the upper *D. swanense* Iris Marl (synrift) is overlain by Tithonian clastic rocks (Gorter and Kirk, 1995). In Upper Jurassic failed rift arms where sedimentation continued uninterrupted the event corresponds to an increase in clastic sediment input.

BASE BERRIASIAN MAXIMUM FLOODING SURFACE (K; ONSET OF GREATER INDIA/INDIA BREAK-UP)

Definition

The K (Cretaceous) maximum flooding surface was formed by the onset of the Greater India/India stretching processes during the *K. wisemaniae* Zone (Fig. 5; Jablonski, 1997; Bint and Marshall, 1994). It corresponds to a marine flooding of sandy Tithonian systems in the Westralian Superbasin. This event is only preserved in the Upper Jurassic failed arm rift systems. In the Perth Basin and southern part of the Carnarvon Basin where sediment input is active, flooding is minor. In published

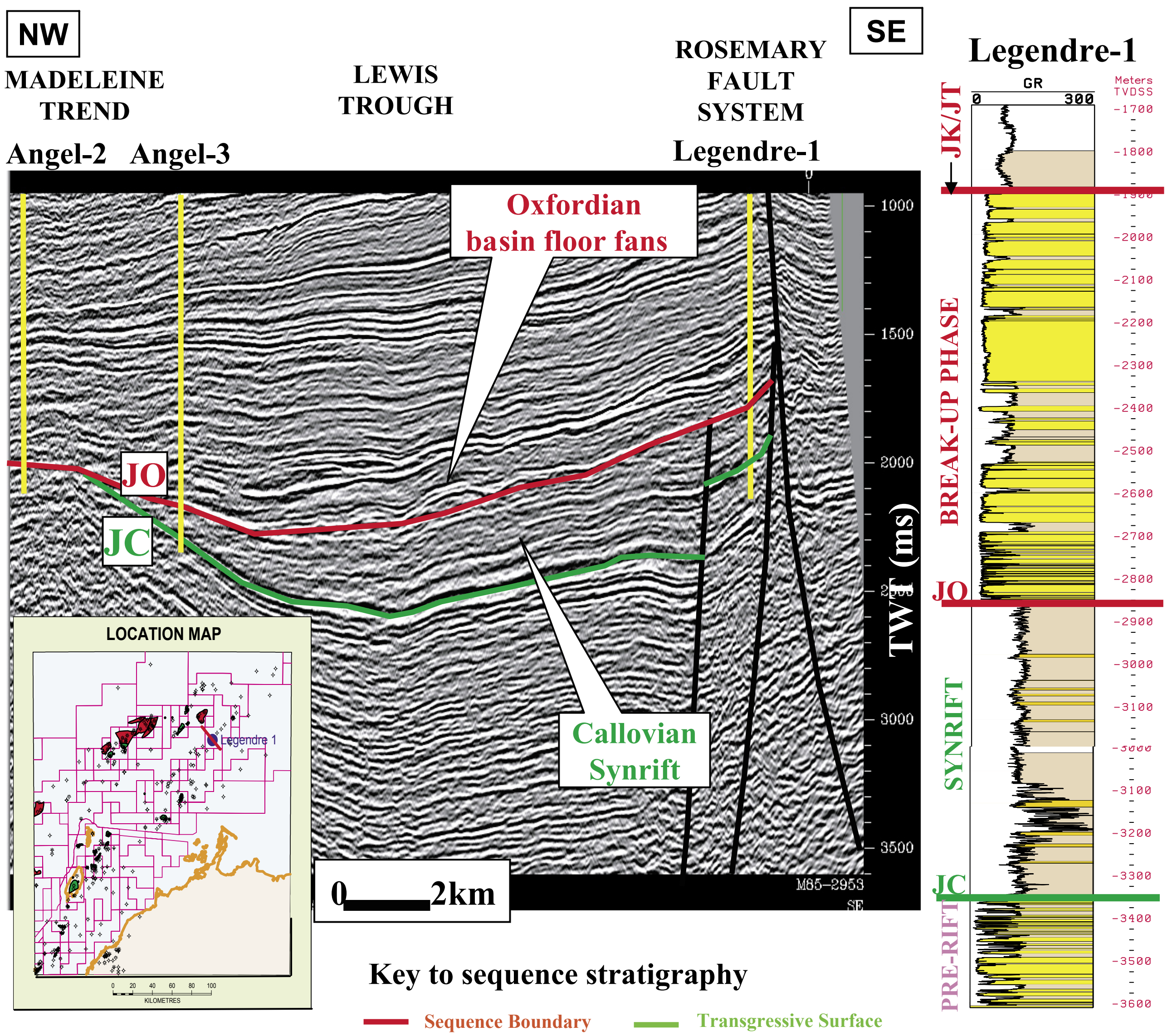


Figure 7. Carnarvon Basin (Lewis Trough)—Callovian rifting.

literature the event is often confused (marked) with the base Cretaceous unconformity.

VALANGINIAN SEQUENCE BOUNDARY (KV; BREAK-UP OF GREATER INDIA/INDIA)

Definition

The KV (Cretaceous Valanginian) unconformity/ sequence boundary is associated with break-up of the Greater India micro-continent in the lower *S. areolata* Zone (Fig. 5). A major uplift (up to 5 km in places) and erosion occurred in the Perth Basin with most sediments re-deposited in the southern Barrow Sub-basin (Fig. 8).

APTIAN TRANSGRESSIVE SURFACE (KA; SEPARATION OF GREATER INDIA/INDIA)

Definition

The KA (Cretaceous Aptian) transgressive surface is associated with final separation of Greater India from Australia–Antarctica during the lower *O. operculata* Zone (Fig. 5). This event corresponds to an onset of carbonate sedimentation caused by free oceanic circulation around India and Greater India.

Tectono-stratigraphic evolution

A regional tectonic approach requires the synthesis of a number of data sources. Such data may, however, be incom-

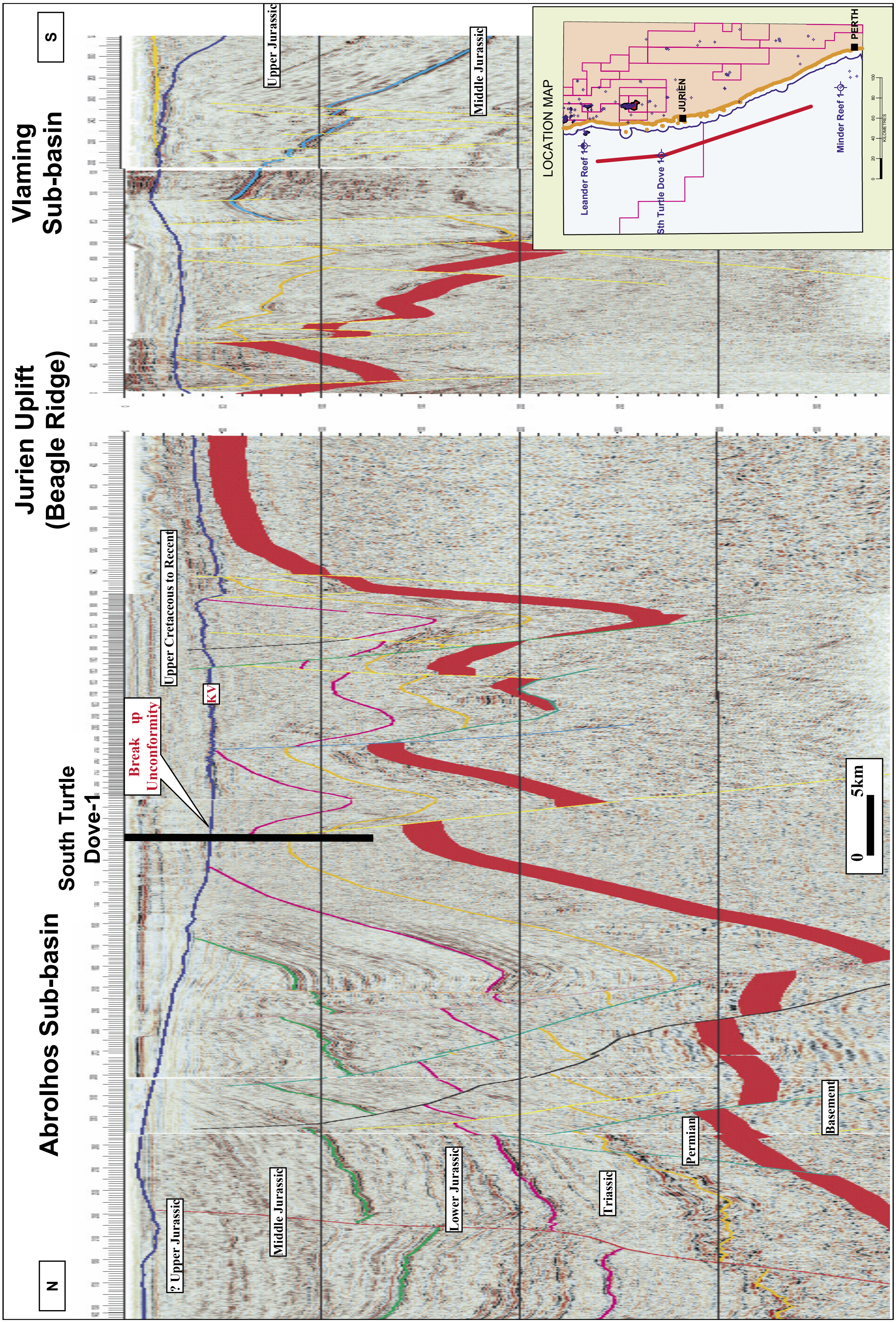


Figure 8. Perth Basin—KV uplift.

plete or non-existent in areas where plate subduction and accretion processes have been active. Consequently, some of the statements presented further on are only indirectly supported by well (including deepwater) and geophysical data, igneous activity data, and palaeoclimate modelling. New logging techniques allowing measurement of palaeomagnetism in boreholes will improve our understanding of continental orientation. In addition, the link between absolute time scale and biostratigraphic zonations is imperfect, so errors in absolute age dating of oceanic crust or other igneous bodies are often difficult to assess. In the following discussion the timing of tectono-stratigraphic events is derived from biostratigraphy, mostly based on palynology.

The pre-Oxfordian tectono-stratigraphic history of the Westralian Superbasin and Perth Basin can only be properly understood in the context of the geological history of onshore Australian basins, eastern Africa, India, and central and southeast Asia. Whilst the neighbouring basins and detailed Asian accretion history is beyond the scope of this paper, areas such as the Godavari (India) and Cooper–Eromanga Basins give information about type of sediment, transport processes, its direction and timing. In this analysis, onshore Phanerozoic basins of Australia are regarded as aborted rifts or sag basins connected to the Westralian Superbasin and Perth Basin, and providing conduits for sediments eroded mainly from Australia's Great Dividing Range and the Trans-Antarctic Mountains (Jablonski, 1997). Throughout most of the pre-Oxfordian these areas were located in high palaeolatitudes with significant annual rainfall and erosional slopes.

The following discussion concentrates on explaining the observed tectono-stratigraphy in terms of the proposed rifting model. This approach also allows facies distribution and hence petroleum prospectivity of individual basins to be evaluated.

PRE-PERMIAN

The geological and structural evolution in the Westralian Superbasin region commenced in the Cambrian, although no offshore wells have penetrated this section (Kennard et al, 2002). Cambrian to Lower Carboniferous sections have been intersected in the Petrel Sub-basin and Canning Basin (Jonasson and Reiser, 2002; Kennard et al, 1994; Mory, 1988; Lavering and Ozimic, 1988). Most of the Perth Basin, on the other hand, appears to have remained inactive until the Carboniferous when glacially influenced sediments (Nangetty Formation) were deposited (GSWA, 1975). This is also the onset of widespread deposition in the Canning Basin. A Lower Carboniferous or older section in the deeper part of the Perth Basin may be tested by future drilling in the Coolcalalaya Sub-basin (onshore Northern Perth Basin) but this area has strong affinities with the Southern Carnarvon Basin (Mory, pers. comm., 2003).

This section is outside the scope of this study, but the existence of well-defined marine and non-marine formations offers an opportunity to subdivide this section according to the proposed rifting model.

VISEAN–EARLY PERMIAN (CV–PA–PK; *G. MACULOSA* TO UPPER STAGE 4B)

The event marks the first postulated extrusion of oceanic crust in the Carboniferous. During this time a mosaic of microplates, Simao, Indochina and south China, separated from the northern edge of Gondwana (Fig. 9). Significant intensification of erosional processes is indicated by the thick sand-rich succession deposited in the Fitzroy Trough of the Canning Basin in response to rift margin uplift (Redfern and Williams, 2002).

In the Westralian Superbasin and Perth Basin, Upper Carboniferous to Permian sedimentation commenced as a result of post-rift subsidence when the oceanic ridge began its northward drift. The Perth Basin, being further from the break-up zone, began subsiding in the mid-Carboniferous (*S. ybertii* Zone) (Redfern and Williams, 2002; Jonasson and Reiser, 2002; Kennard et al, 1994). In the Late Carboniferous to Early Permian both regions were located at high palaeolatitudes with extensive glaciers. Glacial deposits (Grant Group) accumulated in the onshore and offshore Canning Basin (Playford, 2002). At the same time in the Petrel Sub-basin thick glacial sediments of the Kuriyippi Formation were also deposited (Mory, 1988). In the northern and southern Perth Basin the glacial deposits (Nangetty Formation and Cullens Diamicrite, respectively) transgressed over Pre-cambrian basement (Crostella and Backhouse, 2000). All formations were deposited during the post-rift transgression phase, after uplift associated with upwelling of the asthenosphere, and extrusion of oceanic crust gave rise to a gradual increase in subsidence and accommodation space in which glacial outwash sediments accumulated. The Fitzroy Trough, the Petrel Sub-basin and Merlinleigh Sub-basin all continued to receive sediments as subsidence outstripped rate of uplift.

As the southeast Asia plate conglomerate and the oceanic spreading ridge drifted further north, subsidence in the northern Perth Basin accelerated, resulting in further marine transgression and deposition of post-rift thermal subsidence fine-grained clastics (Holmwood Shale). By comparison fine-grained clastics are relatively rare in the southern Perth Basin, Carnarvon Basin, Canning Basin and Petrel Sub-basin at this time, indicating relative proximity to sediment sources (Fig. 10).

When rifting processes along the northern edge of Gondwana ceased in the lower part of the Stage 3a/*P. pseudoreticulata*/*P. confluens* Zones (Sakmarian/Early Permian), subsidence decelerated and new wedges of less marine clastic sediment began to prograde into the basins. A short period of relative tectonic quiescence resulted in favorable conditions for the deposition of sandy non-glacial pre-rift sediments. This, together with the northward movement of Gondwana, is shown by warming of the palaeoclimate . The fluvial–deltaic High Cliff Sandstone and the Woodynook Sandstone in the northern and southern Perth Basin respectively, the Callytharra Formation in the Carnarvon Basin, the Poole Sandstone in the onshore Canning Basin and the Keyling Formation in the Petrel Sub-basin were deposited during this time.

LEGEND

ABBREVIATIONS

A - ARKARINGA BASIN
AP - ASHMORE PLATFORM
B - BOWEN BASIN
BP - BONAPARTE BASIN
BR - BROWSE BASIN
B-D - BARROW-DAMPIER FAILED RIFT
BH - BIRDíS HEAD (IRIAN JAYA)
C - CANNING BASIN
CE - COOPER-EROMANGA BASIN
CR - CARNARVON BASIN
CT - CENTRAL RANGES (IRIAN JAYA)
D - DENMAN BASIN
EAR - EAST ANTARCTIC RIFT
G - GOULBURN GRABEN
GD - GODAVARI BASIN (INDIA)
H-V - HEYWOOD-VULCAN FAILED RIFT
L - LAMU BASIN (KENYA)
LR - LAMBERT RIFT (ANTARCTICA)
M - MALITA FAILED RIFT
MG - MADAGASCAR
MR - MAHANADI RIFT
MZ - MOZAMBIQUE
NP - NORTHERN PERTH BASIN
P - PERTH BASIN
PM - PATERNOSTER-MERATUS
PG - PANAGARH AREA (INDIA)
PNG - PAPUA NEW GUINEA
PT - PETREL SUB-BASIN
R - ROEBUCK BASIN
S - SYDNEY BASIN
SH - SAHUL PLATFORM
SK - SIKULEH (WESTERN SUMMATRA)
SP - SOUTHERN PERTH BASIN
T - TIMOR
WB - WEST BURMA
WS - WEST SULAWESI

PLATE/BLOCK BOUNDARIES

PRESENT DAY COASTLINE/ BLOCK BOUNDARY
ACTIVE SPREADING RIDGE/VILCANISM
FAILED SPREADING RIDGE/SPORADIC VOLCANISM
EXTINCTSPREADING RIDGE
COMPRESSION/COLLISION

OTHER

SEDIMENT INPUT
OCEANIC CURRENT

ENVIRONMENTS

OCEANIC CRUST, DEEP

CONTINENTAL MARGIN

- DISTAL SHELF/BASIN
- PROXIMAL SHELF
- DELTAIC- NEARSHORE-SHELF
- LIMESTONE NEARSHORE-SHELF
- EVAPORITES
- NON-MARINE
- NON-DEPOSITION
- UPLAND,UPLIFT,SIGNIFICANT EROSION,MOUNTAINS

ICE COVER (MAINLY EROSION)

NOTE:

PALAEOGEOGRAPHIC MAPS ILLUSTRATE MAXIMUM LITHOFACIES DISTRIBUTION DEPOSITED DURING INDICATED TIME SLICE (PRESERVED PRESENT DAY DISTRIBUTION NOT SHOWN)

Legend applies to Figures 9–18.

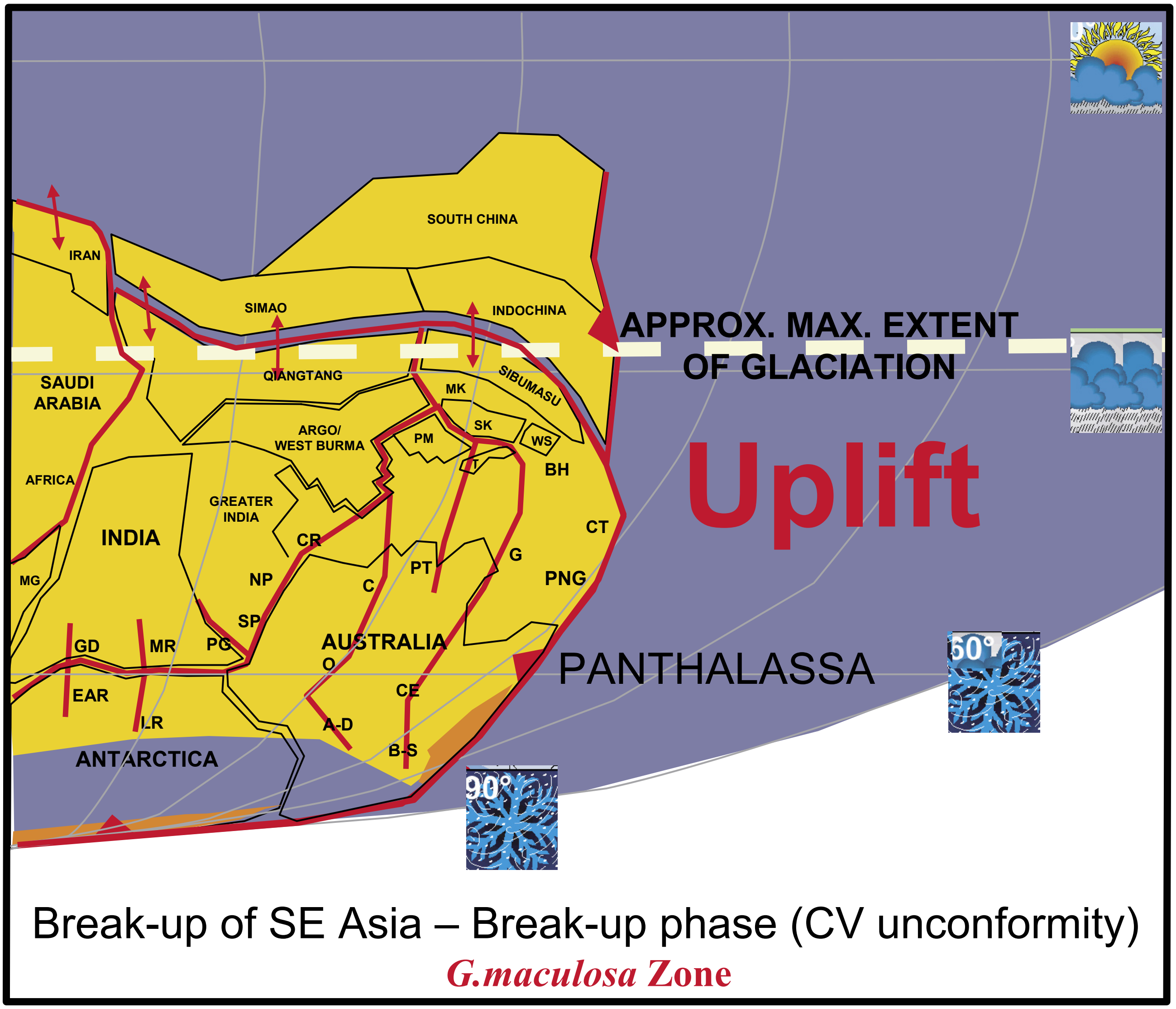


Figure 9. Approximate 325 My Visean plate reconstruction. Legend on previous page.

The next period of rifting commenced in the *M. tristina*/Stage 3b Zone (Artinskian/Early Permian) and is marked by the PA transgressive surface. During this time the Sibumasu–Qiangtang microplate complex began to break off. Similar to southeast Asian microplates, Subimasu–Qiangtang was subjected to the same rifting stages. The location of the Late Permian rift is uncertain, although thickness variations along the Perth Basin axis and offshore part of the Bonaparte and Canning Basins suggest that these areas acted as stress release centres for active break-up processes further north. The breakaway microplate can only be inferred as the Permian oceanic crust has long been destroyed though subduction and continent accretion processes in present central Asia. During this time the northeast–southwest fault network was established in the Westralian Superbasin, which is roughly at right angles to pre-existing Carboniferous and older rifts.

As the asthenosphere began to stretch northern Gondwana continental crust, subsidence accelerated flooding pre-rift mostly non-marine depocentres. In the Canning Basin, marine shelfal clays and limestones (Noonkanbah Formation) were deposited (Backhouse, 1998). In the Petrel Sub-basin, relatively fine-grained shelfal sediments (Fossil Head Formation) began to dominate the area. In the Browse Basin and eastern part of the Bonaparte Basin thick limestones (Hyland Bay Formation) were deposited (Gorter, 1998). In the Carnarvon Basin marine transgression is initially reflected by deposition of coarser grained sediments (Wooramel Group) followed by storm deposits and fine-grained siliciclastics (Byro Group). In the Perth Basin a landward shift to finer grained facies occurred with deposition of transgressive deposits (Irwin River Coal Measures) followed by the marine sediments (Carynginia Formation). Only the Southern Perth Basin continued to receive non-marine sediments (Ashbrook Sandstone and the Redgate Coal Measures).

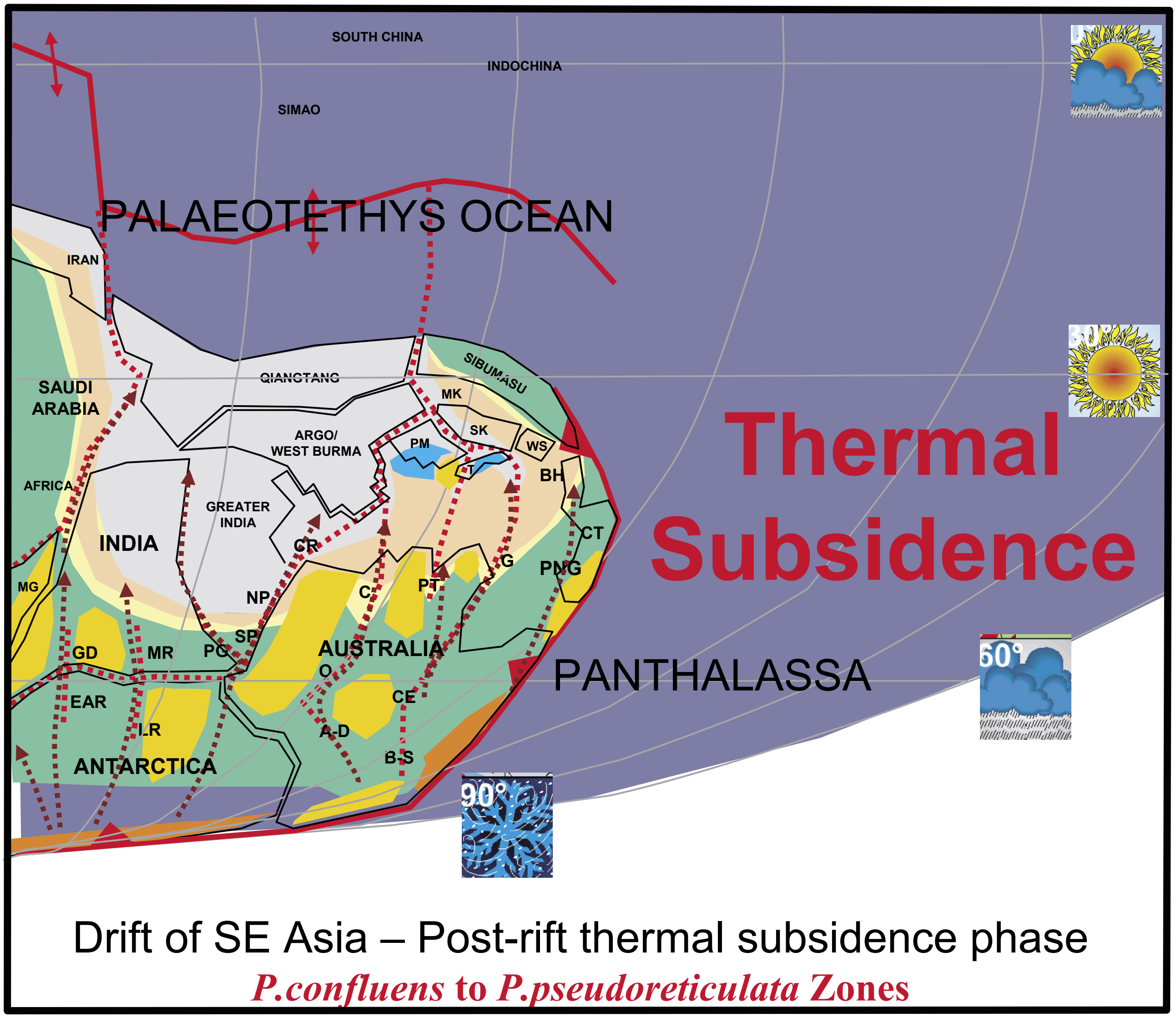


Figure 10. 293–285 My Sakmarian plate reconstruction. Legend for Figure on page 24.

LATE PERMIAN (PK–TR; STAGE 5)

During the upper Stage 4b/*M. villosa* Zone Sibumasu and Qiangtang finally separated from the rest of the northern Gondwana with first extrusion of the Early Permian oceanic crust. This resulted in uplift of the northern Perth Basin, the Petrel Sub-basin and the Carnarvon and Canning Basins and is marked by the PK sequence boundary/unconformity. Non-marine sediments (Willespie Formation) continued to be deposited in the Southern Perth Basin indicating the region's proximity to the sediment source.

Permian facies in the southern Perth Basin are more proximal than in the north. This is also true for sediments deposited immediately on the downthrown side of the Darling Fault system. The petroleum community has been traditionally regarded the Yilgarn Block as a primary sediment source. Such an assumption, however, requires unusually high erosional rates (even for glacial erosion) to account for the up to 5 km thick Permian sequences in the Perth Basin and Merlinleigh Sub-basin. Northerly palaeocurrents measured from outcrop do not support this assumption (Le Blanc Smith and Mory, 1995). Glacial striations also show an overall northerly direction indicating direction of ice movement and glacial outwash (Playford, 2002; Veevers 2001). Cawood and Nemchin (2000) indicate a significant sediment provenance from the south in the Late Permian, which would explain the distribution of Permian facies and the excessive volume of sediment. Thus Permian sediment thickness variations are a reflection of varying subsidence, not sediment provenance. Thick Permian succession can be inferred from seismic in the central Exmouth Plateau with a thinner rim adjacent to the northern Yilgarn Block. In the Perth Basin depocentres developed along downthrown sides of active faults. Traditional interpretations infer proximal facies in these depocentres, whereas Cawood and Nemchin's (2000) provenance studies imply that these depocentres acted mainly as conduits capturing only a relatively small portion of the total sediment input that was transported further north and deposited in the central part of the Exmouth Plateau.

Late Permian (248–272 Ma) intrusive and extrusive igneous rocks are also present in the Roebuck, Canning and Perth Basins (Gorter and Deighton, 2002; Reeckman and Mebberson, 1984; Fig 3b). Assuming that the majority of volcanic activity during rifting is associated with the first extrusion of oceanic crust, the Late Permian age (270 +/-3Ma) of Sibumasu and Qiangtang break-up falls within the time bracket quoted in the literature. It should be noted, however, that this conclusion may be coincidental, as no direct link exists between the absolute time scale and biostratigraphic zones in Western Australia.

As Sibumasu and Qiangtang commenced its drifting phase, subsidence rates once again increased and exposed areas were flooded (Fig. 11). In the northern Perth Basin deposition of fluvial sands (Wagina Formation) and more massive shallow marine sands (Dongara Sandstone) (Mory and Iasky, 1996) were coeval with carbonate deposition (Beekeeper Formation) in more quiescent areas sheltered by exposed blocks from the predominantly northerly clastic sediment direction.

TRIASSIC (TR–TRC1–TRR–JH; *P.MICROCORPUS* TO *A.REDUCTA*)

During the *P. microcorpus* Zone (Scythian) the continued northward drift of volcanic activity, associated with the newly formed Late Permian oceanic spreading ridge, resulted in thermal subsidence of the Perth Basin and the Westralian Superbasin. As a consequence, transgressive sandy facies gave way to widespread shallow marine clays deposited on the broad shallow shelf with sandy facies confined to the eastern edge of the Perth Basin and

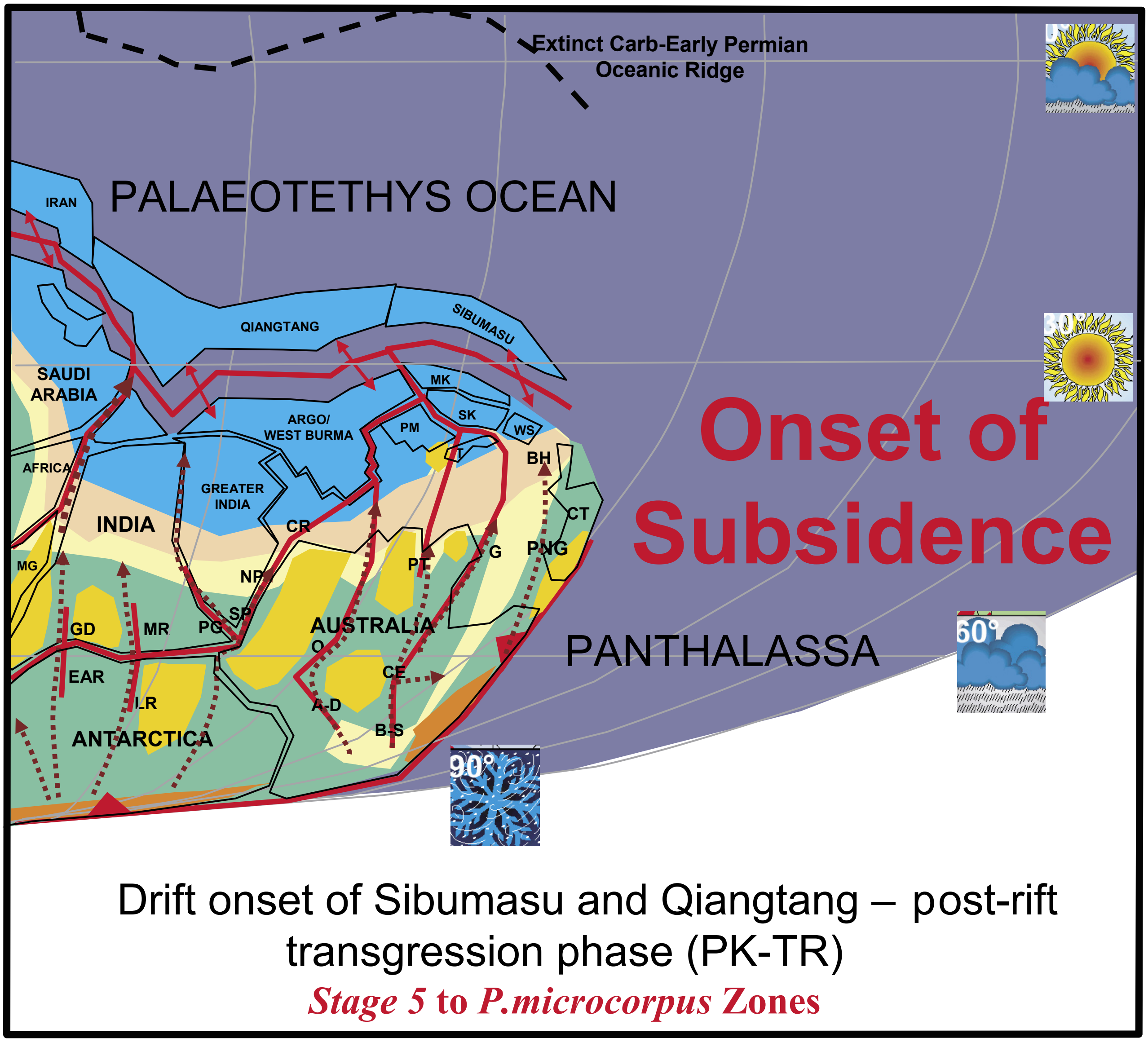


Figure 11. 271–248.2 My Ufimian to Dorashamian plate reconstruction.Legend for Figure on page 24.

the Westralian Superbasin. The TR transgressive surface marks the onset of widespread marine transgression. In offshore areas where elevation after exposure was minimal, marine transgression was rapid and no basal sands were deposited. This often corresponds to the top of limestones, particularly in the Bonaparte Basin where the Hyland Bay Formation is overlain by the fine-grained clastics (Gorter, 1998; Fig. 3b).

Thermal subsidence of northern Gondwana slowed down during the *T. playfordii* Zone (Late Scythian). More proximal sandy and limestone facies once more began to prograde into both regions. This continued with increasing clastic input until the earliest Norian (the lowermost *M. crenulatus* Zone). During that time, Eastern Australia was subjected to thrusting, low grade metamorphism and pluton intrusions marking the Bowen Orogeny. The whole Australian plate was uplifted and compressional features were formed. This explains the steeply deepening unconformity in the Browse Basin, folds in the Bonaparte Basin and the large time break in the Perth Basin and along the eastern side of the Westralian Superbasin (TRC1 unconformity). The inboard part of the Westralian Superbasin was uplifted, and erosion of older strata took place with their subsequent re-deposition further north (Fig. 12).

As thrusting ceased soon after the onset of the *M.crenulatus* Zone, increasingly non-marine clastic sedimentation resumed in the central and eastern parts of the Westralian Superbasin, and relatively rapidly subsiding parts of the Perth Basin. This was interrupted at the end of Norian when another rifting process began, this time associated with the break-up of the Mangkalihat plate. The base of this succession is marked by the TRR transgressive surface. Parts of the southern Exmouth Plateau began to subside flooding non-marine sediments with shallow marine clays (Leatherback–1, Fig. 1). In the northern part of the Rankin Trend marine sands and clays of the *A. reducta* Zone replaced mainly non-marine sediments of the *M. crenulatus* Zone. Whilst there are some older marine intervals within the *M. crenulatus* Zone, these appear to be of local significance only, and as such are thought to have been of eustatic origin rather than related to plate tectonic processes. Accelerated subsidence is also evident on seismic sections as synrift wedges developed in the southern Exmouth Plateau.

Break-up of the Mangkalihat plate is not readily identifiable and the JH unconformity associated with uplift at the start of the *C. torosa* Zone is often merged with TRC1 (Fig. 13). In the areas where sedimentation continued uninterrupted, more proximal facies were deposited. Some evidence of red beds (indicating exposure under arid conditions) at the base of the *C. torosa* Zone has been reported in the Beagle Sub-basin (Osborne, 1994). In North Rankin–5 (Fig.1) the stratigraphically equivalent section has been cored with no evidence of erosion (Beston, 1986). Backhouse et al (2002) reported a significant spore-pollen extinction event marking the onset of *C. torosa* Zone. This may be due to break-up and extrusion of the first Hettangian oceanic crust that changed water chemistry, and by the sudden onset of widespread volcanic activity in the Browse Basin during the Late Triassic to Early Jurassic (Gorter et al, 2002). Perhaps rifting processes associated with the break-up of Mangkalihat rather than the Bowen Orogeny formed the angular unconformity in the Browse area. This, however, cannot be resolved as the unconformity incorporates both events. The *C. torosa* and younger section above this break record only the post-rift transgressive phase.

EARLY TO MIDDLE JURASSIC (JH–JS–JC; *C. TOROSA* TO *W. INDOTATA*)

After a brief exposure at the base of the *C. torosa* Zone, the Perth Basin and Westralian Superbasin once again began to subside as the Hettangian spreading ridge commenced its northward drift. In the exposed areas onset of transgression varied depending on initial elevation of Triassic and older blocks. In the western part of the Westralian Superbasin acceleration of subsidence rates associated with the post-rift thermal subsidence phase is recorded by the JS transgressive surface. Most of the northern Exmouth Plateau and Dampier Sub-basin were flooded pushing well established deltaic fronts some 500 km into entry points in the offshore Canning Basin (Jablonski, 1997). In the Bonaparte and Perth Basin floodings were less dramatic. Sandy facies continued to pour into neighbouring areas reflecting the strength of sediment input and the lack of rapidly subsiding depocentres in front of deltas.

This rifting phase broadly established zones of tectonic weakness that became the loci for future plate break-ups. For example, the Ashmore Platform in the western Bonaparte Basin, a rapidly subsiding area during the Early to Middle Triassic, became a rigid landmass that resisted subsidence until the Early Cretaceous. This landmass formed a western barrier for the Lower to Middle Jurassic fluvio-deltaic sediments (Plover Formation) and subsequent Upper Jurassic deposition (Fig. 14). The Ashmore Platform also sheltered fluvio-deltaic sediments from an open marine circulation allowing the establishment of restricted environments favourable to source rock generation.

CALLOVIAN–OXFORDIAN (JC–JO–JK; LOWER *W. DIGITATA* TO *W. SPECTABILIS*)

In the Callovian, the Argo/West Burma, Sikuleh blocks commenced breaking off. The asthenosphere once again began to stretch increasing subsidence and subsequently flooding the Middle Jurassic deltas (top of the succession, where preserved, is marked by the JC transgressive surface). Fine-grained shallow marine sands were deposited predominantly in the east with more distal clays in the west. The Callovian section is usually thin and confined to the synrift wedges. The thickest synrift wedge in the Lewis Trough of the Dampier Sub-basin is up to 500 m thick (Jablonski, 1997).

The synrift phase was interrupted in the Oxfordian during the lower *W. spectabilis* Zone, as two plates finally separated from Australia (JO composite sequence boundary/

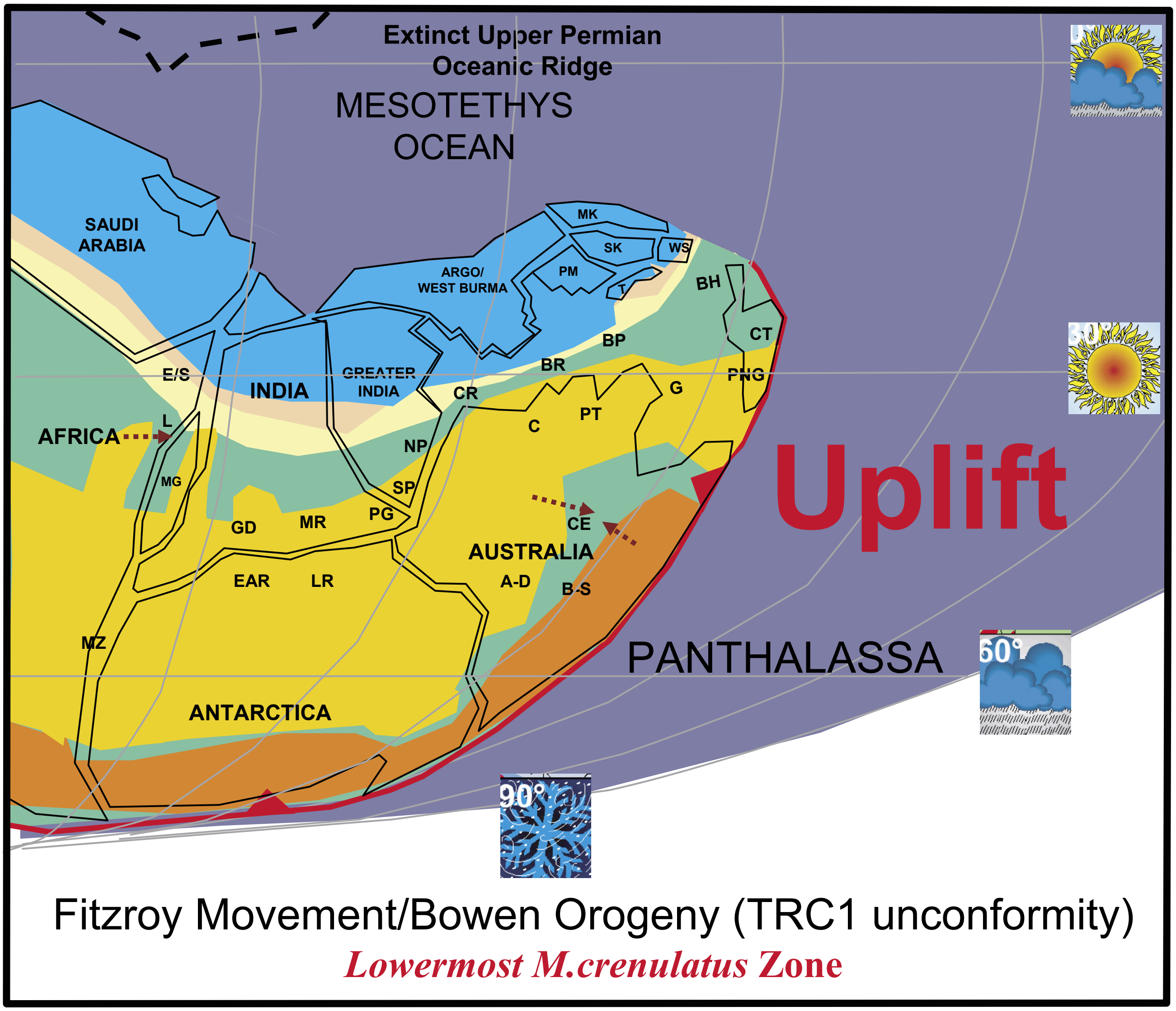


Figure 12. 226 My Carnian plate reconstruction. Legend for Figure on page 24.

unconformity). The emplacement of oceanic crust uplifted the Australian continent, leaving only rapidly subsiding rift arms underwater. This compartmentalised sediment deposition into elongate depocentres.

The break-up was controlled by up to three triple junctions (Fig. 15). The southernmost of these (and the only one readily identifiable in the region) is located at the juncture of the northern Exmouth Plateau, the offshore Canning Basin and Argo Abyssal Plain. It connects failed rifts of the Barrow and Dampier Sub-basins, Cossigny Trough and the Early to Middle Jurassic depocentre east of Whitetail–1 (Fig. 1). The middle triple junction, controlling subsidence of the Cartier Trough and Swan Graben in the Vulcan Sub-basin, was probably located north of Timor. This area underwent severe deformation associated with the Miocene Australia–Eurasia plate collision (Keep et al, 2002). The Malita Graben and probably the Upper Jurassic section of the Goulburn Graben were probably connected to a third junction since subducted into the Timor Trough in the Banda Arc region.

As the first oceanic crust extruded, the margins of active and failed rift arm were uplifted with up to 1,600 m eroded in places. While the extruding oceanic crust controlled the uplift mechanism along active rift arms, such control along failed rift arms was unlikely as uplift was contemporaneous with rapid subsidence in Late Jurassic depocentres — footwall uplift probably explains this differential uplift and subsidence. As a result of erosion, rapid re-deposition of sandy facies took place on the fringes of depocentres in the form of backstepping fourth order lowstand deltas with associated distal basin floor fans. These deltas are of limited extent reflecting an uneven depositional floor and sporadic subsidence. Oxfordian oceanic crust preserved along the eastern edge of the Argo Abyssal Plain is a remnant of break-up. Various absolute ages are attributed to this event, but it is obvious that the break-up is younger

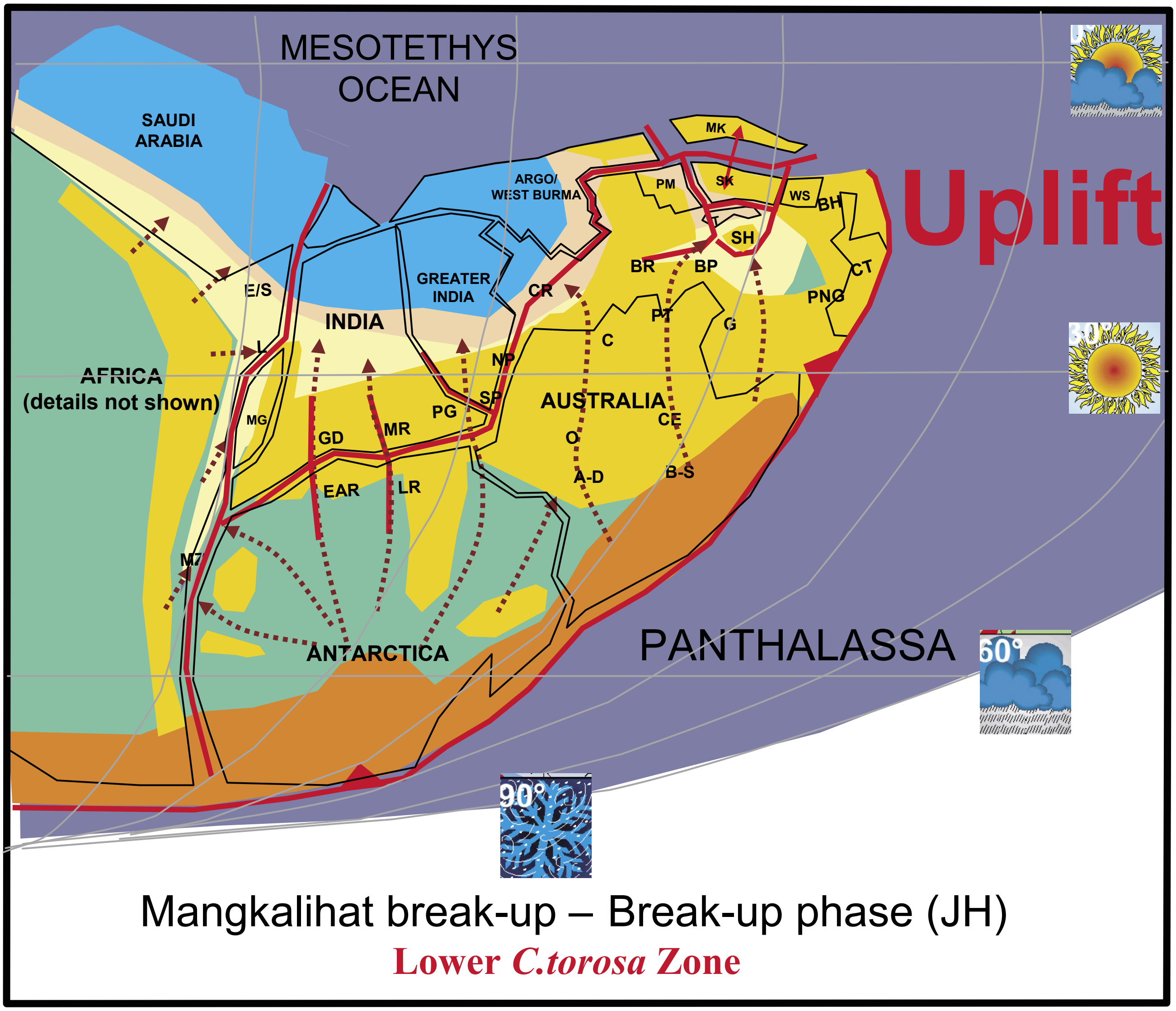


Figure 13. 204 My Hettangian plate reconstruction. Legend for Figure on page 24.

than the Callovian (Heine et al, 2002). Extensive *D. caddense* to *W. spectabilis* (Bathonian to Oxfordian) volcanism has been reported in the Offshore Canning and Browse Basins (Gorter and Deighton, 2002). Individual lava flows from single point sources have been interpreted from magnetic data and seismic sections. Widespread Middle Jurassic volcanic activity does not support the assumption that most of volcanic activity is contemporaneous with continental break-up. Oxfordian break-up, however, is also evident in the offshore Kenya where oceanic crust of this age has been reported (Alconsult, 1997). Late Jurassic break-up was also recorded in the North Sea (Doreé and Steward, 2002). This suggests that Oxfordian rifting was on a massive scale affecting most of Gondwana, and that Middle Jurassic volcanism cannot be properly understood without incorporating data from areas beyond the Australian plate.

KIMMERIDGIAN
(JK–JT; *W. CLATHRATA* TO *D. SWANENSE*)

As Oxfordian tectonic activity waned, local sediment sources became progressively less significant. At the onset of the *W. clathrata* Zone the West Sulawesi microplate broke off. Synrift limestone in Leeuwin–1 is overlain by the JK sequence boundary, which probably represents a break associated with of the formation of the first Kimmeridgian oceanic crust. Synrift geometries are difficult to observe on seismic as the *W. clathrata* section is usually thin. The JK sequence boundary may only reflect re-organisation of Oxfordian spreading centres with the emplacement of new Kimmeridgian oceanic crust in the Argo Abyssal Plain.

Synrift geometries are also recorded during the middle to upper *D. swanense* Zone when the Iris Marl was deposited in the Bonaparte Basin. This event probably corresponds to the onset of break-up of the Paternoster–Meratus mi-

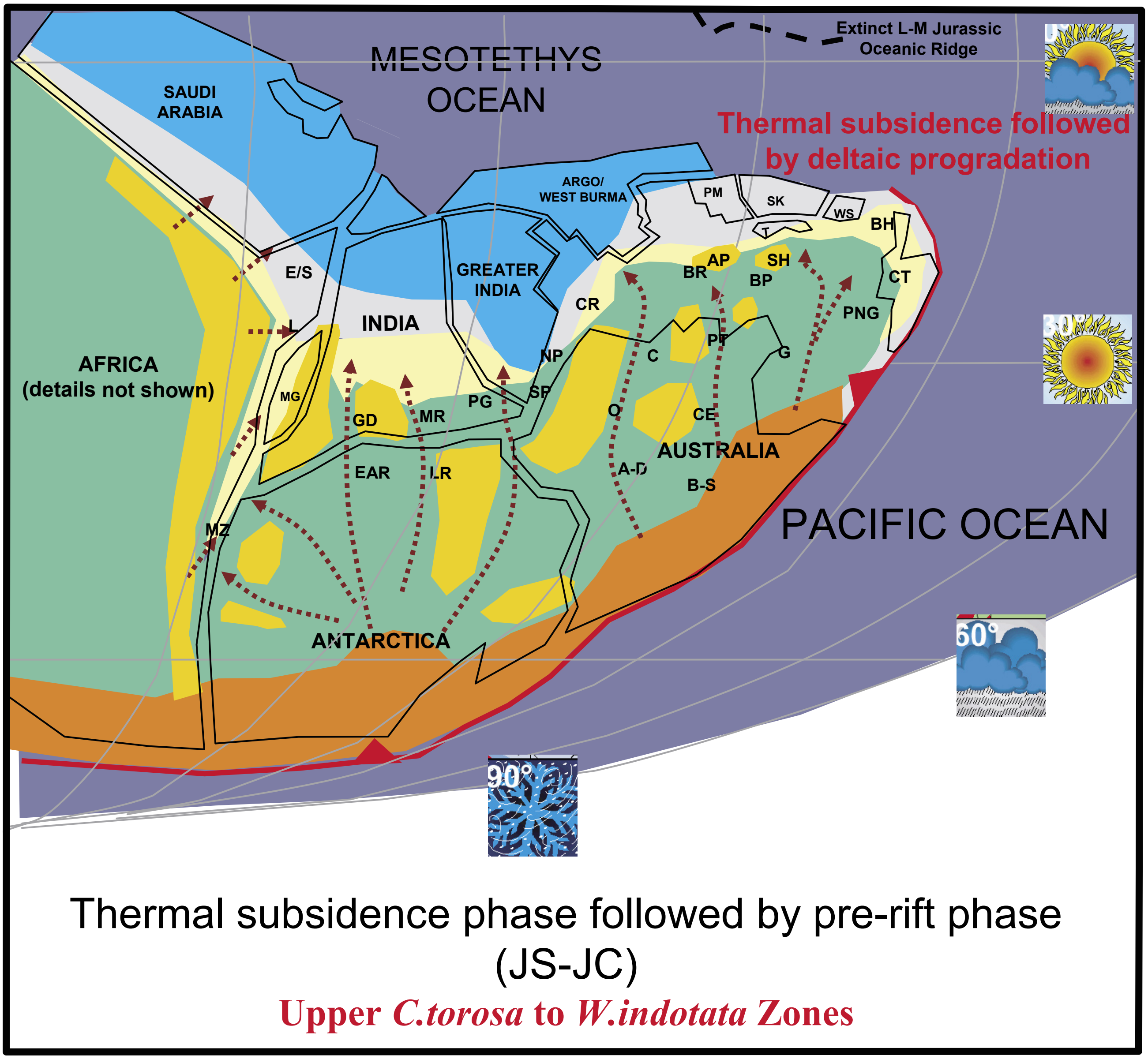


Figure 14. 196–160 My Lower to Middle Jurassic plate reconstruction. Legend for Figure on page 24.

croplate. Deposition of the Iris Marl was interrupted by rapid uplift interpreted to be associated with the formation of the first Tithonian oceanic crust (the JT sequence boundary; Fig. 16).

TITHONIAN
(JT–K; *C. PERFORANS* TO *P. IEHIENSE*)

After Paternoster–Meratus separation, subsidence rates increased allowing a resumption of sedimentation at the onset of the *C. perforans* Zone. Shallow-water sand-prone sediments were deposited in the Canning Basin with deeper facies deposited in the southern Barrow Sub-basin around the Enfield area, Dampier Sub-basin, Vulcan Sub-basin and Malita Graben.

BERRIASIAN
(K–KV; *K. WISEMANIAE* TO LOWER *S. AREOLATA*)

Early in the Cretaceous, during the *K. wisemaniae* Zone, the Perth Basin began to be affected by stretching of the asthenosphere prior to the Greater India/India plate break-up (Fig. 17). This created an acceleration of subsidence rates and flooding of sand-prone Tithonian depositional systems in the Westralian Superbasin (K maximum flooding surface). Since then most of sandy systems have been confined to the east as the whole Westralian Superbasin began to subside. Large continental masses such as the Exmouth Plateau, and the Ashmore and Sahul Platforms were rapidly flooded with distal clays.

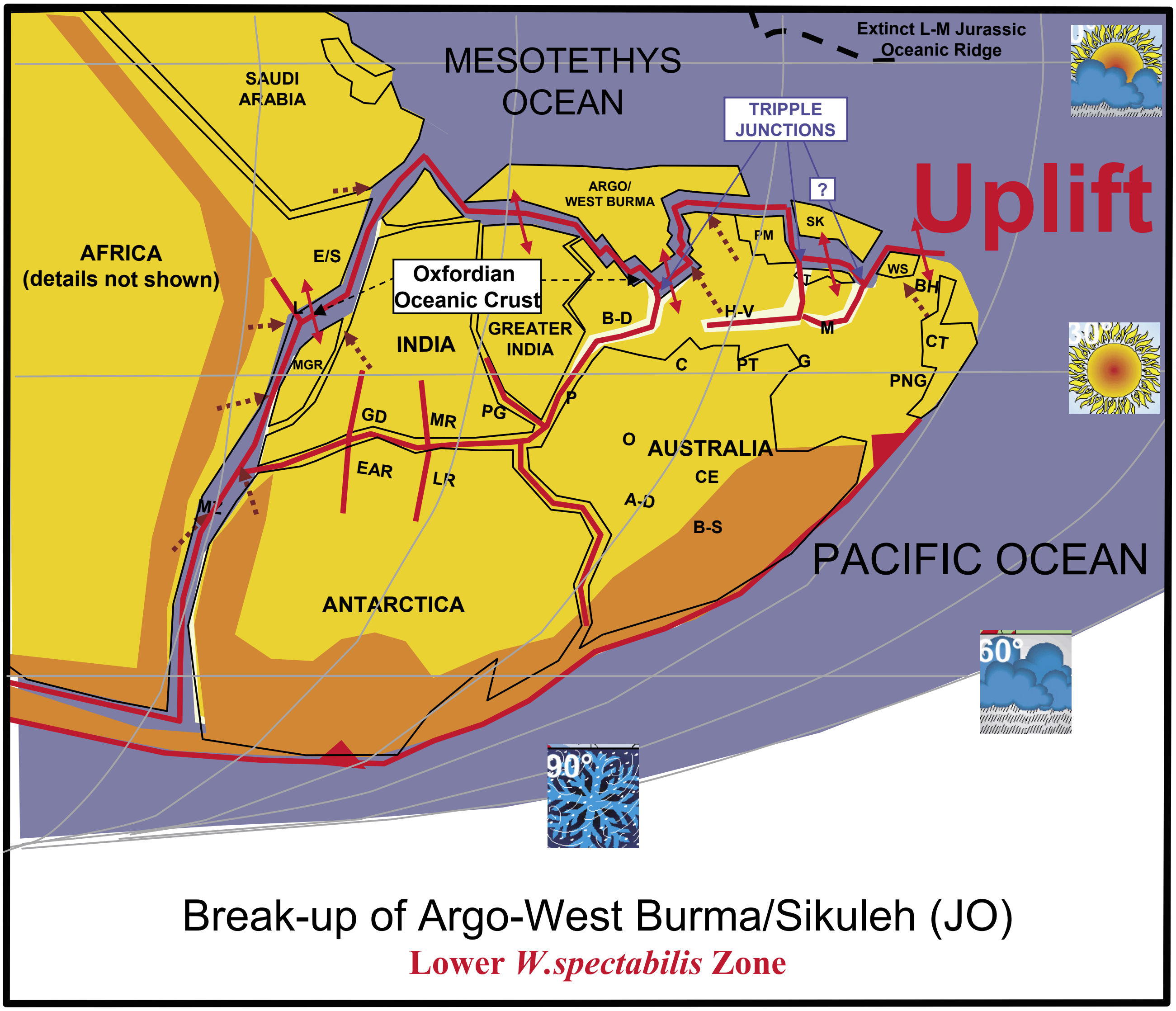


Figure 15. 156 My Lower Oxfordian plate reconstruction. Legend for Figure on page 24.

The Perth Basin also was flooded during the *K. wisemaniae* Zone as indicated by the clay-dominated Otorowiri Formation of the southern Perth Basin (Fig. 5). Tithonian deltaic progradation ceased briefly until the *C. delicata* Zone when a sea level fall rejuvenated sediment source areas allowing progradation into the southern Exmouth Plateau to recommence. Steady progradation of Berriasian deltaic lobes into the southern Barrow Sub-basin reflect the abundance of sediment at this time. Sediment conduits established in the Permian evolved into a very efficient sand-prone delivery system which, despite stretching of the asthenosphere and increased subsidence, had no effect on facies deposited in the Perth Basin.

VALANGINIAN
(KV—KA; UPPER *S. AREOLATA* TO *O. OPERCULATA*)

During the Valanginian, the Greater India/India continent separated from Australia uplifting the Perth Basin and large parts of the Westralian Superbasin (KV sequence boundary). This caused a sudden basinward shift of more proximal facies and erosion of pre-existing delta top facies. The front of the Barrow Delta moved rapidly northward depositing widespread basin floor facies (Flag Sandstone, Fig. 5) to the north. The Perth Basin has been uplifted up to 5 km in places as indicated by the angularity of seismic reflectors beneath the KV unconformity, and porosity/depth trends in commercial wells.

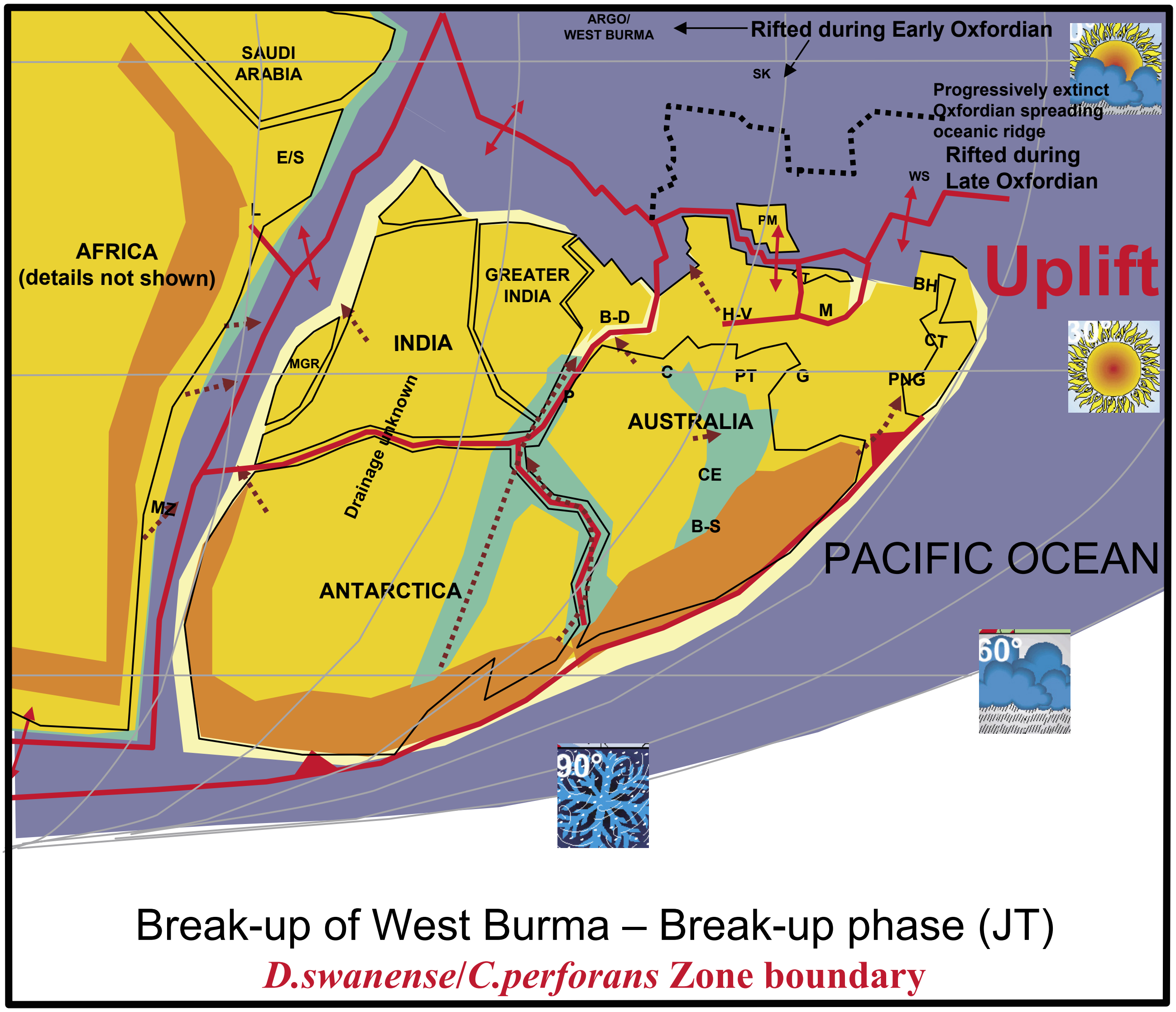


Figure 16. 151 My Lower Tithonian plate reconstruction. Legend for Figure on page 24.

As the Greater India/India continent began its northward drift in the Barremian, the Westralian Superbasin began to subside again so that exposed areas were rapidly transgressed. Offshore clay deposition was established over most of the Westralian Superbasin, including the Barrow Sub-basin with sandy systems confined to the east. By the Aptian the Greater India/India continent drifted away and unrestricted oceanic circulation was established around the Indian plates. This resulted in termination of the clastic systems and commencement of mainly limestone-dominated deposition (Fig. 18). This lithological change is marked by the KA transgressive surface.

CONCLUSIONS

The Permian to Early Cretaceous tectono-stratigraphic history of the Westralian Superbasin and Perth Basin reveals a succession of Gondwanan microplate break-ups, the formation of oceanic crust between them, and their northward migration and final accretion in central and southeast Asia. Our new rifting model subdivides rock section into the following rift phases, each with a specific seismic and well response: pre-rift, synrift, break-up, post-rift transgression and post-rift thermal subsidence.

The Permian to Lower Cretaceous succession records at least eight important plate tectonic events that shaped the stratigraphy of the region:

- Visean break-up of the Simao, Indochina and South China (the CV unconformity);
- Kungurian break-up of Qiangtang and Sibumasu (the PK unconformity);
- Lowermost Norian uplift due to Bowen Orogeny in eastern Australia (the TRC1 unconformity);
- Hettangian break-up of Mangkalihat (northeastern Borneo) (the JH sequence boundary);
- Oxfordian break-up of Argo/West Burma, and Sikuleh

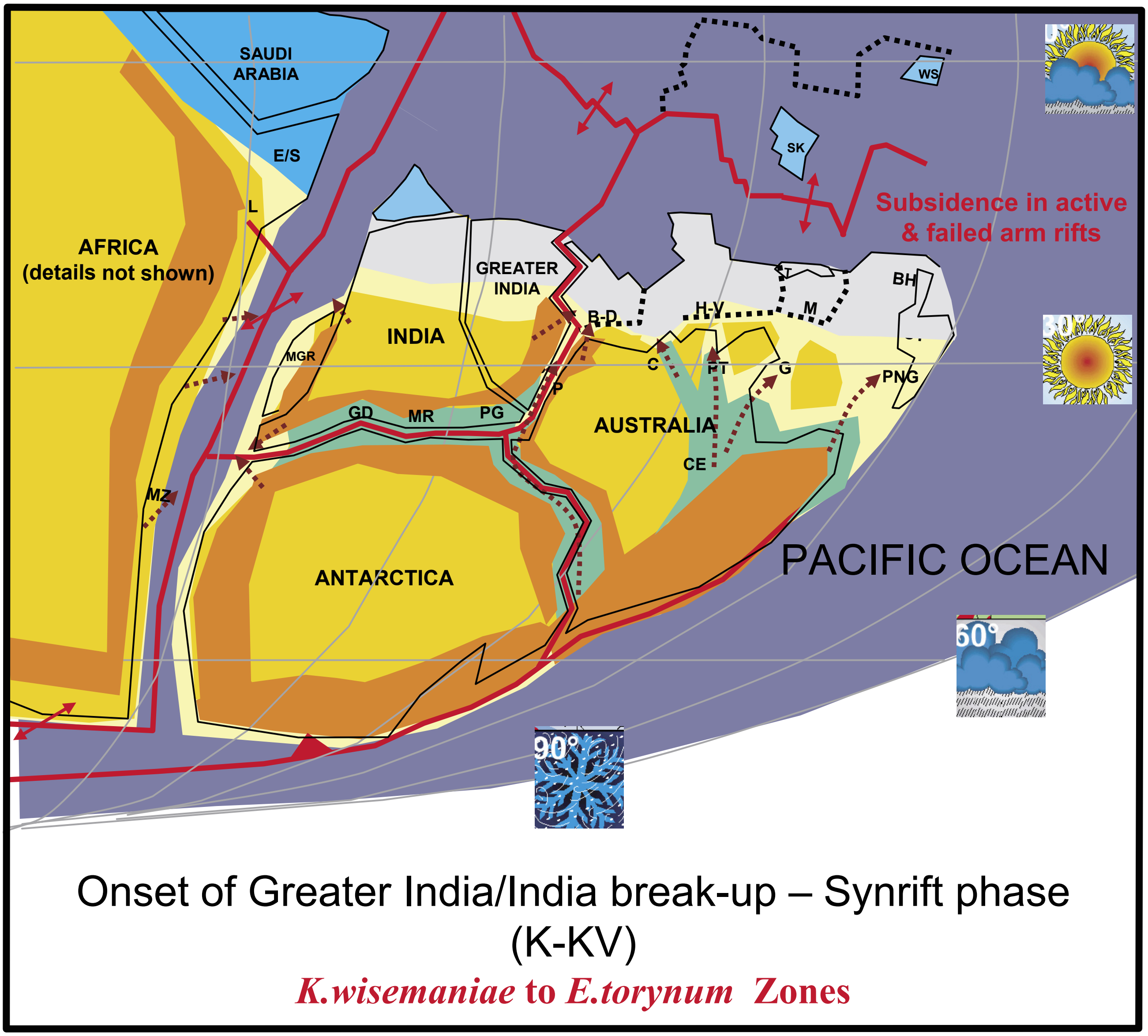


Figure 17. 144–136 My Berriasian plate reconstruction. Legend for Figure on page 24.

(Western Sumatra) (the JO unconformity);

- Kimmeridgian break-up of the West Sulawesi microplate (the JK unconformity).
- Tithonian break-up of Paternoster/Meratus (central Borneo) (the JT unconformity); and
- Valanginian break-up of Greater India/India (the KV unconformity).

Plate tectonics allows an insight into sediment provenance, sediment delivery systems and palaeoclimate. It aids in the synthesis of stratigraphy across broad neighbouring areas, such as the onshore Australian Phanerozoic basins and central and southeastern Asia, in that it provides criteria for the recognition in seismic and well data of the lithologies of breakaway plates, their drifting history and tectonic locations. It also focusses attention on poorly understood aspects of historical reconstruction such as the relationship between various methods used to determine geological age. This approach allows questioning and validation of assumptions made about volcanism and rifting processes. Most importantly, it allows geological frameworks to be simplified through the regional synchronisation of stratigraphy. This approach minimises potential mistakes and omissions caused by lack of data or logical inconsequences in frontier regions.

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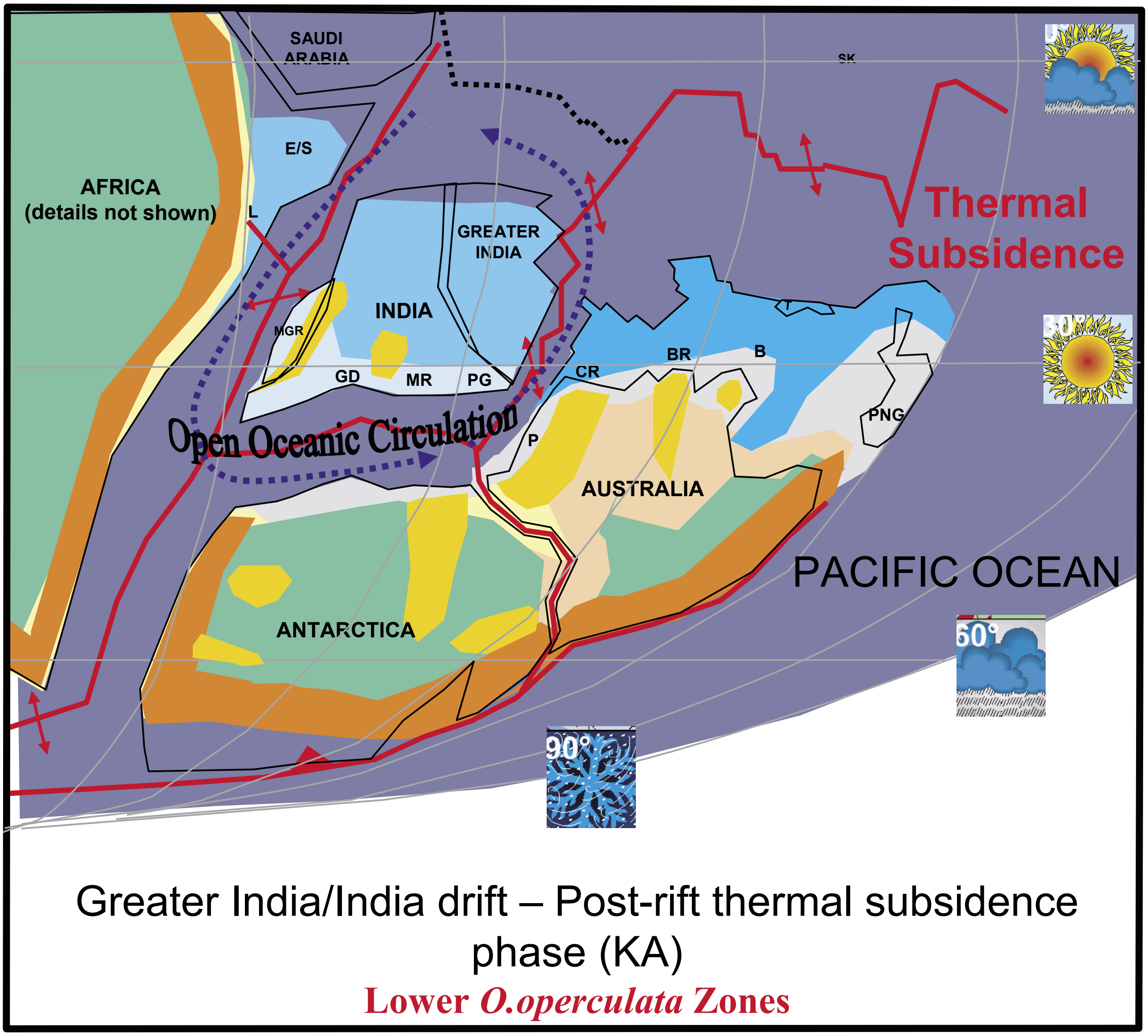

Figure 18. 123 My Aptian plate reconstruction. Legend for Figure on page 24.

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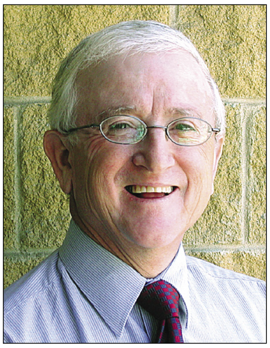

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