Elastic flexure and distributed deformation along Australia's North West Shelf: Neogene tectonics of the Bonaparte and Browse basins

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Abstract: Neogene collision between Australia and the Banda Arc modified the adjacent Bonaparte and Browse basins of the North West Shelf of Australia. Modification comprised both continuous long-wavelength amplification of Permo-Carboniferous basement topography and flexure and normal faulting of Triassic–Recent sedimentary cover. Deformation was continuous across the Browse and Bonaparte basins, despite the basins being separated by a rupture-barrier style accommodation zone, the Browse–Bonaparte Transition. The degree of basement control and mechanisms of fault linkage vary significantly across this transition, and reflect differences in the structural relief, amplitude and depth of rifted basement either side of the transition. Neogene collision amplified the architectural divide. Amplification of basement topography over wavelengths of several hundred kilometres was associated with negligible horizontal length change. The transcurent component of Neogene deformation was partitioned outboard of any continuous flexural amplification.

Australia's North West Shelf formed originally as part of an intra-continental rift that commenced during the early stages of Gondwana breakup in the Devonian, and defined several thousand kilometres of the future Australian margin (Yeates *et al.* 1987). Additional rift events in the Devonian to Permian, Late Carboniferous and Late Triassic to Jurassic created the regional basement architecture and controlled the distribution of source and reservoir horizons of the local hydrocarbon province (e.g. Australian Geological Survey Organisation (AGSO) North West Shelf Study Group 1994; Etheridge & O'Brien 1994). During the Jurassic–Cretaceous, the punctuated separation of the West Burma blocks resulted in dramatic changes in palaeogeography along the northern and southern parts of the future North West Shelf, resulting in the passive margin that would become the North West Shelf (Etheridge & O'Brien 1994; Longley *et al.* 2002). Diachronous collision between Australian continental crust and the Banda Arc from the early Miocene reactivated and modified the Devonian–Cretaceous architecture of the North West Shelf (Fig. 1) (e.g. Baillie & Jacobsen 1995; Keep *et al.* 2002).

Despite the currently convergent plate-margin setting, Neogene deformation on the North West Shelf is dominated by normal faults and depocentres rather than by shortening structures (Fig. 2) (Woods 1988; Shuster *et al.* 1998). Three mechanisms have been proposed to explain this paradox:

(1) localized extension in pockets of the North West Shelf (e.g. Woods 1988); (2) flexural tension of Australia's partially subducted leading edge (O'Brien *et al.* 1999); and (3) penetrative strike-slip modification of the Timor Sea region (Shuster *et al.* 1998). Although such models provide a plausible explanation of some depocentre shapes, they are inconsistent with the style and distribution of Neogene deformation.

The adjacent Browse and Bonaparte basins (Fig. 1), thought to represent upper- and lower-plate Lister-style rift compartments (Lister *et al.* 1991) respectively of the North West Shelf (O'Brien *et al.* 1999), are separated by a lineament known as the Browse–Bonaparte Transition (Fig. 1) (O'Brien *et al.* 1993, 1999; Etheridge & O'Brien 1994; Struckmeyer *et al.* 1998). The Bonaparte Basin, with its broad outer margin plateau and a narrow margin-parallel graben (Fig. 3a), represents a salient upper-plate rift margin (UPRM), whereas the deeper and more extensive Browse Basin (Fig. 3b) is interpreted as a lower-plate rift margin (LPRM) embayment (O'Brien *et al.* 1993, 1999). Despite this asymmetry, basement faults trend consistently NE–SW on both sides of the Browse–Bonaparte Transition (Fig. 2) (Pattillo & Nicholls 1990; Struckmeyer *et al.* 1998; de Ruig *et al.* 2000).

The NW–SE trending Browse–Bonaparte Transition coincides with deep linear geophysical anomalies (Elliott 1994) and with present-day bathymetry, including dramatic bathymetric

Fig. 1. Bathymetry (AGSO) and tectonic setting of NW Australia. Basement compartmentalization corresponds to basin subdivisions and rectilinear steps in the modern continent/ocean boundary (dashed). Position and geophysical expression of the Browse–Bonaparte Transition is indicated (red). Ongoing collision between Australia and the Eurasia/Pacific Arc system (inset) occurred from the Miocene onward.

changes across the lineament (O'Brien *et al.* 1993, 1999; AGSO 1994). This transition is interpreted as the accommodation zone across which polarity of the Permo–Carboniferous rift reversed (O'Brien *et al.* 1993; Etheridge & O'Brien 1994). Whether the structure represents a fault-bound 'transfer' style (e.g. Hayward & Ebinger 1996) or continuous 'rupture-barrier' style (e.g. Faulds & Geissman 1992) feature of basement architecture remains unclear. The Browse–Bonaparte division reflects compartmentalization of the wider North West Shelf over length scales of 600–700 km, corresponding to the Carnarvon, Browse/Canning and Bonaparte basins (Fig. 1) (O'Brien *et al.* 1993, 1999).

We present a synthesis of Neogene tectonism in the Browse and Bonaparte basins and attempt to reconcile the growth of major Neogene depocentres with brittle normal faults in a convergent plate boundary setting. In particular, we relate apparent Neogene subsidence to modification of the basement architecture. Structural and stratigraphic data from the Bonaparte and Browse basins are presented and we examine differences in the style and intensity of the Neogene deformation across

the Browse–Bonaparte Transition. In addition we describe the nature of the Browse–Bonaparte Transition and relate long-lived compartmentalization of the North West Shelf to weak episodic tectonic modification.

Geological framework and tectonostratigraphy

A 2D two-way-time (TWT) seismic grid spanning the Browse and Bonaparte basins was mapped and tied using around 40 wells for which Tertiary Q1 picks were determined (Fig. 4). This grid, comprising more than 4000 open-file lines with an average line spacing of around 5–10 km, was used to construct structural cross-sections and to correlate fault projections across the area. Stratigraphic mapping of the Bonaparte Basin (Fig. 5) shows detailed isochores at selected intervals from the Permian to the seafloor. Similar maps for the Browse Basin (Fig. 6) appear courtesy of Woodside Energy Ltd, after Longley *et al.* (2002).

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Fig. 2. Basement fault trends across the Browse and Bonaparte basins after Pattillo & Nicholls (1990), Struckmeyer *et al.* (1998) and de Ruig *et al.* (2000), superimposed upon the Oxfordian isochore (after Longley *et al.* 2002).

The Bonaparte upper-plate is marked by the outer-margin highs of the Ashmore (AP) and Sahul (SP) platforms, separated from the Londonderry High (LH) by the Vulcan (VG) and Malita (MG) grabens and Nancarrow Trough (NT). The Browse-Bonaparte Transition is shown by the red line. Major basement faults of the Browse Basins (bold) after Struckmeyer *et al.* (1998): (1) Scott Reef Fault Trend, (2) Caswell Fault, (3) Brewster Fault and (4) Bassett Fault. The earlier structural grain of the Petrel Basin (dashed) reflects failed Devonian-Carboniferous rifting (O'Brien *et al.* 1993).

structural highs, is thought to be Precambrian in age, the oldest and deepest horizon that can be correlated across the Bonaparte and Browse basins is the regional Oxfordian (JO) unconformity (Fig. 7a). However, locally in the Bonaparte Basin the top Permian surface can also be identified (Fig. 5a). Within this local top Permian surface the basement architecture of the Bonaparte Basin, including major troughs and highs, can be identified (Fig. 5). Above this surface the top Permian-Aptian isochore (Fig. 5b) reflects both Permo-Triassic infill and more localized syntectonic Jurassic-Cretaceous sedimentation.

The Oxfordian (JO) horizon map clearly illustrates changes in Mesozoic structural relief between the Browse and Bonaparte basins. In the southern Bonaparte Basin, the amount of Oxfordian structural relief (Fig. 7a) is virtually identical to that of the top Permian (syn-rift) surface (Fig. 5a). By comparison, Oxfordian (JO) structural relief in the Browse Basin was probably of lesser amplitude

than the underlying syn-rift architecture (Fig. 7). In both basins, the amplitude of Oxfordian structural relief exceeds that of all younger horizons.

Limited Oxfordian-Valanginian (JO-KV) deposition was confined to the Vulcan Graben and a depocentre in the central Browse Basin (Fig. 7b), whilst the Valanginian-Aptian (KV-KA) isopach only records a depocentre in the Browse Basin (Fig. 7c). This limited deposition in both the Browse and Bonaparte basins at this time reflects a combination of protracted post-Oxfordian underfill of the Browse Basin (Longley *et al.* 2002) and late Jurassic uplift and Aptian erosion of the Bonaparte Basin (Duddy *et al.* 2004). Both are consistent with structural relief between the two basins during the early Cretaceous and greater accommodation space within the Browse Basin at that time.

Infill of Oxfordian structural relief within the Browse Basin was completed during the late Cretaceous (Longley *et al.* 2002). Peak eustatic

Fig. 3. Published cross-sections across the (a) Browse Basin (AGSO, 1994) and (b) Bonaparte Basin (Harrowfield *et al.* 2003). Black arrow marks approximate axis of saddle topography. See Figure 2 for section locations.

sea levels during the Turonian (Blevin *et al.* 1998) culminated in onlap of the Scott Reef Trend (Fig. 3a) and infill of relief across the Browse–Bonaparte Transition (Fig. 7d), permitting convergence of Maastrichtian fan systems across the two basins (Blevin *et al.* 1998). The core of the Aptian–base Tertiary (KA–T) depocentre lay adjacent to the mouth of the Vulcan Graben and well inboard of the Scott Reef Trend (Fig. 7e). The Bonaparte Basin, having been eroded to a low-relief shelf during the Aptian (KA), was subsequently covered by a relatively uniform Aptian–Miocene blanket that has no obvious sensitivity to older topography (Fig. 5d) (Harrowfield *et al.* 2003). Apparent thinning of this blanket across the

Ashmore Platform (Fig. 7e) reflects subsequent Neogene erosion (Hillis 1992). The Oligo–Miocene unconformity (Fig. 5e) preserves a similar topography to that of the Aptian unconformity. This topography must therefore post-date deposition of the Aptian–Oligo–Miocene succession.

In the Bonaparte Basin the Neogene–Recent isochore (Fig. 5f) illustrates thick deposits in the Cartier and Nancar troughs and Malita Graben, mimicking those seen in the top Permian surface (Fig. 5a). Thickness variations in this Neogene to Recent isochore reflect infill of the underlying base Tertiary (TO) unconformity (Fig. 5e) and corresponds to Neogene fault trends across the North West Shelf (Fig. 2).

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Fig. 4. Seismic base map of the Timor Sea region illustrating open-file seismic lines and selected commercial wells used in the course of this study. The locations of strike-normal (cross-sections A–F) and the location of Figures 5 and 8 are also shown.

Fig. 5. Tectonostratigraphy of the Timor Sea region, indicating major physiographic features (see Fig. 4 for field of view): (a) Top-Permian (T.Perm) time surface map with two-way travel time (TWT) contoured at 400 ms intervals; (b) Top-Permian–Aptian (KA) isochore, contoured at 200 ms intervals; (c) time-surface map of the KA unconformity, contoured at 200 ms intervals; (d) Aptian–Oligo-Miocene (TO) isochore contoured at 200 ms intervals; (e) time-surface map of the TO unconformity contoured at 200 ms intervals; (f) TO–sea floor isochore contoured at 200 ms intervals. VG, Vulcan Graben; SS, Sahul Syncline; MG, Malita Graben; AP, Ashmore Platform; LH, Londonderry High; SP, Sahul Platform; CT, Cartier Trough; NT, Nancar Trough.

The Neogene sedimentation history of the Bonaparte Basin therefore mimics that of the underlying Permian surface, and all major Neogene–Recent depocentres (Vulcan Graben, Malita Graben, Sahul Syncline) directly overlie older Palaeozoic–Mesozoic troughs (compare Fig. 5a, b & f). This virtually identical topographical growth in the post-Permian and the Neogene occurs despite the change in tectonic regime from extensional to contractional in the intervening 120 Ma of continuous passive margin sedimentation. The

distribution of Neogene sediments appears to have been structurally controlled and associated with a fault-propagated topography (Figs 2 & 5f).

In the Browse Basin the longevity of the depocentres is more subtle than in the Bonaparte Basin. Depocentres in the base Tertiary-water-bottom isopach (Fig. 7f), differ significantly from those in the upper Cretaceous interval (Fig. 7d & e) in that the Tertiary depocentre did not form along-strike from the palaeo-Vulcan Graben (compare Fig. 7e & f), even though that feature experienced

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Fig. 6. Detail of the late Cretaceous and Tertiary (Albian-seafloor) history of the Browse Basin, mapped from (a) local 2D seismic grid; (b) pre-tectonic Aptian (KA)–Oligocene (TO) isochore; (c) early syn-tectonic Oligocene (TO)–base Pliocene isochore; and (d) base-Pliocene–water bottom isochore. Major basement faults as per Figure 2.

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subsidence during the Neogene (Chen *et al.* 2002; Harrowfield *et al.* 2003). Instead, deposition migrated westward and southward (Fig. 6a & b), with the greatest thicknesses accumulating above the deepest regions of Oxfordian structural relief (compare Fig. 7a & f). The Pliocene–Recent component of this depositional wedge is bound by a margin-parallel trough with linear discontinuities that coincide with syn-rift basement faults (Fig. 6d).

Tertiary sedimentation in the Browse Basin therefore reflects a combination of depocentre progradation and the influence of structural relief associated with the Scott Reef Trend, Oxfordian

depocentre and Browse/Bonaparte Transition. These features were not relics of Jurassic architecture, which had been infilled during the mid-late Cretaceous (Figs 6 & 7). Neogene rejuvenation of these structural elements was spatially and temporally associated with Neogene faulting and syn-tectonic sedimentation across the Browse and Bonaparte basins.

Neogene deformation

In the Bonaparte Basin the top Permian surface (Fig. 5a) displays fault-bound grabens associated

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Fig. 7. Major tectonostratigraphic intervals across the Browse and Bonaparte basins after Longley *et al.* (2002), courtesy of Woodside Energy Ltd. (a) the Oxfordian (JO) unconformity, the oldest and deepest horizon that may be traced continuously across the two basins; (b) the Oxfordian–Valanginian (KV) isopach; VG, Vulcan Graben; (c) the Valanginian–Aptian (KA) isopach; (d) the Aptian–Turonian (KT) component (Blevin *et al.* 1998; no scale given) of (e) the Aptian (KA)–base Tertiary (T) isopach; black line shows position of the Scott Reef Trend (SRT); and (f) base Tertiary–water bottom isopach. See Figure 2 for location.

with deep-seated listric detachments (e.g. Australian Geological Survey Organisation (AGSO) North West Shelf Study Group 1994; O'Brien *et al.* 1999). The Oxfordian surface in contrast (Fig. 7a) reflects Jurassic subsidence and renewed

subsidence of pre-existing toughs, with infill of these lows prior to the Aptian (e.g. Longley *et al.* 2002).

Internally, the Aptian–Oligocene sequence (Fig. 3b) displays continuous sedimentary packages

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that prograde offshore, and generally reflects an advancing sedimentary wedge. This sequence has been distorted about a younger saddle-like topography (Fig. 3b).

Neogene–Recent sedimentation reflects infill of the fault-bound saddle-like topography (since the onset of plate collision), with portions of the sequence thinning across developing highs or thickening above deepening troughs (Fig. 8). As the margin is currently shortening, resulting in an overall decrease of accommodation space, the thinning and thickening of sediments reflect only apparent uplift and apparent subsidence. The coincidence of thinned, fault-bound segments in successive packages (Fig. 8) indicates that thinning was related to both differential uplift and topographic drape. In all cases, synsedimentary thinning and apparent uplift appear to have begun in the late

Oligocene or early Miocene and to have continued well into the Plio-Pleistocene.

Structural highs bounded by brittle normal faults in the Bonaparte Basin have previously been attributed to a horst-like architecture (Woods 1988; de Ruig *et al.* 2000; Chen *et al.* 2002). However, these highs (Fig. 8) are not associated with discrete structural thickening. Between major faults the Tertiary horizons commonly exhibit convex-up geometries (Fig. 8), that are harmonic throughout the stratigraphy and are thought to reflect minor distributed shortening within fault-bound segments. Neogene depocentre margins are marked by prominent normal faults (Fig. 8), many of which are coincident with down-to-basement faults at Mesozoic levels. Apparent subsidence and fault growth appear to have peaked during the late Miocene or Pliocene.

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Fig. 8. Interpretation of apparent Neogene topography, based on variations of sedimentary thickness ($\times 3$ vertical exaggeration). Deepening depressions in the unconformity at the top of the Oligo-Miocene (orange) were bound outboard by diffuse horst-like structural highs. The Cartier Trough, (C–C') is also bound inboard by zones of lesser uplift; an apparently similar phenomena on the inboard margin of the Malita Graben (A–A') reflects a salt diapir beneath the Gull-1 well. Locations of cross-sections given on Figure 4.

The proliferation of seaward-dipping and landward-dipping normal faults, commonly coincident with the older syn-rift architecture at depth (Woods 1988; Nelson 1993; O'Brien *et al.* 1993) makes characterizing Neogene deformation kinematics difficult. However, in the Bonaparte Basin, clear relationships between normal faulting, distortion of pre-collisional cover and the distribution of syn-tectonic (collisional) sediment assist the identification of long wavelength deformation kinematics and four structural domains (Fig. 9):

- (I) a zone of dominantly seaward-verging normal faults that may be traced around the inboard margins of the Vulcan Graben;
- (II) a zone of dominantly landward-verging normal faults, bounding the outboard margin of the Vulcan Graben;
- (III) a zone of dominantly seaward-verging fault kinematics that envelope the outboard flank of the Ashmore Platform; and
- (IV) weak, dominantly outboard-dipping normal faults in the vicinity of the Scott Reef Trend, along strike from the Lynher/Lombardina trend of the outer Browse Basin (Fig. 10).

In the central Bonaparte Basin these Neogene faults commonly preserve modern seafloor offsets (Fig. 9A–A'). Domains I and II (Figs 9 & 10) illustrate down-warping of Cretaceous horizons beneath the Neogene fill of the Vulcan Graben; in domains II and III faults shed pre-collisional cover from the rising and eroding Ashmore Platform (Figs 9 & 10).

Reduced structural relief in the Browse Basin makes extrapolation of these domains from the Bonaparte Basin into the Browse Basin difficult, and is exacerbated by the low intensity of brittle deformation and the thinness of the Neogene fill in the Browse Basin. However, coarse extrapolation of the structural domains may be achieved via correlation of Neogene subsidence/uplift, Pliocene sedimentary growth and, locally, by rare kinematic consistency of normal faults (Fig. 11).

The structural grain of Neogene faults across the Bonaparte and Browse basins changes from NE–SW-trending across the Ashmore Platform and Vulcan Graben, the Browse–Bonaparte Transition and the northern reaches of the Browse Basin to east–west trending in the centre of the Browse Basin (Fig. 10). There is no discrete structural

Fig. 9. Neogene deformation vergence, extrapolated southward from the Bonaparte Basin (A–A') on the basis of syn-tectonic Mio–Pliocene sedimentation. Dissection of the Ashmore Platform is continuous with buckling of Cretaceous–Oligocene horizons and sedimentary thinning west of Mt Ashmore. These zones of uplift bound Plio/Pleistocene depocentres within the Vulcan Graben and above Mt Ashmore (B–B'). The central Browse Basin is dominated by sparse, NW-verging faults and deformation associated with the Scott Reef Trend (C–C'). Approximate vertical exaggeration $\times 12$.

Fig. 10. Interpreted Neogene fault trends across the Browse and Bonaparte basins, coloured according to maximum post-Oxfordian TWT offset. Inferred structural zonation and generalized fault vergence directions (inset) are extrapolated southward from the Bonaparte Basin (Fig. 11).

expression of the NW-trending Browse–Bonaparte Transition. We make several observations of Neogene deformation in the Browse Basin:

- Neogene faults are predominantly confined to the centre of the basin (Fig. 10);
- individual fault segments have negligible expression in Tertiary surface/isochore maps (Figs 6 & 7f) and rarely have maximum displacements greater than 100 ms;
- faults do not penetrate the Yampi Shelf or vicinity of Mt Ashmore; and
- pervasive faulting north and west of Mt Ashmore is continuous with deformation of the Ashmore Platform (Fig. 10).

Neogene modification of the Browse Basin is also manifested as continuous deformation of pre-collisional strata. The present-day bathymetric profile across the Browse–Bonaparte Transition coincides with continuous down-warping of Cretaceous–Miocene horizons (and ponding of Pleistocene–Recent sediments above the Mt Ashmore intrusion) (Fig. 9B–B’).

Continuous Neogene deformation is also observed along the outer margin of the Browse Basin, with Mio-Pliocene prograde expansion and concave-up warping on the outboard side of the Scott Reef Trend (Fig. 11c), and increased relief between the Scott Reef Trend/Browse Basin and

Scott Plateau (O’Brien *et al.* 1993). Likewise, tapering of the Pliocene wedge behind this topographic front (Fig. 9b), corresponding to linear expressions in the Tertiary isopach and Pliocene isochore (Figs 6c & 7f) suggests uplift or amplification of the Scott Reef Trend. The uplifted outer flank of the Scott Reef Trend and its along-strike equivalents formed a locus for Pliocene canyon development (Fig. 11c & d).

Throughout the region, and particularly in the Bonaparte Basin, Neogene faults commonly coincide with larger displacements at Mesozoic levels (Fig. 9) (e.g. Woods 1988; de Ruig *et al.* 2000; Chen *et al.* 2002). This inheritance of extensional architecture, seemingly at odds with the contractional setting of Neogene deformation, has been variously explained in terms of tensional (Woods 1988), strike-slip (Keep *et al.* 2000) and flexural deformation (Harrowfield *et al.* 2003). Although cover and basement faults are typically continuous in 2D seismic cross-section, their displacement profiles are not continuous down-plane (Woods 1988; de Ruig *et al.* 2000). Typical faults have maximum displacements at late Miocene/Pliocene levels, coincident with peak syn-sedimentary Neogene growth (Fig. 9). This growth declines abruptly below the Base Tertiary unconformity; however, and displacements penetrate pre-collision levels and decay down-plane towards typical

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Fig. 11. Continuous Neogene deformation in the Browse Basin (see Fig. 9 for section locations): (a) down-warping of Tertiary strata across the Browse–Bonaparte Transition and buckling of pre-tectonic packages above Mt Ashmore; (b) rotational distortion of package boundaries between adjacent Neogene normal faults, kinematically consistent at right; (c) down-warping of pre-tectonic horizons, and confinement of the Pleistocene wedge across the Scott Reef Trend. Uplift of this trend (c), and its along-strike equivalents (d), induced canyon incision on the outboard flank. Approximate vertical exaggeration $\times 12$.

minima around the Campanian or Aptian unconformity (de Ruig *et al.* 2000). Displacement increases abruptly again near the Oxfordian unconformity, culminating in large offsets and growth at syn-rift (Mesozoic) levels (Fig. 9) (Chen *et al.* 2002). Such profiles are not consistent with temporally continuous displacement at all levels of the pile (Walsh & Watterson 1987). Rather, these profiles are thought to reflect juxtaposition of Permian, Jurassic and Neogene offsets. Although fission-track annealing episodes might indicate basalinal brine transport and basement fault reactivation (Duddy *et al.* 2004), the connectivity of Lower Cretaceous hydrocarbon seals suggests that such reactivation was not necessarily continuous with brittle deformation of the upper sedimentary pile (de Ruig *et al.* 2000). This uncoupling of basement and cover faulting is thought to have permitted flexure of cover rocks about reactivated basement architecture (Harrowfield *et al.* 2003).

Discussion

We believe Neogene modification of the Bonaparte Basin reflects an amplification of syn-rift basement topography. This amplification appears to have decreased inboard over wavelengths of 200–300 km, penetrating to inboard depocentre margins only in the more highly deformed Cartier and Nancarrow troughs (Fig. 12). We attribute apparent Neogene subsidence in the Timor Sea to forebulge flexure, and suggest that propagation of this flexure was limited to the leading several hundred kilometres of the Australian margin. This limitation probably reflects the rapid lateral decay of elastic potential and increasing lithospheric thickness toward the continent proper.

Deformation of the Bonaparte Basin is thought to have absorbed minor margin-parallel shortening, oblique to the trajectory of the Indo-Australian Plate (Fig. 1). Although this shortening must have been accompanied by a component of left-lateral deformation (e.g. Shuster *et al.* 1998), our observations suggest that this strike-slip component was partitioned outboard of the major Neogene depocentres, and may have been localized against the outboard margins of the Sahul and Ashmore platforms (Fig. 2) (Nelson 1993; Keep *et al.* 2002).

The Browse–Bonaparte Transition has no discrete structural expression. Neogene fault trends, although oblique to the transition, are continuous across it (Fig. 10). We identify a correlation between the trend and vergence of Neogene normal faults and the architectural topography of the Oxfordian (JO) unconformity. The rotation of Neogene structural grain across the Browse–Bonaparte Transition mimics the curvature of JO

Fig. 12. Conceptual evolution of Neogene architecture. In contrast to these schematic illustrations, Neogene shortening is thought to have been minuscule: approximating a 1.5 km amplitude parabolic flexure across the *c.* 100 km wavelength Ashmore Platform yields an effective shortening of 0.05%.

topographic contours and the arcuate geometry of the Yampi/Leveque Shelf (Fig. 10). This rotation describes an architecture in which normal faults throw broadly perpendicular to JO architectural topography (Fig. 10, inset).

The control on Neogene faulting by basement architecture changes across the Browse–Bonaparte Transition. Neogene deformation of the Bonaparte Basin was tightly controlled by fault-bound basement structural relief (Harrowfield *et al.* 2003), with flexure and normal faults co-axial with syn-rift architecture (Figs 9A–A', 13). This suggests hard-linkage of parallel cover and basement faults (e.g. Nelson 1993; Shuster *et al.* 1998). In the Browse Basin, shallow Neogene normal faults and structural domains trend oblique to syn-rift structure, suggesting Neogene faults were probably soft-linked to basement architecture. For example, in the central Browse Basin shallow Neogene faults localize above structural culminations bound by the JO unconformity. We envisage three probable reasons for this relaxation of basement control: first, reduced amplitude and

Fig. 13. Neogene deformation of the Bonaparte upper-plate compartment after Harrowfield *et al.* (2003); abbreviations as per Figure 2. The structural relief of the (a) buried Permian rift is mimicked by (b) fault-bounded thickness variations (TWT) in the Neogene–Recent isochore. Harrowfield *et al.* (2003) interpreted Neogene faulting to reflect flexure of cover about amplified basement topography; (c) Driven by a north–south remote compressive stress (red arrows), pure-shear flexure of the Bonaparte Basin (blue region and arrows) is inferred to reflect partitioned sinistral strike-slip (i.e. simple shear) deformation outboard of the Ashmore Platform (yellow region).

increased wavelength of Jurassic and syn-rift architecture (Fig. 7a); second, increased basement depth and thickness of Cretaceous–Recent cover (Etheridge & O'Brien 1994; Blevin *et al.* 1998);

and third, reduced Neogene strain accumulation at distance from the collisional margin. The first explanation is consistent with the transition to soft-linked lower-plate rift margin architecture at basement levels (Struckmeyer *et al.* 1998), i.e. syn-rift architecture itself was less controlled by discrete faults, more influenced by ductile relay ramps and thus more continuous over greater length scales than the hard-linked Bonaparte compartment. The second cause is characteristic of increased subsidence of lower plate compartments during post-rift thermal recovery or 'sag' (as per Lister *et al.* 1991) and resultant inter-compartment relief across the Browse–Bonaparte Transition (Fig. 7a). The third reason is consistent with the apparent decline of Neogene structural relief and deformation intensity southward across the Browse–Bonaparte Transition.

Locally, similar rotations of Neogene structural grain are associated with intra-compartment relief and corresponding variations in cover thickness. At the northern end of the Vulcan Graben, low-amplitude Mesozoic architecture and thicker post-Jurassic cover coincide with structural rotations and east–west Neogene fault trends in the Nancarrow Trough and across the Laminaria High (Fig. 10) (Shuster *et al.* 1998; de Ruig *et al.* 2000). Conversely, in the southern Browse Basin, where post-rift cover thins over the Leveque Shelf, Neogene fault trends and isopach lineaments trend parallel to basement faults of the lower-plate margin (Fig. 10) (Keep *et al.* 2000). Thus the Neogene structural grain is observed to rotate towards greater obliquity with the convergence vector of the Indo-Australian plate (Fig. 1) and inferred driving stress of Neogene deformation with inferred relaxation of basement control.

Neogene modification of the Browse Basin was associated with subtle amplification of Jurassic and older structural relief, accommodated by both faulting and continuous deformation of pre-tectonic Aptian–Oligocene cover (Fig. 9). The Miocene–Recent depocentre was constrained by the Scott Reef Trend, the Browse–Bonaparte Transition and the palaeobathymetry of the Oxfordian depocentre. Thus modification of both the Browse and Bonaparte basins was associated with (1) the subtle amplification of basement structural relief and (2) a continuum of normal faulting. We therefore interpret Neogene deformation of the Browse Basin to be continuous with contractional flexure of the adjacent Bonaparte Basin (Fig. 12) (Harrowfield *et al.* 2003).

In both basins, Oxfordian structural relief was itself a low-amplitude replica of Jurassic architecture (Figs 3 & 9) (Chen *et al.* 2002). Thus both Neogene and Oxfordian structural relief mimicked the architecture of syn-rift basement. These two phases of modification, associated with virtually

identical patterns of sedimentary infill (Fig. 7a & f), heightened relief between the Browse and Bonaparte compartments, and both phases resulted in amplification and erosion of outboard highs, subsidence of inboard troughs (O'Brien *et al.* 1993) and a decline in architectural relief southward across the Browse–Bonaparte Transition. Neither compartment shows evidence of any significant shortening or lengthening normal to strike (Chen *et al.* 2002). Whereas Neogene deformation reflects plate-margin collision, Jurassic modification was spatially and temporally associated with seafloor spreading at the continent–ocean boundary (Muller *et al.* 1998). Similar correlations between seafloor spreading and weak contractional modification of passive margins have been described from SE Australia (Holdgate *et al.* 2003), the North American passive margin (Withjack *et al.* 1998), the North Atlantic Margin (Doré *et al.* 1999) and, locally, the diachronously equivalent Cretaceous interval within the Carnarvon Basin (Baillie & Jacobson 1995). However, in the Browse Basin there was one substantial difference between Jurassic and Neogene architecture: whereas Jurassic faults paralleled syn-rift structure (Fig. 2) (Struckmeyer *et al.* 1998), Neogene faults were obliquely oriented (Fig. 10).

Basement and cover fault trends are continuous across and oblique to the architectural relief of the Browse–Bonaparte Transition (Figs 2 & 10). The Browse–Bonaparte Transition is thus more akin to soft-linked rupture-barrier style accommodation zones (i.e. a continuous basement ridge; e.g. Faults & Geissman 1992) than to transfer style (i.e. fault bound) accommodation zones (e.g. Coffield & Schamel 1989; Hayward & Ebinger 1996). A rupture-barrier style origin, thought to reflect compartmentalization of syn-rift extension (Faults & Geissman 1992), is consistent with both continuous Neogene amplification of the Browse–Bonaparte Transition and the inferred change in fault linkage mechanism (i.e. uncoupling of the two fault populations) between the Browse and Bonaparte basins. The linear geophysical expression of the Browse–Bonaparte Transition, uncharacteristic of accommodation zones in modern rift settings (e.g. Upcott *et al.* 1996) and apparently unrelated to syn-rift faulting (Fig. 2), possibly reflects inheritance of the older Devonian–Carboniferous structural grain of the Petrel Basin (Fig. 2).

The Browse–Bonaparte Transition compartmentalized infill of both Jurassic and Neogene structural relief. Jurassic flexure, presumed to have been driven by orthogonal seafloor spreading, was coaxial with and hard-linked to syn-rift (Mesozoic) architecture. Neogene flexure, driven by oblique collision, varied complexly between

hard-linked/coaxial deformation and soft-linked/oblique deformation because of variations in basement structural relief and cover thickness. Regardless, both episodes caused amplification of long-wavelength relief between the Browse and Bonaparte Basins. Thus, weak flexural deformation, driven by both rifting and early-stage orogenesis, is interpreted to have actively contributed to long-lived compartmentalization of the North West Shelf (Fig. 12).

Conclusions

We conclude that Neogene modification of the Timor Sea region reflects contractional deformation of a collisional plate margin; in effect, early-stage orogenesis. Our model has several interesting ramifications.

1. Any elastic amplification at basement levels (in accordance with Etheridge *et al.* 1991) might have been recoverable following accretion of the Banda Arc. This may explain why Ashmore Reef, a structural high and erosional locus during the Plio-Pleistocene, is now stranded below the apex of shelf topography.
2. Neogene deformation and depocentre growth did not result from penetrative strike-slip modification of the North West Shelf. Neogene depocentres represent troughs of apparent subsidence contained by zones of diffuse uplift.
3. Neogene–Recent tectonism amplified basement topography over wavelengths of several hundred kilometres. This vertical exaggeration was associated with negligible horizontal length change (i.e. very small distributed strain).
4. Shallow Neogene faulting accommodated thin-skinned gravitational collapse of detached sedimentary cover. At depth, Neogene deformation was manifested as continuous flexural shortening. This shortening was oblique to the trajectory of the Australian continent and the inferred tectonic stress.
5. The transcurrent component of Neogene deformation was partitioned outboard of any continuous flexural amplification. We speculate that left-lateral shear was partitioned adjacent to the present-day Timor Trough.

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