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A new model for active intraplate tectonics in western Australia

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ABSTRACT: The Western Australia Shear Zone (WASZ) is a 2000 km long fault system with evidence of late Neogene to historical deformation within the intraplate region of Australia. The WASZ reoccupies older rift related structures that initially formed during periods of continental-scale fragmentation in the Paleozoic and Mesozoic Eras. Structures within the WASZ have caused local inversion of older rift-era faults, in places have offset or folded the seafloor, folded late Pleistocene marine terraces, folded and faulted late Pleistocene alluvial deposits, and accommodated large historical earthquakes.

Neotectonic crustal strain in west central Australia is focused within an antecedent structural architecture that is now favourably oriented for reactivation under the current plate boundary configuration. Stresses generated at the plate margin are being transmitted into the Australian plate interior along former passive margin structures. Reactivated extended crust within the WASZ is effectively acting as a transform plate boundary between more rigid Indo-Australian oceanic crust and rigid non-extended Australian Precambrian continental crust. We hypothesize that the western margin of the Australian continent is not behaving as a discrete tectonic block, but rather as a group of smaller blocks, some of which are experiencing incipient disaggregation. As demonstrated by regional tectonic geomorphology, at least two of these blocks meet along the WASZ. The components of this hypothesis are hardly novel (e.g., far-field plate boundary forcing reactivating structurally favourable zones of weakness), however collectively they provide a fundamentally different tectonic framework to that which has been applied to SCRs in general and Australia in particular.

1 INTRODUCTION

In recent decades growing interest in Stable Continental Region (SCR) earthquake processes has increased research on Australian intraplate tectonics. As a result, the database of neotectonic features and information on the rates and style of intraplate deformation is growing (e.g., Clark et al., 2014 and references therein). Notwithstanding recent advances into our understanding of intraplate earthquakes, the *causes* of intraplate earthquakes remain largely enigmatic.

The current model for earthquake occurrence within SCRs is based on limited data predominately from the SCRs of Australia, the Central Eastern United States (CEUS), and the South American craton (e.g., Bezerra et al., 2011; Bartholomew and Van Arsdale, 2012). New paleoseismological data acquired in the past two decades, though still meager, form the basis of our nascent understanding of how large earthquakes behave in these settings. Though limited, these data broadly corroborate; a number of common characteristics of earthquake occurrence in SCRs are summarized below. Evidence suggests that faults behave episodically with tens of thousands to hundreds of thousands of years of quiescence separated by intervals of clustered activity (e.g., Crone and Machette, 1997; Crone et al., 2003; Clark et al., 2008; 2014). Reverse and strike-slip faulting are the dominant styles of deformation (Zoback et al., 1989; Leonard, 2014) and this faulting occurs in almost entirely compressional stress regimes (e.g., Heidbach et al., 2010). M_{max} appears to be a partial function of crustal type (Johnston et al., 1994; Leonard and Clark, 2011; Clark et al., 2011). Faulting exploits ancient structures (Clark and McCue, 2003; Dentith and Featherstone, 2003; Dentith et al., 2009) and there is a tendency for old (e.g., Proterozoic to Mesozoic) structures to accommodate most of this neotectonic strain (e.g., Johnston et al., 1994; Clark et al., 2012).

Within the Australian plate there is a growing body of evidence suggesting that far-field plate boundary interactions have a first order control on intraplate seismicity and neotectonics (Cloetingh and Wortel, 1986; Molnar et al., 1993; Coblentz and Sandiford, 1994; Coblentz et al., 1995, 1998; Hillis and Reynolds, 2000; Reynolds et al., 2002; Burbidge, 2004; Sandiford and Egholm, 2008; Sandiford et al., 2004, 2005, 2009; Hengesh et al., 2011; Dyksterhuis and Müller, 2008; Müller et al., 2012; Hengesh and Whitney, 2014; Whitney et al., 2014). So how adjacent plate margins have been and are developing can make a significant contribution to tectonic evolution within SCR settings.

This paper presents a summary of recent neotectonic data gathered along the western Australia continental margin. It also presents a summary of the plate boundary conditions along the Sunda and Banda Arcs. Collectively, these data have contributed to a new conceptual model of active tectonic deformation in this region of Australia.

2 A NEW NEOTECTONIC MODEL

2.1 The Western Australia Shear zone

Structures with evidence of late Neogene to historical deformation are present over a length of more than 2000 km along the continental margin of west-central and northwestern Australia (Fig. 1) (Whitney and Hengesh, 2013; 2014). These structures include: the Mt. Narryer fault zone (Whitney et al., 2015) that may have accommodated the 1885 M_L 6.6 and the 1941 M_L 7.1 Meeberrie earthquakes (e.g., McCue, 1990; Leonard, 2008); Tooloonga scarps (McPherson et al., 2013); structures along the Carnarvon alluvial plain (Whitney and Hengesh, 2015a), Lake Macleod, Shark Bay, and the Cape Region (Whitney and Hengesh, 2015b); and offshore structures near Barrow Island (Whitney, 2015; Whitney et al, *in review*), the Rankin Trend, the offshore Canning and Browse basins, and the Sahul Shelf (e.g., Whitney et al., 2014; Hengesh and Whitney, 2014). These structures have caused local inversion of older rift-era faults and in places have offset or folded the seafloor indicating recent activity. This system of active structures is referred to as the Western Australia Shear Zone (WASZ) (Whitney and Hengesh, 2013).

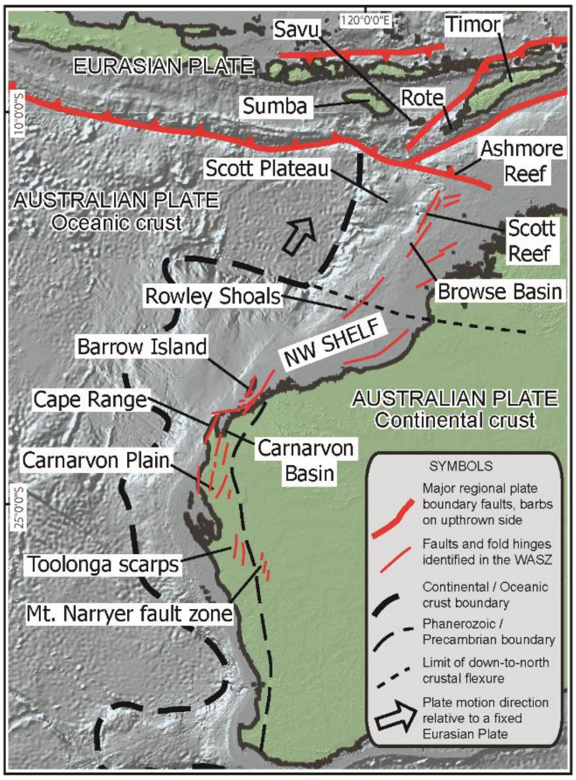

Figure 1. Regional map showing principal geological provinces and structural trends. For legibility, not all structures within the WASZ are shown. Plate motion direction from Bock et al. (2003).

The WASZ structures share a consistent set of characteristics within a concentrated region of historical seismicity. Reactivated faults and folds are concentrated within the formerly extended continental margin compared to adjacent crustal domains. Reactivated structures follow a dominant north to northeast trend along the extended margin. Geological indicators of the maximum principal stress directions estimated on reactivated structures along the continental margin are consistent with models relying on seismological and geotechnical data. Seismicity and geomorphological indicators suggest a regional dextral-oblique sense of motion. Folding in near surface sediments is the predominant style of surface expression of reactivated basement faults. The style of reactivation, consistent throughout the region, indicates fault growth by segment linkage. Near surface fault expression is suggestive of a recent onset of reactivation. Seismicity and geologically derived strain indicators indicate rates of deformation vary systematically within the system decreasing from north to south. Earthquake recurrence within the WASZ is intermediate to plate boundary settings and Stable Continental Regions. Collectively, the WASZ comprises a 2000 km reactivated system of faults and folds that extends from the northern plate boundary along the western continental margin to at least the southern Carnarvon basin (Fig. 1) (Whitney, 2015 and references therein).

2.2 **The Sunda and Banda Arcs Boundaries with the Australian Plate**

Prior to the late Miocene, oceanic crust of the Australian plate was involved in subduction along the entire northern boundary zone (Silver et al, 1983). Blockage of the Banda Trench (no longer existent) occurred as recently as 4 Ma as buoyant continental crust entered the subduction zone (Audley-Charles, 2011). Since then (4 Ma), the northern Australian plate boundary has been characterized by both ocean-continent subduction and continent-arc collision (e.g., Carter et al., 1976; Hamilton, 1979; Audley-Charles, 2004; 2011).

West of Sumba Island (~120ºE) oceanic crust of the Australian plate is subducting beneath the Eurasian plate at the Java trench. Where oceanic crust of the Australian plate is subducting beneath the Sunda shelf and island-arc the mechanical process of slab-pull is active with possible trench advance (Schellart, 2004). The plate boundary is characterized by stable oceanic subduction with low coupling coefficients (Pacheco et al., 1993; Simons et al., 2007). Up to 90% of plate convergence occurs along a narrow zone near the deformation front (Nugroho et al., 2009). Along this portion of the Australian-Eurasian plate boundary a classic Benioff style (Balley, 1983) subduction zone is evident in the seismicity (Hengesh and Whitney, 2014).

East of Sumba Island (~120ºE), oceanic crust has been entirely consumed by subduction and the Banda trench has converted into a tectonic collision zone (e.g., Audley-Charles, 1981; Harris et al., 2009; Roosmawati and Harris, 2009; Rigg and Hall, 2011; Audley-Charles, 2011). Collision initiated when Australian continental crust was unable to enter the subduction zone below the Banda fore-arc. At this time, the former trench became filled by thrust stacking during the northward progression of the Australian continental lithosphere and *Asian* nappes thrust southwards during slab rollback (Spakman and Hall, 2010; Audley-Charles, 2011). After the onset of collision, no continental crust was subducted although subduction of the decoupled oceanic slab continued. Ongoing trench rollback resulted in separation of Australian continental lithosphere from the subducting slab (Spakman and Hall, 2010) and fluid movements into the developing slab window caused rapid uplift (Keep and Haig, 2010).

Along the collision zone up to 70% of plate convergence is partitioned away from the deformation front (Harris, 1991; Nugroho et al., 2009). The Eurasian plate is responding to the transition from a type B (Benioff) style subduction zone to a type A (Ampferer) style tectonic collision zone (Bally, 1983) by becoming progressively coupled to the Australian plate (Genrich et al., 1996). Geodetic measurements west to east across the collisional zone demonstrate the coupling of individual tectonic blocks to the Australian plate (Fig.2) (Bock et al., 2003; Nugroho et al., 2009). GPS derived rates of convergence across the Timor Trough are 15±8 mm/yr (Nugroho et al., 2009) compared with rates of 67±7 mm/yr across the Java Trench subduction zone (Tregoning et al., 1994). The rigid Indian oceanic crust is moving *en masse* into the subduction zone, whereas the deformable extended continental crust is being mechanically impeded by the clogged trench and Banda Arc terranes and the process of southward trench roll-back. As a consequence, a strain gradient exists along the Java trench-Timor trough axis

where the rate of convergence becomes distributed near Sumba Island. Over 20 mm/yr of Australia plate motions is unaccounted for between Timor and Darwin (Fig. 2) (Nugroho et al., 2009).

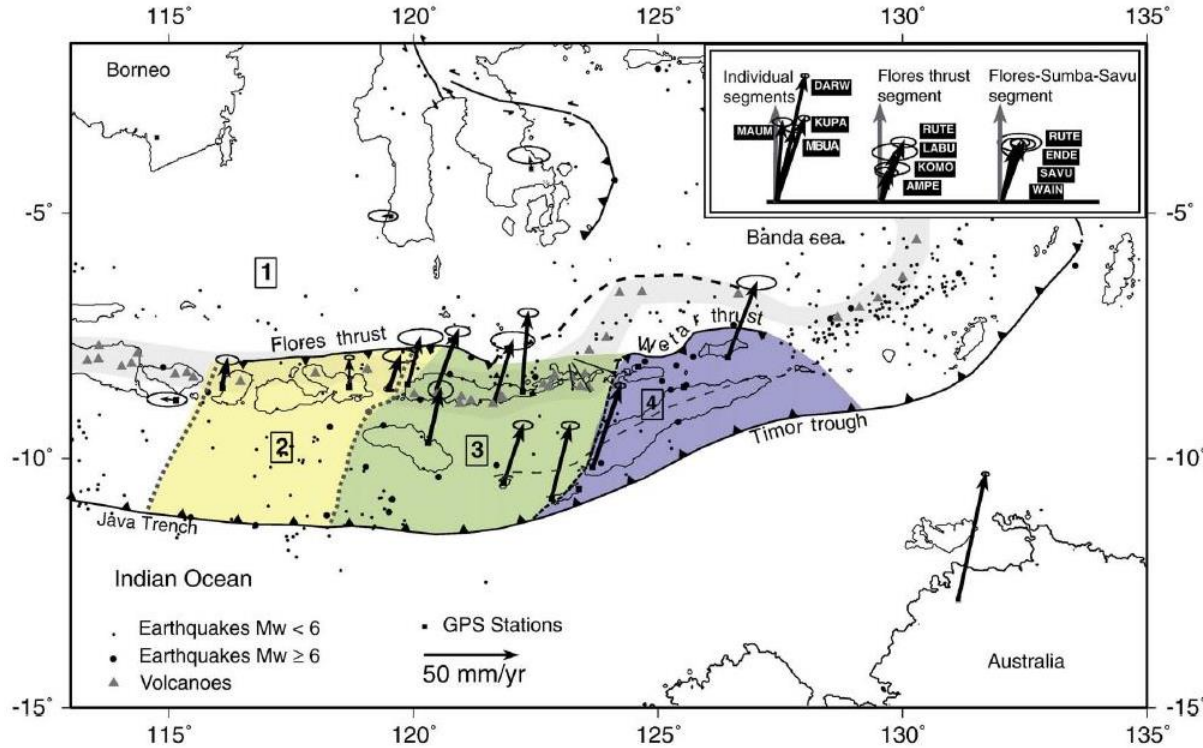

Figure 2. Plate boundary segments in the Banda Arc region from Nugroho et al (2009). Numbers inside rectangles show possible micro-plate blocks near the Sumba Triple Junction (colored) based on GPS velocities (black arrows) with in a stable Eurasian reference frame.

The subduction-collision transition coincides with the contact between oceanic and continental crust within the Australian plate and the intersection of former rifted margin structures (along Australia's west coast) with the Java trench-Timor trough complex (Hengesh and Whitney, 2014). The contrast in lithospheric rheology (oceanic vs. continental crust) and styles of deformation at the plate boundary (subduction vs. collision) is causing varying styles of deformation within the proximal and distal parts the Australian plate. The proximal effects of the continent-arc collision include: slab roll-back (Spakman and Hall, 2010); north-south crustal shortening (McCaffrey, 1988); strain partitioning in the upper plate (Harris, et al., 2009); coupling of Australian continental crust, continental fragments, and volcanic arc terranes of the Banda Arc (Nugroho, et al., 2009); the activation of the Flores-Wetar thrust systems (McCaffrey and Nabelek, 1984); and rapid uplift of the accreted terranes due to post slab-detachment isostatic adjustments (Keep and Haig, 2010).

Distal effects of the continent-arc collision are observed up to 2000 km south of the northern plate boundary. Indicators of these effects include regional crustal warping (Hengesh et al., 2011), a reactivated system of Quaternary faults and folds (e.g., Whitney and Hengesh, 2013; 2014; 2015a, b; Whitney et al., 2015), and elevated levels of historical seismicity including a number of >M6 historical earthquakes compared with adjacent SCR crust (e.g., Leonard, 2008).

Onset of continent-arc collision occurred near the vicinity of Timor (4 to 5 Ma) and has propagated westward diachronously at an average rate of 110 km/Ma (Harris, 1991). Scott Plateau, a crustal promontory similar to Exmouth Plateau, collided with Sumba (1.8 Ma); from here, the collision front propagated southeastward and recently reached the vicinity of Rote (0.2 Ma) (Spakman and Hall, 2010; Audley-Charles, 2011). Scott Plateau is located directly on the former western Australian passive margin. The timing of the collision at Scott Plateau is coincident with the most recent reactivation within the Western Australia Shear Zone (Hengesh and Whitney, 2014).

2.3 A Causal Mechanism for Fault Reactivation

We suggest that the recently established configuration of these major tectonic elements in congress with the associated changes in plate boundary kinematics, sets up a dextral shear couple that is transmitted south along the formerly rifted western Australian margin. The mechanical coupling and wrenching at the collision-subduction transition (near Sumba) is aligned with former passive margin structures. The strain gradient along the trench-trough axis at the plate boundary has initiated deformation along the WASZ system of faults and caused an increase in the rates of seismic activity in the region. The WASZ is accommodating part of the differential plate motion through gross dextral-oblique transpressive deformation concentrated within an extended crustal domain that lies between *rigid* Indian Ocean crust and *rigid* non-extended continental crust of the Australian craton (Figs. 1 & 3).

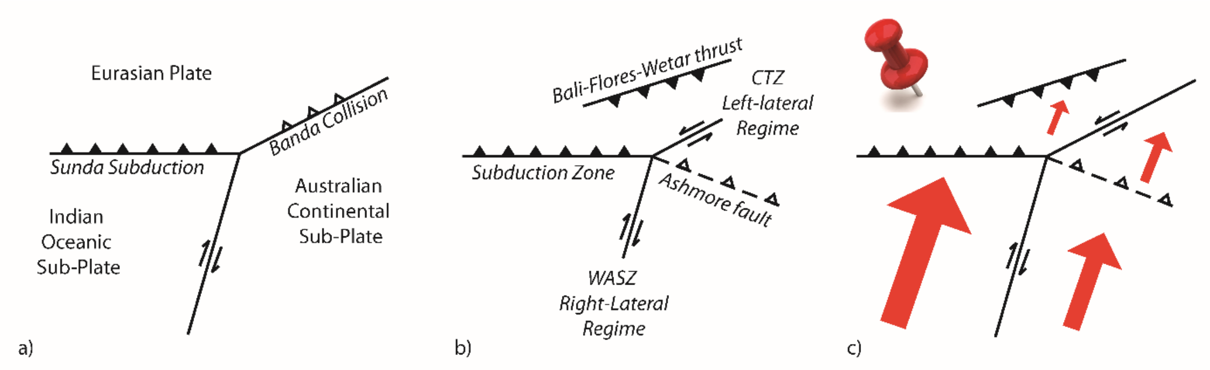

Figure 3. Schematic map views of kinematic relations between major crustal elements in the Sumba Triple Junction region. CTZ= collisional tectonic zone. Red arrow size designates schematic plate motion relations based on geological data relative to a fixed Sunda shelf reference frame (pin).

The exploited structural geometry and resultant kinematics suggest that the WASZ is effectively a nascent plate boundary, or third arm of a triple junction designated the Sumba Triple Junction (STJ) (Whitney, 2015). The STJ occupies the junction of the Eurasian plate, Indian Ocean sub-plate, and Australian sub-plate (Figs. 1 & 3). Within the Australian sub-plate, relative fault motion changes across the STJ from sinistral in the north along the Timor trough and adjacent continental shelves and slopes (Keep and Harrowfield, 2008; Bourget, et al., 2012) to dextral in the south along the WASZ. This transition coincides with an east-west trending lineament with up to 100 m of sea floor relief (Hengesh and Whitney, 2014). This structure has been identified as the Browse-Bonaparte transition and aligns with the Mesozoic Ashmore reef trend (Keep and Harrowfield, 2008). Northeast of the Ashmore reef trend, differential plate motions are accommodated by left-lateral displacements of thrust blocks across the collision zone near Timor (Breen et al., 1989; McCaffrey, 1996; Fortuin et al., 1997). In the Bonaparte basin, southeast of the Timor Trough, faulting in extended crust is dominated by sinistral-transtensional displacements related to the downward flexure of the Australian plate (Bourget et al., 2012; Saqab and Bourget, 2015) and oblique plate convergence along the Banda collision zone. Crustal scale sinistral faulting is partitioning strain between the Australian and Eurasian plates across the Timor trough part of the collision zone (Genrich et al., 1996; Nugroho et al., 2009; Bourget et al., 2012).

Southwest of the Ashmore reef trend, dextral-oblique strain is accommodated along faults and folds in the WASZ. The Barcoo fault (Keep et al., 2000) and Browse basin fault zone exhibit dextral transtensional displacements (Hengesh and Whitney, 2014). In the Carnarvon basin further south, a restraining bend in the Barrow Island region causes dextral-transpressional deformation (Whitney et al., *in review*). South of the restraining bend the component of transcurrent motion appears to decrease while reverse motion increases and hanging-wall folding of surficial units becomes the dominant style of fault expression (Whitney and Hengesh, 2015a, b; Whitney et al., 2015). This tectonic model suggests structures within the WASZ are accommodating a portion of the unaccounted for strain between the Type A collision and Type B subduction plate boundary zones.

3 CONCLUSIONS

Fault reactivation in the WASZ has been observed from Browse basin to the Carnarvon basin and into metamorphic belts along the western margin of the Archean Yilgarn craton. The WASZ consists of numerous faults and folds that are potential seismogenic sources. The WASZ contains youthful structures that appear to have only recently undergone tectonic reactivation. The recency of reactivation is indicated by: folding of surficial sediments above blind faults; multiple segmented structures rather than single continuous structures; lack of progressive deformation to Miocene and younger stratigraphy; youthful stage of hourglass fault development in the Carnarvon basin; and a general lack of tectonically developed topographic relief (e.g., Mt. Narryer fault zone—MNFz). The north to south decreasing strain gradient from the STJ along the WASZ evidenced in the geology (McPherson et al., 2013; Whitney et al., 2014) and the seismicity (Hengesh and Whitney, 2014) suggests strain is propagating from north to south through the system and has possibly just reached the MNfz. The 0.2-1.8 Ma timing of collision at Savu and Rote Islands (Harris et al., 2009) coincides with the most recent activation of structures within the WASZ.

The model suggests that observed active deformation, such as the regional tilting, structural inversions, and folding and faulting is related to the collision along Australia's northern plate boundary and the change in the mechanics of the collision at the intersection of the continental oceanic crust boundary at the Java trench-Timor trough axis. The change from slab-pull driven stable subduction to slab-detachment, mechanical coupling, and subduction rollback at the subduction-collision transition is shearing the western margin of the Australian continent by reactivating older rift related structures. The mechanics of this complex interaction appear to be activating faults and folds as much as 2000 km away from the plate margin. The western Australian intraplate region may be tectonically lethargic, but it is not quiescent, and may be accommodating a new incipient transform plate boundary along its former passive western margin (Hengesh and Whitney, 2014).

This region of the Australian plate is an active tectonic system, rather than a Stable Continental Region. The former rifted margin of western Australia does not satisfy the criteria used to define SCRs due the recency and rates of tectonic deformation observed. This active fault system enables the transfer of strain from an active plate boundary into an intraplate setting along a former rift system. Continued investigation of the WASZ will help further our understanding of the range of processes that drive intraplate earthquakes. Most of the faults identified within the WASZ are not sufficiently quantified to be used directly in probabilistic seismic hazard assessments (PSHA) at this time. Ongoing research is striving to determine slip rates and quantify strain on individual faults within the zone. As these data are gathered, these seismic sources will become useful inputs for PSHA in the region.

REFERENCES:

Audley-Charles, M.G., 1981. Geometrical problems and implications of large-scale overthrusting in the Banda arc–Australian margin collision zone. In: McClay, K., Price, N. J. (eds) *Thrust and Nappe Tectonics*. Geological Society, London, Special Publications 9, 407–416.

Audley-Charles, M. G., 2004. Ocean trench blocked and obliterated by Banda forearc collision with Australian proximal continental slope. *Tectonophysics* 389, 65–79.

Audley-Charles, M. G., 2011. Tectonic post-collision processes in Timor. In: Hall, R., Cottam, M.A., Wilson, M. E. J. (eds), *The SE Asian Gateway: History and Tectonics of the Australia–Asia Collision*. Geological Society, London, Special Publications 355, 235–260.

Bally, A. W., (ed.) 1983. Seismic Expression of Structural Styles. Studies in Geology, *American Association of Petroleum Geologists*, 15 (3 volumes).

Bartholomew, M.J., Van Arsdale, R.B. 2012. Structural controls on intraplate earthquakes in the eastern United States. In *Recent advances in North American paleoseismology and neotectonics east of the Rockies*. R.T. Cox, M.P. Tuttle, O.S. Boyd, J. Locat (eds). pp 165-190.

Bezerra, F.H.R., do Nascimento, A.F., Ferreira, J.M., Nogueira, F.C., Fuck, R.A., Brito Neves, B.B., Sousa, M.O.L. 2011. Review of active faults in the Borborema Province, intraplate South America—integration of seismological and paleoseismological data. *Tectonophysics*, 510, 269-290.

Breen, N. A., Silver, E. A., Roof, S., 1989. The Wetar back-arc thrust belt, Eastern Indonesia; effect of accretion against an irregularly shaped arc. *Tectonics* 8, 803–820.

Bourget, J., R.B. Ainsworth, G., Backe, Keep, M., 2012. Tectonic Evolution of the "Giant" Bonaparte Continental Shelf: Impact on Sediment Distribution during the Pleistocene. *Australian Journal of Earth Sciences* 59, 877–897.

Burbidge, D. R. 2004. Thin plate neotectonic models of the Australian plate. *Journal of Geophysical Research*, 109, B10405, doi:10.1029/2004JB003156.

Carter, D. J., Audley-Charles, M. G., Barber, A. J., 1976. Stratigraphical analysis of island arc–continental margin collision in eastern Indonesia. *Journal of the Geological Society* 132, 179–189.

Clark, D., McCue, K. 2003. Australian Palaeoseismology: towards a better basis for seismic hazard estimation. *Annals of Geophysics*, 46, 1087-1105.

Clark, D., Dentith, M., Wyrwoll, K. H., Yanchou, L., Dent, V., Featherstone, C. 2008. The Hyden fault scarp, Western Australia: paleoseismic evidence for repeated Quaternary displacement in an intracratonic setting. *Australian Journal of Earth Sciences* 55, 379-395.

Clark, D., McPherson, A., Collins, C.D.N., 2011. Australia's seismogenic neotectonic record: a case for heterogeneous intraplate deformation. *Geoscience Australia Record 11*.

Clark, D., McPherson, A., Van Dissen, R., 2012. Long-term behaviour of Australian stable continental region (SCR) faults. *Tectonophysics* 566-567, 1-30.

Clark, D., McPherson, A., Allen, T., 2014. Intraplate earthquakes in Australia. In: Talwani, P. (ed.), *Intraplate Earthquakes*. Cambridge University Press, New York, 8-49. isbn: 9781107040380

Cloetingh, S., Wortel. R, 1986. Stress in the Indo-Australian plate. *Tectonophysics*, 132, 49–67.

Coblentz, D., Sandiford, M., 1994. Tectonic stress in the African plate: constraints on the ambient stress state. *Geology* 22, 831–834.

Coblentz, D.D., Sandiford, M., Richardson, R. M., Shaohua, Z., Hillis, R., 1995. The origins of the intraplate stress field in continental Australia. *Earth and Planetary Science Letters*, 133, 299–309.

Coblentz, D.D., Zhou, S., Hillis, R. R., Richardson, R. M, Sandiford, M., 1998. Topography boundary forces and the Indo-Australian intraplate stress field. *Journal of Geophysical Research*, 103, 919–938.

Oklahoma: Geological Society of America Bulletin, v. 102, p. 1-17.

Crone, A.J., Machette, M.N., 1994, Paleoseismology of Quaternary faults in the "stable" interior of Australia and North America; insight into the long-term behavior of seismogenic faults: USGS Open-file report [0196-1497], p. 40-42.

Crone, A.J., DeMartini, P.M., Machette, M.N., Okumura, K., Prescott, J.R., 2003, Paleoseismicity of Two Historically Quiescent Faults in Australia: Implications for Fault Behavior in Stable Continental Regions: *Bulletin of the Seismological Society of America*, v. 93, p. 1913-1934.

Dentith, M.C., Clark D. J., Featherstone, W. E. 2009. Aeromagnetic mapping of Precambrian geological structures that controlled the 1968 Meckering Earthquake (Ms 6.8): Implications for intraplate seismicity in Western Australia. *Tectonophysics* 475, 544-553.

Dentith, M.C., Featherstone, W. E. 2003. Controls on intra-plate seismicity in southwestern Australia. *Tectonophysics* 376, 167-184.

Dyksterhuis, S., Müller, R.D., 2008. Cause and evolution of intraplate orogeny in Australia. *Geology*, 36, 495–498.

Fortuin, A.R., Van der Werff, W., Wensink, H. 1997. Neogene basin history and paleomagnetism of a rifted and inverted forearc region, on- and offshore Sumba, Eastern Indonesia, *Journal of Asian Earth Science* 15, 61-88.

Genrich, J.F., Bock, Y., McCaffrey, R., Calais, R., Steven, C.W., Subarya, C., 1996. Accretion of the southern Banda arc to the Australian plate margin determined by Global Positioning System measurements. *Tectonics* 15, 2, 288-295.

Hamilton, W., 1979. Tectonics of the Indonesian Region. *U.S. Geological Survey Professional Paper*, 1078.

Harris, R. A., 1991. Temporal distribution of strain in the active Banda orogen: a reconciliation of rival hypotheses. *Journal of Southeast Asian Earth Sciences* 6, 373–386.

Harris, R., Vorkink, M. W., Prasetyadi, C., Zobell, E., Roosmawati, N., Apthorpe, M., 2009. Transition from subduction to arc-continent collision: Geologic and neotectonic evolution of Savu Island, Indonesia. *Geosphere* 5, 152-171.

Heidbach, O., Tingay, M., Barth, A., Reinecker, J., Kurfess, D., Muller, B. 2010. Global crustal stress pattern based on the World Stress Map database release 2008. *Tectonophysics*, 482. p. 3-15.

Hengesh, J.V., Wyrwoll, K.H., Whitney, B.B., 2011. Neotectonic deformation of northwestern Australia and implications for oil and gas development. In: Gourvenec, S., White, D., (Eds.), Proc. 2nd *International Symposium on Frontiers in Offshore Geotechnics*, Perth, Western Australia, Taylor and Francis. pp. 203-208.

Hengesh , J.V., Whitney, B.B. 2014. Quaternary Reactivation of Australia's Western Passive Margin: Inception of a New Plate Boundary? INQUA Focus Group on Paleoseismology and Active Tectonics, 5th INQUA Meeting on Paleoseismology, Active Tectonics and Archeoseismology (PATA), 21-27 September, Korea. 207-210.

Hillis, R.R., Reynolds, S.D., 2000. The Australian stress map. *Journal of the Geological Society*, London 157, 915–921.

Johnston, A.C., Coppersmith, K.J., Kanter, L.R., Cornell, C.A., 1994. The earthquakes of stable continental regions. *Electric Power Research Institute Publication* TR-102261-V1, Palo Alto, California.

Keep, M., Bishop, A., Longley, I., 2000. Neogene wrench reactivation of the Barcoo sub-basin, northwest Australia: implications for Neogene tectonics of the northern Australia margin. *Petroleum Geoscience*, 6, 211-220.

Keep M., Harrowfield, M. 2008. Elastic flexure and distributed deformation along Australia's North West Shelf: Neogene tectonics of the Bonaparte and Browse basins. In H. Johnson, A.G. Dore, R.W. Gatliff, R. Holdsworth, E. Lundin, J.D. Ritchie (eds), The Nature and Origin of Compressive Margins. *Geological Society*, London, Special Publications 306, 185–200.

Keep, M., Haig, D., 2010. Deformation and exhumation in Timor: distinct stages of a young orogeny. *Tectonophysics* 483, 93–111.

Leonard, M., 2014. Self-consistent earthquake fault-scaling relations: update and extension to stable continental region strike-slip faults. *Bulletin of the Seismological Society of America*, 104, 2953-2965.

Leonard, M., 2008. One hundred years of earthquake recording in Australia. *Bulletin of the Seismological Society of America* 98, 1458-1470.

Leonard, M., Clark, D., 2011. A record of stable continental region earthquakes from Western Australia spanning the late Pleistocene: insights for contemporary seismicity. *Earth and Planetary Science Letters*, 309, 207–212.

McCaffrey, R., 1988. Active tectonics of the eastern Sunda and Banda Arcs: *Journal of Geophysical Research*. 93, 15,163–15,182.

McCaffrey, R., 1996. Slip partitioning at convergent plate boundaries of SE Asia. In: Blundell, D. (eds), *Tectonic Evolution of Southeast Asia,* Geological Society Special Publication No. 106, 3-18.

McCaffrey, R., Nabelek, J., 1984. The geometry of back arc thrusting along the eastern Sunda arc, Indonesia: Constraints from earthquake and gravity data. *Journal of Geophysical Research* 89, 6171-6179.

McCue, K., 1990. Australia's large earthquakes and recent fault scarps, *Journal of Structural Geology* 12, 761-766.

McPherson, A., Clark, D., Whitney, B., 2013. Neotectonic evidence for a crustal strain gradient on the central-west Western Australian margin. In: Moss, S., Keep, M. (Eds.), *Proceedings of the Western Australian Basins Symposium* 16 pp.

Molnar, P., England, P., Martinod, J., 1993. Mantle dynamics, the uplift of the Tibetan plateau, and the Indian monsoon. *Reviews of Geophysics* 31, 357–396.

Müller, R.D., Dyksterhuis, S., Rey, P., 2012. Australian paleo-stress fields and tectonic reactivation over the past 100 Ma. *Australian Journal of Earth Sciences* 59, 13-28.

Nugroho, H., R., Harris, A.W., Lestariya, Maruf, B., 2009. Plate boundary reorganization in the active Banda Arc-continent collision: Insights from new GPS measurements: *Tectonophysics* 479, 52-65.

Pacheco, J.F., Sykes, L.R., Scholz, C.H., 1993. Nature of seismic coupling along simple plate boundaries of the subduction type. *Journal of Geophysical Research* 98: doi: 10.1029/93JB00349. issn: 0148-0227.

Reynolds, S.D., Coblentz, D.D., Hillis, R.R., 2002. Tectonic forces controlling the regional intraplate stress field in continental Australia: results from new finite element modeling. *Journal of Geophysical Research*, Solid Earth, 107(B7) 2131, 10.1029/2001JB000408.

Rigg, J. W., Hall, R., 2011. Structural and stratigraphic evolution of the Savu Basin, Indonesia. Geological Society, London, Special Publications 355, 225-240.

Roosmawati, N., Harris, R., 2009. Surface uplift history of the incipient Banda arc-continent collision: Geology and synorogenic foraminifera of Rote and Savu Islands, Indonesia. *Tectonophysics* 479, 95-110.

Sandiford, M., Wallace, M., Coblentz, D. 2004. Origin of the in situ stress field in southeastern Australia. *Basin Research*, 16, 325–338.

Sandiford, M., Coblentz, D., Schellart, W.P., 2005. Evaluating slab-plate coupling in the Indo-Australian plate. *Geology* 33, 113–116.

Sandiford, M., Egholm, D.L., 2008. Enhanced intraplate seismicity along continental margins: some causes and consequences. *Tectonophysics*, 457, 197–208.

Sandiford, M., Quigley, M., De Broekert, P., Jakica, S. 2009. Tectonic framework for the Cenozoic cratonic basins of Australia. *Australian Journal of Earth Sciences*, 56, 5-18.

Saqab, M.M., Bourget, J., 2015. Structural style in a young flexure-induced oblique extensional system, north-western Bonaparte Basin, Australia. *Journal of Structural Geology* 77, 239-259.

Schellart, W.P., 2004. Quantifying the net slab pull force as a driving mechanism for plate tectonics. *Geophysical research letters* 31, L07611 doi:10.1029/2004GL019528.

Silver, E.A., R., Reed, R., McCaffrey, Joyodiwiryo, Y. 1983. Back arc thrusting in the eastern Sunda arc, Indonesia: A consequence of arc-continent collision: *Journal of Geophysical Research* 88, 7429–7448, doi: 10.1029/JB088iB09p07429.

Simons, W. J. F., Socquet, A., Vigny, C., Ambrosius, B.A.C., Abu, S.H., Promthong, C., Subarya, Sarsito, D.A., Ma-theussen, S., Morgan, P., Spakman, W., 2007. A decade of GPS in Southeast Asia: resolving Sundaland motion and boundaries. *Journal of Geophysical Research* 112, B06420.

Spakman, W., Hall, R., 2010. Slab rollback and active crustal delamination during Banda Arc subduction. *Nature Geoscience* 3, 562–566, doi: 10.1038/ngeo917.

Tregoning, P., 2003. Is the Australian plate deforming? A space geodetic perspective, IN: Hillis, R.R., and Müller, R.D., eds., *Evolution and dynamics of the Australian plate*, Special Paper 372, Geological Society of America 41-48.

Whitney, B.B., 2015. Neotectonic deformation in the Western Australia Shear Zone. PhD Thesis. The University of Western Australia, Perth.

Whitney, B.B., Hengesh, J.V., 2013. Geological constraints on Mmax values from Western Australia: implications for seismic hazard assessments. *Australian Geomechanics Journal* 48, 15-26.

Whitney, B.B., Hengesh, J.V., 2015a. Geomorphological evidence of neotectonic deformation in the Carnarvon basin, Western Australia. *Geomorphology* 228, 579-596.

Whitney, B.B., Hengesh, J.V., 2015b, Geomorphological evidence for late Quaternary tectonic deformation of the Cape Region, coastal west central Australia. *Geomorphology* 241, 160-174.

Whitney, B.B., Hengesh, J.V. Clark, D.J., 2014. The Western Australia Shear Zone. INQUA Focus Group on Paleoseismology and Active Tectonics, 5th INQUA Meeting on Paleoseismology, Active Tectonics and Archeoseismology (PATA), 21-27 September, Korea. 162-165.

Whitney, B.B., Clark, D.J., Hengesh, J.V., Bierman, P., 2015. Paleoseismology of the Mt. Narryer fault zone, west central Western Australia: a multi-strand intraplate fault system. *Geological Society of America Bulletin*

Whitney, B.B., Hengesh, J.V., Gillam, D. *in review*. Styles of fault reactivation within a formerly extended continental margin, North West Shelf, Australia. *Tectonophysics.*

Zoback, M.L., M.D. Zoback, J. Adams, M. Assumpqao, S. Bell, E.A. Bergman, E Blumling, N.R. Brereton, D. Denham, J. Ding, K. Fuchs, N. Gay, S. Gregersen, H.K. Gupta, A. Gvishiani, K. Jacob, R. Klein, P. Knoll, M. Magee, J.L. Mercier, B.C. Muller, C. Paquin, K. Rajendran, O. Stephansson, G. Suarez, M. Suter, A. Udias, Z.H. Xu, and M. Zhizin. 1989. Global patterns of tectonic stress, *Nature* 341(6240), 291-298.