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TOPO-OZ: Insights into the various modes of intraplate deformation in the Australian continent

Mike Sandiford [a,*], Mark Quigley [b]

[a] School of Earth Sciences, University of Melbourne, 3010, Australia
[b] Department of Geological Sciences, University of Canterbury, Christchurch 8140, New Zealand

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ABSTRACT

As the fastest, lowest, flattest and amongst the most arid of continents, Australia preserves a unique geomorphic record of intraplate tectonic activity, evidencing at least three distinct modes of surface deformation since its rapid northward drift commenced around 43 million years ago. At long wavelengths (several 1000s km) systematic variations in the extent of Neogene marine inundation imply the continent has tilted north–down, southwest–up. At intermediate-wavelengths (several 100s km) several undulations of ~100–200 m amplitude have developed on the 1–10 myr timescale. At still shorter wavelengths (several 10s km), fault related motion has produced local relief at rates of up to ~100 m/myr over several million years. The long-wavelength, north–down tilting can be related to a dynamic topographic effect associated with Australia's northward drift from the geoid low, dynamic topography low now south of the continent to the geoid high, dynamic topography low centred above the south-east Asian and Melanesian subduction zones. The short wavelength, fault-related deformation is attributed in time to plate-wide increases in compressional stress levels as the result of distant plate boundary interactions and, in space, in part to variations in the thermal structure of the Australian lithosphere. At the intermediate wavelengths, transient, low amplitude undulations can be ascribed to either lithospheric buckling or the development of instabilities in the thermal boundary layer beneath the lithosphere. In the latter case, topographic asymmetries suggest the Australian lithosphere is moving north with respect to the mantle beneath, providing a unique attribution to the progressive alignment of seismic anisotropy and absolute plate motion observed near the base of the Australian lithosphere.

1. Introduction

Australia is the lowest and flattest of all continents, consistent with relatively low-levels of tectonic activity to be expected for a continent that has remained remote from active plate boundaries throughout the Cainozoic (Veevers, 1984). However, low-level tectonic activity is indicated by widespread earthquake activity (Leonard, 2008), and seismic moment release rates are elevated relative to many other stable continental regions (Braun et al., 2009; Johnston et al., 1994). A rich palaeo-seismic record of surface fault breaks and Quaternary faults (Crone et al., 2003; Crone et al., 1997; Quigley et al., 2006) raises intriguing questions about the longer-term record of tectonic activity in the continent. As part of the Indo-Australian plate (IAP), Australia is also the fastest moving continent having drifted northwards ~3000 km over the last 45 myr (Fig. 1). In so doing it has passed over a complex deep mantle density structure as revealed partly by a ~60 m differential in the geoid field across the continent, as well as the unusual ocean bathymetry of the Southern Ocean in the vicinity of the Australian–Antarctic discordance — or AAD (Gurnis et al., 1998). The dynamic topographic effects of such differential motion between the plate and the underlying mantle are significant, and most clearly evident in a fundamental asymmetry in the morphology and stratigraphic relations of its margins (Sandiford, 2007).

A further attribute of geomorphic significance is that Australia is amongst the most arid of continents. Aridity has affected much of the interior part of the continent through the late Cainozoic (Bowler, 1976), providing it with a remarkable geomorphic 'memory'. The exquisite detail preserved in extremely old landforms, such as the Eocene beach barrier systems and associated lagoons on the eastern Nullarbor Plain (Fig. 2), imply surface processes have been remarkably ineffective. This preservation of ancient palaeo-shorelines and lake systems, in particular, allows for unambiguous reconstruction of subtle deformations of the landscape, the memory of which would have been greatly obscured or obliterated in environments characterised by more active surface processes.

The last few years have seen a resurgence of interest in the tectonic geomorphologic record of the Australian continent (Celerier et al., 2005; Quigley et al., 2007a,b; Sandiford, 2003a,b, 2007, 2004). Parallel studies have established a basic framework for understanding key neotectonic

* Corresponding author.
E-mail address: mikes@unimelb.edu.au (M. Sandiford).

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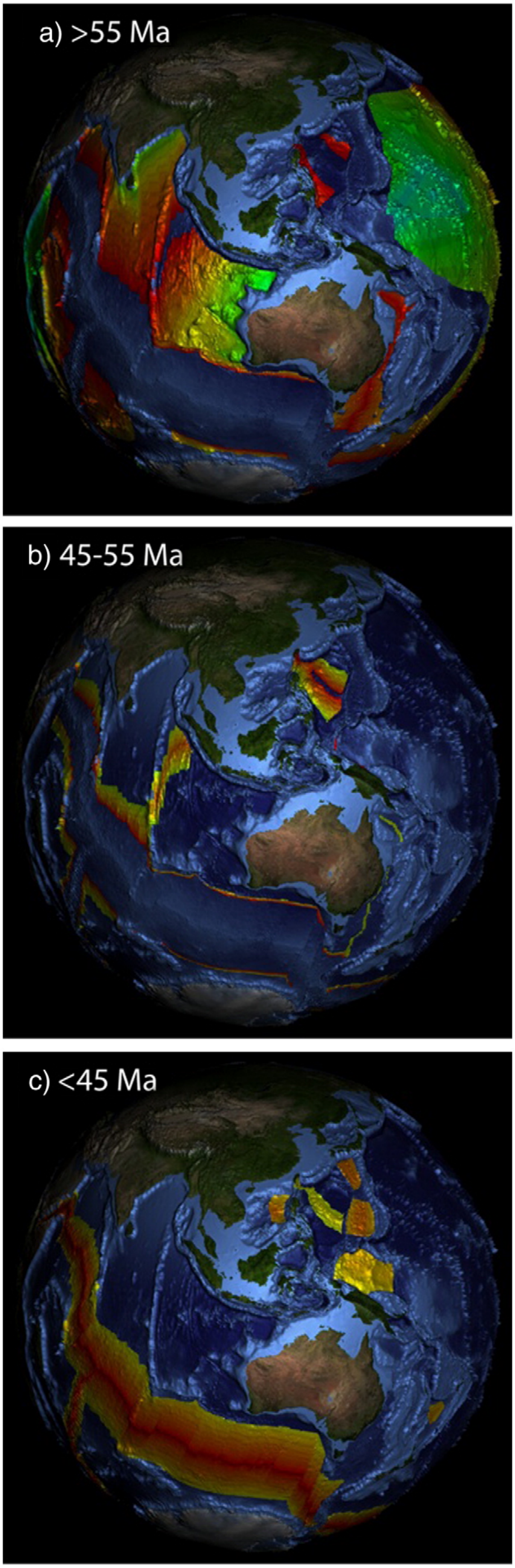


'drivers' such as the *in situ* stress state (Coblentz et al., 1998; Hillis and Reynolds, 2000; Reynolds et al., 2002; Sandiford et al., 1995, 2004) mantle structure (Debayle et al., 2005; Kennett et al., 2004) and thermal regime (McLaren et al., 2003; Neumann et al., 2000). In this paper we review the main insights gained from these studies. We begin with a brief summary of the current geodynamic state of the Australian continent, including our current knowledge of the *in situ* stress and geoid fields and constraints on deformation rates provided by the seismic record. We then explore the neotectonic record at a variety of scales. This record in interpreted in terms of three distinct modes of deformation each with a characteristic temporal and spatial scale. At the shortest wavelength (order 10^1–10^2 km) active faulting is demonstrably shaping the landscape in several parts of the continent and can be related to propagation of stress from distant plate boundaries. At intermediate wavelengths (order 10^2–10^3 km) low amplitude undulations have produced distinctive patterning of continental relief most clearly associated with modern and palaeo-lake systems. Finally, at the longest wavelength (>10^3 km) a pattern of continental tilting can be related to dynamic topography associated with its northward passage from the geoid low, dynamic topography high now lying south of the continent, to a geoid high, dynamic topographic low centred over the subduction zones of South East Asia and Melanesia.

Our prime concern is on the topographic record of the Australian continent in the context of the evolution of the IAP. The IAP was born of a complex sequence of correlated events that saw the fusion of the Indian and Australian plates around 45 million years ago (Fig. 1). The critical element of this was the termination of spreading in the north-central Indian Ocean that accompanied deceleration of the Indian plate during the initial stages of Himlayan collision (Patriat and Achache, 1984), and the associated northward acceleration of the Australian Plate (Gaina and Muller, 2007). Prior to 50 million years ago Australia formed the core of a much more slowly moving plate largely surrounded mid-ocean ridges. As such, its palaeo-geographic setting was more reminiscent of the present-day Africa, in the sense of having a higher degree of symmetry in the plate boundaries compared to today (Fig. 1b). With termination of spreading in the north central Indian Ocean and the Tasman Sea to the east of Australia, Australia became one of two continental crustal fragments (the other being India) fused into a fast moving plate with strongly asymmetric boundary configurations (mid-ocean ridges to the south, convergent margins to the north). The onset of the modern compressional intraplate stress field (see below) most probably dates to this transition, with the pre-Eocene continent likely to have been subject to mild extensional stress regimes, in analogous fashion to the African continent (Coblentz and Sandiford, 1994; Sandiford and Coblentz, 1994; Sandiford et al., 1995).

Understanding just how the Australian landscape has been modified by, and records, subtle tectonic processes should inform how to isolate comparable signals in other slower moving, faster eroding settings such as Europe (Cloetingh et al., 2005). With international programs such as TOPO-EUROPE now focussing inter-disciplinary work on all manner of phenomenon related to the topographic evolution of the continents, our purpose here is simply to briefly summarise our recent insights from Australia that link the active deformation to the contemporary geodynamic setting and

Fig. 1. (a) Ocean-floor evolution in the Indo-Australian plate as reflected in the surrounding ocean floor ages. Prior to 45 million years India and Australia formed parts of distinct plates separated by spreading in the central Indian Ocean (a, b). At this time Australia was largely surrounded by active ridge systems, much like modern Africa. Australia's rapid northward drift commenced after amalgamation of the Indian and Australian plates at ~43 Ma (c). Colors reflect relative sea floor age from green (old) – yellow – red (young). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

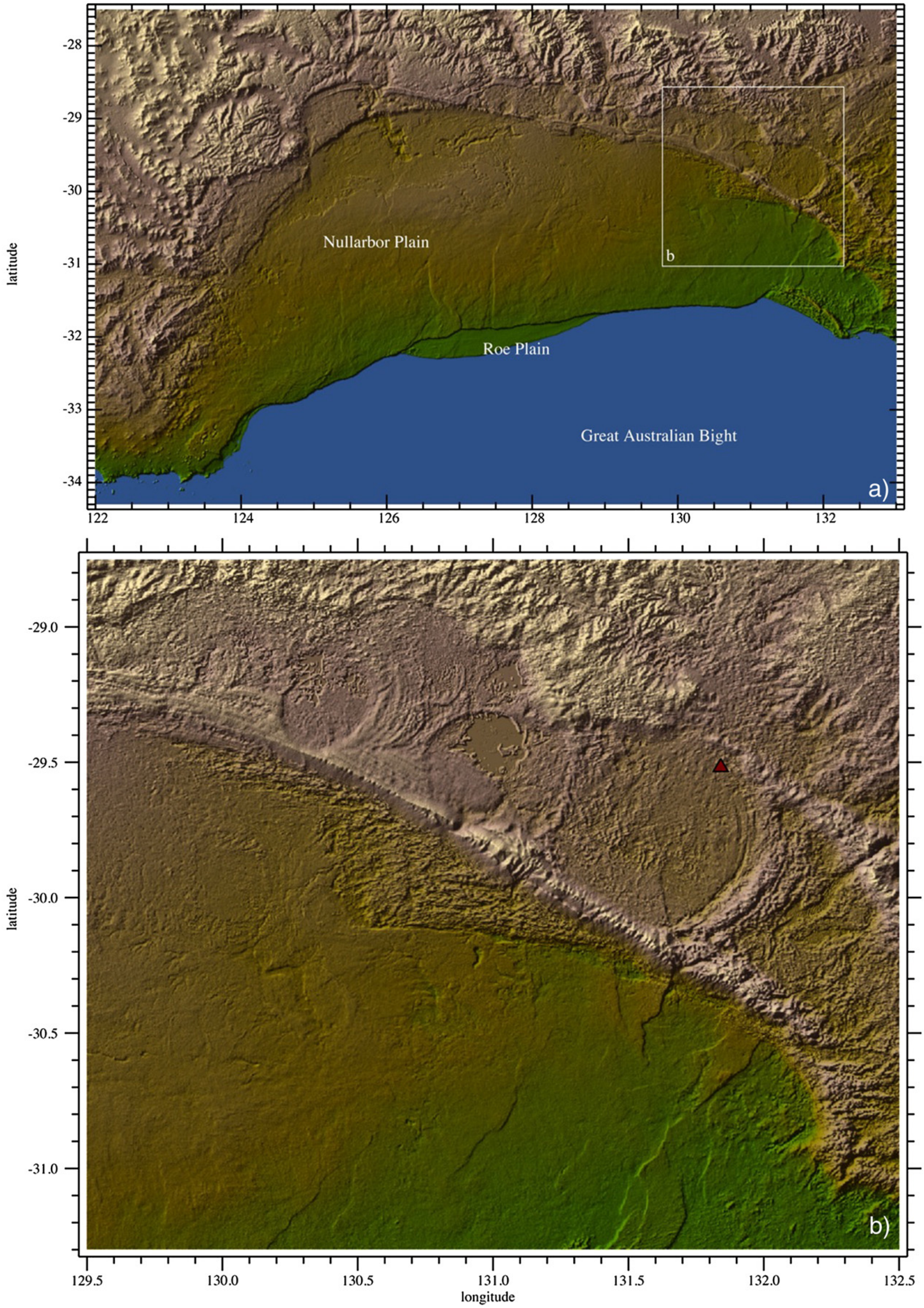
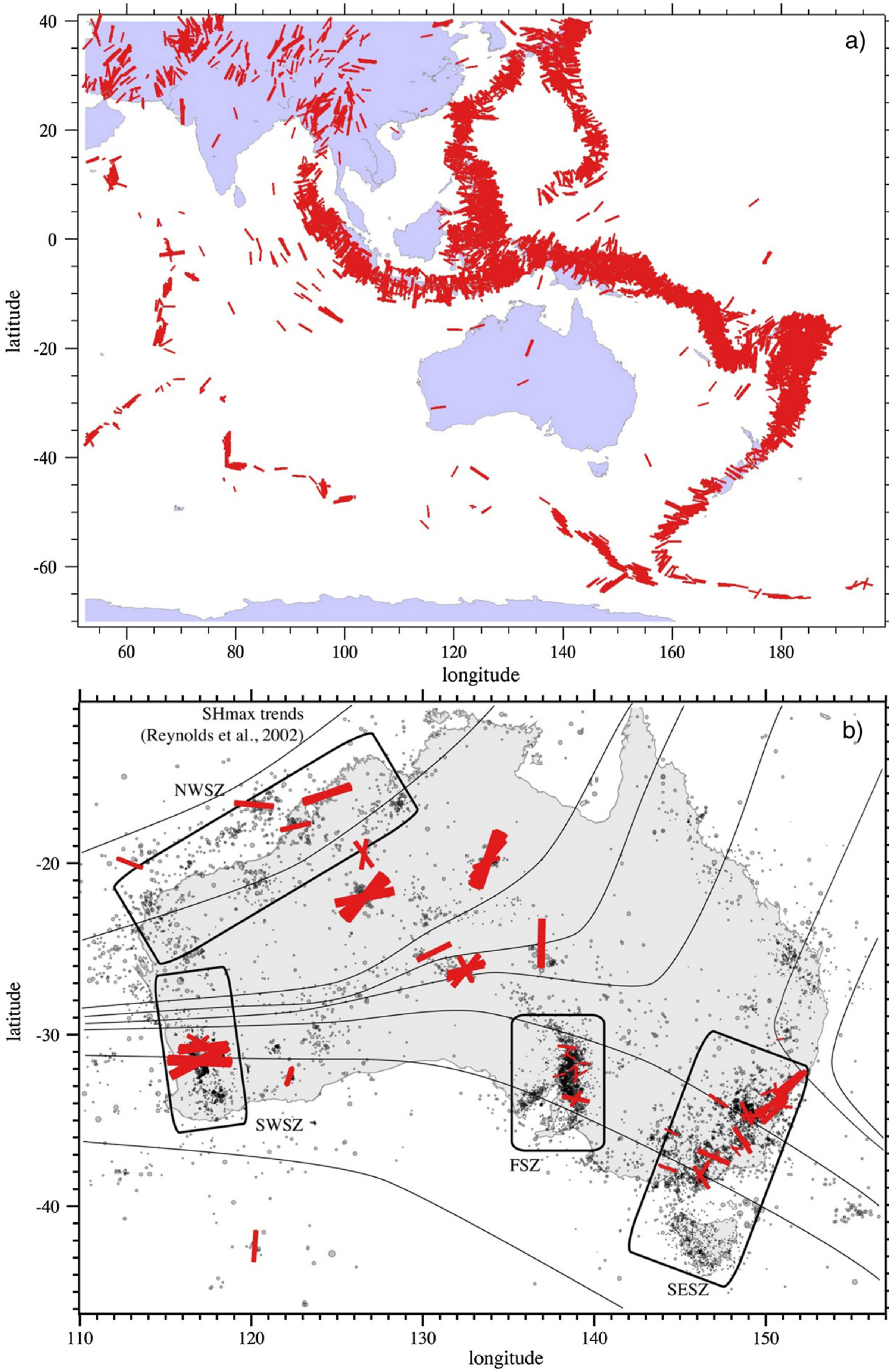


Fig. 2. (a) The stratigraphic relations of the southern margin of the Australian continent is best exemplified by the Nullarbor plain, an uplifted Eocene–Mid Miocene limestone plateau, extending inboard to remarkably well preserved shoreline system of beach barriers and lagoons (Hou et al., 2008). The Roe Plain is a Pliocene marine bench. (b) Detail of Eocene age coastal beach-barrier–lagoon systems on the eastern edge of the Nullarbor Plain. These features provide testimony to the remarkable geomorphic memory of this ancient landscape. Note the fault offsets of the barrier systems and limestone plateau.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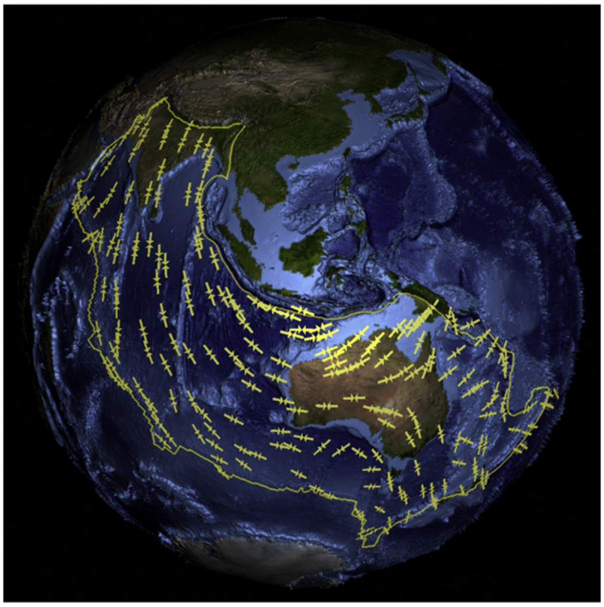


Fig. 4. Modelled S_{Hmax} trends for the IAP adapted from solutions in Sandiford et al. (2005) modified from the solutions (Reynolds et al., 2002).

various geophysical parameters, such as *in situ* stress, seismic strain rate, geoid and dynamic topographic fields.

2. The *in situ* stress field

Focal mechanism solutions provide the most comprehensive source of information relevant to the *in situ* stress state at the plate scale as shown in Fig. 3, and these data are augmented by other indicators in and around the continent, most notably bore-hole breakout data (Hillis and Reynolds, 2000). Fig. 4 shows the computed stress field based on minimising misfits with *in situ* stress indicators (Reynolds et al., 2002). The distributed seismicity in the central Indian Ocean calls into question the notion of a single, unified plate (Delescluse and Chamot-Rooke, 2007; DeMets et al., 2005; Sandiford et al., 2005; Van Orman et al., 1995) and some authors consider the IAP to better described in terms of three distinct plates — the Indian, Australian and Capricorn plates (DeMets et al., 2005). However, the continuous pattern of *in situ* stress indicators across this zone (Fig. 3) implies a high degree of mechanical coupling between the bounding aseismic regions — and the question of whether there is one plate or three is somewhat semantic. What is clear is that this region has been progressively fragmenting for ~8 million years, and the mechanical coupling across it is expected to decrease into the geological future as new plate boundaries emerge (Delescluse and Chamot-Rooke, 2007; DeMets et al., 2005; Sandiford et al., 2005; Van Orman et al., 1995).

One of the more intriguing features of the *in situ* stress field in the IAP is the disparity between the maximum horizontal stress (S_{Hmax}) orientation and the absolute plate velocity azimuth (Coblentz et al., 1995; Hillis and Reynolds, 2000; Reynolds et al., 2002; Sandiford et al., 2004). This is at odds with other, relatively fast-moving, continental plates such as the North American and South American plates where S_{Hmax} is aligned with absolute plate motion (Zoback, 1992; Richardson, 1992). The IAP is characterised by an arcuate S_{Hmax} trend from N–S in India and the north Indian Ocean, through E–W from the central Indian Ocean to the western Australian margin, to NE–SW in northern Australia (Figs. 3b and 4) (Hillis and Reynolds, 2000). These trends can be understood in terms of a balance between plate driving and resisting torques. Specifically, the Himalayan and Papua New Guinea plate boundary segments act as sources of resistance, and stress foci, to the more distributed plate driving torques associated with Indonesian subduction and the cooling ocean lithosphere ("ridge push") along the southern boundary of the plate (Cloetingh and Wortel, 1986; Coblentz et al., 1995, 1998; Reynolds et al., 2002). Similarly, the E–W to SE–NW S_{Hmax} trends in southeastern Australia (Sandiford et al., 2004) are attributed to compression emanating from IAP–Pacific Plate transpression between the south island of New Zealand and the Macquarie Ridge.

Absolute stress magnitudes within plates interiors are not well constrained, making comparative assessment of lithospheric stress states difficult. However several lines of evidence suggest that intraplate stress levels in the IAP are high, at least relative to other intraplate settings. The central Indian Ocean is the only region of old ocean lithosphere showing evidence for distributed deformation at an appreciable rate, suggesting higher stress levels than in any other oceanic plate realm. Similarly, high stress levels are suggested by the high seismic moment release rates inferred from peninsula India and, to a lesser extent, Australia compared to comparable stable continental cratonic regions such as northern Europe, Africa and Brazil as shown in Table 1 (Johnston et al., 1994).

3. The seismic strain rate field

To estimate seismic strain it is important to assess the degree of completeness of the relevant seismic catalog at various magnitudes. The completeness levels of the Australian earthquake catalog have recently been reviewed by Leonard (2008). Completeness levels are $M_{\mathrm{L}}=3.5$–4, 1980+, $M_{\mathrm{L}}=4$–5, 1970+, $M_{\mathrm{L}}=5$–5.5, 1960+ and $M_{\mathrm{L}}=5.5+$, 1910+ (Fig. 5). Seismicity shows significant spatial variability, suggesting corresponding variability in seismic strain rates (Braun et al., 2009; Leonard, 2008). This spatial variability has lead to the recognition of a number of distinct distinct zones (Fig. 3b; Leonard, 2008). The south-west, south-east and north-west zones are located along the continental margin and in the case of the first two along margins highly oblique to the S_{Hmax} trends (Sandiford and Egholm, 2008). The fourth zone, the Flinders seismic zone, extends almost 1000 kms into the continent along a trend at ~90° to the S_{Hmax} trend.

Several studies have now tried to provide quantitative constrains on seismic moment release and associated deformation rates across Australia (Braun et al., 2009; Celerier et al., 2005; Leonard, 2008). Following Johnston (1994), the studies utilise the idea that notional moment release rate can be estimated from activity rates under the assumption the moments of individual earthquakes sum:

$$M_o \approx \frac{1}{t}\left(\frac{b\left(10^{(a+d)}\right)}{c-d}\right)\left(10^{(c-b)}M_{max}\right)$$

where t is the time-span of the seismic record, $M_{\max}$ is the maximum expected magnitude for earthquakes in the region of interest, a and b are the Gutenberg–Richter measures of activity rate, and c and d are factors that relate to the conversion of magnitude scale to seismic moment (Hanks and Kanamori, 1979).

Since the majority of the moment is carried by the largest, most infrequent, earthquakes, the main uncertainties in the calculation of the seismic strain rates using this approach are in the value of $M_{\max}$ and the validity of the assumption that moments of individual quakes sum. For intraplate regions such as Australia, it seems improbable that the historical record of less than 100 years duration encompasses an

Fig. 3. (a) *P*-axis trends for the IAP and neighbouring plates, for events from the Harvard CMT database with epicentral depths less than 50 km. (b) Earthquake epicentres from the Geoscience Australian earthquake catalog. *P*-axis trends for all available focal mechanism solutions, scaled for magnitude of the event. Maximum magnitude events are $M_{\mathrm{w}}=6.8$. Generalised S_{Hmax} trends derived for all in situ stress datasets from (Hillis and Reynolds, 2000).

earthquake of magnitude M_{max}. The historical limit therefore provides a lower bound on M_{max}. The largest instrumentally recorded earthquake in Australia was the 1941 M_w ~6.8 Meeberrie event in Western Australia. On longer timescales we would expect somewhat larger earthquakes, and thus the maximum earthquake expected on geological timescales could conceivably be greater than M_L 7, consistent with palaeoseismic studies (Quigley et al., 2006) (see further discussion below). Assuming $M_{max} = 7$, the maximum seismic strain rate calculated for Australia is ~10^{-16} s^{-1}, while the area-averaged strain rate is no more than ~10^{-17} s^{-1} (Celerier et al., 2005; Braun et al., 2009; Leonard, 2008). The highest seismic strain rates are more than an order of magnitude greater than background levels, and are associated with four distinct zones termed the south-west, north-west, south-east and Flinders seismic zones (Fig. 3).

While such calculations are clearly subject to very large uncertainties, they provide an insight into fault-slip rates derived from neotectonic studies. For example, a bulk strain rate of 10^{-16} s^{-1} in uniaxial compression implies a total shortening of ~250 m/myr across the ~100 km wide zone (as appropriate to the Flinders seismic zone). Such shortening could be accounted for with slip on 10 faults each accommodating between 25 m of horizontal slip per million years. Accounting for some aseismic slip, actual fault slip maybe even larger, and suggest slip rates to the closest order of magnitude in the range between 10^1–10^2 m/myr in the most active parts of the continent.

4. The geoid and dynamic topography fields

Density anomalies that source the long-wavelength geoid also drive mantle flow and thus contribute to the dynamic topographic field (Richards and Hager, 1984, 1988, 1989). In this context it has long been recognised that zones of plate convergence are characterised by geoid highs and dynamic topographic lows. Thus continents like Australia drifting towards zones of convergence should be expected to experience dynamic subsidence (Lithgow-Bertelloni and Gurnis, 1997). Australia is centred astride a long-wavelength gradient in the geoid field, which extends from a low (−20 m) in the Southern Ocean to a high in Melanesia (+80 m). Australia's northward motion at ~6.5 cm/years is inducing relative changes in the geoid around the Australian continent (Fig. 6). Along the northern margin the instantaneous rate of change in geoid height is ~+2 m/myr. Along the southern margin it is lower and more varied, typically between −0.2 to +1 m/myr, with the lowest rates in the south-west. As the long-wavelength geoid contains important contributions from the lower mantle where viscosities are high, and motions are likely retarded with respect to surface plate motion, the geoid field is likely to evolve more slowly than plate motion. Thus the variations in 'instantaneous' rate of change in the geoid are likely to reflect longer term differences in the dynamic topography signal around Australia.

Independent constraints on the nature of the dynamic topography field in the vicinity of Australia require understanding the record of marine inundation, as discussed in following sections. However

Table 1
Comparison of seismic strain rates for stable continental regions after Johnston (1994).

SCR region	Seismic moment release rate dyn-cm/year/105 km^2	Annualised seismic strain rate	Percent of India
India	3.3×10^{23}	25×10^{11}	100%
China	1.17×10^{23}	8.9×10^{11}	36%
North America	1.05×10^{23}	8.0×10^{11}	32%
Australia	0.89×10^{23}	6.7×10^{11}	27%
Africa	0.40×10^{23}	3.0×10^{11}	12%
Europe	0.25×10^{23}	1.9×10^{11}	8%
South America	0.115×10^{23}	0.87×10^{11}	3.5%
Asia (east of Urals)	0.008×10^{23}	0.61×10^{11}	0.25%
Antarctica	0.0019×10^{23}	0.14×10^{11}	0.05%

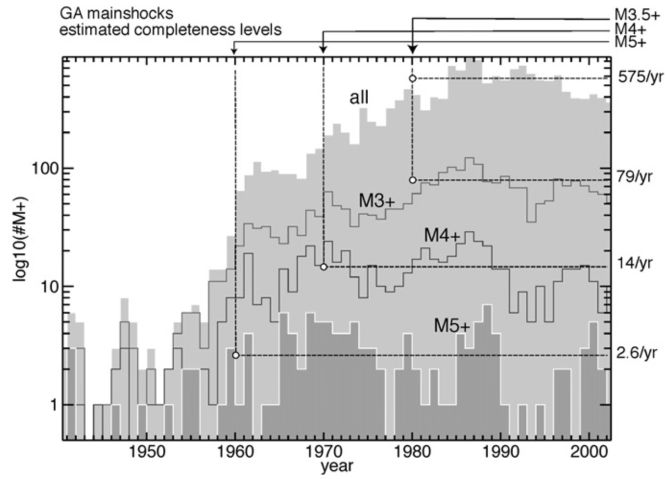


Fig. 5. Catalog completeness inventory for the Geoscience Australia database, afterLeonard (2008). The database has been screened to remove aftershocks.

several general observations can be made with regard to the dynamic topography field in the broader region. The unusually submerged nature of the continental crust of the Sunda Block to the north of the Indonesian subduction zones, points to a prominent dynamic topography low associated with this zone of convergence. Similarly, the unusually deep bathymetry of the mid-ocean ridge along the AAD in the Southern Ocean also points to a prominent dynamic topography low (Gurnis et al., 1998). Interestingly, the lows to the north and south of Australia have very different geoid expressions, implying they are sourced by different mechanisms. The dynamic low–geoid high to Australia's north reflects density anomalies located primarily in the lower mantle, and a converging flow regime penetrating the whole mantle. Specifically it relates to the accumulation of large slab systems in and beneath the transition zone as indicated by seismic tomographic studies (eg. Replumaz et al., 2004). The dynamic low–geoid low to the south probably reflects density anomalies and flow confined to the upper mantle (Sandiford, 2007), such as the slab remnant inferred by Gurnis et al. (1998). In summary, these observations suggest the northward plate motion is driving Australia between two discrete dynamic topography lows and from a geoid low to a geoid high separated by more than 5000 km. Both the progression of the north coast towards a dynamic low–geoid high and the south coast from a dynamic low–geoid low should contribute to an apparent north–down tilting.

5. The Neogene and Quaternary faulting record

The clearest evidence for active tectonic deformation in the Australian landscape is found in the fault-related landscapes around upland systems in southeast part of the continent (Sandiford, 2003b). The most extensively documented faulting record occurs in the Flinders and Mount Lofty Ranges of South Australia (Bourman and Lindsay, 1989; Quigley et al., 2006), and in southern Victoria, in upland systems such as the Otway Ranges bordering the southern coastline (Sandiford, 2003a).

The Flinders and Mount Lofty Ranges in South Australia are bounded by N–S to NE–SW trending linear scarps providing dramatic testimony to the role of active faulting in shaping the landscape (Fig. 7). Exposures of the main range-bounding faults characteristically reflect steep reverse motion with a hanging-wall of ancient (>500 million year old) rock above a footwall typically comprising thin Quaternary fan-glomerates shed from the developing upland systems in the last 1–2 million years (Fig. 7c). Fault-slip kinematics are consistent with structures having formed in response to reverse stress regime with S_{Hmax} trending between N080°E and N125°E. Earthquake

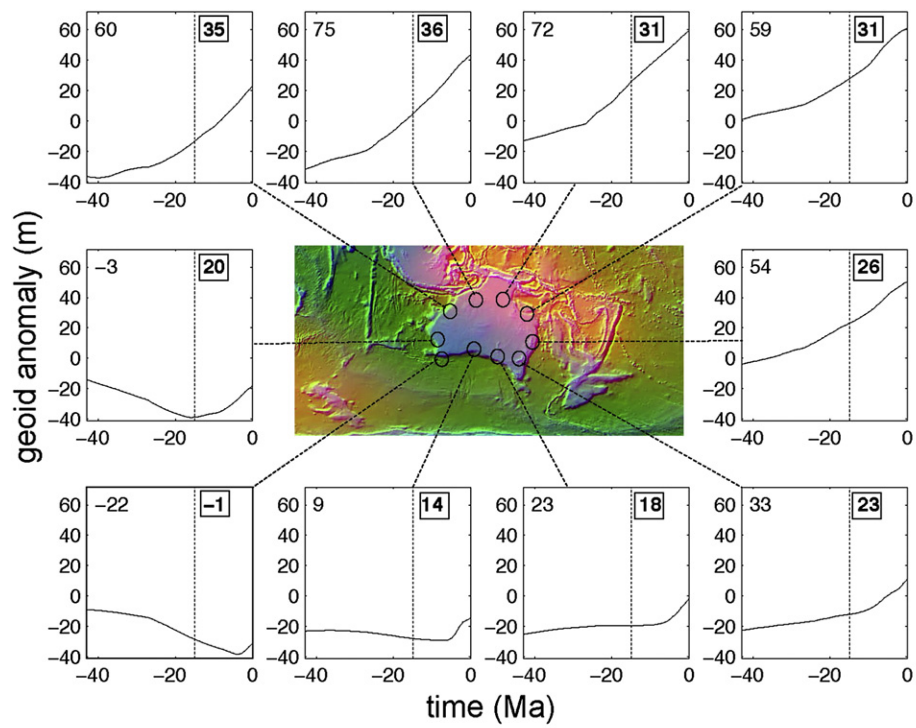


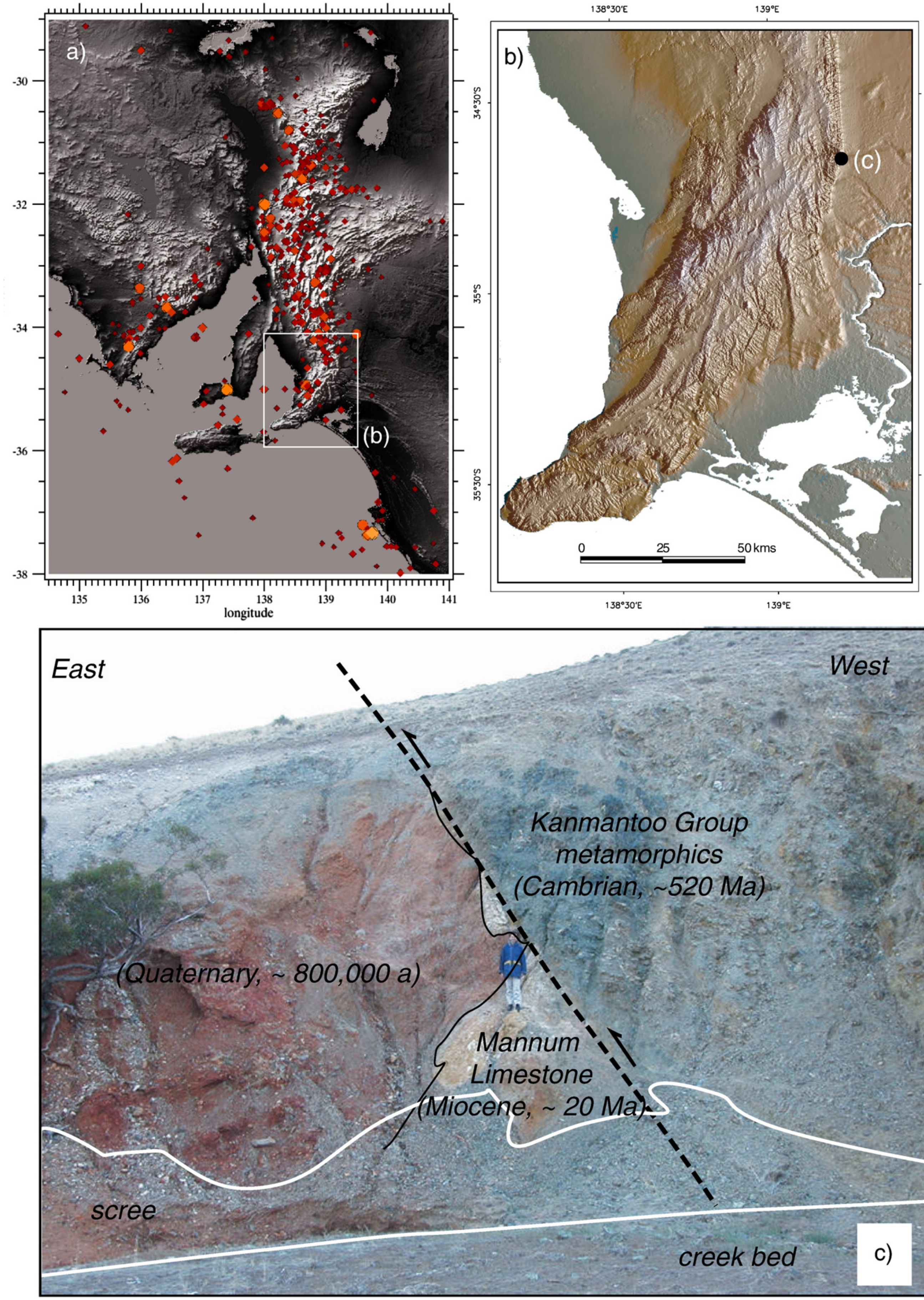
Fig. 6. Inferred instantaneous, time evolution of the geoid field around the Australian continent resulting from Australia's northward motion. The differential geoid anomaly over the last-15 myr is indicated by the number in the box in the top right of each panel, while the much more uncertain estimate of last-43 myr differential is indicated by the number in the top left of each panel.

mechanisms show both reverse and strike slip mechanisms for this region (Clark and Leonard, 2003), typically, though not exclusively with E–W trending *P*-axes (Fig. 3b). Slip rates on the major range-bounding faults have been estimated at between 20–100 m/myr. The cumulative vertical displacement on the fault network that forms the western front of the Mount Lofty Ranges is estimated to be ~240 m, with ~80 m offset of early Quaternary (~1.6 million year old) strata. Stratigraphic relations suggest that this displacement has accumulated in the last 5–6 million years (Sandiford et al., 2004) giving time averaged displacement on bounding faults ~40–50 m/myr, in line with that inferred from historical seismicity rates as discussed earlier. Palaeoseismic studies show maximum magnitude earthquake events of M_w~7.3 with recurrence intervals of order 104 years (Quigley et al., 2006). On the northern flanks of the Otway Range, in southern Victoria, the remnants of an Pliocene strandplain rise ~120 m over a series of ENE trending faults and monoclines to elevations of ~250 m (Sandiford, 2003a; Sandiford et al., 2004). Along with its correlative in the Murray Basin, this strandplain developed during falling sea levels following a 6 Ma high stand at ~65 m above present day sea level (Brown and Stephenson, 1991) and thus imply almost 200 m of fault-related tectonic uplift. Faulting trends are consistent with S_{Hmax} directions inferred from borehole breakout studies in nearby offshore basins (Hillis et al., 2008; Nelson et al., 2006) and earthquake focal mechanism studies. In summary, these observations are consistent with fault-slip rates approaching ~40–60 m/myr on bounding faults in the Finders and south-east seismic zones, and therefore are of the order implied by moment summation estimates (Celerier et al., 2005).

In other parts of the continent, the connection between seismic activity and ongoing geologic activity is far less clear. For example, some of the largest recorded earthquakes in Australia and the largest moment release occurs in the south-west seismic zone in Western Australia (Braun et al., 2009; Leonard, 2008). The only feature with appreciable relief in this part of the continent is the Darling Scarp. Despite its association with a long-lived fault that has accrued up to 15 km of slip in the Phanerozoic (as evidenced by a gravity anomaly of ~100 mgals) there is no recorded historical seismicity associated with the scarp (Sandiford and Egholm, 2008). The absence of evidence for ongoing fault-related relief generation in this part of the continent implies that seismic activity has either only recently commenced or that, unlike south-east Australia, has not localised on discrete structures at geological timescales.

The factors that localise seismic activity and associated fault related deformation within the Australian continent have been addressed in number of studies. At the local scale reactivation of pre-existing structures almost certainly plays a fundamental role (Dentith and Featherstone, 2003), however other factors are needed to explain differences in seismicity at the regional scale. Celerier et al. (2005) showed how variations in both absolute abundance and depth of heat producing elements provide a plausible thermal control on lithospheric strength that helps localise deformation in the Flinders Ranges. The Flinders Ranges form part of a zone of anomalous surface heat flow (Neumann et al., 2000), with an average surface heat flow of 85 $\mathrm{mWm^{-2}}$ reflecting unusually elevated heat production in the Proterozoic basement. Celerier et al. (2005) calculate that the upper most mantle beneath the Flinders seismic zone maybe 50–100 °C hotter than surrounding zones, simply due the way this heat production is distributed within the crust. Noting the general correspondence between elevated earthquake activity and proximity to the edge of the continent, Sandiford and Egholm (2008) argued that thermal effects associated with the ocean–continent transition may also help control the pattern of active deformation in the south-west seismic zone. They showed that steady-state lateral heat flow across transitional lithosphere can effectively weaken the lithosphere up to 100–200 km inboard of the ocean–continent transition.

In time, stratigraphic relationships establish the active deformation regime in the south-east part of the continent as commencing in the late Miocene in the interval 10–6 Ma (Sandiford et al., 2004). Using inferences drawn from stress modelling studies, Sandiford et al. (2004) attributed this to the synchronous development of transpression along the IAP–Pacific plate boundary segments of southern New Zealand, the Puysegur trench and the Macquarie Ridge (House et al., 2002; Lebrun et al., 2003, 2000; Walcott, 1998). However, it is also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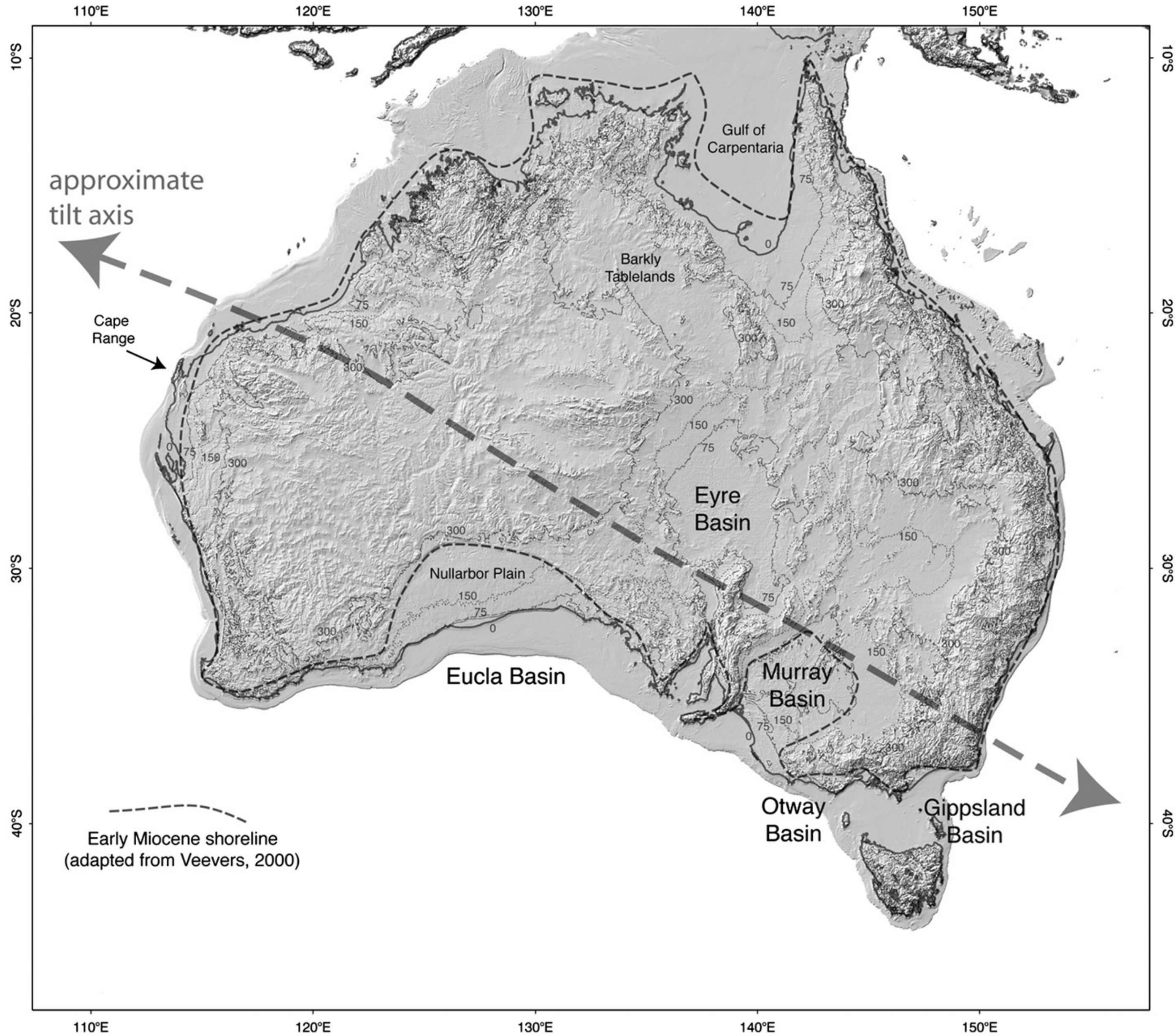

Fig. 8. Shaded relief image of the Australian continent and its continental shelf (at elevations greater than 200 m) derived from Geoscience Australia's 9 arcsecond dataset. Contours are shown for +75, +150 and +300 m. The thin dashed line shows the inferred position of mid Miocene (~15 Ma) shorelines after (Veevers, 2000; Sandiford, 2007). The thick, arrowed line shows the approximate tilt axis and demarcates the region of the continent that contains onshore marine Miocene to the south and West from the region that has no onshore marine Miocene record.

worth noting that the onset of deformation in the central Indian Ocean at around this time has been attributed to increases in stress levels propagated from the Himalayan–Tibet system (Martinod and Molnar, 1995; Molnar et al., 1993). Thus, the IAP seems to have responded with increasing intraplate compression to a complex evolving plate boundary scenario over the last 10 myr and the onset of faulting at specific location probably reflects rising stress levels related to the combination all plate boundary forcings.

6. Continental-scale tilting

As summarised by Sandiford (2007), significant variations in the Cainozoic vertical movements around Australia implicate a profound dynamic topographic signal. Differential motion, including both absolute uplift and subsidence, is evidenced by a north–south asymmetry in the elevation of marine sediments, stratal relations (vis-a-vis onlap versus offlap) and the width of the present-day continental shelves (Fig. 8).

The southern margin is characterised by an extensive onshore Cainozoic marine record, reflecting widespread inundation. Marine sediments are now stranded at elevations up to ~300 m ASL, and at distances of up to 400 km inland of the present coast (Fig. 8) as most dramatically evidenced by the Nullarbor Plain (Fig. 2a). Periodic inundation prior to ~15 Ma, and again in a more limited fashion after ~6 Ma implies a subtle interplay between eustatic and tectonic processes in controlling relative sea-level height (de Broekert

Fig. 7. (a) Seismicity map of the Flinders Seismic zone. (b) topographic image showing the fault scarps that bound the Mount Lofty Ranges in the southern part of the Flinders Seismic zone. c) outcrop of one of the active faults that bounds the Mount Lofty Ranges, showing reverse motion of Cambrian rocks (grey) over footwall Quaternary conglomerate (red) and Miocene Limestone (yellow). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

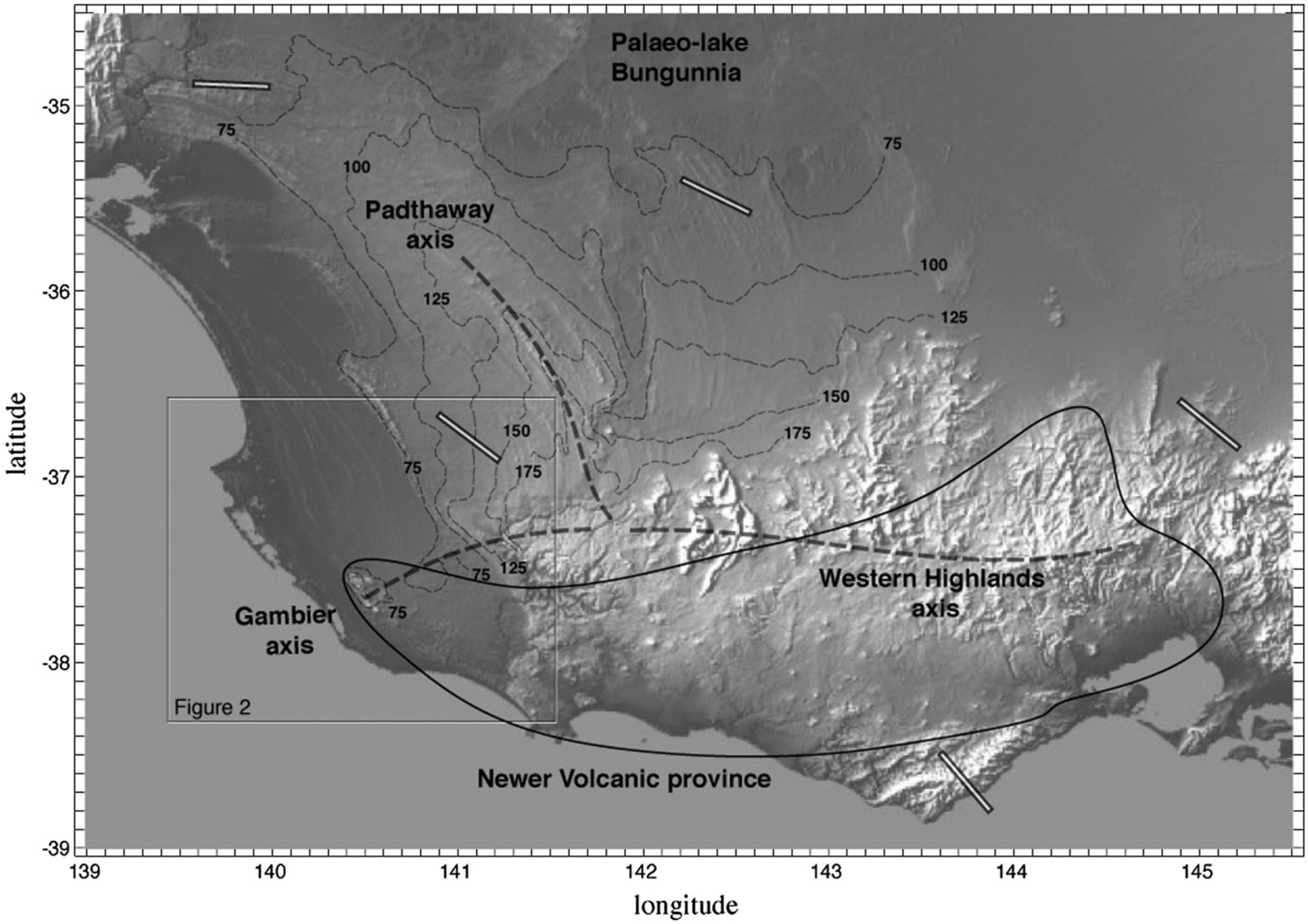

Fig. 9. Digital topography (SRTM 3 arcsecond) of SE South Australia and western Victoria, showing distribution of the Newer Volcanic Province and the main axes of Neogene uplift (Demidjuk et al., 2007). Contours show elevation of the Pliocene strand plain of the Murray Basin showing ~200 m of uplift along the Padthaway axis. Bars show regional trends of the maximum compressive stress (see Sandiford et al., 2004).

and Sandiford, 2005; Hou et al., 2008; Sandiford et al., 2009). The long-term stratigraphic relationships along the southern margin clearly involve progressive offlap. In stark contrast, the almost complete absence of Cainozoic marine sediments along the northern and eastern margins (Sandiford, 2007; Veevers, 1984, 2000) imply sea-levels are now as high as at any time in the Cainozoic with a long-term stratigraphic framework of stratal onlap (Fig. 8). The differential motion between the north and southern motions has contributed a ~300 m differential, north–down, tilting over the last 15 myr at a rate of ~20 m/myr (Sandiford, 2007).

These contrasting stratigraphic relationships are mirrored in the present widths of the continental shelves. Along the southern margin the continental shelf is everywhere less than 200 km wide and locally as little as 30 km wide in the western sector. In contrast, the northern shelf is almost everywhere greater than 200 km wide, and locally as wide as 500 km. Of course, the contrasting stratigraphic records of offlap on the southern margin and onlap on the northern margin imply that this asymmetry in widths must have developed progressively during the Cainozoic and particularly over the last ~15 million years and therefore provides a profound record of dynamic topography (Sandiford, 2007).

The subsidence along the northern coast exceeds the long-term eustatic sea-level fall of ~100 m, and is most easily understood in terms of dynamic topography generated by Australia's northward motion into the geoid high–dynamic low associated with Indonesian and western Pacific subduction. At the scale of the continent, this dynamic topographic effect is the apparent tilting downwards in the sense of plate motion. The notion that the continental-scale asymmetry in the Cainozoic stratigraphic record of Australia is dynamic is supported by a general parallelism of the inferred tilt axis and the geoid field (Sandiford, 2007).

In-as-much-as eustatic sea levels are unlikely to have been much greater than about ~100 m above the present day over the last 43 Ma, much of the southwestern margin of the Australian continent must have experienced absolute uplift (Hou et al., 2008; Sandiford et al., 2009). While the reason for the absolute uplift of this part of the continent is less obvious than the north–down subsidence, the long wavelength of the topographic anomaly as clearly evidenced by the >100 m differential in shoreline features across the Nullarbor Plain (Fig. 2a) implies it is also dynamic in nature (Sandiford et al., 2009). Dynamic uplift most plausibly relates to the progressive movement of the continent away from a dynamic topographic low associated with the AAD in the Southern Ocean. The nature and significance of the Cainozoic tilting record of Australia is discussed in further detail by Sandiford (2007).

7. Deformation at the intermediate wavelength

Arguably the most enigmatic signal of Cainozoic deformation is provided at intermediate wavelengths (100–1000 km) where a number of 100–200 m, landscape "undulations" have developed, and in some cases disappeared, on timescales of 1–10 myr. For example, (Celerier et al., 2005) noted that the pattern of deformation of the Flinders Ranges and the surrounding basins such as the Torrens and Frome Basins includes an undulation of several hundred metres amplitude over about 200 km between the basins bounding the ranges. The absence of any marine sediment in the Torrens Basin, which is now separated from the sea by a sill only ~30 m above sea level, implies that this undulation must have developed in the late Neogene, and probably since the early Pliocene, and includes absolute subsidence of the basins (Quigley et al., 2007c). Along the southwestern part of the Murray Basin, the Pliocene strandplain has been bowed up ~200 m along the Padthaway ridge (Demidjuk et al., 2007), without any obvious fault related deformation (Fig. 9). Similar amplitude undulations have affected the Lake Eyre Basin, the southwestern part of the Eucla Basin and the western desert country around Lake Mackay, and the southwestern part of the Eucla Basin (Sandiford et al., 2009).

The Lake Eyre Basin is particularly instructive since it includes a large, late Miocene palaeolake – termed Lake Billa Kalina – that now sits on the drainage divide along the southern edge of the basin (Sandiford et al., 2009). At its fullest, Lake Billa-Kalina was equally as large as the modern Lake Eyre, and its associated drainage basin clearly extended across much of the present-day Torrens and Lake Eyre Basins. The implied drainage inversion of greater than 140 m implies undulations with wavelengths in excess of about 500 km have propagated through the landscape on a timescale of 1–10 million years. The modern Lake Eyre playa has a ~13 m tilt on the salt-crust surface, lower in the south than the north. Most palaeo-environmental reconstructions show that earlier incarnations of the lake extended further north than the modern lake. Although this is not well documented, it suggests that the modern lake system maybe migrating southwards, further evidencing transience in the "Eyre undulation".

Noting a weak positive coherence between topography and Bouguer gravity (Celerier et al., 2005) proposed that the long wavelength pattern of deformation associated with Flinders Ranges and surrounding basins is best understood in terms of lithospheric-scale buckling. As such, it shows analogies to the deformation of the central Indian Ocean lithosphere (Gerbault, 2000) attributed to increases in intraplate stress levels due the rise in the Himalayan–Tibetan orogen (Martinod and Molnar, 1995) as well as in parts of other continents (Burov et al., 1993; Cloetingh et al., 2002). For the Flinders Ranges, the notion of lithospheric-scale buckling along an N–S axis is consistent with the prevailing E–W S_{Hmax} trend in this part of the continent.

Elsewhere, the landscape undulations are less explicable in terms of a lithospheric response to the in-plane stress field, and the causative factors are less clear. For example, the Padthaway axis is roughly parallel to the inferred SE S_{Hmax} trend (Hillis and Reynolds, 2000; Hillis et al., 2008; Nelson et al., 2006). The uplift of the Padthaway Ridge was accompanied by the onset of mild basaltic volcanism as well as gentle subsidence that formed a large palaeo-lake (Lake Bungunnia) in the more internal parts of the Murray Basin several hundred kilometres further north. (Demidjuk et al., 2007) argued that dynamic mantle process associated with a small-scale, secondary mode of convection beneath the Australian plate provides a plausible explanation of these associated phenomena. An important consequence of this hypothesis is that it demands northward motion of the lithosphere relative to the flow in the sublithospheric upper mantle (Demidjuk et al., 2007), allowing unique attribution to the observed alignment between seismic anisotropy at ~200–300 km depths and absolute plate motion (Debayle et al., 2005).

8. Discussion

The geomorphic record of Australia provides several unique insights into the subtle dynamics of plate interiors. The first relates to the propagation of stresses from distance plate boundaries. As part of a complex plate, it is now well understood that plate boundary activity contributes to the *in situ* stress field within the plate (Cloetingh and Wortel, 1986; Coblentz et al., 1995, 1998; Reynolds et al., 2002). Because the active continental orogenic systems bordering the Indo-Australian plate, including the Himalaya, Timor, New Guinea and New Zealand, as well as a complex array of subduction zones bordering the northern and eastern plate boundaries evolve independently, the tectonic geomorphology of the Australian continent provides an excellent test case to evaluate just how intraplate settings respond to plate-boundary forcing. In southeastern Australia the faulting record can be dated back to the late Miocene, where it continues to be expressed to this day in earthquake activity. This response is now well understood in terms of the general increase in intraplate stress levels due to plate boundary forcing, that have initiated deformation in a number of locations across the IAP, including the central Indian Ocean, arguably to the level that is now beginning to break the plate apart.

Secondly, as part of the IAP the Australian continent has drifted further and faster than any other continent over the last 45 million years; its ~3000 km northward drift achieved at the rate of ~6.5 cm/year. In so doing it has passed over a complex deep mantle density structure as revealed partly by the long-wavelength geoid field anomaly of ~60 m across the continent, as well as the unusual ocean bathymetry of the Southern Ocean in the vicinity of the Australian–Antarctic discordance (AAD). Since the surface plate motion cannot be entirely decoupled from the deeper mantle density anomalies that give rise to the long-wavelength geoid anomalies, these observations beg important questions related to the way the surface of the plate has been deformed by the mantle beneath during its northward journey. For example, if any continent preserves a geomorphic record related to its passage across the complex structure of the deeper mantle beneath it is likely to be Australia. Here we have shown that the geomorphology of Australia provides profound insights into the dynamics of the plate, with special insights provided by the unique combination of plate speed, low relief and aridity. The egacy of the fast, flat and dry continent is a unique insight into the subtle tectonic processes that shape continental interiors, and particularly those related to lithosphere–mantle interactions at a variety of scales.

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