Tectonic framework for the Cainozoic cratonic basins of Australia

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Abstract

Variations in the extent of Cainozoic marine inundation of Australia, as revealed by the distribution of marine and near-shore deposits, points to a tectonic regime involving three distinct modes of deformation. At the longest wavelengths (order $10^3$ kms), the continent has experienced SW-up, NE-down tilting with an amplitude of ~300 m since the late Eocene. We attribute this tilting to the dynamic topographic response to the northward motion of Australia towards the subduction realm of Indonesia and the western Pacific, as well as its passage across a complexly structured mantle. At short wavelengths (order $10^1$ kms), variations in elevation are associated with cumulative fault movements up to order 100 m. Fault slip vectors are generally compatible with the prevailing in-situ stress field and therefore can be allied to distant plate boundary forcing. At intermediate wavelengths (order $10^2$ kms), undulations with amplitudes of order $~10^2$ m reflect, at least in part, lithospheric buckling due to relatively high levels of intraplate stress arising from plate boundary forcing. Understanding the patterns of surface deformation associated with each of these deformation modes provides a tectonic framework against which the broader significance of the Australian Cainozoic record for such things as eustasy must be evaluated.
Introduction

The distribution of Cainozoic marine and near-shore sediments around the Australian continent provides a powerful testament to relative changes in sea-levels over the last 50 million years. As would be expected for a stable continent situated in an intraplate tectonic setting, a key factor in controlling the distribution of Cainozoic sedimentation has been a long-term eustatic regressive regime associated with the progressive development of the ‘ice-house’ world in the latter part of the Cainozoic. This is most spectacularly evidenced by the Nullarbor Plain, as well as numerous other places along the southern coastline of the continent, where Cainozoic marine sediments extend hundreds of kilometers inland from the present day shoreline. However, the present distribution of Cainozoic sediments also indicates significant differentials in vertical motion within the Australian continent during the Cainozoic. This is most startlingly evidenced by the north-south asymmetry in the elevation of marine sediments around the modern Australian coastline. Whereas the extensive distribution of marine sediments onshore along the southern margin indicates widespread inundation in the early to mid-Cainozoic, with marine sediments found to elevations locally now up to ~300 m ASL, the almost complete lack of onshore marine sediments along the northern margin implies present sea-levels are now as high, relative to the continent, as at any time during the Cainozoic.

The elevation of Cainozoic palaeo-shorelines around the Australian continent, as deciphered from the record of marine and near-shore deposits, varies at a variety of length-scales, from the continental scale (order $10^3$ kms) to the scale of individual fault blocks (order $10^1$ kms). In this contribution we propose that a number of distinct tectonic processes, or deformation modes, are responsible for the vertical deformation at the different length-scales. Understanding the characteristics of these modes, such as their temporal and spatial patterns in topographic expression, is fundamental to understanding the broader significance of the Australian Cainozoic record. For example, any unambiguous picture of the global eustatic sea-level variations must explicitly address the impact of the apparent, long-wavelength, deformation mode. For the Australian Cainozoic, there is strong evidence that such long-wavelength dynamic topographic effects contribute at least as much apparent sea-level variation as do eustatic processes, reflecting the fact that Australia is a relatively fast moving continent traversing a complexly structured deeper mantle. Our objective is to explore the various modes of deformation that have helped shape the surface of the Australian continent during the Cainozoic, particularly those that have impacted on the distribution of Cainozoic sediments around the periphery of the continent. Our focus is particularly directed to those regions that have largely been immune from ongoing subsidence related to prior continental margin...
rifting events associated with the fragmentation of the Gondwana in the Mesozoic. In this context, we focus on such regions as the onshore Eucla and Murray Basins in southern Australia and the Karumba Basin in northern Australia, which may be classed as ‘cratonic basins’. We provide only a brief summary of the most important constraints on the nature of tectonic movements as evidenced by the present-day distribution of marine and near-shore Cainozoic sediments.

Our analysis highlights three apparently distinct modes that have deformed the interior of the Australian continent since the onset of fast spreading in the Southern Ocean some 43 myrs ago, at the time when the modern Indo-Australian plate formed by the amalgamation of the pre-existing Indian and Australian plates (e.g., Veevers, 2000). These three modes are:

1. a long-wavelength (order $10^3$ kms) continental-scale **tilting**-mode,

2. a short-wavelength (order $10^1$ kms) **seismogenic**-mode, and

3. an intermediate-wavelength (order $10^2$ kms) **buckling**-mode.

In describing these three deformation modes we seek to provide an insight into how they relate to the larger-scale dynamics of the Indo-Australian plate. Our analysis makes use of the shuttle radar topography mission 3-arcsecond digital elevation data (SRTM3). The SRTM3 data reveals an unprecedented view of the Australian topographic field at horizontal resolutions of about 90 m and vertical resolutions estimated at less than 16 m. In view of this, we cite elevation data to the nearest 10 m contour.

**A brief synopsis of the Australian onshore record of Cainozoic marine inundation**

As recently summarised by Sandiford (2007), the distribution of marine and near-shore Cainozoic sediments provides an insight into differential vertical movements of the crust around the Australian continent, revealing a strong asymmetry in vertical motions with respect to the present-day coastline. Along the southern margin, extensive onshore marine deposits indicate periodic inundation prior to ~15 Ma, and again in a more limited fashion after ~6 Ma. Maximum marine incursions often extend several hundred kilometres inland of the present-day southern coast, to elevations now several hundred metres above present-day sea level (ASL). In contrast, equivalent aged marine sediments are mostly absent from the present-day onshore northern margin and eastern margins, or limited to elevations less than ~10 m ASL, with most interpretations placing Cenozoic shorelines offshore (e.g., Veevers, 1984, 2000; Figure 1). Here we provide a brief synopsis relevant
to the subsequent discussion of the tectonic processes that have contributed to the deformation of the Australian continent over the last 43 myrs.

Along the southern margin of the continent, the most extensive inundation is evident on the Nullarbor Plain, which constitutes the onshore part of the Eucla Basin, and in the Murray Basin (Figure 1). In the Eucla Basin, the northern-most extent of inundation is delineated by a set of palaeo-shorelines (Figure 2). Along the north-western Eucla Basin margin, Eocene (~41 Ma) palaeo-shorelines occur at elevations now up to ~300 m ASL (de Broekert & Sandiford, 2005), while younger Miocene (> 15 Ma) shorelines associated with deposition of the Nullarbor Limestone are some 80 m lower (e.g., Hou et al., 2003, 2006, 2007, Figure 3a). As shown in Figure 3b, the elevations of these palaeo-shorelines drop systematically eastwards over a distance of ~1000 kilometres across the Nullarbor Plain; down to about 150 m ASL for the Eocene palaeo-shorelines and down to about 60 m ASL for the Miocene shorelines. Pliocene marine sequences in the Eucla Basin are restricted to elevations less than about 30 m ASL on the Roe Plain (Figure 2). While small fault related offsets are clearly observable on the Nullarbor Plain (Figure 2), a notable feature of the Eocene coastal barrier systems is the systematic long wavelength variation in elevation that implies a differential vertical tectonic motion with amplitude of order $10^3$ kilometres (Figure 3b). Inset-valleys ("palaeochannels") also provide strong evidence for uplift of the Eucla Basin and indeed the Yilgarn Craton during the Cainozoic (de Broekert & Sandiford, 2005).

The Murray Basin was extensively flooded in the early to mid Cainozoic, up until ~15 Ma, and again after ~6 Ma (Brown & Stephenson, 1991). The Pliocene sequences are evident in a strandplain comprising over 150 individual arcuate shorelines clearly evident in the SRTM3 data (Brown & Stephenson, 1991; Roy et al., 2000; Figure 4). The limit of Pliocene flooding approximately coincides with earlier flooding levels inferred from the distribution of Oligocene - mid Miocene limestones. In the central part of the basin the maximum marine incursions corresponds to the 70 m ASL contour (Brown & Stephenson, 1991). In the southern parts of the basin, where the Murray Basin onlaps onto the Western Victorian highlands, the Pliocene strandlines occur at elevations up to ~180 m ASL (Sandiford, 2003b; Wallace et al., 2005) along the southern end of a south east trending-ridge termed the ‘Padthaway high’ (Figure 4). The order $10^2$ km wavelength ‘Padthaway high’ arch has risen about 110 m relative to the more internal parts of the basin. Quaternary shorelines along its southern flank on the Gambier Plain indicates uplift at a rate of ~75 m/myrs from ~780 ka to the present day (Sprigg, 1979, Huntley et al., 1993, Figure 5).
On the northern flanks of the Otway Ranges in southern Victoria, Oligocene-Miocene limestones and Pliocene marine and shoreface deposits step up across a set of ENE-trending faults from ~120m to 240 m ASL (Dickinson et al., 2002; Sandiford, 2003b; Wallace et al., 2005). Similar fault related offsets are observed around the Mount Lofty Ranges in South Australia where the elevation of Oligocene-Miocene limestone varies from near sea-level to up to 190m across range bounding faults such as the Willunga Fault (Sandiford, 2003a). In what is arguably the most spectacular example of Cainozoic deformation to be seen in Australia, near vertical dipping Oligocene-Miocene limestones are exposed on shore platforms 50 kilometers south of Adelaide in the footwall of the Willunga fault (Figure 6), with correlative sequences in the hangingwall just a few kilometres inland now at elevations of 190 m ASL. In these locations, differences in elevations of Cainozoic sedimentary sequences can clearly be related to fault movements with individual fault blocks having dimensions of order 101 kms. Exposures of these faults show that they are reverse faults with characteristic dips of ~ 50° (Williams, 1973; Bourman & Lindsay, 1988; Quigley et al., 2006). In the Flinders Ranges, quantitative measures of erosion rates of order 100 m/myrs derived from cosmogenic dating provide constraints on relief production by active faulting over the last few million years (Quigley et al., 2007a,b), consistent with cumulative fault motions in excess of 100 meters.

Apart from the extraordinary Cainozoic marine sedimentary blanket that covers much of the onshore southern margin, early-mid Cainozoic sequences of unequivocal marine origin at significant levels above present day sea level are known only from the North West Cape region on the western sea board (Quilty, 1977). Here, Miocene limestones are exposed in a NNE-trending antiformal culmination up to 250 m ASL that defines the Cape Range (Hillis et al., in prep). Seismic reflection profiling across the offshore northern continuation of the Cape Range anticline clearly relate it to subsurface reverse faulting (Hillis et al., in press).

In view of an almost complete lack of onshore exposure of marine deposits along the northern and eastern margins of the continent, the precise location of Cainozoic shorelines is poorly constrained. An implication is that the present-day sea levels are, relative to the continent, as high as at any time during the Cainozoic. Based on interpolations derived from the coastward thinning of offshore sequences, Vevers (1984, 2000) places Cainozoic shorelines at between 0 and 50m beneath sea level around much of the northern and eastern coast (Figure 1). Probably the best constraints come from the Karumba Basin, around the Gulf of Carpentaria, where a number of onshore exposures along the western coast of the Cape York Peninsula place the position of Miocene and Pliocene shorelines close to the present-day shoreline (Doutch, 1976; Smart et al., 1980). A
possible exception to this is provided by the report of scattered outcrops of Miocene limestone on the Barkly Tablelands in the Northern Territory, ~ 500 kms south-west of the Gulf of Carpentaria at elevations of ~250 m ASL (Lloyd, 1968, see also Veevers, 1984, 2000). Lloyd (1968) suggested a possible marine influence on the basis of the occurrence of the euryhaline foraminifera, *Ammonia beccarii*, which is known as a marginal marine species. It is also known from lagoon and inland lake systems (Cann et al., 1999) and thus its environmental significance is doubtful. The absence of any diagnostic marine fauna amongst the species reported by Lloyd (1968), together with the limited extent of outcrop suggests these more likely formed part of a system of terrestrial lake deposits (e.g., Doutch, 1976), rather than a widespread marine incursion across Northern Australia.

The pattern of Cainozoic marine inundation of the continent is further informed by the absence of marine sediments from a number of low lying interior basins. For example, the Eyre basin with a present-day minimum elevation of 10 m BSL is confined by a sill at ~ 80 m ASL from the Torrens Basin that, in turn, is separated from Spencers Gulf by a sill at ~40 m ASL. Despite this low elevation, neither the Torrens Basin nor the Eyre Basin has any record of Cainozoic marine sedimentation. Intriguingly, the present day-divide between the Torrens and Eyre Basin is marked by deposits of a large palaeo-lake, Lake Billa Kalina, of probable late Miocene age (Callen & Cowley, 1998), clearly evidenced by a set arcuate strandlines along its former eastern shoreline (Figure 7). At its maximum size of ~15,000 km² this lake would seem to require a catchment that included much of the present Eyre and Torrens basins. In this region, a post-late Miocene topographic inversion of ~130 m, over a wavelength of order 10² kms, is implied by the difference in elevation between the base of the Billa Kalina deposits at ~120m ASL and the present elevation of Lake Eyre (Figure 8).

In summary, arguably the most extraordinary feature of the Australian Cainozoic stratigraphic record is the profound asymmetry in the pattern of preservation of marine sediments at the scale of the continent. This pattern demands a relative N-down, S-up tilting. Intriguingly the asymmetric pattern of early-mid Cainozoic onshore sediments around Australia is mirrored by elevations in Holocene shoreline elevations, which tend to be elevated along the southern margin by relative to the northern margin by several metres (Belperio et al., 2002) suggesting that this tilting may continue to the present day. In detail, the pattern of apparent tilting is informed by the systematic variation in elevation of palaeo-shoreline features across the Nullarbor that suggests the southwest part of the continent has risen significantly relative to the south-east. Thus, the distribution of preserved onshore marine sediments suggest a tilt axis that trends NW-SE across the continent from the northern part of Western Australia through to the south-east corner of the continent.
Smaller wavelength variations in the distribution and elevation of Cainozoic sediments points to deformation modes operating at the sub-continental scale, associated with faulting at the 10^1 km wavelength and undulations at the 10^2 kms wavelength. In the following sections we address the causative factors associated with each of these distinct deformation modes.

The long wavelength deformation mode (order 10^3 kms)

As outlined in the previous section even a cursory appreciation of the distribution of the onshore Cainozoic marine record of the Australian continent reveals a startling asymmetry between the southern and northern Australian margins. While a number of authors have proposed subsidence of the Australian continent over the Cainozoic, relative to other continents, (e.g., Bond, 1978; Veevers, 1984; 2000) there has been surprisingly little scientific attention focused on the asymmetry. One of the few comments comes not from the scientific literature but from the popular science writing of Bill Bryson (2003) who, in “A Short History of Nearly Everything”, astutely observed “Australia meanwhile has been tilting and sinking. Over the past 100 million years, as it has drifted north towards Asia, its leading edge has sunk by nearly 200 metres. It appears Indonesia is very slowly drowning and dragging Australia down with it”. Much of this insight seems to derive from Gurnis (2001), who provides an excellent introductory account of how convection in the Earth’s mantle impacts on the surface elevation of the continent, arguing that through the Cainozoic that dynamic processes in the mantle have caused Australia to sink by at least 200 metres. The notion of a Cenozoic sinking was motivated in part by Bond (1978) who derived estimates of relative vertical motions of the continents by comparing changes in the proportion of apparent flooding taking into account the hypsometry. Because of the use of an index based on the proportion of continent flooding, Bond (1978) was only able to provide estimates of average continental elevation changes. As we have outlined, the distribution of Cainozoic marine sediments indicates that the pattern of long-wavelength deformation of the Australian continent is far more complex than a simple sinking. Indeed, in as much as eustatic sea levels are unlikely to have been much greater than about 100-150 m above the present day over the last 43 Ma, much of the southwestern margin of the Australian continent must have risen in an absolute sense, rather than sunk. In this section we provide a framework for understanding the long wavelength tilting of the continent in terms of the concept of dynamic topography.

Variations in the elevation of the Earth’s surface are supported either by the isostatic compensation of density anomalies within the lithosphere or by dynamic processes beneath the lithosphere. At short wavelengths (order 10^1 kms) variations in surface elevation mostly relate to the
compensation of lithospheric density anomalies, and thus are essentially isostatic in nature. At wavelengths comparable to the thickness of the lithosphere (i.e., order $10^2$ kms) deviations from local isostacy can usually be related to flexural strength of the lithosphere, and give rise to the notion of regional isostacy. At the scales of order $10^3$ kms, compatible with the dimensions of mantle circulation, surface elevations may reflect variations in vertical stress transmission between convective mantle and the lithosphere, termed dynamic topography. In the general case of steady convection in the mantle, the mass anomaly that drives the mantle flow should be associated with a deflection of a density interface (such as the upper or lower surface) sufficient to ‘compensate’ the driving anomaly (e.g., Richards & Hager, 1984; Figure 9). The nature of the dynamic topography signal has been subject to significant debate (e.g. Gurnis, 1993; Wheeler & White, 2000), partly because we do not fully understand the mechanical properties of the deeper mantle in sufficient detail to provide realistic physical simulations. Numerical modelling studies of mantle convection with overlying plates frequently predict a dynamic topographic signal of several kilometers (Lithgow-Bertollini & Gurnis, 1997). However such predictions seem inconsistent with the record of continental interiors that show them to have been immune from complete inundation, with some authors suggesting that dynamic effects have no significant role on the Earth’s surface topographic field (e.g., Wheeler & White, 2000)

The expected pattern of dynamic topography should relate primarily to planform of mantle circulation, with zones of mantle downwelling characterized by dynamic topographic lows and zones of upwelling characterized by dynamic topographic highs. Regions above zones of persistent downwelling, such as regions associated with subduction, are characterized by dynamic topographic lows, as is illustrated by the Sunda Block to the north of Australia, which constitutes one of the most submerged regions of continental crust on the modern Earth. Such a dynamic topographic effect is arguably the reason for the relative broad continental shelf along Australian northern margin, that contrasts the generally much narrower southern shelf. Because the density anomalies driving mantle circulation are at depths of order $10^3$ kms in the mantle, the expected spatial scale of the dynamic topographic expression is also of order $10^3$ kms (Figure 9). Thus a continent that has a long-lived history of movement towards a zone of persistent subduction, such as Australia, should be expected to experience a tilting, downwards in the sense of plate motion. The geological indicators of this tilting will be further augmented by the fact that downwelling zones are not only characterized by a dynamic topography low but also by a geoid high. This association is attributed to the impact of the viscosity structure of the mantle on the way in which the dynamic topographic response is partitioned between upper and lower boundaries of the convective mantle
(e.g., Richards & Hager, 1984, Figure 9). In Australia, the observed long wavelength increase in the geoid height from SSW to NNE is ~60 m (Figure 10a).

The notion that the continental-scale asymmetry in the Cainozoic stratigraphic record of Australia is a dynamic topographic signal is supported by the general parallelism of the inferred tilt axis and the long-wavelength geoid (Figure 10a), and is readily explicable in terms of the northward motion of the continent towards the equatorial western Pacific realm. Since this region has been the site of plate convergence and subduction throughout the Cenozoic (e.g., Lithgow-Bertelloni & Richards, 1998), it is a region of low dynamic topography and high geoid extending over many thousands of kilometres. Thus the downward tilting of the northern part of the Australian continent inferred from the absence of onshore Cainozoic shorelines can be interpreted to represent the combination of a real dynamic subsidence as well as an increase in sea level height associated with the elevated geoid. The later effect contributes ~20 m per 1000 kms of northward motion, and given that the total apparent subsidence must exceed the eustatic sea-level fall over the Cainozoic, the contribution of the dynamic subsidence is likely to be about 100 m along the north coast of Australia.

The reason for the absolute uplift of the south-western part of the continent is less obvious. However, by similar logic, we may assume that an absolute dynamic uplift must relate to the progressive movement of the continent away from a dynamic topographic low. That such a dynamic topographic low exists to the south of Australia is indicated by the anomalously low elevation of the mid-ocean ridge along the Australian Antarctic discordance, which contributes one of the lowest residual bathymetric anomalies known from the oceans. Gurnis et al. (1998) have argued that this low reflects the existence of a relict of a former slab, now elevated above the mantle transition zone due to the opening of the Southern Ocean. They argue that this piece of slab is a remnant of a subduction system to the east of the Gondwana margin, and showed how dynamic topography associated with this slab system provides an elegant explanation for anomalous Cretaceous subsidence in the Eromanga Basin in central-east Australia due to Australia’s then eastward motion. By analogy, the Cainozoic northward motion of Australia away from this anomalous mantle, that to this day helps lower the bathymetry in the southern Ocean, will have caused a dynamic topographic uplift of Australia’s southern margin, estimated to be up to ~200 m in amplitude. The nature and significance of the Cainozoic tilting record of Australia is discussed in further detail by Sandiford (2007).

**The short wavelength deformation mode (order 10^1 kms)**
At the short wavelengths, a seismogenic deformation is indicated by the record of mild faulting evidenced in most onshore Cainozoic basins. As summarized in Sandiford (2003a,b) and Sandiford et al. (2004), the distribution of this faulting in south-eastern Australia correlates with the distribution of active seismicity, while the style and orientation of faults is largely consistent with the inferred in situ stress field (Celerier et al., 2005, Quigley et al., 2006). More recently, Hillis et al. (in press) have shown similar relationships apply in the north-west shelf region, including the Cape Range.

A useful framework for understanding this ongoing faulting is provided by the modeling studies of Coblentz et al. (1995, 1998) who have shown that the pattern of in situ stress in Australia is best explained with reference to the balance of forces operating at the plate-scale. The Coblentz et al. (1995; 1998) analysis highlights the role of collisional forces generated by the Himalayan, New Guinea and New Zealand collision zones in balancing plate driving forces of ridge push and slab pull, with the SHmax aligning to a near-orthogonal direction in the vicinity of each of these collisional orogens (Figure 10b). These modeling studies provide for testable hypotheses, in-as-much as the nature of plate forcing stemming from these collisions has changed considerably through the Cainozoic. For example, the convergence between the Pacific and Indo-Australian plates responsible of the South Alps collision zone in New Zealand is related to progressive changes in plate rotation poles in the period 10 - 5 Ma (Sandiford et al., 2004). That south-east Australia feels this change in plate boundary forcing is corroborated by the evidence for increased faulting activity commencing at around 6 Ma (e.g., Sandiford et al., 2004).

The intermediate wavelength deformation mode (order $10^2$ kms)

Arguably the most enigmatic signal of Cenozoic deformation is provided by the evidence for developing undulations with amplitude of order $10^2$ m and wavelength of order $10^2$ kms, as perhaps best illustrated by the Padthaway Ridge in SE South Australia. In another setting, Celerier et al. (2005) noted that the long wavelength pattern of deformation of the Flinders Ranges and the surrounding basins was characterized by an similar undulation pattern of ~400 m amplitude (Figure 12), with the implied downward deflection of the Torrens Basin providing an explanation for the absence of early-mid Cainozoic marine inundation. Similar wavelength undulations may also have contributed to the change in the location of the depocentre from the Billa Kalina to the Eyre and Torrens Basins (Figures 7 & 8). Other indicators that such undulations are a relatively widespread mode of Cainozoic deformation within the Australian continent are to be found in western desert country around Lake Mackay, where a significant section of the northern part of the palaeo-
drainage system appears internally confined, as much as 80 m below the level of formerly down-
stream reaches (Figure 11). Further south, in the Bremer Basin, immediately west of the Eucla Ba-
sin, marine sediments now occur to elevations now beneath about 180 m ASL, significantly lower
than equivalent sequences in the western Nullarbor Plain and associated incursions into the Lefroy
palaeo-drainage, reflecting deformation about a WSW-ENE trending axis variously termed ‘Jarrah-
wood Axis’ or ‘Ravensthorpe Ramp’ (Cope, 1975; Clarke, 1994; de Broekert & Sandiford, 2005).

Celerier et al. (2005) have proposed that the long wavelength pattern of deformation associ-
ated with Flinders Ranges and surrounding anomalously low basins (such as the Torrens and Frome
basins) could be understood in terms of lithospheric-scale (10^2 km) buckling phenomenon (Figure
12). This interpretation stems in part from the observed positive coherence between topography
and Bouguer gravity fields (Figure 12), as well as regional structural trends on deformed surfaces.
As such, the deformation is analogous to the proposed deformation of the central Indian Ocean
lithosphere which commenced at around 8 million years ago (e.g., Gerbault, 2000), and which has
been attributed to increases in intraplate stress levels due to an increase in plate forcing induced
by the rise in the Himalayan-Tibetan orogen at this time (e.g. Martinod & Molnar, 1995). For the
Flinders Ranges, the notion of lithospheric scale buckling along a N-S axis is consistent with the
prevailing E-W SHmax trend in this part of the continent. Elsewhere, the undulation axes trends
are less explicable in terms of the prevailing stress field, and the causative factors are less clear.
For example, the Padthaway axis is roughly parallel to the inferred SE SHmax trend (e.g. Coblentz
et al, 1995, 1998). Here, Demidjuk et al. (2007) have suggested the uplift reflects a dynamic mantle
process associated with a small-scale, secondary mode of convection beneath the Australian plate
that has sourced the late Neogene mafic volcanism along the Gambier Plain (Figure 5) as well as
along the southern flanks of the Western Victorian Highlands. Resolving the mechanisms responsi-
ble for this enigmatic intermediate-wavelength pattern of surface deformation remains a significant
challenge.

Conclusions

[1] The Australian continent is well known for its relative tectonic stability, consistent with its in-
traplate setting. However, it is also the fastest moving continent in arguably one of the most dy-
namic of the Earth’s large tectonic plates, and therefore has not been totally immune from tectonic
activity.

[2] The ongoing role of tectonism is evidenced by a variety of indicators including variations in the
extent of marine inundation around the Australian continent during the Cainozoic. Variations in the
extent of marine inundation around the Australian continent during the Cainozoic indicate three distinct deformation modes. Each of these deformation modes can, to various degrees, be allied to the plate-scale dynamics, and reflects the fact that Australia is a relatively highly stressed, fast moving continent in a complex plate.

[3] Of particular note is Australia’s dynamic topographic response due to its northward motion towards the subduction realm of the western Pacific, as well as it’s passage across a complexly structured mantle. This NE-down, SW-up tilting at the continental scale has an amplitude of about 300 m, and provides a unique signal of how dynamic processes in the Earth’s convective mantle impact on the surface topographic field.

[4] Understanding the patterns associated with each of these deformation modes provides a tectonic framework against which the broader significance of the Australian Cainozoic record for such things as the global eustatic record must be evaluated.

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Figure 1. Shaded relief image of the Australian continent and its continental shelf (at elevations greater than -250 m) derived from Gesocience Australia’s 9 arcsecond ‘bathytopo’ dataset. Contours are shown for +75, +150 and +300 m. The thick dashed line shows the approximate position of Early Miocene shorelines, adapted from Veevers (2000).
Figure 2. Shaded relief of the Nullarbor Plain showing various palaeo-shoreline features of Eocene to mid Miocene age (> 15 Ma) along its northern margin. The Roe Plain is Pliocene feature. N-S trending faults crossing the Nullarbor Plain have cumulative throws of up to 20 m.
Figure 3. Topographic profiles across the Eucla Basin showing interpreted inundation extents at various times in the Cainozoic (see Figure 2 for profile locations). Topographic data form the Shuttle Radar Topographic Mission 3-arcsecond data. (a) section A-B normal to the palaeo-shorelines in the northwestern part of the Basin (profile length is 130 kms). (b) section C-D parallel to the interior most limits of the Nullarbor Plain showing the interpreted limit of Miocene limit (line-of-sight profile length is 760 kms). Much of the noise in the signal can be attributed to secondary erional processes, and at least in one case, subsequent faulting. However the greatest power is in the lowest frequency component (indicated by the gray band) at wavelengths of order $10^3$ kms, implying a deep mantle origin related to dynamic topography.
Figure 4. Shaded relief image of the Murray Basin and Western Victorian highlands. The dashed line shows the approximate limits of marine inundation prior to 15 Ma and again at ~ 6 Ma. In the internal parts of the basin this inundation coincides with the 70 m contour, but reaches elevations as high as 180 m along the Padthaway axis. The arcuate ridge systems within the Murray Basin, form part of the Pliocene-Quaternary, regressive strandplain, with the Padthaway axis rising by up to 110 m relative to the internal parts of the basin since the late Pliocene (for further details see Figure 5).
Figure 5. Shaded relief image of a portion of the Murray Basin, showing Quaternary beach ridges on the Gambier Plain. The age structure of shoreline features (e.g., Murray-Wallace et al., 2001) indicate uplift of the Padthaway ridge at a rate of at least 75 m/myr over the 780 kyrs. Mt Burr, Mt Gambier and Mt Schank are sites of Quaternary mafic volcanism, and represent the youngest and western most limits of an active field of Neogene volcanism that extends eastwards some 400 kms to Melbourne in Victoria, straddling the southern flanks of the western Victorian highlands.
Figure 6. Near-vertical dipping Oligocene-Early Miocene Port Willunga Limestone exposed on beach platform at Sellicks Beach south of Adelaide in the footwall to the Willunga Fault. On the hanging wall block, ~ 5 kms to the south-east, correlative sequences occur at elevations up to 170m ASL in the Myponga Basin (e.g., Sandiford, 2003a).
Figure 7. Shaded relief image of Billa Kalina Basin, South Australia, showing distinctive arcuate palaeo-shoreline features of Lake Billa Kalina of probable Miocene age. The inferred approximate maximum extent of the lake is indicted by the dashed line, based on limits of relict palaeoshorelines. Note that Lake Billa Kalina is now perched on the present drainage divide between the Torrens and Eyre Basins (see also Figure 8) implying significant topographic inversion since the lake formation. The topographic profile along the line A-B-C-D is shown in Figure 8.
Figure 8. Topographic profile corresponding to profile line A-B-C-D as shown on Figure 7, showing a significant topographic inversion since the formation of the Billa Kalina Lake of presumed of Miocene age (Callen & Cowley, 1995).
Figure 9. Schematic illustration of dynamic topography in the Earth, driven by a density anomaly in the convective mantle such as a subducting slab. The induced flow will deform the boundaries of the convective layer in a way that reflects the viscosity structure of the convective layer. The pattern of dynamic topography (a measure of the deformation of the upper surface) and geoid (a measure of the driving density anomaly and associated compensating deflections on both lower and upper surfaces) imply a lower mantle some 30 times more viscous than the upper mantle (e.g., Richards & Hager, 1984; Hager, 1984; Gurnis, 1993). A continent, such as Australia, moving towards a long-lived zone of subduction will feel a real tilting caused by the dynamic topographic subsidence as well as an apparent tilting caused by the increasing height of the geoid. The amplitude of the dynamic topographic signal is several times that of the geoid signal. The horizontal length scales are of the same order as the thickness of the convecting layer and therefore of order $10^3$ kms. Note that for clarity the deflections and geoid anomalies of order $10^2$-$10^3$ m are not to scale.
Figure 10. (a) Representation of the variation in the geoid field across Australia, illustrated by mapping a satellite derived image of the Earth’s surface onto a greatly exaggerated view of the geoid field. The magnitude of the geoid field variations are indicated by the contours with 20m intervals, with the geoid field rising ~90 m across Australia from SW to NE. The trend of the geoid anomaly corresponds to the apparent tilt axis derived from the longest wavelength variations in elevation of Cainozoic near-shore deposits around the Australian coastline. The slightly NNE trajectory of the Indo-Australian plate means the Australian continent has moved progressively into a region of higher geoid contributing an apparent N-side down tilting. (b) The pattern of in situ stress in the Indo-Australian plate deduced by plate scale modeling studies (e.g., Coblentz et al., 1995; 1998). Arrows indicate the orientation of the maximum horizontal stress vector (SHmax). Note how the complex pattern of stress in Australia is controlled by trends that point respectively to New Guinea (in the north-east), New Zealand (in the south east) and to a west trending arcuate pattern (in the west) that links eventually to the Himalayas. This pattern reflects the role of these collisional orogenic systems in providing the resistive forces that balance the forces of ridge-push and slab-pull that drive the plate northwards.
Figure 11. Shaded relief image of the Lake Mackay palaeo-drainage, Western Australia, with associated channel profile. The upper reaches of this palaeo-drainage, between points A and B, now drain internally to depths ~ 80 m lower than the highest parts of the formerly, downstream reach, between points B and C. To the extent that the surface expression of this palaeo-drainage has not been significantly altered by differential filling, the drainage must have been deranged as a consequence of an order $10^2$ km undulation.
Figure 12. Topographic (a) and buoguer gravity (b) profiles across the Flinders Ranges and surrounding low-lying basins combined with models of thin elastic plate deformation for various flexural parameters, from Celerier et al. (2005). The positive coherence between topography and gravity precludes an isostatic mechanism for the support of the topography and suggests a lithospheric buckling mode at wavelengths of order $10^2$ kms (Celerier et al., 2005).