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The tilting continent: A new constraint on the dynamic topographic field from Australia

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Abstract

A pronounced latitudinal asymmetry in the present-day morphology of the Australian continental shelf is reflected in Neogene stratigraphic relationships. The northern Australian margin has a broad shelf, typically 200–500 km wide and a Neogene record of stratal onlap. Relative to the continent, sea levels are currently as high as at any stage during the Neogene. In contrast, the southern shelf is typically less than 100 km wide and shows a record of progressive offlap with Neogene palaeo-shorelines commonly many hundreds of kilometres inland, at elevations up to ~250 m above present-day sea level. This continental-scale 'reciprocal' stratigraphy implies 250–300 m N-down, SSW-up apparent vertical motion with respect to sea level since the mid-Miocene. The apparent vertical motion can be attributed to variations in dynamic topography and the geoid along Australia's NNE plate circuit; specifically, the movement of the southern margin off the dynamic topography low, geoid low presently centred on the Australian–Antarctic discordance, and the northern margin towards a dynamic topography low, geoid high associated with the subduction realm to the north. Variations in the geoid appear to account for about 10% of the total apparent motion, depending on assumptions about how the geoid field has evolved during Australia's northward motion. This inferred Neogene, continental-scale dynamic N–S tilting rate of ~15–20 m/myr provides a compelling new constraint on the nature of the Earth's dynamic topographic field.

Keywords: dynamic topography; geoid; intraplate tectonics; Australia; epeirogeny

1. Introduction

The pattern of dynamic topography and its relation to the geoid field provides a powerful constraint on mantle viscosity structure (Hager, 1984; Richards and Hager, 1984) and so there has been considerable interest in elucidating the Earth's dynamic topographic field (Gurnis, 1993; Russell and Gurnis, 1994; Lithgow-Bertelloni and Gurnis, 1997; Lithgow-Bertelloni and Richards, 1998; Wheeler and White, 2000; Gurnis, 2001; Cadek and Fleitout, 2003). This has proved difficult since most of the power in the topographic field arises from isostatic compensation of shallow density anomalies within the lithosphere. In the ocean lithosphere the residual topographic field, obtained by subtracting the age dependent isostatic component of the topographic field induced by the cooling of the ocean lithosphere, should provide a powerful constraint on the dynamic topography field. Maps of residual topography suggest a dynamic topography field with amplitude of ~1–2 km, although even this is debated with some authors favouring a much more subdued dynamic signal (Cazenave and Lago, 1991) (see discussion in Panasyuk et al., 2000). The difficulty is highlighted by the anomalously low segment of the mid-

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ocean ridge system along the Australian–Antarctic discordance (AAD) to the south of Australia where the residual anomaly is ~1.5 km. However, at least some of this is attributable to thinner than normal oceanic crust and therefore is partly isostatic in nature. In the continents the pattern of dynamic topography is even more poorly constrained since the concept of residual topography cannot be rigorously defined and, despite numerous studies, the question of just how mantle convection impacts on the surface topographic field of the continents remains a major unresolved issue.

Modelling studies that couple surface topography to mantle dynamics consistently predict dynamic topographic effects of several kilometres (Lithgow-Bertelloni and Gurnis, 1997). However, there is little direct indication that the geological record of the continents involves dynamic vertical motions of a kilometre or more since the continents seem to have been immune from periods of almost total inundation. While some workers have questioned whether there is any significant dynamic topographic record preserved on the continents (Wheeler and White, 2000), the analysis of Palaeozoic and Mesozoic flooding records from various continental interiors does seem to implicate dynamic topography of an amplitude of around 500 m (Mitrovica et al., 1989; Bond and Kominz, 1991; Gurnis, 1993; Russell and Gurnis, 1994; Gurnis et al., 1998). For example, Gurnis (1993) showed that differences in the timing of Cretaceous flooding of the Australian continent, relative to other continents, is best explained in terms of the dynamic topographic effects associated with Australia's eastward motion across the anomalous mantle. This anomalous mantle is now inferred to reside beneath, and presumably sources, the dynamic component of the residual bathymetric anomaly associated with the AAD. With the exception of some very general estimates of the relative vertical motion of different continents (Bond, 1978a,b; Lithgow-Bertelloni and Gurnis, 1997) there has been little attempt to elucidate the detailed geological record of the dynamic topographic evolution of the continents over the last few 10′s of million years. In one such study, Wheeler and White (2000) concluded that Cainozoic dynamic subsidence of the south-east Asian margin has an upper bound of ~300 m, largely accumulated in the last 5–10 Myr. This conclusion is in significant conflict with modelling studies that predict 1–2 km of Cenozoic dynamic subsidence in this region (Lithgow-Bertelloni and Gurnis, 1997).

If dynamic topography produces geologically significant vertical motions of the continents then it should be evinced as a record of differential sea-level change around a large, tectonically stable, but fast moving continent such as Australia. Importantly, a record of differential sea-level change around such a continent would allow the clear separation of the eustatic and tectonic signals. This would not only provide a better understanding of the way dynamic topography impacts on continents but help improve our understanding of the eustatic sea level. Because the dynamic topographic field is associated with mantle convection, its surface expression has a spatial wavelength of order 10^3 km. The temporal record of accumulation of such differential dynamic motion around a continent such as Australia that moves at 6–7 cm/yr can be expected over a period of ~15 million years, and therefore should be apparent in the Neogene record. This contribution focuses on the record of the Neogene differential motion around Australia inferred from palaeo-shorelines, and the morphological and stratigraphic development of its leading and trailing margins.

Australia arguably provides the best laboratory for seeking such a Neogene record of differential dynamic topography because of the following considerations:

1. at least since 43 Ma, Australia has been the fastest moving continent. In this time it has traversed a

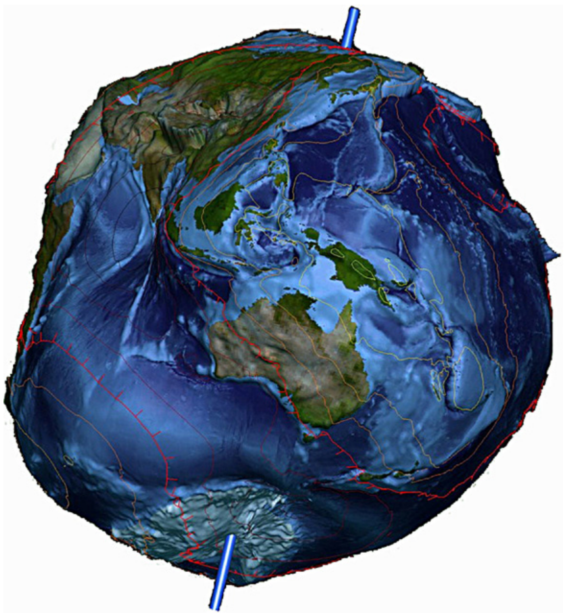

Fig. 1. Representation of the variation in the geoid field across Australia, illustrated by mapping a satellite derived image of the Earth onto a greatly exaggerated view of the geoid field. The magnitude of the geoid field variations are indicated by the contours with 20 m intervals, with the geoid 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.

relatively large amplitude geoid anomaly now expressed as a differential of about +80 m from the south-west corner to the north-east tip of the continent (Figs. 1 and 2).
2. in tectonic terms Australia is relatively stable, although not entirely inactive (Sandiford et al., 2004; Celerier et al., 2005).
3. although some distal parts of its northern shelf are affected by flexure from adjacent plate boundary activity, all of the present coastline is well beyond the flexural response wavelength (~200–300 km) of adjacent active plate boundary to the north (Fig. 2).
4. the rifting responsible for the development of its northern, western and southern passive margins dates to more than 120 Ma (eg., Veevers, 2000), and so thermal subsidence can be excluded as a cause of differential vertical movements in the Neogene.
5. finally, its relatively arid late Neogene climates have resulted in exceptionally low erosion rates (Biermann and Caffe, 2002) allowing preservation of an extraordinary archive of Cainozoic palaeo-shoreline features (Hou et al., 2006).

As can be deduced from the Lithgow-Bertelloni and Gurnis' (1997) analysis, Australia's northward motion towards the subduction realm in Indonesia and the western Pacific should induce a dynamic subsidence that progressively sweeps southward across the continent resulting in apparent N-side down tilting, if dynamic topography is significant. This is because subduction realms are dynamic topography lows and geoid highs. It is this pattern of Neogene continental-scale tilting of Australia that I seek to elucidate in this contribution. Since any apparent vertical motion must be deduced with reference to the ambient sea-level or geoid height, such differential changes in pattern of sea-level height hold the potential for decomposing the inferred vertical motions into an apparent component caused by the motion of the continent relative to the geoid and a real component induced by dynamic topography. In the following, the term *apparent vertical motion* is used to signify the combination of dynamic topography and geoid variation, without implying the unique attribution to either. The relative contributions of dynamic topography and geoid variation to the inferred apparent vertical motion are assessed in Section 4.

One obvious difference in the various continental margins around Australia relates to the present-day widths of the continental shelves. The southern or trailing continental shelf has a characteristic width (measured to the 250 m bathymetric contour) of ~100 km, 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. This morphotectonic asymmetry between the leading and trailing margins suggests that they may indeed preserve a record of differential relative vertical movement. This idea that can be tested with reference to the evolution of Neogene shorelines, and associated stratigraphic relations, such as evidence for progressive marine onlap or offlap.

2. Comparative Neogene evolution of Australia's continental margins

One of the most striking aspects of the geology of Australia is provided by the asymmetric distribution of marine and near-shore Cainozoic sediments around the Australian margin. Along the southern margin, extensive onshore marine deposits indicate periodic inundation prior to ~15 Ma, and again in a more limited fashion

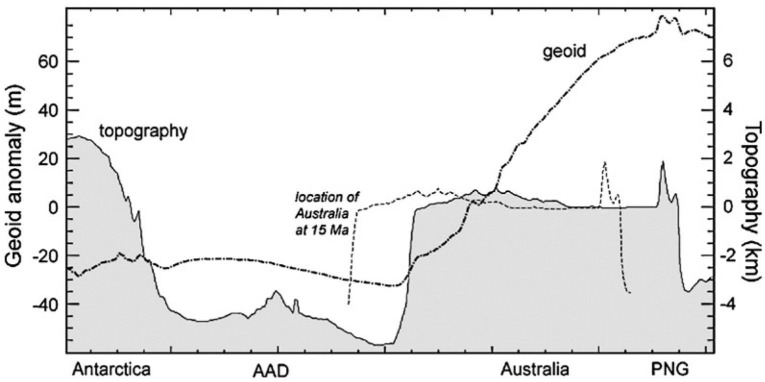

Fig. 2. Topographic (solid line) and geoid (heavy dashed line) profiles from Antarctica across the Southern Ocean, Australia and Papua New Guinea. Profiles are sources the ETOPO2 global topography and WW15MGH geoid datasets. The approximate position of the Australian continent at 15 Ma is indicated by the light dashed line. AAD is the Antarctic–Australian discordance.

after ~6 Ma. Maximum Cainozoic marine incursions often extend hundred's of kilometres inland of the present-day coastline, to elevations now up to 300 m above present-day sea level (ASL). In contrast, equivalent-aged marine sediments are almost entirely absent from the present-day onshore northern and eastern margins, or limited to elevations less than ~10 m ASL, with most interpretations placing Cainozoic shorelines offshore (Veevers, 1984, 2000) (Fig. 3). This distribution provides a profound insight into differential vertical movements, demanding a strong asymmetry in vertical motions with respect to the present-day coastline and implying that the present-day morphotectonic asymmetry of the continental shelves developed in the Neogene. This section summarises known constraints on the distribution and comparative stratigraphic relationships of Neogene marine sequences (and, where relevant, older Cainozoic sedimentary sequences) relevant to the subsequent discussion of the differential vertical motion of the Australian continent.

2.1. The southern margin stratigraphic record

Evidence for significant Cainozoic marine incursion into the now onshore realm can be found along virtually the entire length of the margin in the Bremer, Eucla, St Vincent, Murray, Otway, Port Phillip and Gippsland

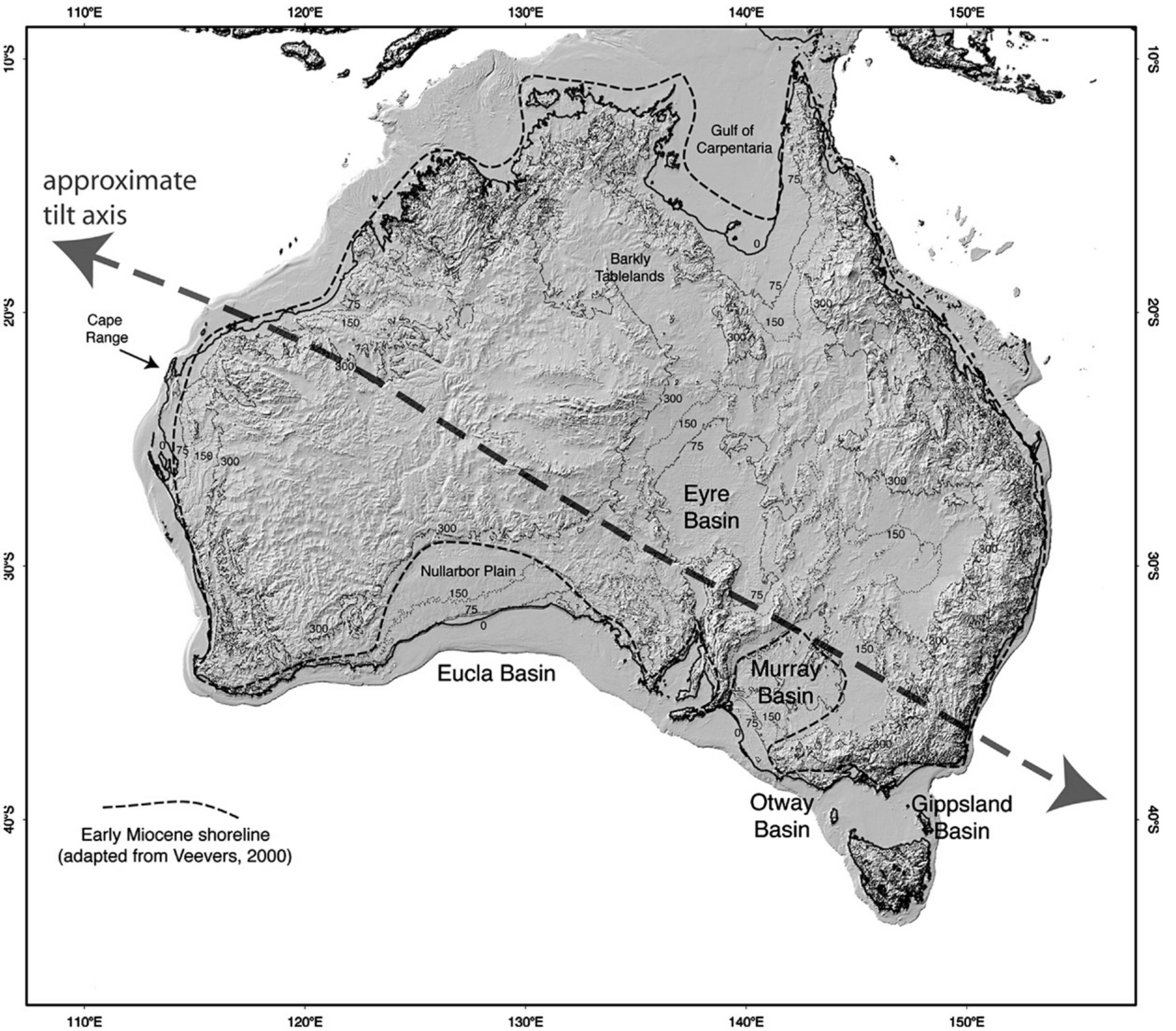

Fig. 3. Shaded relief image of the Australian continent and its continental shelf (at elevations greater than −200 m) derived from Geoscience Australia's 9″ 'bathytopo' dataset. Contours are shown for +75, +150 and +300 m. The thin dashed line shows the inferred position of mid-Miocene (~15 Ma) shorelines after (Veevers, 2000; Hou et al., 2006). 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.

Basins. The most extensive incursions are evident in the onshore part of the Eucla Basin on the Nullarbor Plain, and in the Murray Basin (Fig. 3). In the Eucla Basin, the northern-limit of marine incursion is delineated by a remarkable set of palaeo-shorelines (Figs. 4 and 5) extending up to ~400 km inland of the present-day shoreline. The palaeo-shoreline features include offshore barrier systems, marginal lagoons and inundated valleys dating back to the mid–late Eocene (~41–39 Ma). Along the north-western Eucla Basin margin, maximum marine flooding occurred at ~39 Ma to levels now ~300 m ASL. In the eastern Eucla Basin, Eocene shore-lines are significantly lower (as low as 160 m ASL) with a differential across the ~1000 km wide Eucla basin of at least 140 m. Inferred early Neogene (>15 Ma) shorelines associated with deposition of the Nullarbor Limestone generally follow the older Eocene shorelines, but are systematically lower by between 30 and 80 m (Hou et al., 2006). The maximum elevations of early Neogene shorelines occur in the central west part of the Eucla Basin along the northern most limit of the Nullarbor Plain at around 250 m ASL (Hou et al., 2003, 2006). The elevations of these early Neogene palaeo-shorelines drop systematically eastwards over a distance of ~1000 km across the Nullarbor Plain, down to about 100 m ASL, implying that much of the differential vertical displacement observed across the Nullarbor dates from after the mid-Neogene (<15 Ma). Pliocene marine sequences in the Eucla Basin are restricted to elevations less than about 40 m ASL on the Roe Plain (Fig. 4), with the absence of marine Pliocene from the surface of the Nullarbor Plain implying late Neogene sea never encroached onto land surfaces now more than ~70 m ASL. While small fault related offsets are clearly observable on parts of the Nullarbor Plain, a notable feature of the palaeo-shoreline systems is the systematic long-wavelength (1000 km) variation in elevation (Fig. 5) suggesting that the differential vertical tectonic motion is of epeirogenic, rather than seismogenic, character.

The Murray Basin (Fig. 3), in the eastern sector of the southern continental margin, also preserves extensive onshore Cainozoic marine sequences testifying to flooding in the early to mid-Cainozoic up until ~15 Ma, and again after ~6 Ma, to distances up to 450 km inboard of

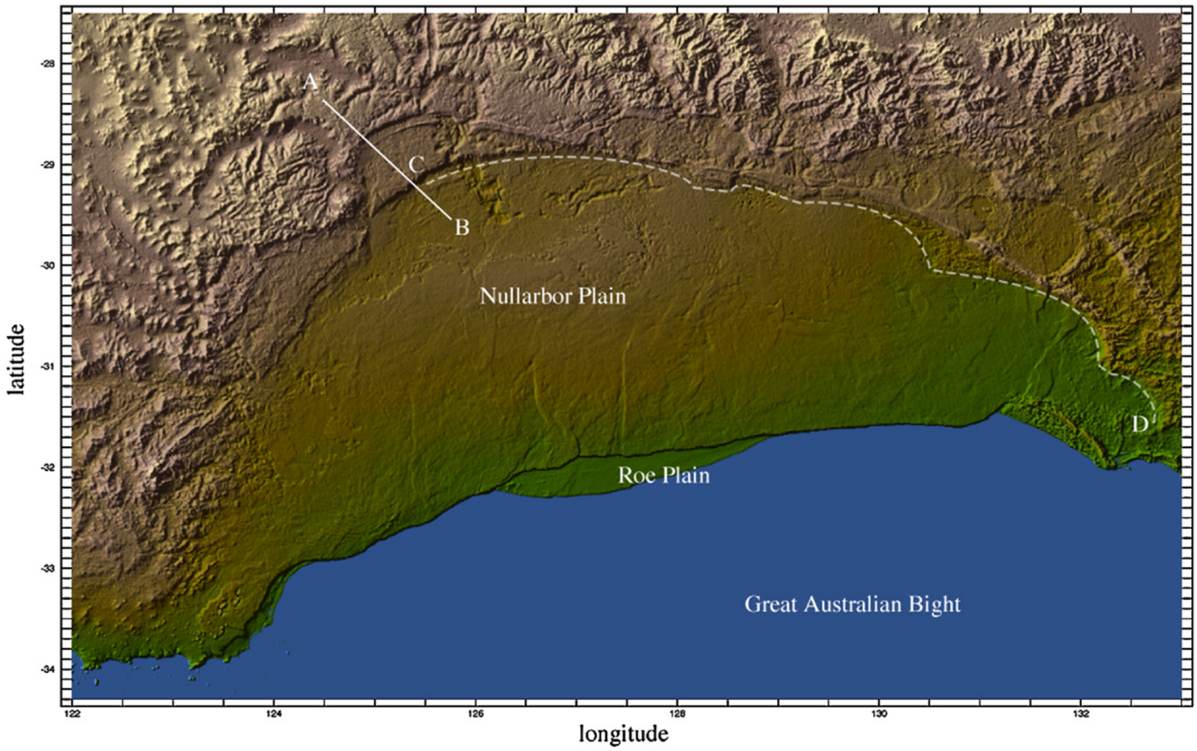

Fig. 4. Shaded relief of the Nullarbor Plain showing various palaeo-shoreline features of Eocene to mid-Miocene age (>15 Ma) along its northern margin. The Roe Plain is Pliocene marine bench bounded by the Eucla cliffs. Minor N–S trending faults crossing the Nullarbor Plain have cumulative throws of up to 20 m. See Fig. 5 for detailed topographic profiles and ages of the various shoreline features along the profile A–B, oblique to the palaeo-shorelines, and profile C–D parallel to the palaeo-shorelines.

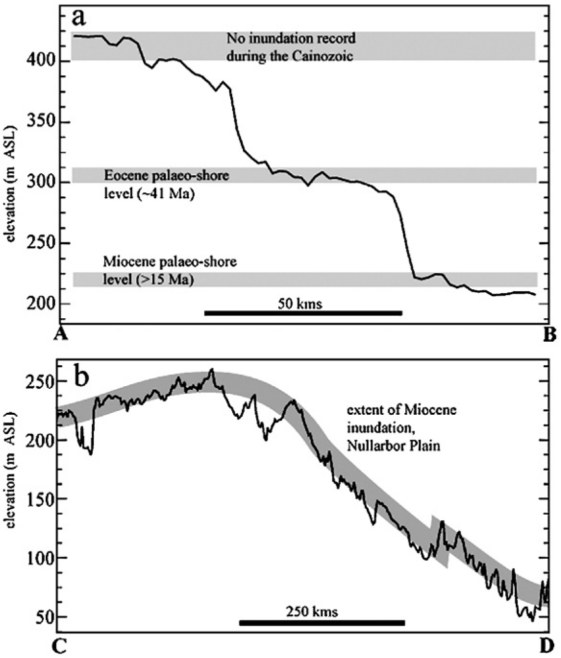

Fig. 5. SRTM3 topographic profiles across the Eucla Basin showing interpreted inundation extents at various times in the Cainozoic (see Fig. 4 for profile locations). (a) Section A–B oblique to the palaeo-shorelines in the north-western part of the basin (profile length is 130 km). (b) Section C–D parallel to the interior most limits of the Nullarbor Plain showing the interpreted limit of Miocene limit (line-of-sight profile length is 760 km). Much of the noise in the signal can be attributed to secondary erosional processes, and at least in one case, subsequent faulting. However the greatest power is in the lowest frequency component (indicated by the grey band) at a wavelength of order ~1000 km, implying a sub-lithospheric origin related to dynamic topography.

the present-day coastline (Brown and Stephenson, 1991). Of particular note is an extraordinary Pliocene–Quaternary strand-plain comprising a regressive system track of ~150 individual shoreface strandlines (Brown and Stephenson, 1991; Roy et al., 2000). The maximum extent of Pliocene marine incursion occurred at around 6 Ma, and coincides approximately with earlier marine flooding levels inferred from the distribution of Oligocene to mid-Miocene limestones. In the central part of the basin, the maximum marine incursions extend to about 70 m ASL (Brown and Stephenson, 1991). Along the southern margin of the basin, equivalent sequences can be found at elevations of up to 180 m, indicating localised uplift along the western Victorian highlands that probably relates to the late Neogene volcanic province in this region (Demidjuk et al., submitted for publication).

The stratigraphic relationships along the southern margin point to progressive offlap during the Neogene, although the extent and timing of this offlap appears to vary systematically across the margin. For example, in the western Eucla Basin the Oligocene–mid-Miocene Nullarbor Limestone extends to elevations of ~250 m ASL whereas Pliocene sequences are restricted to <~70 m ASL. In the central Murray Basin the approximate extent of Miocene and Pliocene are equivalent, with Pliocene stand-plains recording progressive offlap from elevations of ~70 m ASL. This pattern of progressive offlap reflects both differential vertical motion, and a long-term eustatic-controlled regression during the Neogene. The differential motion between the Eucla and Murray Basin mainly occurred prior to the Pliocene, in the period 15–5 Ma. In view of the fact that eustatic Neogene sea levels were unlikely to be much more than about ~100–150 m higher than the present day, the western Eucla Basin shows an apparent uplift of at least ~100–150 m relative to any eustatic sea-level changes. The long-wavelength, epeirogenic character of this uplift is clearly evident in the topographic profiles along Eocene and early Neogene shorelines. Differences in the elevation of correlative mid-Miocene marine sequences in the Eucla and Murray Basins imply a differential uplift of ~180 m across the southern margin since the mid-Miocene, with the central Murray Basin arguably showing little relative vertical motion since that time, or possibly sunk by around 50 m.

2.2. The northern margin stratigraphic record

In contrast with the southern margin, there is an almost complete lack of Cainozoic marine sequence preserved onshore around Australia's northern margin. Based on interpolations derived from the coastward thinning of offshore sequences, Veevers (2000, 1984) placed Cainozoic shorelines at between 0 and 50 m beneath sea level around much of the northern and eastern coast (Fig. 2). The best constraints come from the Karumba Basin, around the Gulf of Carpentaria, where a small 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). One case cited as an exception to this is the report of isolated scattered outcrops of fossiliferous ?late Miocene limestone on the Barkly Tablelands in the Northern Territory (Fig. 3), some 500 km 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 foram, *Ammonia beccarii*. However, this euryhaline species, is well known for its occurrence in lakes and lagoons as well as estuaries

(Cann et al., 1999). Paralic lake deposits of late Neogene age are widespread across this part of northern Australia (Doutch, 1976). In the absence of any diagnostic marine fauna amongst the species reported by Lloyd (1968), these scattered outcrops are therefore almost certainly lake deposits, rather than indicators of widespread Neogene marine incursion across Northern Australia.

While the lack of onshore marine sequences means that the precise location of Cainozoic shorelines is poorly constrained, the important implication is that present-day sea levels are, relative to the northern margin, as high as at any time during the Cainozoic. A further aspect of the northern margin that contrasts the southern margin record is provided by the offshore stratigraphic record for progressive onlap during the Neogene (Veevers, 1984, 2000). This is most strikingly evinced by the now extensive seismic profiling along the northwest shelf, that reveals a characteristically onlapping succession from Oligocene through Miocene into the Pliocene, with the Pliocene sequences extending much closer to the modern coastline than the older sequences. The onlap record implies that the northern margin has subsided during the late Neogene at rates significantly greater than the long-term, Neogene eustatic sea-level fall (ie., ~100–150 m).

2.3. Summary

One of the most extraordinary features of the Australian Cainozoic stratigraphic record is the profound asymmetry in the distribution and stratigraphic relations of marginal marine sequences, reflected ultimately in the contrasting present-day morphotectonic character of the northern and southern continental shelves. Stratigraphic relationships indicate that this morphotectonic asymmetry developed in the mid–late Neogene, after about 15 Ma. For example, in the central Eucla Basin, the width of the southern margin shelf must have exceeded 400 km at around 15 Ma, compared with its present-day width of ~100 km. In contrast, the northern margin coastlines were offshore implying a narrower shelf than present. The implication is that in mid-Neogene times the northern and southern continental shelves were of comparable widths. The development of this morphotectonic asymmetry therefore demands a relative NNE-down, SSW-up apparent vertical motion, the chronological sequence of which is constrained by the stratigraphic relationships.

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 several metres, relative to the northern margin (Murray-Wallace and Belperio, 1991) suggesting that this apparent tilting may continue to the present day. In detail, the pattern of apparent vertical motion in the Neogene is informed by the systematic variation in elevation of palaeo-shoreline features across the Nullarbor that suggests the south-west part of the continent has risen significantly relative to the south-east. Thus, to first order the distribution of preserved onshore marine sediments suggest an apparent tilt axis that trends WNW–ESE across the continent from the northern part of Western Australia through to the south-east corner of the continent (Fig. 2). The most northerly occurrence of onshore marine Miocene at Cape Range (Veevers, 1984) on the west coast supports this notion of WNW–ESE apparent tilt axis.

3. Australia: the tilting continent!

In view of the remarkable asymmetry in the distribution of marine sediments around Australia, it seems extraordinary that the idea of Australia as the 'tilting continent' has not received more attention. It seems almost too obvious to ask the question: *why no Nullarbor Plain along the northern Australian margin*? Yet the conclusion is stunningly obvious, Australia must be 'tilting', preserving an extraordinary record of continental dynamic topography. There have been surprisingly few direct references to this. One is the few studies to infer such tilting is by Murray-Wallace and Belperio (1991) who did so on the basis of a ~2 m difference in last interglacial marine bench heights around Australia, attributing the lower inferred sea levels along the northern margin to "continental-scale tilting associated with Australia's northward drift" citing a personal communication by Kurt Lambeck as the source of this insight. One other significant reference comes not from the scientific literature but from the popular and remarkably prescient science writing of Bryson (2003) who 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 m. It appears Indonesia is very slowly drowning and dragging Australia down with it". Much of this insight seems to derive from Gurnis (2001) who, in an excellent introductory account of how convection in the Earth's mantle impacts on the surface elevation of the continent, argued that through the Cainozoic that dynamic processes in the mantle have caused Australia to sink by at least 200 m. Gurnis' (2001) notion of a Cainozoic sinking was motivated in part by Bond (1978a,b) 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 his use of an index based on the proportion of continent flooding, Bond (1978a,b) was only able to provide estimates of average continental elevation changes. However, the distribution of Cainozoic marine sediments, and associated stratigraphic relations, indicates that the pattern of long-wavelength deformation of the Australian continent is 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 south-western margin of the Australian continent shows a Neogene record of uplift rather than subsidence. In this section I provide a framework for understanding the long wavelength tilting of the continent in terms of dynamic topography.

As noted in the Introduction, 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. That regions above zones of persistent downwelling, like subduction realms, are characterized by dynamic topographic lows is well illustrated by the Sunda Block north of Australia, which constitutes one of the most submerged regions of continental crust on the modern Earth. The same dynamic topographic effect that depresses the Sunda Block also helps explain the extreme width of the continental shelf along Australia's northern margin. Thus, any continent that has a long-lived history of movement towards a zone of persistent subduction, such as Australia, should experience downwards tilting in the sense of plate motion. The geological indicators of this tilting will be further augmented by the fact that downwelling zones are also typically characterized by geoid highs, with the effect of dynamic subsidence augmented by an "apparent" seal level rise created by the rise in geoid height. In the context of Australia, this notion that the continental-scale asymmetry in the Cainozoic stratigraphic is dynamically supported, rather than isostatically, is emphasised by the general parallelism of the tilt axis and contours in the long-wavelength geoid.

Importantly, the apparent sinking of the northern part of the Australian continent inferred from the absence of onshore Cainozoic shorelines must exceed the Neogene eustatic sea-level fall typically estimated at least 100 m. The evidence for systematic progressive onlap of offshore Neogene sequences suggests that this apparent tilting continues to the present day, as does the analysis of last interglacial marine bench heights around Australia (Murray-Wallace and Belperio, 1991), that suggests sea levels where ~2 m lower along the northern coast than in southern Australia. This late Pleistocene sea-level record of differential vertical motion between northern and southern Australia is remarkably consistent with the longer-term, Neogene rate of 15–20 m/myr inferred below.

The reason for the absolute uplift of the south-western part of the continent is less obvious. However, by similar logic, it may be assumed that absolute dynamic uplift relates 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 AAD, 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 remnant slab fragment, now elevated above the mantle transition zone due to the opening of the Southern Ocean, along the AAD. They further argued that this remnant slab originated from an early–mid-Mesozoic subduction system along the east Gondwana margin, and showed how dynamic topography associated with the eastward motion of Australia across a foundering Cretaceous slab provides an elegant explanation for anomalous subsidence in the Eromanga Basin. By analogy, the Cainozoic northward motion of Australia away from this anomalous mantle provides a plausible physical explanation for the apparent vertical motion of the south margin of up to ~150 m in the Neogene. The amplitude of the apparent vertical motion decreases eastwards across the southern margin, apparently declining to negligible values in the central Murray Basin in the south-east part of the continent.

4. Implications for the Earth's dynamic topography field

The Neogene tilting record of Australia provides a profound constraint on the dynamic topography field of the continents. The combined N-down, SSW-up differential in apparent vertical motion of the continent is at least 250 m and more probably 300 m, with the uncertainty mainly depending on the depth of early Miocene shorelines on the northern shelf (eg. Veevers, 2000). This differential has accumulated since ~15 Ma, when the Nullarbor Plain finally became emergent, and apparently affects last interglacial shoreline features at comparable rates to the Neogene average (Murray-Wallace and Belperio, 1991).

The apparent vertical motion reflects contributions from variations in both the geoid and the dynamic topography fields, both of which evolve as a consequence of the mantle flow associated with plate motion. Because both the dynamic topography and geoid fields in the Australasian region are likely to have evolved during the 43 myr period of Australia's northward drift, decomposing their relative contributions to Australia's apparent tilting record is not straight forward, and requires assumptions about the relativities in the dynamic topographic/geoid field evolution. One end-member scenario, addressed here, is provided by the assumption that there has been little change in the geoid field. Such an assumption may be reasonable if the long-wavelength geoid field reflects mainly deep mass distributions including those accumulated in the highly viscous lower mantle, because any retardation of slab penetration, or downward flow, into the viscous lower mantle will mean that geoid anomalies evolve at a slower rate than surface plate motions. That long-wavelength geoid anomalies in the Australasian region are sourced from appropriately deep levels is implicit in the distinctive association of a geoid high and dynamic topography low in the south-east Asian and western Pacific subduction realm (Hager, 1984; Richards and Hager, 1984, 1988). Further, tomographic imaging suggests significant slab accumulation immediately beneath the transition zone has played an important role in subduction history of the south-east Asian region (Replumaz et al., 2004) providing an obvious candidate for the source of the geoid high. This slab accumulation presumably reflects the long-term history of subduction in this region dating back to at least the Cretaceous (Whittaker et al., 2007), and thus is likely to have a characteristic time-scale of order 100 myr. These arguments suggest that the present-day long-wavelength geoid may provide a relatively robust guide to the structure of the geoid field in the Australasian region on timescales of ~10 myr relevant to recent plate motions, allowing the present-day field to be used as a reference frame for decomposing the apparent Neogene tilting record of Australia into its geoid and dynamic topography contributions.

Of the 250–300 m apparent differential motion inferred from the Australian margins, a maximum of 80 m can be attributed to variations in the geoid across Australia. However, since the continent has only tracked across about ~1/3 of this 80 m variation in the last 15 myr, the total geoid contribution to apparent vertical motion is likely to be as little as 30 m or about ~10% of the total apparent vertical motion. As such the estimated contribution of dynamic topography to the apparent differential vertical motion is in the range 220–270 m, with the implied continental-scale dynamic tilting rate of ~15–20 m/myr. The fact that this estimate is essentially the same the independent, but much shorter-term estimate derived from last interglacial sea bench height variation is important, since variations in long-wavelength geoid field cannot plausibly have contributed to apparent tilting on the 100,000 yr timescale. The correspondence between independently derived, long-term and short-term tilting records therefore seems to validate the assumption employed here that the geoid field is essentially invariant on the relevant timescales.

This unique record of dynamic tilting evinced by the Australian continent warrants two further points of discussion relevant to the broader issues of the dynamic topography field. The first relates to the debate about the total amplitude. In as much as the Australian Neogene plate motion has tracked across only a small portion of the Australasian geoid anomaly, further northward motion of Australia should produce an even greater dynamic response, particularly through further subsidence in the north. Thus the total amplitude of dynamic topography must be significantly larger than the 220–280 m inferred for the Australian Neogene. Exactly how large is still something of an open question, and not one that is uniquely solved by the observations reported here. However it seems reasonable to assume that the total amplitude is at least twice that preserved in the Australia's Neogene tilting record, and therefore compatible with the ~500 m amplitude dynamic motions inferred by Gurnis and others (Bond and Kominz, 1991; Gurnis, 1993, 2001) to explain Palaeozoic inundation of various continental interiors. Intriguingly, along Australia's southern margin, Eocene shore lines formed at around 41 Ma, soon after the onset of fast-spreading, are generally not significantly higher than Miocene shorelines except in the western Nullarbor Plain where they are up to 80 m higher (Figs. 4 and 5). Thus the total amplitude of dynamic topography since the onset of fast spreading in the southern Ocean is not much greater than that of the Neogene. It therefore seems unlikely that the 1–2 km dynamic topographic expression indicated in the numerical models of Lithgow-Bertelloni and Gurnis (1997) is supported in the Australian Cainozoic record.

The second point of discussion concerns the ratio of the geoid field and the dynamic topography field. Since the classic studies of Hager and Richards (Hager, 1984; Richards and Hager, 1984, 1988), it has been known that the ratio of geoid height and dynamic topography, or admittance, provides a powerful constraint on the dynamics and viscosity structure of the mantle. As outlined above the apparent vertical motion of the Australian Neogene record is estimated to reflect a geoid contribution of about 10%. However, the possibility that the admittance might vary across Australia is suggested by the fact that the present-day geoid variation across the southern ocean is minimal (Figs. 2 and 6), raising the prospect that the apparent vertical motion of the southern margin is almost entirely due to variations in dynamic topography. Certainly, the large variation in dynamic topography from west to east is matched by little geoid variation when mapped onto the past 15 myr of plate motion (Fig. 6). In contrast, the geoid gradients across the northern margin of the continent are consistent with ~30–40 m of relative motion over the last 15 myr, suggesting an admittance of about 20–25%. Such variations in admittance presumably reflect differences in the nature of the generative circulation processes and associated density anomalies in the mantle. In regions where the mantle flow penetrates into a more viscous lower mantle, such as expected in the long-lived subduction realm to the north of Australia, the dynamic topographic induced by the flow response will be preferentially partitioned away from the upper boundary layer to the lower boundary layer of the flow regime. Indeed it is this very partitioning that gives rise to the positive geoid anomaly (Richards and Hager, 1984), and yields a relatively high admittance. In regions where flow is restricted to the upper mantle, dynamic topography will be expressed mainly in the upper boundary layer, and admittance will be lower. This analysis suggests then the source for the dynamic typographic uplift of the southern margin of the Australian continents relates to a mantle flow regime confined to the upper mantle, producing the distinctive, but rather unusual, association between a dynamic topography low and a geoid low along the AAD. However, a word of caution is required since in this case it is quite possible that the geoid field in the southern ocean may evolve rates comparable to plate motion and the assumption of the plate movement in a relatively static geoid field may be grossly inadequate, at least for understanding the tilting record of Australia's southern margin.

In summary, the observations presented in this paper provide a new constraint on the dynamic topographic field of the continents. The Neogene record of Australia points to a dynamic topography field of several hundred metres, that has clearly left a profound imprint in the geological record of the continent. The recognition of an

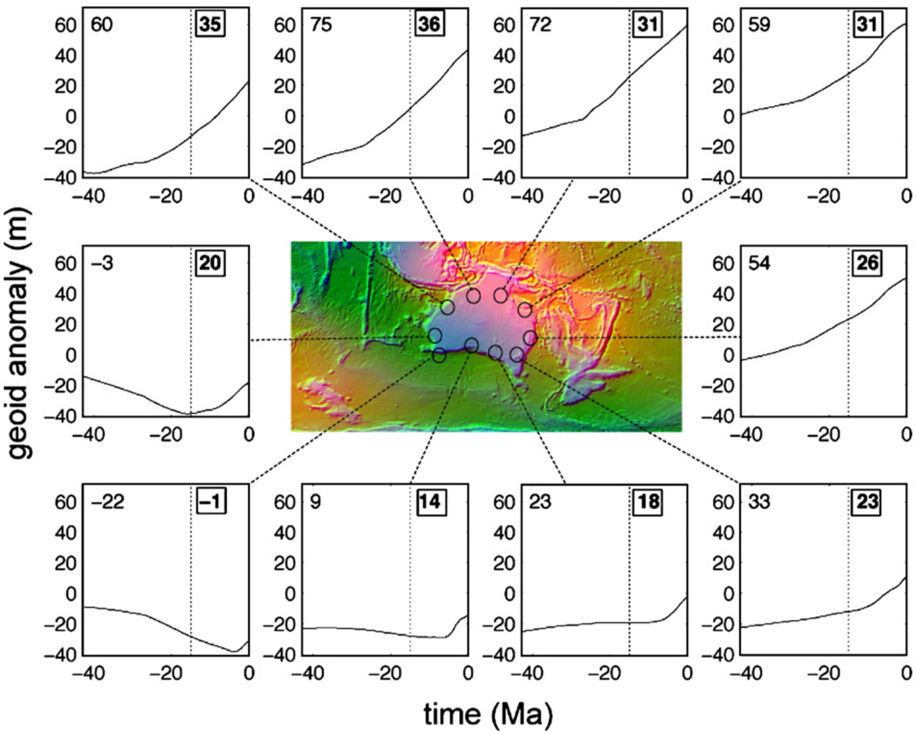

Fig. 6. Inferred geoid variations as a function of time for selected points around the Australian continent, based on the assumption that the present-day geoid provides an adequate representation of the geoid in the past (ie., Australia is moving in a static geoid field). As discussed in the text this assumption may be reasonable for the last 15 myr period encompassing the Neogene tilting record of Australia, but not for longer time-scales appropriate to the 43 myr record of fast northward motion, particularly for northern Australia where increase in the geoid high relates to a much longer-term slab accumulation in the deep mantle (see text for further discussion). The origin of the geoid low beneath the AAD is less clear and its dynamics may have much shorter characteristic timescales, and so this assumption may be inadequate for understanding the southern margin. The inferred 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 for the past 43 myr differential is indicated by the number in the top left of each panel.

unambiguous dynamic topographic record of several hundred metres amplitude in the recent geological past, in a tectonically stable continent such as Australia, clearly has profound import for unravelling the longer term eustatic sea-level record and must be considered, for example, when using the continental stratigraphic record to as a constraint on the growth of ice-sheets during the Neogene. In this regard the Australian tilting record shows that while dynamic topography vertical motions accumulate at rates (10–20 m/myr) several orders of magnitude lower than maximum eustatic sea-level changes, the amplitude of dynamic topography variation is significantly larger the eustatic variation, at least over the duration of the Neogene. Thus this study further highlights the problem of attribution of long-term (1–100 myr) sea-level variations to eustatic processes even in relative stable continental settings, because all continents ride on a dynamic mantle, necessarily contributing a dynamic topographic signal. While the peculiar features of the Australia's geodynamic setting have conspired to make this dynamic topographic signal seemingly obvious, it is salutary to think that it has, until now, gone largely unnoticed and more-or-less unreported. Revealing such a signal in the ancient geological record, or on slower moving continents, via the methods employed here would seem therefore to be a formidable task, and for such cases it is probable that other comparators such as relative continental hypsometries are likely to provide more definitive indicators of the dynamic topographic signal (eg Gurnis, 1993).

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