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Integrating deep Earth dynamics in paleogeographic reconstructions of Australia

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ABSTRACT

It is well documented that the Cenozoic progressive flooding of Australia, contemporaneous with a eustatic sea level fall, requires a downward tilting of the Australian Plate towards the SE Asian subduction system. Previously, this large-scale, mantle-convection driven dynamic topography effect has been approximated by computing the time-dependent vertical shifts and tilts of a plane, but the observed subsidence and uplift anomalies indicate a more complex interplay between time-dependent mantle convection and plate motion. We combine plate kinematics with a global mantle backward-advection model based on shear-wave mantle tomography, paleogeographic data, eustatic sea level estimates and basin stratigraphy to reconstruct the Australian flooding history for the last 70 Myrs on a continental scale. We compute time-dependent dynamic surface topography and continental inundation of a digital elevation model adjusted for sediment accumulation. Our model reveals two evolving dynamic topography lows, over which the Australian plate has progressively moved. We interpret the southern low to be caused by sinking slab material with an origin along the eastern Gondwana subduction zone in the Cretaceous, whereas the northern low, which first straddles northern Australia in the Oligocene, is mainly attributable to material subducted north and northeast of Australia. Our model accounts for the Paleogene exposure of the Gulf of Carpentaria region at a time when sea level was much higher than today, and explains anomalous Late Tertiary subsidence on Australia's northern, western and southern margins. The resolution of our model, which excludes short-wavelength mantle density anomalies and is restricted to depths larger than 220 km, is not sufficient to model the two well recorded episodes of major transgressions in South Australia in the Eocene and Miocene. However, the overall, long-wavelength spatio-temporal pattern of Australia's inundation record is well captured by combining our modelled dynamic topography with a recent eustatic sea level curve. We suggest that the apparent Late Cenozoic northward tilting of Australia was a stepwise function of South Australia first moving away northwards from the Gondwana subduction-related dynamic topography low in the Oligocene, now found under the Australian–Antarctic Discordance, followed by a drawing down of northern Australia as it overrode a slab burial ground now underlying much of the northern half of Australia, starting in the Miocene. Our model suggests that today's geography of Australia is strongly dependent on mantle forces. Without mantle convection, which draws Australia down by up to 300 m, nearly all of Australia's continental shelves would be exposed. We conclude that dissecting the interplay between eustasy and mantle-driven dynamic topography is critical for understanding hinterland uplift, basin subsidence, the formation and destruction of shallow epeiric seas and their facies distribution, but also for the evolution of petroleum systems.

1. Introduction

The motions of continents relative to large-scale patterns of mantle convection can contribute to the creation and destruction of sediment accommodation space due to transient, dynamic displacement of the surface topography, usually referred to as dynamic topography (Gurnis, 1990; Burgess and Gurnis, 1995; Lithgow-Bertelloni and Gurnis, 1997; Gurnis et al., 1998). A significant dynamic topography effect has been demonstrated in particular for Cretaceous and Cenozoic Australian continental paleogeography based on the misfit between the global flooding patterns and the Australian continental flooding, which appears to be out-of-sync with eustasy (Russell and Gurnis, 1994; Gurnis et al., 1998; Veevers, 2001; Sandiford, 2007; DiCaprio et al., 2009). Large-scale, mantle-driven dynamic topography can be approximated by the time-dependent vertical shifts and tilts of a plane, computed from the displacement needed to reconcile the interpreted pattern of marine incursion with a predicted topography in the presence of global sea level variations (DiCaprio et al., 2009). However, some observed subsidence and uplift anomalies, particularly along the south coast of Australia (Sandiford, 2007; DiCaprio et al.,

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2009), indicate a more complex interplay between time-dependent mantle convection and plate motion than that approximated by vertical shifts and tilts of a plane.

Geodynamic models predict between a few hundred meters and up to 2 km of surface vertical motion in response to mantle dynamic processes (Mitrovica et al., 1989; Russell and Gurnis, 1994; Lithgow-Bertelloni and Gurnis, 1997; Lithgow-Bertelloni and Silver, 1998; Gurnis et al., 1998; Conrad and Gurnis, 2003; Conrad et al., 2004; Müller et al., 2008b). Depending on the tomography model used to infer mantle density heterogeneities, Steinberger (2007) found 0.4–1.0 km rms amplitude, when converting vertical stresses to elevation beneath air, compared to 0.4–0.5 km for residual topography (i.e., observed topography corrected for crustal thickness variations and variations in ocean floor age). However, the surface expression of subducted slabs in Southeast Asia is half an order of magnitude smaller than predicted by dynamic topography models (e.g. Wheeler and White, 2000), having an upper bound of only ≈300 m. This has been interpreted as indication that mantle mass anomalies are supported elsewhere, presumably at internal boundaries within Earth.

Here we use a simple mantle backward-advection model to unravel the contribution of mantle convection-induced dynamic topography to the paleogeography of the Australian continent since 70 Ma. Published Australian paleogeographic and geological data are used to match modelled paleo-topography, focusing on the evolution of the large-scale spatial distribution of anomalous subsidence and uplift and to provide better constraints on the amplitudes of mantle-induced topography. Our method facilitates the quick evaluation of global and regional dynamic topography models with geological observations.

2. Australian Cenozoic paleogeography: key regions for this study

The Australian continent is characterised by vast areas of low elevation (Fig. 1), making it an excellent natural laboratory for investigating the effects of eustasy and mantle convection on paleogeography. Australia's continental margins had entered post-rift subsidence stages long before Cenozoic times (Veevers et al., 1991; Stagg et al., 1999). Rifting and breakup of the northern and western margins was completed by Late Jurassic–Early Cretaceous times, along the southern and eastern (Tasman Sea) in the Early Cretaceous and early Late Cretaceous, respectively (Gaina et al., 1998; Norvick and Smith, 2001), with thermal, post-rift subsidence commencing around 110–80 Ma (Norvick and Smith, 2001; Brown et al., 2001). The thermal effects of rifting in landward parts of marginal basins such as the Eucla Basin had likely dissipated by the beginning of the Tertiary along the central southern margin, hence can be largely disregarded for this study.

The Australian plate has undergone major changes in plate boundary forces on its northward motion throughout the Tertiary (Fig. 1b), which profoundly affected the evolution of the intraplate stress field through time, causing reactivation along pre-existing structures or weaknesses (Sandiford et al., 1995; Dyksterhuis et al., 2005; Dyksterhuis and Müller, 2008). Examples where this might have had an effect on the local topography due to significant deformation are the tectonically active Flinders/Mt. Lofty Ranges (Fig. 1; Dyksterhuis and Müller, 2008; Célerier et al., 2005; Sandiford, 2003b) and the Otway Ranges (Dyksterhuis and Müller, 2008; Sandiford 2003a,b). Collisional processes along the eastern and northern margins of the Australian plate are reported to start around Oligocene time in New Caledonia, Papua New Guinea (Cluzel et al., 2001; Schellart et al., 2006) and, later, in the New Zealand region between 25 and 20 Ma (Schellart, 2007; Kamp, 1986) and along the northern Australian margin (Hinschberger et al., 2005; Hall and Wilson, 2000; Hall, 1998). The effects from foreland loading due to orogeny prove to be negligible because of the distance from the flexural load as modelling by Müller et al. (2000b) has demonstrated. Subsidence due to changes in the far field and intraplate stress field is considered to produce elongated, asymmetric patterns (Nielsen et al., 2007; Nielsen et al., 2005) and is not evident at the scale of this work from available Australian data. Here, we focus on subsidence and uplift anomalies at large wavelengths (1000 km and more) which cannot have their origin in structural reactivation or flexure.

The various departures of the Cenozoic Australian flooding history from global eustatic curves have been pointed out by Veevers (1984) and contributors who realised a significant misfit between continental inundation patterns and the eustatic sea level estimate of Bond (1978). Fig. 2 shows the eustatic sea level estimate of Haq and Al-Qahtani (2005) plotted versus the inundation of the Australian continent since 70 Ma. The inundation is determined by the flooded continental area relative to the present-day 200 m isobath. Whereas the eustatic sea level estimates all show a gradual decrease, the inundation of Australia increases from around 5% in early Paleocene to about 25% at present (Fig. 2).

Focusing on the Murray and Eucla Basins, the Gulf of Carpentaria and the inner parts of the North West Shelf (Fig. 1) we investigate anomalies in Cenozoic inundation patterns and their origin utilising a recent eustatic sea level curve by Haq and Al-Qahtani (2005). In middle Miocene times (<11 Ma), Veevers (1984) describes the following anomalies based on a sea level which corresponds to the present-day 20 m contour (80 m according to Haq and Al-Qahtani, 2005), assuming a constant hypsometry.

- In the Nullarbor Plain (Fig. 1), shallow marine middle Miocene limestone slopes occur from an elevation of +200 m inland towards 0 m at the coast, indicating uplift since deposition of about 180 m by tilting about a hinge near the coast. If 80 m is used as reference sea level, the inland limestone section would have been uplifted about 120 m with the coastal parts being about 50–60 m too low.
- In the Murray Basin (Fig. 1) the top of Mid-Miocene shallow marine limestone and clay has an elevation of 0 m in the east and −80 m in the west, indicating subsequent subsidence of at least 100 m about a hinge on the eastern side of the basin. Using the Haq and Al-Qahtani (2005) estimate, the deposits in the western part must have subsided about 160 m.
- The Lake Eyre region (Fig. 1), today at 12 m below sea level, was not covered by the Miocene sea which rose +20 m (or +80 m according to Haq and Al-Qahtani, 2005) above the present sea level. The top of the Miocene lacustrine–fluvial Etadunna Formation is today found at −17 m implying subsidence of about 40 m or 100 m using Haq and Al-Qahtani (2005).
- In the Cape Range area (Fig. 1) of Western Australia's onshore Carnarvon Basin, Mid-Miocene shallow marine limestone is now found at elevations of +300 m, implying local uplift of 280 m (220 m, Haq and Al-Qahtani, 2005) since deposition.

For the Eocene–Miocene times (38–24 Ma), Veevers (1984) assumes a sea level of 75 m above present (Bond, 1978), whereas the work of Haq and Al-Qahtani (2005) indicates a sea level of 220–180 m for this time:

- In southwestern Australia, Late Eocene shallow marine sediments now have an elevation of +250 m near Norseman, resulting in a net uplift of 175 m (Haq and Al-Qahtani, 2005). At the northern edge of Eucla Basin, along the western and north-eastern margins and off north-eastern Queensland, the Eocene and Miocene shorelines coincide, indicating a subsidence of 55 m (Haq curve: 100–140 m) in the Oligocene.
- In the Lake Eyre area, the top of the Eocene non-marine Eyre Formation has an elevation of −60 m, implying subsidence of at least 135 m (240–280 m) since the Eocene, comprising at least 60 m in the Oligocene (Veevers, 1984).
- In the Renmark area of the Murray Basin, the top of the Late Eocene shallow marine clay has an elevation of −200 m, indicating 275 m (≈380–420 m) of subsidence since the Eocene.

In summary, there are numerous localities along the Australian continental margins and in the interior where eustatic sea level variations and local tectonics alone cannot explain the large-scale