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Formation of Australian continental margin highlands driven by plate–mantle interaction

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ABSTRACT

Passive margin highlands occur on most continents on Earth and play a critical role in the cycle of weathering, erosion, and atmospheric circulation. Yet, in contrast to the well-developed understanding of collisional mountain belts, such as the Alps and Himalayas, the origin of less elevated (1–2 km) passive margin highlands is still unknown. The eastern Australian highlands are a prime example of these plateaus, but compared to others they have a well-documented episodic uplift history spanning 120 million years. We use a series of mantle convection models to show that the time-dependent interaction of plate motion with mantle downwellings and upwellings accounts for the broad pattern of margin uplift phases. Initial dynamic uplift of 400–600 m from 120–80 Ma was driven by the eastward motion of eastern Australia's margin away from the sinking eastern Gondwana slab, followed by tectonic quiescence to about 60 Ma in the south (Snowy Mountains). Renewed uplift of ~700 m in the Snowy Mountains is propelled by the gradual motion of the margin over the edge of the large Pacific mantle upwelling. In contrast the northernmost portion of the highlands records continuous uplift from 120 Ma to present-day totalling about 800 m. The northern highlands experienced a continuous history of dynamic uplift, first due to the end of subduction to the east of Australia, then due to moving over a large passive mantle upwelling. In contrast, the southern highlands started interacting with the edge of the large Pacific mantle upwelling ~40–50 million years later, resulting in a two-phase uplift history. Our results are in agreement with published uplift models derived from river profiles and the Cretaceous sediment influx into the Ceduna sub-basin offshore southeast Australia, reflecting the fundamental link between dynamic uplift, fluvial erosion and depositional pulses in basins distal to passive margin highlands.

1. Introduction

A wide range of mechanisms has been suggested to account for the formation and evolution of passive margin highlands. A recent review (Japsen et al., 2012) pointed out that most passive margin plateaus are too wide to be a product of plate flexure (Weissel and Karner, 1989) and they frequently exhibit renewed post-rift uplift, whereas rift-shoulder uplift would only produce one phase of uplift, accompanying continental rifting. Japsen et al. (2012) favoured lithospheric-scale folding at craton boundaries as a universal explanation for highland uplift, but observations supporting this idea are scarce, including a lack of evidence for lithospheric-scale folding in these regions, and some prominent highlands such as the eastern Australian highlands have formed entirely in relatively young Phanerozoic crust (Lambeck and Stephenson, 1986). Deformation and significant uplift due to intraplate stress changes through time can be accompanied by significant crustal deformation, expressed by thrust and reverse faults, which is readily observed in regions where it is the primary driver of uplift, for instance along the Flinders Ranges in South Australia (Célérier et al., 2005; Dyksterhuis and Müller, 2008). No such deformation is observed along the eastern highlands of Australia, driving the search for alternative hypotheses to explain their uplift. It has alternatively been argued that the eastern highlands represent an ancient remnant of the Paleozoic Lachlan foldbelt, and have experienced no post-Paleozoic tectonic uplift at all, in which case the Mesozoic–Cenozoic uplift of the highlands would be entirely driven by erosional unloading (Lambeck and Stephenson, 1986; Stephenson and Lambeck, 1985) and the highlands should currently be in regional isostatic equilibrium. In contrast, Czarnota et al. (2014) suggested that the eastern highlands are not in iso-

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static equilibrium, but dynamically supported, based on their large positive gravity–topography admittance ratio. The idea that mantle dynamic topographic support may account for the elevation of passive margin highlands has been explored for the Brazilian Highlands (Flament et al., 2014), the South African escarpment (Braun et al., 2014; Flament et al., 2014; Gurnis et al., 2000; Lithgow-Bertelloni and Silver, 1998) and the Ethiopian and East African plateaus (Moucha and Forte, 2011). These cases all invoke interaction of continental margins with the African superswell, which can account for a single phase of uplift. However, many marginal highlands have experienced more than one uplift event. The Eastern Australian highlands display an initial uplift phase in the Late Cretaceous, followed by a mid-late Cenozoic renewal in uplift, with the timing and magnitude of uplift differing along strike (Czarnota et al., 2014). The age of the onset of uplift is constrained by elevated marine Cretaceous sedimentary rocks in the north and by uplifted Triassic deltaic sequences of the Sydney Basin in the south (Wellman, 1987). Renewed Cenozoic uplift has been particularly well documented in the southernmost portion of the eastern highlands. Uplifted Cenozoic fluvio-lacustrine deposits on the East Highlands in Victoria suggest deposition in lowland paleovalleys, incised into a widespread paleoplain surface that had a maximum paleorelief in the Eocene of less than 600 m, in contrast with their current location at elevations greater than 1400 m (Holdgate et al., 2008).

The successive phases of uplift and exhumation of the eastern highlands have resulted in erosion, transport and deposition of large volumes of sediments. South of the Snowy Mountains, the "Bassian Rise" within the Bass Strait is estimated to have been unloaded by 2.1 km (O'Sullivan et al., 2000). The southern coalfield of the Sydney Basin records 1.5 km of unroofing (Faiz et al., 2007), while the Bathurst batholith along the crest of the eastern highlands in New South Wales is estimated to have been uplifted between 1–2 km (O'Sullivan et al., 1995). Further north the Cooper–Eromanga Basin records unloading by ∼200–1000 m (Mavromatidis, 2006). In the Early Cretaceous the transcontinental Ceduna River is thought to have transported sediment from Queensland and New South Wales into the Ceduna sub-basin, forming a large delta (Lloyd et al., 2015; Norvick et al., 2008), whereas others (MacDonald et al., 2013) have argued that most Ceduna delta sediments are relatively locally-derived. The products of the Cenozoic uplift of the southern portion of the eastern highlands have been linked to sedimentary sequences in the Murray, Otway, Bass and Gippsland basins (Jones and Veevers, 1982).

Analysis of apatite fission track data has demonstrated rapid Early Cretaceous uplift within the eastern highlands in New South Wales (O'Sullivan et al., 1995), as well as rapid Cenozoic uplift around the Bass Strait at the southernmost extent of the eastern highlands (O'Sullivan et al., 2000), incompatible with the model of Lambeck and Stephenson (1986). O'Sullivan et al. (2000) speculate that exhumation is triggered by the opening of the Tasman Sea, whereas Czarnota et al. (2014) argue for a dynamic support mechanism driving the uplift, identifying temperature anomalies in the lithosphere as its potential cause. Here we provide a plausible mechanism for both exhumation events, linking plate motions to mantle convection through time, building on the work by Gurnis et al. (1998), and we test competing hypotheses for the distal versus proximal origin of Ceduna Delta sediments. We demonstrate that the time-dependent interaction of the Australian continental margin with a sinking Cretaceous eastern Gondwana slab and the large-scale mantle return flow in response to circum-Pacific subduction can explain most of the observed spatio-temporal uplift history.

2. Methods

We model global mantle flow based on the subduction history predicted by topologically-evolving plate boundaries (Seton et al., 2012), including a deforming plate model that accounts for the extension of the continental margins south and east of Australia, leading to an improved reconstructed geometry of plate boundaries through time. The location of subduction along the eastern margin of Australia through time is a key parameter in the models, as it determines how the overriding plate has interacted with mantle convection since the Cretaceous. The subduction zone location depends on the existence or absence of back-arc basins through time, and on how we account for deformation during the Cretaceous rifting and breakup of East Gondwana. The Cretaceous was a time of major change in the geodynamic setting of the East Gondwana margin, with the previous long-lived active margin postdated by rifting, continental breakup, and initiation of seafloor spreading. The rifting resulted in the formation of a largely submerged continent (the northern part of Zealandia) separated from Australia by oceanic crust of the Tasman Sea (Gaina et al., 1998) and from Antarctica by the Amundsen Sea (Larter et al., 2002). The switch to dominant extension is dated to around 105 Ma based on evidence from New Zealand and West Antarctica (Mortimer, 2014; Siddoway, 2008; Tulloch et al., 2009).

How Australia interacted with sinking slabs through time also depends on the absolute plate motion model. Here we use a hybrid absolute reference frame that minimizes net lithospheric rotation (Shephard et al., 2014) and test two alternative regional subduction models. The first tectonic model (Fig. 1, Reconstruction A) includes a large (∼1000 km width at its maximum extent) Early Cretaceous (140–120 Ma) back-arc basin east of the Lord Howe Rise, representing the now subducted South Loyalty Basin which may have formed due to eastward rollback of the long-lived west-dipping eastern Gondwana subduction zone (Matthews et al., 2011); the alternative scenario (Fig. 1, Reconstruction B) is based on the premise that west-dipping subduction is continuous to the east of the Lord Howe Rise between 140–85 Ma, without a large intervening back-arc basin, and the South Loyalty Basin opens as a back-arc basin from 85–55 Ma, after which it is consumed by subduction (Matthews et al., 2015).

The plate models incorporate revised reconstructions of the eastern margin of Gondwana that include quantitative estimates of crustal deformation during East Gondwana breakup. The relative motion between Australia and Antarctica during the Cretaceous is constrained by restoration of extended continental crust (Williams et al., 2011) combined with additional kinematic constraints along the plate boundary described by Whittaker et al. (2013). For the rifting between eastern Australia and northern Zealandia (Lord Howe Rise), we build on previous studies focused on the seafloor spreading history (Gaina et al., 1998) by using estimates of crustal thickness within the extended crust of Zealandia (Grobys et al., 2008) and the eastern Australian passive margin (Aitken, 2010). We adapt the method of Williams et al. (2011) to restore the crust within northern Zealandia to its pre-rift extent, thus defining the geometry of the margin of the East Gondwana continent in the early Cretaceous. We assume that extension occurred along small circles orthogonal to the trend of the continental ribbon and to the extensional basins formed within it, and consistent with the subsequent opening of the Tasman Sea defined by fracture zones within oceanic crust. The crustal restoration approach requires assuming a value for the average crustal thickness before the onset of extension, for which an appropriate value is poorly constrained. We tested a range of plausible values for crustal thickness along an active margin (Mantle and Collins, 2008), with the inferred locations of the restored East Gondwana margin reconstructed along small