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Australian plate motion and topography linked to fossil New Guinea slab below Lake Eyre

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ABSTRACT

Unravelling causes for absolute plate velocity change and continental dynamic topography change is challenging because of the interdependence of large-scale geodynamic driving processes. Here, we unravel a clear spatio-temporal relation between latest Cretaceous–Early Cenozoic subduction at the northern edge of the Australian plate, Early Cenozoic Australian plate motion changes and Cenozoic topography evolution of the Australian continent. We present evidence for a ∼4000 km wide subduction zone, which culminated in ophiolite obduction and arc-continent collision in the New Guinea–Pocklington Trough region during subduction termination, coinciding with cessation of spreading in the Coral Sea, a ∼5 cm/yr decrease in northward Australian plate velocity, and slab detachment. Renewed northward motion caused the Australian plate to override the sinking subduction remnant, which we detect with seismic tomography at 800–1200 km depth in the mantle under central-southeast Australia at a position predicted by our absolute plate reconstructions. With a numerical model of slab sinking and mantle flow we predict a long-wavelength subsidence (negative dynamic topography) migrating southward from ∼50 Ma to present, explaining Eocene–Oligocene subsidence of the Queensland Plateau, ∼330 m of late Eocene–early Oligocene subsidence in the Gulf of Carpentaria, Oligocene–Miocene subsidence of the Marion Plateau, and providing a first-order fit to the present-day, ∼200 m deep, topographic depression of the Lake Eyre Basin and Murray–Darling Basin. We propound that dynamic topography evolution provides an independent means to couple geological processes to a mantle reference frame. This is complementary to, and can be integrated with, other approaches such as hotspot and slab reference frames.

1. Introduction

Large changes in absolute plate velocity of 5–15 cm/yr have been documented for several tectonic plates, such as the Indian plate and Farallon plate, and have been ascribed to changes in plate boundary forces or changes in drag forces applied by the sub-lithospheric mantle (Patriat and Achache, 1984; Schellart et al., 2010; Cande and Stegman, 2011; van Hinsbergen et al., 2011). Changes in plate boundary forces are generally linked to changes in subduction dynamics, such as initiation or termination of a subduction zone. Indeed, geodynamic subduction models show that transient subduction phases, including progressive slab lengthening (Schellart and Moresi, 2013) and slab detachment (Burkett and Billen, 2010; van Hunen and Allen, 2011), affect lithospheric plate velocities. Once detached, a slab continues to affect the Earth's surface due to its sinking into the viscous mantle, thereby producing dynamic topography (Hager et al., 1985; Gurnis et al., 1998; Braun, 2010; Heine et al., 2010; DiCaprio et al., 2011; Flament et al., 2013). Such dynamic topography is difficult to detect considering its long-wavelength, low-amplitude signal, which is superimposed on the dominant, high-amplitude, isostatically-supported topography. The Australian continent, however, forms an ideal location for investigating signals of slab-induced dynamic topography considering it is the flattest continent on Earth that sits in the middle of the Australian plate, far from current plate boundaries. Also, it has a long history of subduction along its eastern and northern margins during the Phanerozoic (Veevers, 2000; Schellart et al., 2006; Hall, 2012). These phases of subduction can impose novel constraints on absolute plate velocities if linked to mantle structure (van der Meer et al., 2010), while Australian plate motion over such slab material could induce transient dynamic topography.

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Previous work on the connection between sinking slabs and transient dynamic topography in the Australian region was either based on advection of a mantle density field derived from seismic tomography implicitly assuming (unidentified) subduction contributions (Heine et al., 2010), or on surface tectonics (Gurnis et al., 1998; DiCaprio et al., 2011). Here we provide a complete and documented account: (1) We identify latest Cretaceous–Early Cenozoic subduction north of Australia from the geological record; (2) We predict the remnant of this subduction phase to be located in the mantle under central-southeast Australia using plate tectonic reconstructions that are tied to modern absolute plate motion models; (3) We identify this slab remnant in independent seismic tomography models; and (4) We successfully predict dynamic topography change of the Australian continent during passage over the sinking slab remnant using a numerical model of slab sinking and mantle flow. Furthermore, we provide the first clear example of how long-term continental topography evolution provides new constraints on mantle reference frames of plate tectonic evolution. This new approach is complementary to, and can be integrated with, other approaches that couple geological processes and plate kinematics at the surface with the deep mantle through the use of hotspot reference frames (e.g. O'Neill et al., 2005; Doubrovine et al., 2012) or slab reference frames (e.g. van der Meer et al., 2010; Schellart, 2011; Butterworth et al., 2014).

This paper is organized as follows. After describing the numerical modelling method and the tomographic model in the Methods section, we analyze the geological evidence for latest Cretaceous to early Cenozoic subduction north of Australia. Next we cast this subduction system in several plate tectonic reconstructions of the Australia region using absolute plate positions from two modern mantle reference frames for plate tectonic evolution. Assuming vertical slab sinking, this analysis predicts slab remnants to be presently situated in the mantle under central-southeastern Australia. We identify these slab remnants in two independent tomography models of P-wave and S-wave velocity. Lastly we turn our attention to the dynamic topography evolution which Australia would have undergone as a result of passing over the sinking slab remnant where we test topography evolution as predicted form our 3-D numerical modelling with observations of present-day topography and Cenozoic topography change.

2. Methods

2.1. Numerical model

We present a numerical model that has specifically been designed to investigate the dynamic topography at the surface induced by sinking of a dense, negatively buoyant, fossil slab in the mantle. The numerical model uses the code *Underworld* (Moresi et al., 2003, 2007; Stegman et al., 2006), in which mantle flow is modelled in a three-dimensional Cartesian box by compositional buoyancy contrasts in an incompressible Boussinesq fluid at very low Reynolds number. Distinct volumes are represented by sets of Lagrangian particles that are embedded within a standard Eulerian finite element mesh, which discretizes the problem and solves the governing equations. For additional information on the numerical technique and the nondimensional equations used the reader is referred to earlier work (Moresi et al., 2003, 2007; Stegman et al., 2006). Velocities and stresses in the model are scaled following the scaling formulations presented in Schellart and Moresi (2013).

We use a Cartesian modelling domain that is 2900 km deep, which represents the entire mantle. The top surface and bottom surface have free-slip boundary conditions and represent the Earth's surface and the core–mantle boundary, respectively. Considering the low Reynolds number and the geometrical symmetry of the problem along two vertical planes (one at $x = 4000$ km and one at $z = 4000$ km), we use a box that is 4000 km long by 4000 km wide with free-slip boundary conditions at the symmetry planes, which effectively represents a modelling domain that is 8000 km long and 8000 km wide. The outer side walls (one at $x = 0$ and one at $z = 0$) have zero velocity boundary conditions. Mesh resolution in the $4000 \times 4000 \times 2900$ km^3 numerical domain is 196 (length) by 196 (width) by 160 (depth) elements, resulting in cells with spatial dimensions of 20.4 km (length) by 20.4 km (width) by 18.1 km (depth). Initial particle distribution is 20 particles per cell (total of 122,931,200 particles).

The model involves a three-dimensional layered mantle volume incorporating a dense, negatively buoyant, slab at different depth ranges from 400–800 km depth (representing the slab depth range at ~50–40 Ma) to 800–1200 km depth (present-day depth range of the slab). The anomaly is 400 km thick, 500 km wide and 1200 km long to mimic the shape of the central (high-amplitude) portion of the high-velocity anomaly we identify in our global P-wave tomography model (described in Section 5). We use a layered mantle system with a 200 km thick top layer (representing Australian continental lithosphere) with non-linear stress-dependent viscosity with maximum $\eta_{\mathrm{L(Max)}} = 500\eta_{\mathrm{UM}}$ and stress exponent $n = 3.5$ (following Mackwell et al., 1990), a 460 km thick sub-lithospheric upper mantle layer with Newtonian viscosity η_{UM} (scaling to 2.5×10^{21} Pa s in nature), and a 2240 km thick lower mantle with a three-layered Newtonian viscosity structure with $\eta_{\mathrm{LM\text{-}T}} = 10\eta_{\mathrm{UM}}$ at 660–1400 km depth, $\eta_{\mathrm{LM\text{-}M}} = 30\eta_{\mathrm{UM}}$ at 1400–2200 km depth and $\eta_{\mathrm{LM\text{-}B}} = 10\eta_{\mathrm{UM}}$ at 2200–2900 km depth. The lower mantle viscosity layering is a first-order approximation for the implied high-viscosity zone in the middle of the lower mantle (Mitrovica and Forte, 2004). We have run numerous models in which the viscosity of the plate, upper mantle and lower mantle layers have been varied, with $\eta_{\mathrm{L(Max)}} = 100\text{–}1000\eta_{\mathrm{UM}}$, $n = 1\text{–}3.5$, $\eta_{\mathrm{LM\text{-}T}} = 10\text{–}100\eta_{\mathrm{UM}}$, $\eta_{\mathrm{LM\text{-}M}} = 10\text{–}100\eta_{\mathrm{UM}}$, and $\eta_{\mathrm{LM\text{-}B}} = 10\text{–}100\eta_{\mathrm{UM}}$. The model presented in the paper (Section 6) is most in agreement with observations in terms of present day lower mantle slab sinking velocity, as well as amplitude and wavelength of surface deflection.

We use a density contrast of 33 kg/m^3 between slab and ambient mantle, which is reasonable considering a coefficient of thermal expansion of 2.4×10^{-5} K^{-1} for peridotite and a density of ~4500 kg/m^3 at 800–1200 km depth (Turcotte and Schubert, 2002), implying an average temperature contrast between ambient mantle and slab of ~306 K. We calculate the dynamic topography (surface deflection h) from the vertical normal stress at the free-slip top surface (σ_{yy}) using $\sigma_{yy} = \Delta\rho g h$, where $\Delta\rho$ is the density contrast between mantle rocks and air and g is the gravitational acceleration (Flament et al., 2013).

2.2. Seismic tomography model

We use the global P-wave mantle tomography model UU-P07 (Amaru, 2007; van der Meer et al., 2010) to investigate the mantle structure below Australia down to 2500 km depth. The global P-wave model is based on a travel time data set of ~20 million P-wave phases. The model is parameterized with constant wave-speed anomaly cells (blocks) of variable dimensions depending on the local degree by which the mantle is sampled by seismic rays (ray density) using the adaptive cell parameterization technique (Spakman and Bijwaard, 2001). The adaptive meshing technique optimizes the possibility to image detail of mantle structure exploiting the resolving power of the travel time data. Assessment of the spatial model resolution is done by sensitivity tests using synthetic velocity models of seismic wave speed (Online Supplementary Information). The resolution tests indicate that model UU-P07 can at least detect anomalies on a scale of 3° in the mantle region below Australia at a depth range of 700–1300 km.