

The dynamic history of the Australian region since the Mesozoic

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Abstract

Unlike some of our celestial neighbours, our planet displays plate tectonic motion in response to deep earth processes. Plate tectonic motion is not random but driven by a combination of gravity and frictional forces related to the convective processes in the mantle. It seems a natural progression to propose that if deep earth processes move the plates laterally they might also influence the surface topography vertically. In fact, a benchmark study was able to demonstrate the relationship between mantle convection and vertical plate motion by relating disparate geological, geophysical and geochemical observations from Australia with models of mantle convection (Gurnis et al., 1998). If topography can be generated by deep earth processes what can our geological, geophysical and geochemical observations tell us about these deep earth processes? The Australian region is an attractive case study for observing dynamically driven topography since it is a stable craton which exhibits past and present topographic signatures that are inexplicable by traditional notions

of plate kinematics (Russell and Gurnis, 1994);(Gurnis et al., 1998);(Lithgow-Bertelloni and Gurnis, 1997);(Müller et al., 2000). This research provides a quantitative geodynamic examination of enigmatic topographic signatures of the Australian region in order to provide a link between disparate geological, geochemical and geophysical observations with a plate consistent model of thermal convection.

Aims

In this study we pose the question: How have mantle dynamics influenced Australian surface topography since the Mesozoic? Previously it was proposed that the Australian continent underwent quantifiable vertical translations related to dynamic forces which could connect several seemingly disparate or enigmatic geological, geochemical and geophysical observations from the Australian region. However, several outstanding questions still remain. Thus, this new 3D dynamic modeling of evolving mantle buoyancy will address the following questions:

1. How has the eastward motion of Australia and Antarctica away from Africa around 160 Ma effected the subsidence in the eastern continental basins of Australia?
2. What is the influence of an attached rather than detached slab on the eastern continental basins of Australia?
3. Similarly, how can the incorporation of a realistic mantle wedge tell us about the subsidence and thermal history of the eastern interior basins?
4. How has the subduction to the north of Australia contributed to the dynamic motion of the continent, and in particular the subsidence of the northeastern marginal plateaus?

5. Is there a dynamic cause for the southeastern Australian stranded beach ridge exposures along the coast of the Great Australian Bight during the Tertiary?
6. Has the Australian continent been uplifted or depressed since the end of the Cretaceous?
7. Can the uplift of the east of Australia be quantified?
8. Which model (asthenosphere or subducted plate) best describes the cause for the excess depth of the Australian Antarctic Discordance (AAD)?
9. What is the cause of the apparently enigmatic timing of formation of the Norfolk Basin?

Background

Previously, Gurnis et al. (1998) and Gurnis et al. (2000) linked two observations in the Australian region to the same convective process: the anomalous Cretaceous vertical motion of Australia from sediment records in the Eromanga and Surat Basins and the geochemistry and geophysics of the Australian Antarctic Discordance (AAD) (figure ??). These observations were linked by forward modeling numerical models with imposed palaeo plate tectonic motions described as velocities as the surface boundary to a spherical 3D eulerian mantle convection model.

In this model plate tectonic reconstructions went as far back as the Mesozoic (130 Ma) in order to incorporate the restored eastern margin of Australia during a supposed period of subduction of the Phoenix-Pacific plate ridge. Now, a new plate rotation model with a moving hotspot absolute reference frame can be used. From 0-65 My we can incorporate O'Neill et al. (2003) revised absolute finite rotations for the Indian plate based on the motion of hotspots. We can extend these rotations using O'Neill et al. (2005b) rotations for times greater than 80 Ma. These rotations are derived by an evolutionary approach which constrained the motion of hotspots from

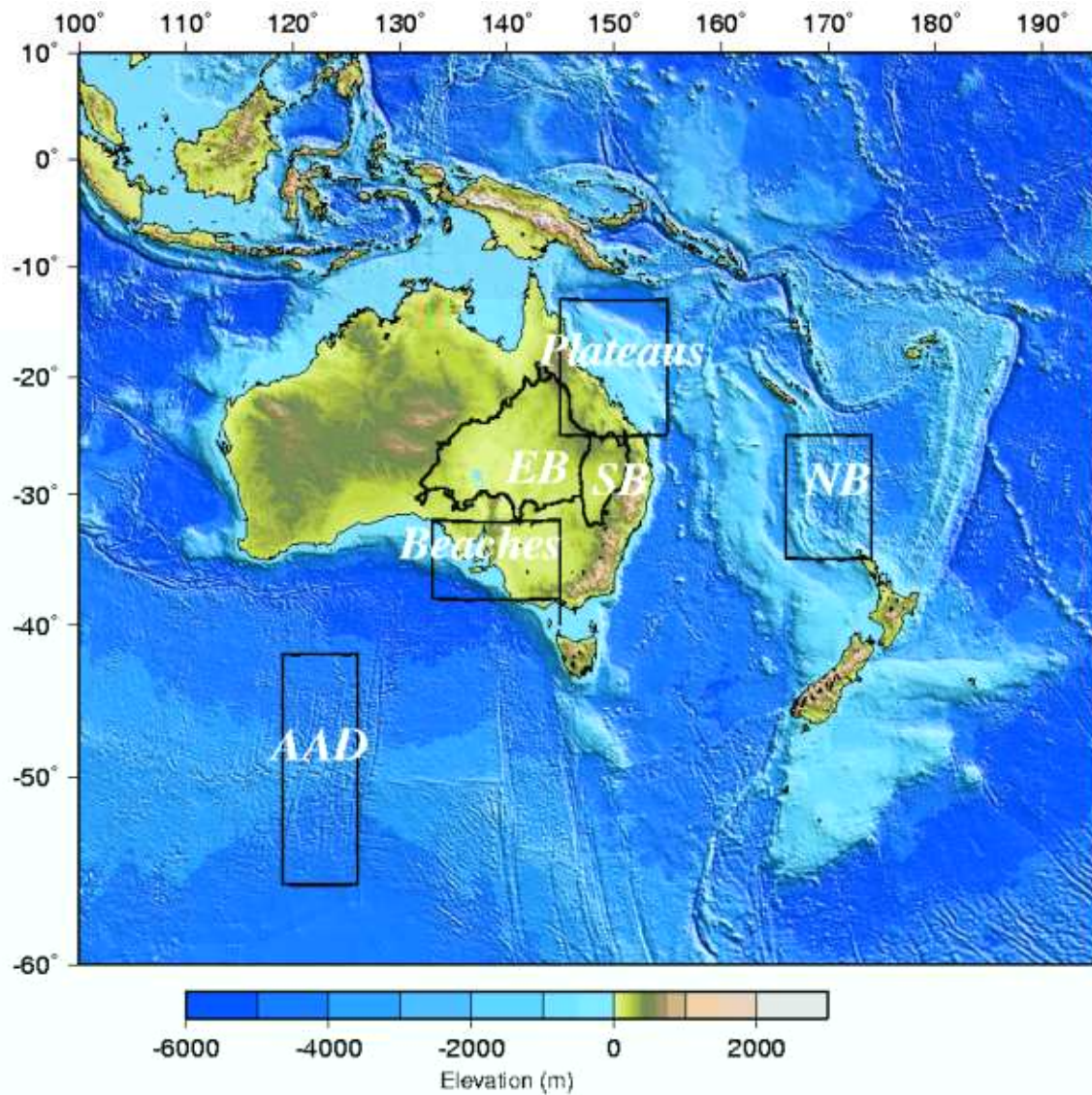


Figure 1: The Australian region with the areas of interest: AAD is the Australian Antarctic Discordance, Beaches are the exposed beach ridges, EB, is the Eromanga Basin, SB is the Surat Basin, NB is the Norfolk Basin, Plateaus shows the area where the eastern marginal plateaus are located

convection models by paleomagnetic data. In the O'Neill et al. (2005b) rotations the models for hotspot motions are extended until 120 Ma by combining dynamic simulations of plume motion with paleomagnetic and tomographic constraints. Next a palaeomagnetically derived model of plate motions is used to extend our rotations back to 170 My. The benefit of doing so becomes apparent when the plates are animated through time. Clearly, there is an early phase of eastward motion of Australia and Antarctica toward the trench at around 160 Ma in addition to the later phase which place the eastern interior basins over the subducted slab noted by Gurnis et al., (1998). The continent is then relatively motionless between 140 and 120 My until it again begins to move eastward and northward. The early motion is coincident with the opening of the Somali and Mozambique basins to the east of Africa. Thus what is the influence of this earlier phase of eastward motion of Australia and Antarctica on subsidence in the eastern interior basins?

There is some suggestion of the influence of this earlier subsidence from the subsidence of the eastern interior basins, namely the Eromanga and Surat Basins (Figure 1). These basins are part of a large Jurassic-Cretaceous sedimentary deposition area in eastern Australia that is called the Great Artesian Basin overlying older (Devonian-Carboniferous and Permo-Triassic) basins. Previous backstripping of the Eromanga basin by (Finlayson, 1990) shows that in general the backstripped curves can be divided into an early and a late phase of tectonic subsidence. The first phase seems to start around 200 Ma and there is a clear distinction between the magnitude of subsidence towards the east and the west with subsidence rate increasing towards the coast and less subsidence to the west than the east. The second phase of subsidence appears to occur slightly earlier in the east (around 118 Ma) than the west (100 Ma). Previously, this second phase of subsidence was related to the passing of the detached subducted slab beneath the basin Gurnis et al. (1998), however this first phase of subsidence might be related to the earlier motion of the Australian plate towards the east as Australia and Antarctica separated from Africa. Thus

how do the tectonic subsidence curves from the eastern interior basins compare to geodynamic models for the past 170 Ma?

The model by Gurnis et al. (1998) incorporated subduction on the eastern edge of Australia which ceased at 130 Ma due to the collision of the Pacific-Phoenix spreading center with the subduction zone. However, we now know that subduction east of Australia continued until it underwent a radical change between 100-90 Ma. The subduction of the Pacific-Phoenix spreading

90 Ma on the east of Australia influence the subsidence record in the eastern interior basins?

The model by Gurnis et al. (1998) accounted only for subduction in the east of Australia. There was no contribution from the northern margin subduction or from heat loss at spreading centers. This meant that there is possibly a significant contribution towards the evolving buoyancy in the mantle which is left unaccounted for. By including a complete history of plate boundaries and subduction this provides us the opportunity to investigate other areas of anomalous subsidence. For example, the northeastern marginal plateaus (Figure 1). Towards the late middle Miocene (Late Miocene/Pliocene) the northeastern margin of Australia underwent a period of accelerated tectonic subsidence in an area too distally located from a plate margin to be accounted for by plate forces (Müller et al., 2000). Using evidence from tomographic models (van der Hilst et al., 1998) Müller et al. (2000) suggested that a subducted slab may have passed beneath the northeastern marginal plateaus causing the subsidence. However, a comparison of various P,S and surface wave tomography models ((Bijwaard and Spakman, 2000); (Debayle and Kennett, 2003); (Fishwick, 2004); (Ritsema et al., 1999); (van der Hilst et al., 1998)) shows much discrepancy of density variations between the models (Taylor, 2004). Therefore, it is difficult to attribute the anomalous subsidence of the northeastern marginal plateaux to a subducted slab from tomographic models alone. This opens the possibility for this area to be investigated in terms of the geodynamics involved at the subduction zones to the north, the Melanesian arc, and to the east, the Tonga-Kermadec trench. Thus can the subsidence of the northeastern marginal plateaus be explained by geodynamic models?

Another vertical shift of the Australian continent can be addressed with geodynamic models. Geological observations record uplift on the southern margin of Australia since the Cretaceous. For example the Eucla platform of deep shelf limestones now sitting beneath the Nullarbor plain (Stokes et al., 2003) may have undergone 160 m of uplift (Veevers, 2000 Chapter 15 P93). Massive

Plio-Pleistocene sea beach and back-shore dune deposits were preserved along the southeast coast of Australia (Figure 2). The uplift is thought to have been a gradual and progressive regional arch uplift in the southeast highlands and Murray basin which is often linked to distal plate forces (M et al., 2004). Uplift in the Ottway ranges may have reached magnitudes of vertical translation between 174-240m (Sandiford, 2003), while fossilized beaches of South-East Australia have undergone regional uplift of 250 m (Wallace et al., 2005). These beaches show acceleration in the rate of uplift during the Quaternary ((Sprigg, 1979); (Wallace et al., 2005)). Can geodynamic models account for the vertical translation of the southern margin of Australia?

Isolating the vertical shift of the Australian continent from the eustatic sea level record and the effect of sediment loading provides an estimate of the vertical translations of the continent which might be dynamically driven. Previously, Russell and Gurnis (1994) performed a study where they found that the Australian continent subsided in bulk with little tilting since 119 Ma to 66 Ma. In fact, for the most part the Australian continent underwent a DC shift with very little tilting. This is particularly interesting since it would suggest that the continent sat above a broad scale dynamic topography high. By comparing present day topography and the Cretaceous topography, Russell and Gurnis (1994) proposed that a similar story might be true for the Cainozoic.

Several observations might suggest that Australia has undergone broad scale vertical motions during the Cainozoic. Firstly, the Eustatic Sea level record shows a gradual decrease in the height of sea level during the Cainozoic (figure ??). Despite this gradual decrease the pattern of inundation on the Australian continent shows that at least two phases of inundation occurred on the Southern margin (figure ??). Between Antarctica and Australia there is a dynamic topography low called the Australian Antarctic Discordance (AAD) (Figure 1) (Gurnis et al., 1998); (Gurnis et al., 2000). Thus, one would expect that as Australia has moved northwards

it might have been uplifted. Australia is much lower today than it was during the Cretaceous (Russell and Gurnis, 1994). In contradiction to the previous expectation, this would suggest that it must have moved from a relative dynamic topography high. Indeed, Australias separation from Antarctica marks Australias motion away from the hotter mantle of Gondwanaland. The mantle is inferred to have been hot either due to a large shallow thermal anomaly or due to the abundance of magmatism involved in the breakup of Gondwanaland in the form of plumes (Storey, 1995). For example extensive magmatism is found on the western margin of Australia (including the Wallaby and the Naturaliste submarine plateaus) until at least 115 Ma during the breakup of Australia-Antarctica and India. Apparently plume related rifting occurred between New Zealand and Marie Byrd Land after 100 Ma although rifting between Antarctica and Australia was predominantly marked by an absence of volcanism (Storey, 1995). Furthermore, as the Australian plate moved towards subduction in the north along Indonesia, northern Australia may have subsided (Lithgow-Bertelloni and Gurnis, 1997). Thus what is the nature of the subsidence of the Australian continent during the Cainozoic and did it subside in bulk as it had during the Cretaceous?

Further complicating the history of the vertical motion of the Australian continent since the end of the Cretaceous is the history of volcanism on the Australian eastern margin (Figure 1). Volcanism uplifting the eastern highlands (Jones and Veevers, 1982) gradually moved southwards as the plate moved north above a hotspot (R, 1994). Contemporaneously, late Miocene-Quaternary faulting (Sandiford) and late Pliocene normal fault movement in the Mt Lofty Ranges caused up to 100 m displacement (Sandiford). Thus how can an estimate of Australian vertical motion resolve the uplift of eastern Australia?

The Australian Antarctic Discordance (AAD) lies between 120°-125° E (Figure 1) lying between Antarctica and Australia and is the deepest spreading ridge in the global mid-oceanic

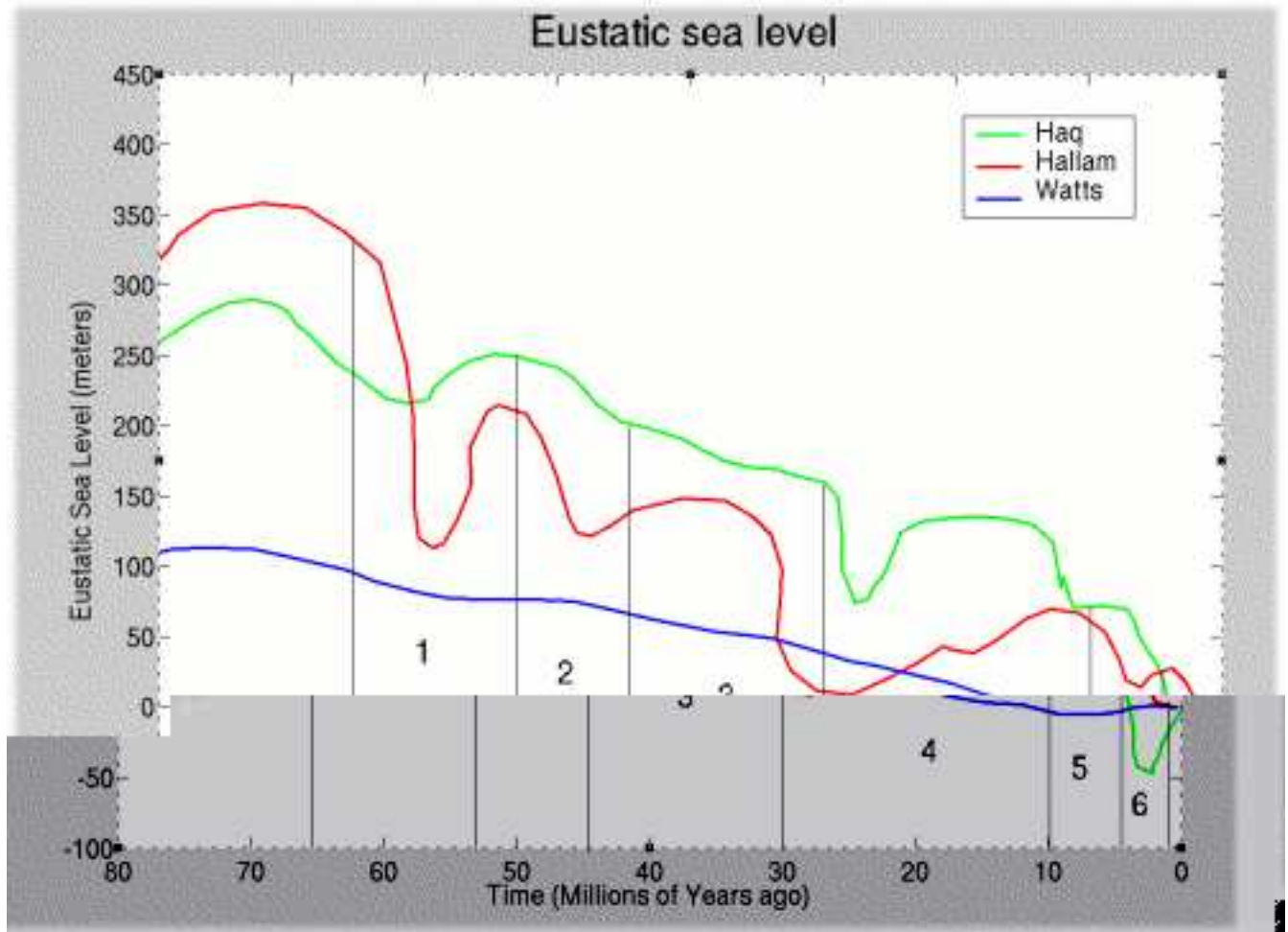


Figure 2: The Eustatic sea level curves. Showing Haq 1975, Williams 1980 and Hallam 1988. All show a general decrease in the magnitude of eustatic sea level during the Cenozoic

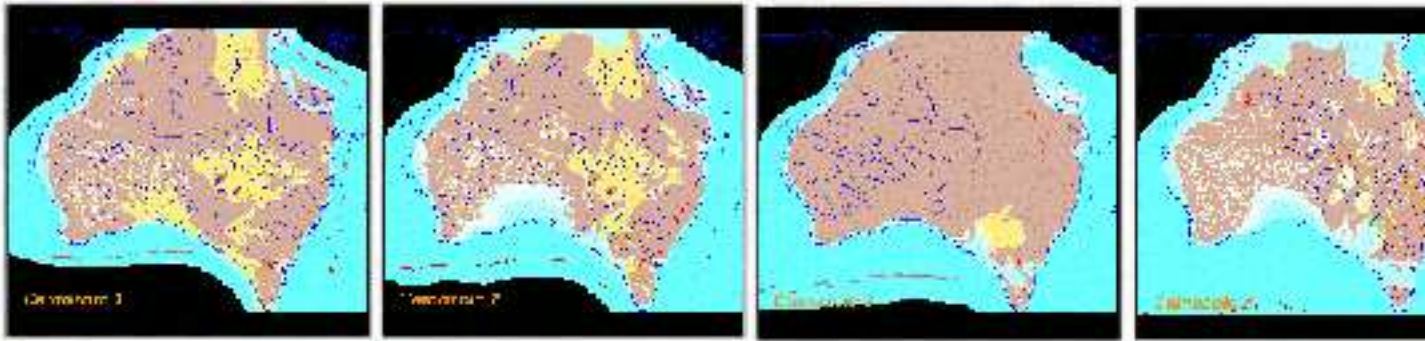


Figure 3: The pattern of inundation of the Australian continent showing that there are at least two time slices (2 and 4) where there is clearly inundation of the Australian continent on the southern margin. These slices correspond to the intervals :30 Ma -10 Ma (slice 4) and 52 Ma - 37 Ma (slice 2)

spreading system. It is characterized by closely spaced fracture zones and a rugged ridge flank morphology which is usually associated with slow spreading ridges however here it is thought to be associated with the change in geochemistry between the Pacific and Indian Ocean mantle domains (Christie et al., 2004).

Two models for the formation of the AAD currently exist. Firstly, the plate model describes the motion of subducted material from the Phoenix plate as it passes beneath the Australian continent and stalls at the transition zone south of Australia. This cool material is then drawn up by the South East Indian Ridge (SEIR). However, since this mantle material is cooler than usual spreading ridge mantle, viscous stress is exerted by the cold heavy mantle on the spreading ridge, pulling the topography down (Gurnis et al., 2000).

Another model, which has recently been proposed, suggests that a low viscosity hot and buoyant layer exists beneath the lithosphere and within the asthenosphere. This layer is produced by pervasive small plumes. Faster spreading and migrating ridges cause this asthenospheric layer to spread out and thin by removing asthenospheric material from the mantle to create plates.

This is thought to produce a deeper ridge axis (Buck, pers comm). For example, the East Pacific Rise (EPR) is thought to be about 400 m deeper than the Pacific-Antarctic Rise (Small and Danyushevsky, 2003) since the East Pacific Rise is thought to consume 3 times the amount of asthenosphere as the Pacific Antarctic Rise (PAR) (Small and Danyushevsky, 2003). This model would propose that the formation of the AAD was due to the intermediate-fast spreading rate of the AAD which was sufficient to thin the asthenospheric reservoir beneath the AAD causing the observed subsidence.

Immediate problems are then presented by this model. Firstly, the spreading rate of the AAD is not sufficiently different to the adjacent sections of the SEIR (AAD spreads at 74 mm/yr (Christie et al., 2004) the South East Indian Ridge 58-76 mm/yr (Sempere and Klein, 1995)). Secondly, the AAD is known to be associated with low magma production and relatively cool upper mantle temperatures (Christie et al., 2004). The asthenospheric model describes the loss of hot mantle material at fast spreading ridges. Furthermore, tomographic images show a cool anomaly (Australian-Antarctic Mantle Anomaly) trending northwest-southeast at a depth of 120-150 km (Ritzwoller et al., 2003).

Thus which model can most closely recreate the observed bathymetric anomaly, the geochemistry and the seismic tomography?

Similarly, the Norfolk Basin is an area whose formation is a subject of hot debate.

Research Plan and Methodology

Research Design

The approach towards answering some of the outstanding questions regarding the Australian history of geodynamics since the Mesozoic is two fold. Firstly an investigation of the continental

motion during the Cainozoic is conducted. Secondly the evolving dynamic history of the area is modeled.

The following questions will be addressed in order to determine the dynamic component of vertical translations of the Australian continent since the Mesozoic.

1. What is the nature of the subsidence of the Australian continent during the Cainozoic?
2. Did Australia descend from a dynamic topography high since the end of the Cretaceous as the plate moved northwards towards a dynamic topography low or from a dynamic topography high and what was the nature of the continents tilt?
3. Did the Australian continent subside in bulk as it had during the Cretaceous?
4. What can the tilt of the continent reveal about the lack of synchronization between the eustatic sea level curve and the geological history of continental exposure and inundation in particular the stranded beaches in the southern margin of Australia?
5. Can the tilt of the Australian continent reveal an explanation for part of the permanent subsidence of the Australian continent observed since the Cretaceous?

The following questions will be addressed in order to determine the influence of evolving buoyancy in the mantle on surface topography and the geological record:

1. What is the influence of the 180 Ma phase of eastward motion of the Australia and Antarctica on the subsidence of the eastern interior basins?
2. How do the tectonic subsidence curves from the eastern interior basins compare to geodynamic models for the past 170 Ma?
3. How do new geodynamic models incorporating the collision of the Pacific-Phoenix spreading ridge at around 100 Ma influence the subsidence history of the eastern interior basins?

4. Can the subsidence of the northeastern marginal plateaus be explained by geodynamic models?
5. Can geodynamic models account for the vertical translation of the southern margin of Australia?
6. Which mantle model, subducted slab or pervasive plumes can most closely recreate the observed bathymetric anomaly, geochemistry and seismic tomography from the AAD

In addition seismic reflection data will be interpreted in order to further our understanding of the evolution of the Norfolk Basin.

Vertical motion history

A quantitative investigation of vertical translations provides constrain to convection models. In order to look at the history of Australian dynamic vertical motion I will employ a similar method to Russell and Gurnis (1994) however this study will be performed for the Cainozoic and will provide poignant information about the nature of the vertical uplift of the Australian continent in the most recent past. This method compares sediment unloaded and inundated topography to palaeogeographic data sets. This comparison allows an estimate of the additional motion in order to produce the inundation of the continent as observed. Isopach data comes from Geoscience Australia where a collection of well data provides unit thickness and the isopach point data can then be extrapolated according to the environment type. Eustatic sea level data will be taken from Haq or Hallam. Calculations of the plane of best fit and matrix algebra are done using matlab, while data visualization can be performed using GMT.

Firstly a present day model is taken for the Australian region from recent Digital Elevation Models with 1km resolution. Next isopach data is determined from wells and borehole

unit thickness data and extrapolate to palaeogeography for time slices through the Cainozoic and Cretaceous. Lithology type is also assigned to each grid node with its corresponding density. Tectonic subsidence due to the weight of the sediments is removed assuming airy isostatic equilibrium and water filled deposition.

is the decompacted sediment thickness, is the density of the mantle (3300 kgm-3), is the density of water (1000 kgm-3) and is the sediment density at that point. The equation is applied to both the lithology and unit thickness data which has been gridded for the palaeo-environment values. The new elevation of the continent is then flooded or exposed according to the Eustatic sea level curve and a pattern of inundation for a modeled topography is observed. This pattern is then compared to the pattern of inundation actually observed in the geological record. Then a plane is used to fit the difference between the modeled topography and the observed palaeo environment. The plane describes the dynamic motion of the continent.

Geodynamic History since the Mesozoic

The geodynamic history will be reconstructed using a forward modeling approach which uses explicit plate motions and mantle flow to calculate the imposed surface forces by the convecting mantle. Our approach will differ from previous models of regional geodynamics in several important respects.

In order to model the evolution of the dynamic influences on surface topography in the Australian region we will employ a similar method to Gurnis et al (1998). This study however will go far beyond the earlier exploratory models. A much larger region will be incorporated in this research in order to include more complex plate boundaries which have contributed towards the evolving buoyancy within the Australian region mantle. The plate tectonic reconstructions can now be produced with self-consistent plate boundaries and with more precise detail (1 Myr inter-

vals instead of 10) through the use of newly developed software (GPlates). Our plate rotations are no longer restricted by an older plate model and we can extend our models back to the Jurassic using palaeomag models for the moving hotspot absolute reference frame. Furthermore, I will use a new generation of spherical models of mantle convection and lithospheric deformation; such models will be greatly improved in terms of their spatial resolution, geometry and boundary conditions. Finally, I will be able to use seismic tomographic images as direct constraint on the dynamic models where such constraints did not yet exist for the testing of first generation models

There are two essential components to this work. Firstly, in order to achieve a reconstruction of the dynamic history of the Australian region since the Mesozoic the plate boundary history for the area must be known and rotations which describe this history must be applied. Plate boundaries are determined from literature reviews and I will use a combination of O'Neill et al. (2003) O'Neill et al. (2005a) rotations with extended rotations calculated from convecting density anomalies for times older than 100 Myr. Secondly, the surface velocity vectors which can be calculated for plate motion through time must be applied as boundary condition for a convecting mantle. I will be one of the first to use the GPlates software in order to close plate polygons and calculate velocity vectors to input into a 3D spherical mantle convection code. The code I will use is CitcomS (3D mantle convection code California Institute of Technology Convection in the Mantle, Spherical) in order to calculate the evolving mantle buoyancy. This will provide a benchmark for combining such self-consistently generated plate tectonic motions with mantle convection for future investigations.

Finally, these models can be constrained to look at several features of the Australian topography. In order to investigate each area the model can be run using the plate velocity boundary conditions and variables changed for the mantle. For example, the Clayperon slope (controls the speed of the descent of a subducted slab), the size of the subducted slab using tomographic mod-

els as indicators of mantle properties, the viscosity and layering of the mantle, thermal extension of the lithosphere.

The first region of focus will be analyzing the Australian northeastern marginal plateaux, for which there will be a number of case models run based on the intrinsic unknowns of the mantle in this region. This part of the modeling is initially expected to incorporate only the subducted material and relate it to the dynamically driven vertical motions of the northeast of the Australian plate during the Tertiary without incorporating a realistic mantle wedge.

The second focus region will be the Australian Antarctic Discordance and the sedimentary basins from the east of Australia during the Cretaceous that has previously been related to the subduction of the phoenix plate. Several new things can be investigated by using a geodynamic history model:

1. New models will be created incorporating the broad scale motions of the entire Australian continent
2. Heat production will be sampled incorporating a more realistic mantle wedge for investigation of the heat flow in the Surat and Eromanga Basins
3. Geochemistry using geochemical tracers will be sampled from the AAD and compared to the latest observations from ODP Leg 187 and (Ritzwoller et al., 2003). Resolving the model to the new boundaries between Pacific and Indian ocean MORB domains will enable us to constrain the validity of our models
4. A comparison of the asthenospheric and plate models can be run by altering the properties of the mantle inside the CitcomS code

The third focus region will involve the exposure of the south Australian beaches. This will require sampling the dynamically driven stresses at points across the Australian plate. This

6. Norfolk Basin draft paper. I have spent some time on the background and body of a paper on the Norfolk Basin with more interpretation to be completed shortly.

7. Created web page for NSF proposal

<http://www.gps.caltech.edu/~gurnis/TongaKermadec/index.html>

Timetable

Month	Objective
2005	
December 15	complete sediment unloading section
2006	
January	Complete draft of Vertical Motion section
February-March	Norfolk Basin Interpretation and submit draft
April	Submit draft and finish off Vertical motion section
May	Complete plate closures for first run
June	
July	
August	
September	
October	
November	Review of Progress
December 2006	Present at AGU
2007	
January	South Australia and SE Asia
November	Review of progress
December 2007	Present at AGU
2008	
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