Mantle upwelling after Gondwana subduction death explains anomalous topography and subsidence histories of eastern New Zealand and West Antarctica

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ABSTRACT

West Antarctica and adjacent seafloor have topographic elevations 0.5–1.2 km greater than expected from models of lithospheric age and crustal structure. Ocean crust near New Zealand has no equivalent depth anomaly, but tectonic subsidence histories from Campbell Plateau petroleum wells show anomalously high subsidence rates during the Paleogene, and total subsidence 0.5–0.9 km greater than expected from rift basin models. Geophysical and geochemical anomalies suggest that upward mantle flow supports the anomalous topography beneath Antarctica, and the Campbell Plateau subsidence history indicates that topographic support mechanisms were long lived (>80 Ma) and recoverable over a period of ~30 m.y. as plate motions moved New Zealand from Antarctica. We construct models of Late Cretaceous and Cenozoic mantle flow with a slab graveyard and upwelling above that is initially rooted at 1000–1500 km depth. Our models match topography and subsidence history anomalies, and are consistent with mantle seismic wave speed anomalies and the geoid. We suggest that when thermally driven slab downwelling ceased ca. 100 Ma, low-density material that was fertilized within a broad zone in the lower mantle during the previous ~400 m.y. of Gondwana subduction was released and able to rise. Mantle upwelling from depths of 700–1500 km, lasting for periods of ~100–200 m.y., with enriched chemistry related to the prior subduction history may be a general process that follows subduction death, and has not previously been recognized.

INTRODUCTION

Igneous rocks and arc-derived sediment grains found in New Zealand and Antarctica attest to late Paleozoic and Mesozoic magmatism associated with subduction beneath Gondwana (Adams et al., 2007; Bradshaw, 1989). Cessation of subduction was later toward the east: 130–110 Ma in New Zealand (Kimbrough et al., 1994; Waight et al., 1998); ca. 95 Ma in Marie Byrd Land (Bradshaw et al., 1997; Mukasa and Dalziel, 2000); and not until Cenozoic time in the Thurston Island and Antarctic Peninsula regions (McCarron and Larter, 1998; Storey and Nell, 1988). Rifting followed termination of subduction in the New Zealand sector, and this episode culminated in seafloor spreading in the Tasman Sea and South Pacific ca. 90–80 Ma, leading to the final fragmentation of Gondwana (Cook et al., 1999; Eagles et al., 2004; Gaina et al., 1998; Sutherland, 1999). Tectonic hypotheses to explain these temporal changes in crustal deformation, exhumation, and igneous chemistry include ridge subduction (Bradshaw, 1989; Weaver et al., 1994), subducted slab capture (Luyendyk, 1995), and mantle plume activity (Storey et al., 1999; Weaver et al., 1994).

We reconsider suggestions of mantle upwelling in the context of Gondwana subduction death. We analyzed bathymetry to determine the spatial scale and amplitude of proposed mantle upwelling, and the history of surface subsidence recorded in Campbell Plateau petroleum wells. We constructed a model of mantle circulation that makes predictions of dynamic topography and geoid through time and tested it against observations. We are thus able to constrain the scale and timing of mantle upwelling, and suggest that the pattern is causally related to subduction death through the escape of low-density material from viscous drag and downward advection associated with slabs descending into the lower mantle.

EVIDENCE FOR MANTLE UPWELLING

Cenozoic alkaline magmatic centers have been attributed to incursion of hot low-density upper mantle near the Ross Sea, but opinions differ on how deeply seated this putative mantle upwelling may be (Behrendt et al., 1991; Finn et al., 2005; Rocchi et al., 2002). The distinctive geochemical signatures are metasomatically enriched in incompatible elements and have isotopic ratios characteristic of a high-U/Pb mantle reservoir (HIMU trend) that may be indicative of an active deep-seated mantle plume (Behrendt et al., 1991; Lanyon et al., 1993; LeMasurier and Landis, 1996; Storey et al., 1999; Weaver et al., 1994), mantle plume material "fossilized" at the base of the lithosphere (Panter et al., 2000; Rocholl et al., 1995), or metasomatism of the lithospheric mantle by long-lived subduction and later remobilization by incursion of warm mantle beneath (Finn et al., 2005). Mantle flow models that involve several discrete phases have been invoked to explain the full range of geochemical parameters (Nardini et al., 2009; Rocchi et al., 2002). Plume-like geochemical signatures are typical in Cenozoic igneous rocks from both New Zealand and Antarctica, but not in most Cretaceous rocks of Antarctica (Mukasa and Dalziel, 2000; Weaver et al., 1994).

Studies of surface waves reveal anomalously slow (~6%) shear wave velocities above 200 km depth beneath West Antarctica (Morelli and Danesi, 2004; Ritzwoller et al., 2001). Global shear wave models show a broad (>2000 km) zone of relatively slow velocities at mid-mantle depths (~400–1100 km), but high velocities at the base of the mantle beneath the Ross Sea (Becker and Boschi, 2002; Ritsema et al., 2004).

Marie Byrd Land has Cretaceous–Cenozoic erosion surfaces that are locally 3 km above sea level, and there is a similar regional erosion surface in New Zealand that is below sea level everywhere except in regions of Cenozoic deformation (LeMasurier and Landis, 1996). This has been suggested as evidence for Late Cretaceous and Cenozoic Antarctic mantle plume activity (LeMasurier and Landis, 1996). We note that the elevated Antarctic surfaces do not require that the average elevation of Marie Byrd Land has increased, but rather that rock uplift has occurred (England and Molnar, 1990). Available evidence suggests that the crustal thickness of Marie Byrd Land is ~25 km, similar to that offshore eastern New Zealand, yet the region remains near or above sea level (Gohl et al., 2007; Grobys et al., 2008; Ritzwoller et al., 2001; Winberry and Anandakrishnan, 2004).

BATHYMETRIC ANOMALIES

We computed oceanic bathymetric anomalies (Fig. 1) by subtracting an age-depth model from the GEBCO (General Bathymetric Chart of the Oceans; http://www.gebco.net/) 2008 grid. Model bathymetry was constructed from a seafloor age grid and an empirical relationship between age and sediment-corrected depth, as determined from the North Pacific (Crosby et al., 2006). Ocean crust adjacent to the southern margin of New Zealand has reversed-polarity

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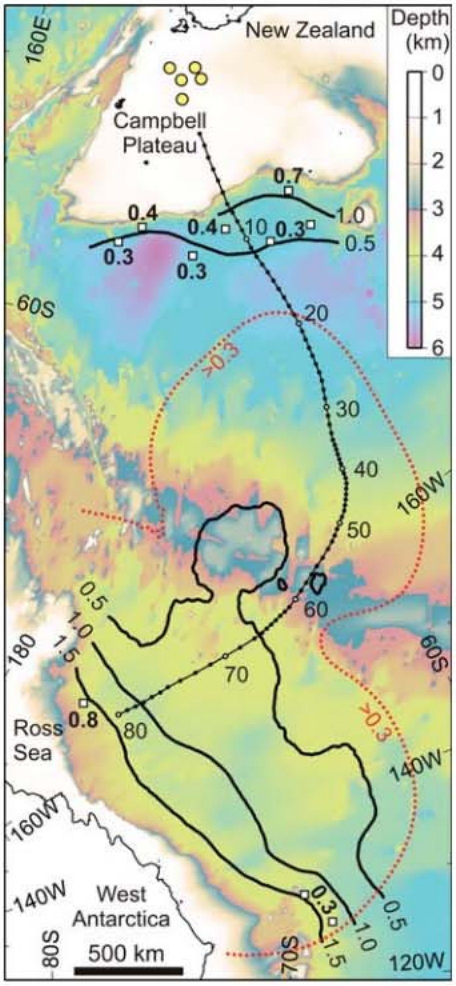

Figure 1. GEBCO (General Bathymetric Chart of the Oceans; http://www.gebco.net/) bathymetry (image) and model depth anomalies (bold lines, km). White squares are isostatic corrections (km) for sediment thickness (Crough, 1983) that must be subtracted from model anomaly, adjacent to Campbell Plateau (Carter and McCave, 1997). Western Antarctic location is from open-file data collected by R.V. *Polar Duke* in 1990; eastern location is from cruise by R.V. *Nathaniel B. Palmer* in 1996 (Heinemann et al., 1999). Dotted line shows relocated southern Campbell Plateau with respect to Marie Byrd Land since 80 Ma (1 Ma increments). Circles on Campbell Plateau are petroleum wells (Fig. 2). Red dashed line shows extent of dynamic topography >0.3 km predicted from our mantle flow model.

remnant magnetism correlated with chron 33r (79–83 Ma) (Sutherland, 1999), and hence our age grid was modified from a published grid (Muller et al., 1997) by interpolating toward the Ross Sea and Marie Byrd Land continental margins with a bounding age of 83 Ma. Our bathymetry model assumes no sediment cover, which we consider in the following.

Results show a narrow (~200 km) zone of bathymetric anomalies with amplitudes of <1.0 km adjacent to the Campbell Plateau, and a broad (~1000 km) zone of anomalies with amplitudes of 0.5–2.0 km adjacent to the Ross Sea (Fig. 1). When isostatic corrections for sediment thickness (Crough, 1983) are considered (Fig. 1), it is clear that anomalies adjacent to the Campbell Plateau may be explained by observed sediment thicknesses. However, the southern bathymetric anomaly has a large amplitude of 0.5–1.5 km, and it reaches out to the active spreading ridge (Fig. 1); we suggest that it cannot be explained by sediment cover. This is supported by the shapes of the conjugate continental margins, which are symmetrical, but the Antarctic margin is ~1 km shallower (see the GSA Data Repository[1]).

SUBSIDENCE HISTORY OF THE CAMPBELL PLATEAU

Postrift subsidence is well constrained because marine flooding occurred shortly after rifting, so we are able to establish paleoelevation; the modern water depth and sediment thickness are known; and a correction for sediment loading can be removed precisely. Data from petroleum wells indicate that the area underwent a total postrift tectonic subsidence of 1.2–2.0 km (Fig. 2). Seismic-reflection facies and thickness interpretations away from wells yield tectonic subsidence estimates of 1.2–2.2 km across a region south of New Zealand that is at least 250 km wide (Cook et al., 1999). Stretching factors, based upon crustal structure and measured fault heaves, are in the range 1.2–1.5 near wells (Cook et al., 1999), so tectonic subsidence expected from thermal diffusion is <0.7 km (McKenzie, 1978). The best regional fit to all observations involves anomalous subsidence in the range 0.5–0.9 km.

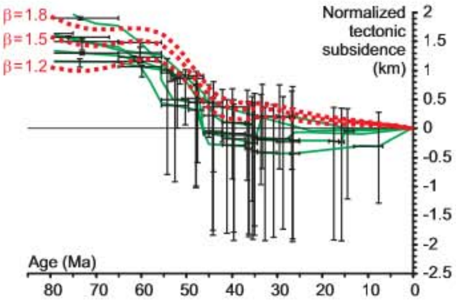

Figure 2. Tectonic subsidence of southern Campbell Plateau petroleum wells with uncertainties of age and paleodepth (Cook et al., 1999). Dotted lines (in red) show model subsidence histories that include dynamic effects of upwelling mantle (this paper) and lithospheric cooling by different stretching factors (β) at 80 Ma (McKenzie, 1978).

If thermal diffusion in the lithosphere were the sole mechanism for subsidence of the Campbell Plateau since 80 Ma, then an exponential shape to the subsidence history is expected (McKenzie, 1978). However, observed subsidence histories are characterized by slow subsidence followed by rapid subsidence during the interval 70–40 Ma, and then little change since then (Fig. 2). Paleodepth estimates after subsidence to bathyal environments have large uncertainties, but the timing of rapid subsidence is well constrained by nonmarine or shelf fauna and flora that persisted into Paleogene time. Well data are supported by rock exposures uplifted by Miocene intraplate volcanic processes on Campbell Island, where Paleocene fossils in sandstones and siltstones are indicative of marginal marine or inner shelf environments, and Eocene deep-water chalks are preserved above (Hollis et al., 1997). The wells and Campbell Island were 200–500 km distant from the evolving Paleogene plate boundary and are surrounded by well-surveyed Cretaceous–Cenozoic sedimentary strata that are not faulted (Cook et al., 1999). We conclude that anomalous subsidence occurred over an interval of ~30 m.y. during the latest Cretaceous and Paleogene, and that there is no obvious lithospheric cause.

MODEL OF MANTLE FLOW

Our objective is to show that a relatively simple and reasonable physical model can be constructed to explain all observables. We use a finite-element method (Tan et al., 2006) with plate-motion surface boundary conditions and material properties that span a range of reasonable values (see the Data Repository). We match general characteristics of seismic-tomographic models, and fit topography, subsidence, and geoid data.

We identify three bodies in seismic-tomographic models: (1) a high-velocity anomaly in the lowermost mantle, ~1000 km thick, that we attribute to a slab graveyard from long-lived Paleozoic and Mesozoic Gondwana subduction; (2) a low-velocity anomaly in the depth range of 400–1000 km centered beneath the Antarctic margin that we suggest is a low-density mantle body related to physical separation or metasomatism from sinking slabs that passed through the lower mantle; and (3) an extensive lithospheric and sublithospheric low-velocity anomaly associated with western Antarctica and Late Cretaceous and Cenozoic ocean crust; we infer this to be low-density upper mantle material that was initially related to upper mantle backarc processes during the demise of subduction, that has since been strongly modified by plate-motion boundary conditions. Our model initial condi-

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[1] GSA Data Repository item 2010031, Figures DR1–DR3 and geodynamic model of mantle flow since 80 Ma, is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

tions contain three ellipsoidal buoyancy anomalies that evolve to produce the general pattern of density inferred from seismic tomography.

The initial depth of the large low-density anomaly (seismic anomaly 2) at 80 Ma must be in the mid-mantle (1000–1500 km), so that the anomaly evolves to the depth range of 400–1000 km now observed by seismic tomography (Ritsema et al., 2004). To fit geoid data we require a steep gradient in mantle viscosity near the 670 km transition zone, with a ratio of lower to upper mantle viscosity of ~100. If we include an additional smaller (<1000 km) and shallower (~500 km) low-density anomaly closer to the location of subduction zone death, then we better fit the amplitude of early (80–40 Ma ago) dynamic topography and the anomaly flows out to contribute to the broad low-velocity zone observed beneath Antarctic lithosphere (seismic anomaly 3). The horizontal size of the deeper low-density anomaly must be several thousands of kilometers across to fit observations. To fit the amplitudes of topography and geoid anomalies, the magnitude of the maximum density anomaly is relatively small, and, if it were thermal in origin, would correspond to an average temperature anomaly of 150–200 K, although there is some trade-off in our models between density and viscosity. The initial surface elevation and then subsidence of New Zealand is related to its history of northward movement in a lower mantle reference frame (Steinberger et al., 2004) that takes it away from the upwelling (Figs. 1 and 2; see the Data Repository).

We suggest that the active deep-seated mantle upwelling we infer beneath West Antarctica may also explain the incidence of volcanism, various aspects of the chemistry of volcanism, and the extent of land and uplifted erosion surfaces onshore, despite a crustal thickness of only ~25 km. We do not see obvious evidence for similar mantle upwelling beneath southeastern New Zealand or its adjacent abyssal plain, but we fit the observed Campbell Plateau subsidence patterns that show it drifted off a region that was anomalously elevated 0.5–0.9 km during latest Cretaceous and Paleogene time.

RELATIONSHIP BETWEEN MANTLE UPWELLING AND SUBDUCTION DEATH

The West Antarctic topographic anomaly is long lived (>80 m.y.), but recoverable when plate motions move lithosphere away from it. The anomaly is spatially and temporally related to subduction death (Finn et al., 2005; Mukasa and Dalziel, 2000; Weaver et al., 1994), and an explanation linked to this geological history is required for the large (~4000 km across) low-density mid-mantle upwelling that we infer.

The seismically slow upper mantle plume beneath the Ross Sea may be less dense because it is warmer (~150–200 K) than surrounding mantle, as is commonly assumed (Simmons et al., 2006; Steinberger et al., 2001), or it may have a chemistry that is different, which, for example, has been suggested to explain upwelling beneath Africa (Ni et al., 2002); or a combination of both. A mid-mantle enrichment process from ~400 m.y. of subduction may, in conjunction with inherited lithospheric components, explain the trace element and isotopic signatures of Antarctic volcanics, which have model mantle enrichment residence times of 250–550 m.y. (Finn et al., 2005).

Though the processes of reaction and physical differentiation from slabs at mid-mantle depths remain uncertain, there is general agreement that the water-carrying capacity of mantle minerals beneath 670 km is low, and movement through this transition zone could trigger melting within descending slabs (Hirschmann, 2006). Experimental work has shown that dehydration reactions may continue to occur within descending slabs beneath the 670 km transition zone and significant reactions could occur to depths of 1200–1500 km (Ohtani et al., 2004). We suggest that some chemical differentiation and physical separation is possible from descending slabs, and that this process led to a broad chemical alteration of the mantle beneath Gondwana as the locations of sinking slabs changed over the ~400 m.y. subduction history.

The low amplitude and large scale of the upwelling density anomaly may relate to how low-density material was able to accumulate over long periods of geological time. The mantle at depths of 1000–2000 km has a viscosity at least one order of magnitude and maybe three orders of magnitude greater than the upper mantle (Simmons et al., 2006). Therefore, the flow field averages density anomalies over a larger volume and is broader and less complex than in the upper mantle. The large high-density anomalies of the continuously supplied subducted slabs may have been sufficient to hold back low-density material derived from the previous passage of descending slabs. However, when the supply of slabs ceased, then low-density material was free to rise over a broad region, as we observe.

We suggest that some of the general characteristics of the density structure we find in the mantle beneath the Ross Sea may be globally more common than previously realized, and subduction death with subsequent mantle upwelling could be relatively common over characteristic time scales of 100–200 m.y. The Ross Sea geoid low is connected with a global ring of geoid lows that are spatially correlated with the location of Mesozoic subduction (Chase and Sprowl, 1983) and fast shear seismic velocity anomalies near the base of the mantle. These geoid lows have either moderately lower seismic velocities or significant lower velocities through the upper half of the lower mantle, especially in the Ross Sea (this paper), off the east and west coasts of North America, and in the Indian Ocean (Ritsema et al., 2004; Simmons et al., 2006). Wider recognition of this type of mantle structure and dynamic process could ultimately improve our understanding of the origin of the long-wavelength geoid and the origin of mantle seismic heterogeneity, and underpin models that quantify mass and chemical fluxes between the deep and shallow mantle.

In summary, we present evidence for a mantle upwelling that has lasted 100 m.y. since Gondwana subduction death, and will likely continue for a similar period before its mid-mantle source has flowed away. We suggest that this upwelling is causally related to the death of long-lived subduction. Mantle upwelling from depths of 700–1500 km, lasting for periods of 100–200 m.y., and with enriched chemistry related to prior subduction may be a universal process that follows subduction death and has not previously been recognized.

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