Curved Andes: Geoid, forebulge, and flexure

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ABSTRACT

Using geoid anomalies determined from satellite observations of the South American plate, we demonstrate the existence of a lithospheric flexural forebulge east of the High Andes. Using the planform and location of the geoid anomalies and accounting for the curvature of the Andean orogen, we can successfully model plate flexure using a uniform elastic thickness. Topography above 3 km elevation between −5° and −30° latitude in the Andes loads the margin of the western side of the Precambrian shield of the continental plate and drives bending of the cratonic plate. Removal of horizontal wavelengths greater than 4500 km from the geoid anomaly reveals a 5–7 m positive anomaly paralleling the trend of the orogen some 400 km east of the mountain front. We interpret the secondary geoid high as a flexural forebulge that developed in response to topographic loading of the South American plate by the Andes. While the topographic expression of this forebulge is hidden by the alluvium shed from the Andes and the vegetative cover of the Amazon jungle, our filtered geoid anomalies and a three-dimensional, single-plate flexural model in spherical geometry are both well fit by a single model with ~50 km effective elastic thickness.

INTRODUCTION

The flexural response of Earth’s lithosphere to topographic loads is well understood (Turcotte and Schubert, 2002). Much progress has been made in evaluating the behavior of the oceanic lithosphere to topographic loads (Parsons and Molnar, 1976; Bodine et al., 1981; Lambeck, 1981; Watts and Ribe, 1984; Watts and Zhong, 2000; Collier and Watts, 2001; among many other studies); although debate remains on some topics such as the origin of flattening of the seafloor bathymetry and geoid at old ages (Doin and Fleitout, 2000). In stark contrast, the relationship between the geoid and flexure on continents remains poorly understood, partly due to the problematic nature of filtering the geoid. Perhaps the best example of a clear relationship is the Indian craton (Bilham et al., 2003). Although the Andes provide a scenario in which the flexure of the continental lithosphere is expected to be quite substantial, quantification of the lithospheric flexure has proven challenging (Royden and Karner, 1984; Cloetingh et al., 1999, 2002; Tassara, 2005).

Here, we evaluate the relationships among the geoid field of the South American plate, topographic load of the Andes, and the lithospheric flexure of the Brazilian Shield. These results inform an analysis as to the role that orogenic curvature, a nearly ubiquitous attribute in planetary compressional systems, plays in flexural response. Two pivotal aspects of our study are: (1) modeling the flexure of the South American plate in response to the Andean orogenic load by using careful filtering of the geoid observations, and (2) evaluating the influence that the curved, three-dimensional (3-D) load geometry has on consequent flexural characteristics. These factors have not been addressed in previous investigations.

Our analysis shows a clear positive geoid anomaly over the high Andes of ~25 m. This was not a surprise (Gotze and Kirchner, 1997). What was a surprise was the existence of a secondary geoid bulge with an amplitude of 5 m or so located ~300–500 km eastward of the orogen front, which we interpret as a flexural forebulge (DeCelles and Giles, 1996). The secondary bulge has little if any topographic expression. These results have useful implications for the flexural evolution of the Andes, and they allow us to assess the distribution of forebulge amplitudes from geologic studies. This will make it possible to compare predictions of the load required by our flexural model, which considers the problem in three dimensions, with gravity data and stratigraphic reconstruction. A combination of the flexural calculations and geoid observations also shows the influence of orogenic curvature relative to two-dimensional (2-D) models. This paper presents a successful calibration of the geoid and flexure models for more than half of the South American lithospheric plate.

ANDES

The Andes are one of the world’s largest mountain ranges, extending more than 5000 km along the western margin of the South American plate and reaching elevations of up to 6500 m (Fig. 1A). The Andean orogenic system is the result of the subduction of the Nazca (and/or the Farallon) plate beneath South America along the Peru-Chile Trench since the Cretaceous. Along the length of the Andean orogenic system, particularly in the Central Andes between −10° and −34° latitude, there is a large region of high topography, often in excess of 3 km (Fig. 1A). We chose to use only elevations above 800 m (Fig. 1B), the most significant topographic load on the plate, because the models are insensitive to lower cutoffs between 1000 and 500 m. Here, the orogen is also the widest (approaching 600 km). The Central Andes are a continental-scale segment of the Andean convergence system that has active plate convergence in a roughly east-west direction at ~85 mm/yr (DeMets et al., 1990). The limits of this segment correlate with abrupt N-S changes from “flat” (~10° dip) to “normal” (~30° dip) subduction in the depth range 100–150 km, and with the intersection of the Nazca and Juan Fernández oceanic ridges with the continental margin (citations in Le Roux et al., 2005). Based on along-strike variations of topography, volcanism, tectonic style, and subduction conditions, the Central Andes can be divided into three, second-order segments (Jordan et al., 1983; Kley,
Figure 1. Topographic, gravitational, and flexural maps of South America, Mercator projection. (A) Topographic map showing the high elevations corresponding to the Andean orogenic system. Note the distinct marked plan-view curvature of the topographic high. Contour interval = 500 m. (B) Topographic map isolating the Andean load (colored above 800 m, gray at lower elevation) used in our flexure model. (C) Geoid anomaly, using high-pass spherical harmonic filter starting at order 7, reaching full value at order 11, and continuing to order 360. The high topography follows the most positive geoid anomaly. The secondary geoid anomaly to the east has at best a subdued topographic expression. Compare with A. Contour interval = 5 m. (D) Flexural model of the eastern side of the Andean orogen, loaded by the topography in B and using an effective elastic thickness of 50 km. Elastic thickness is estimated from the distance from peak of the secondary geoid high to the mountain front. The three labeled swaths represent the profiles displayed in Figure 2. Contour interval = 250 m.
1999); Altiplano (−15° to −23°), Puna (−23° to −28°), and Frontal Cordillera (−28° to −34°).

It is now commonly accepted that the huge crustal volume related to plateau formation in the Andes, with crustal thicknesses of up to 75 km (Beck et al., 1996; Yuan et al., 2002), is due to crustal shortening concentrated at the easternmost edge of the orogen during the Neogene (Allmendinger et al., 1997; Lamb and Hoke, 1997; Baby et al., 1997; Kley, 1999; McQuarrie, 2002). The width and foreland extent of the central part of the Andes draws attention to the arcuate nature of this fold-and-thrust belt; the origin and timing of such curvature have been and are still being investigated (Jordan et al., 1983; Kley, 1999; Richards et al., 2004; Allmendinger et al., 2005; Barke et al., 2007).

The 2-D effect of the topographic load of the Andes on lithospheric flexure has been well studied (Watts et al., 1995). Our models use a single spherical plate with uniform mechanical properties and load it by the arcuate topography. We prefer these models because they successfully approximate the location of flexural arches of the lithosphere as estimated by geoid anomalies, and they do not require radial changes in flexural rigidity along separate 2-D profiles.

**SOUTH AMERICAN GEOID ANOMALIES**

The reference geoid is a spheroid that approximates Earth’s equipotential surface at a value equivalent to mean sea level in the oceans. Geoid anomalies are the difference between the observed equipotential surface (the actual geoid) and this reference surface. Observed geoid anomalies result from mass anomalies in both the lithosphere and deeper mantle and can be used to constrain the structure of the lower lithosphere (Doin et al., 1996; Chase et al., 2002). The spectrum of geoid anomalies changes with the depth of anomalous causative masses, providing a means for isolating the lithospheric contribution to the geoid from total anomalies (Coblentz et al., 1994; Jones et al., 1996, 1998; Sonder and Jones, 1999) and to constrain deep continental structure (Doin et al., 1996; Ebbing et al., 2001). More recently, geoid anomalies have been applied to determine isostatic compensation (Chase et al., 2002; Ebbing and Olesen, 2005) and paleolithospheric structure (Coblentz et al., 2007).

A geoid anomaly map of South America, derived by filtering from GGM02 (Tapley et al., 2005) (Fig. 1C), shows a range of values from >25 m in the Central Andes to ~10 m in the Amazon Basin. Two features in the filtered geoid field are remarkable: (1) the close correlation of the >25 m geoid anomaly with high topography along the western margin of the South American continent (Gotzé and Kirchner, 1997), and, more provocative, (2) a consistent geoid swell of ~5 m east of the Andes where there is little present-day topographic expression (Fig. 1A) or load below 800 m (Fig. 1B).

Numerical experiments using filters limited between orders 4, 7, or 30 down to 360 showed that the secondary bulge was a robust feature, the position of which relative to the mountain front did not vary, though of course amplitude and sharpness varied. We selected the 7–11–360 order filter to provide a reasonable balance among smoothness, ability to determine position of the peak location of the bulge, and low noise content.

Given that the filtered geoid anomalies agree with topography over the High Andes, we hypothesize that the secondary geoid swell observed to the east (Fig. 1C) represents the forebulge component of a foreland basin system currently masked by the alluvial apron of the Andes and vegetative cover of the Amazon rain forest. Next, we analyze the plate-scale geoid anomaly to calibrate models for flexure of the South American continental lithosphere.

**FLEXURE AND FOREBULGES**

In the presence of large tectonic loads, such as a fold-and-thrust belt, the lithosphere responds by flexing, forming a foreland basin system (DeCelles and Giles, 1996). Flexural analysis usually assumes that the continental lithosphere is a 2-D thin elastic plate of variable thickness, h, overlying an inviscid asthenospheric mantle. The model lithosphere is often taken to consist of a crust with density $\rho_c = 2900 \text{ kg/m}^3$ and a lithospheric mantle with density $\rho_m = 3300 \text{ kg/m}^3$. Flexural rigidity, or plate stiffness, is defined as:

$$D = Eh^3/(1-v^2),$$  

where Poisson’s ratio (v) and Young’s modulus (E) are material constants with magnitudes 0.25 and 70 GPa, respectively. In this approximation, across-strike variations in h would control the rigidity distribution of the lithosphere. Under the effect of vertical loading from topography, $\rho_g h(x)$ (where $g = 9.8 \text{ m/s}^2$ and $h(x) = \text{elevation}$), the elastic lithosphere is deflected downward, driving deflection of the embedded Moho. The density contrast between crust and mantle (here 400 kg/m$^3$) generates a long-wavelength geoid or gravity anomaly. Our model assumes a constant $E$ and does not incorporate viscous behavior, for which we have no direct evidence. Seismicity of the Brazilian slab underthrust beneath Peru (Fan et al., 1996) does not show a tight-radius bend that might be expected of plastic failure. The inherent stiffness of the lithosphere distributes stresses efficiently enough that details of rheological variation are difficult to distinguish. The effective flexural plate thickness ($h$) and $D$ are the parameters that ultimately allow us to express the mechanical properties of the plate. Elastic thickness estimates for the South American plate (from the trench to craton) based on 2-D profiles span a large range (Whitman, 1994; Watts et al., 1995; Tassara, 2005), and vary from 6 to 10 km beneath the Bolivian Altiplano (Watts et al., 1995) to more than 100 km under the Brazilian Shield (Tassara, 2005).

$D$ and $h$ are not directly observable, but the distance of the forebulge from the mountain front within an entire plate can be measured by observation. Forebulge width can be approximated by $\pi \alpha$, where the flexural parameter ($\alpha$) is defined as

$$\alpha = \left[ \frac{4D}{(\rho_m - \rho_c)g} \right]^{1/4},$$

in which $\rho_m - \rho_c$ is the mantle–basin-fill density contrast (Brotchie and Silvester, 1969; Walcott, 1970; Turcotte and Schubert, 2002). In particular, Brotchie and Silvester (1969) calculated the effect on a spherical thin shell, assuming a global plate scenario, and using point loads to flex the plate. We assume a similar scenario for the area of interest in the midplate regions of the South American plate, where any influence from offshore breaks in the plate (to the west of the trench) has little effect on the flexure we
are evaluating. Specifically, if the portion of the Brazilian craton–Amazon Basin adjacent to the Andes has an elastic thickness between 20 and 100 km, the flexural wavelength would be less than 220 km. Since the distance from the trench to the peak of the Andean load is as much as 500 km, the trench (e.g., the break in the plate) is sufficiently distant and justifies our assumption of an intact plate for the purposes of this study.

Many flexural analyses of the Andes, such as those by Watts et al. (1995) and Tassara (2005), have evaluated the spatial variation in the apparent elastic thickness of the lithosphere along 2-D profiles. In a quasi–3-D extension, Tassara et al. (2007) used a wavelet formulation of the classical spectral isostatic analysis to invert satellite-derived gravity and topography/bathymetry data for elastic thickness over the entire South America plate and inferred that the elastic thickness is greatest (100 ± 15 km) over the central part of the old Amazonian craton and decreases toward its margins to less than 30 km along the continental margins and oceans. With the exception of the central Brazil basin, their predicted elastic thickness is ≤50 km (Tassara et al., 2007). The combined effect of small topographic variation throughout most of the non-Andean South American plate (Fig. 1B) and the heavy vegetative cover of the Amazonian forest makes primary foreland basin system features, such as the forebulge (an area of flexural uplift and erosion), difficult to delineate. Therefore, there is no clear evidence of the exact geometry of possible topography/tectonic effects of the flexural bulge.

Previous studies have constrained the flexural response of the South American plate to the topographic load of the Central Andes in two dimensions by using Bouguer gravity data (Watts et al., 1995; Horton and DeCelles, 1997; Ussami et al., 1999; Tassara, 2005; Dávila et al., 2007). These investigations are burdened by the limitations associated with inverse modeling; the Bouguer data have to correlate to topography across the plate for the method to be informative, and the Bouguer gravity correction requires a specification of density structure. Flexural rigidity estimates vary and depend on the χ value used (Horton and DeCelles, 1997). Furthermore, 2-D gravity analysis yields variation in calculated parameters such as the distance between the Andean front and forebulge crest, the crest elevation, as well as a lack of correspondence of high Andean peak elevations, and average elevations in the midplate regions of the South American plate. For instance, the estimated distance from the Andean front to the forebulge crest varies from ~250 km (Dávila et al., 2007) to ~400 km (Ussami et al., 1999), and forebulge amplitudes range from ~76 m (Dávila et al., 2007) to ~800 m (Horton and DeCelles, 1997).

On the other hand, our 3-D approach is based on the observed topographic load and forward modeling of the lateral distance of the forebulge peak from the mountain front (Fig. 2). This distance is the diagnostic measurable parameter controlling estimates of flexural strength (Turcotte and Schubert, 2002; Peltier, 2008).

GEOID ANOMALIES, FLEXURE, AND OROCENIC CURVATURE

The ancient land surface of midcontinental South America is poorly mapped due to the present-day vegetative cover and dominance of erosive fluvial processes; the location, wavelength, and amplitude of the Andean flexural bulge are not readily apparent. Because geoid anomalies related to the Andean orogenic system mimic the arcuate nature of the major topographic load, we can use geoid anomalies to evaluate evidence for, and determine the characteristics of, the Andean forebulge. To compare with the observed geoid signal, we impose an Andean topographic load (Figs. 1A and 1B) on an elastic shell (Brotchie and Silvester, 1969) and use a series of forward flexural models to determine deflection. A good match for position of the geoid anomaly bulge east of the Andes is obtained between ~5° and ~35° (and especially between ~12° and ~27°) using an effective elastic thickness of 50 ± 10 km (α = 130 km) and provides a calibration of a single uniform elastic plate model (Fig. 1D). The 500 km wavelength of the geoid bulge restricts its source to lithospheric depths. Our load model provides, relative to an undeformed datum, a forebulge amplitude of ~550 m at latitudes ~10° and ~25° in the flexural model (Figs. 1D and 2). The widest transect of the orogen and the largest load are at ~15°, but the flexural bulge there is lower than areas to the north and the south, and the peak of the forebulge is closer to the mountain front. This is a distinguishing characteristic of the markedly curved load represented by the Andes. The amplitudes for all these sections of the forebulge are on the high side of most previous estimates, but they are appropriate for the height of the range and are markedly influenced by the curvature (Fig. 2).

Calculations of the 3-D distribution of forebulge amplitudes and positions determined from our analysis suggest that 2-D flexural models do not correctly estimate the load and flexural parameter for curved orogens. Since curvature is a nearly ubiquitous attribute in planetary collisional systems, our investigation highlights the importance of 3-D flexure models and brings to light implications for lithospheric structure, orogenic processes, and foreland basin sedimentation. The trace and height of the forebulge suggest a stiff elastic plate loaded by a curved orogen. While the underlying causes of orogenic curvature have been the topic of many investigations (e.g., Hobbs, 1914; Carey, 1955; Marshak, 1988; Hindle and Burkhard, 1999; Sussman et al., 2004), the impact that such an observation has on lithospheric flexure has not been addressed. In light of this investigation, showing that we can measure the mechanical effect of the curvature, it appears that spatial variations in flexural characteristics can be explained in part by the arcuate nature of the load, regardless of the causes for that load.

Distance of the flexural forebulge from the causative load is a diagnostic parameter for lithospheric elastic thickness that is independent of forebulge amplitude, which depends on load magnitude. Figure 3 displays the along-strike changes in distance of forebulge from mountain front (thick black line in Fig. 1D). Both the peak geoid anomaly and the flexural model track well between ~10° and ~30° latitude. The closer approach of both curves to the mountain front at ~15° is consistent with the greatest convex curvature of the arcuate mountain belt there. This is another characteristic of arc curvature. North and south of the ~10° and ~30° latitude zone, the arc is concave to the Atlantic side, and in the south, the topographic and therefore flexural amplitude is low enough that arc-perpendicular structures may cause significant mechanical interference.

DISCUSSION

Several important tectonic implications arise from the 3-D continental flexure described here. We find that simple models can explain disparate data sets acquired from topography, flexural models, and geoid anomalies. Flexural modeling based on observed loads is consistent with geoid modeling using a single parameter fit with an effective elastic thickness of 50 km.

Significant spatial variation of flexural rigidity of the South American plate and its correlation to the amount of foreland deformation, as suggested by previous studies (i.e., Watts et al., 1995), is not required by our results. However, variation in flexural strength of the pre-Cenozoic South American plate (Tassara et al., 2007; Feng et al., 2004) may have exerted an important control on variation in the amount of Andean foreland shortening by promoting thin-skinned deformation. Previous studies that considered only late Miocene and younger deformation in the Sub-Andean zone have suggested that regional variations in flexural rigidity have
influenced the bending of the Andean orogenic system (Watts et al., 1995). The implications of lithospheric flexure as discussed here provide a plausible argument that a relationship between the flexural strength and Andean deformation also applies to the longer-term Tertiary history, and therefore has profound implications for the tectonic evolution of the Andes.

Our analysis demonstrates a recognizable geoid anomaly over the High Andes of ~25 m and determines that the response to topographic loading is a flexural bulge with an amplitude of ~500 m or less located ~300–500 km from the orogen front. These results have important implications for the flexural evolution of the Andes and will allow us to assess the distribution of forebulge amplitudes from geologic studies. We also use flexural calculations and geoid observations to demonstrate the effectiveness of combining results from different methods and to demonstrate the impact of orogenic curvature on 2-D models. This paper presents a successful calibration of the geoid and flexure models for almost all of the South American lithospheric plate.

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