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Crustal balance and crustal flux from shortening estimates in the Central Andes

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Abstract

The Central Andes of South America form the second largest high elevation plateau on earth. Extreme elevations have formed on a noncollisional margin with abundant associated arc magmatism. It has long been thought that the crustal thickness necessary to support Andean topography was not accounted for by known crustal shortening alone. We show that this may in part be due to a two-dimensional treatment of the problem. A three-dimensional analysis of crustal shortening and crustal thickness shows that displacement of material towards the axis of the bend in the Central Andes has added a significant volume of crust not accounted for in previous comparisons. We find that present-day crustal thickness between 12°S and 25°S is accounted for (~−10% to ~+3%)with the same shortening estimates, and the same assumed initial crustal thickness as had previously led to the conclusion of a ~25–35% deficit in shortening relative to volume of crustal material. We suggest that the present-day measured crustal thickness distribution may not match that predicted due to shortening, and substantial redistribution of crust may have occurred by both erosion and deposition at the surface and lower crustal flow in regions of the thermally weakened middle and lower crust.

Keywords: Andes; shortening; balancing; crustal thickness; crustal flow

1. Introduction

The Andean Cordillera between ~10°S–25°S contains the second highest plateau on earth (Altiplano–Puna). The present-day surface elevations (more than 500,000 km^2≥3500 m altitude [1,2]) are known to be supported by crustal thickness of ~40–80 km among the highest values on earth [1,3,4]. The Andean Cordillera is also remarkable for its tectonic setting as a noncollisional orogen formed adjacent to the subduction zone between the Nazca and South American plates. Shortening in the chain is mostly

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localized in the two eastern foreland thrust belts and a transitional zone of shortening, the basement involved Eastern Cordillera (EC), the thin skinned Subandean Ranges (SA), and the transitional Interandean Zone (IA) [5], which mark topographic steps in the mountain chain (Fig. 1). To the west of the Altiplano–Puna lies a volcanic arc and forearc region where little significant crustal shortening is detected. The mechanism of crustal thickening in the Andes remains debatable. It was demonstrated that known tectonic shortening from 2D cross-sections is insufficient to account for known crustal thickness [6,7]. Other processes, including magmatic addition of material [8], tectonic underplating of material derived from the forearc [9], and lower crustal flow [6,10], have been invoked to account for missing volume. Most recently, additional shortening in an Eastern Cordillera back-thrust belt [11] and an earlier (Late Cretaceous–Eocene) phase of shortening located west of the Altiplano–Puna plateau of ~100–200 km [12,13] have been suggested to explain crustal thickness beneath the Altiplano.

We use a map balanced, Central Andean, kinematic model (Fig. 1) [5] which reconciled the variations in estimates of Andean shortening of many authors [6,14–18] along strike and is kinematically compatible

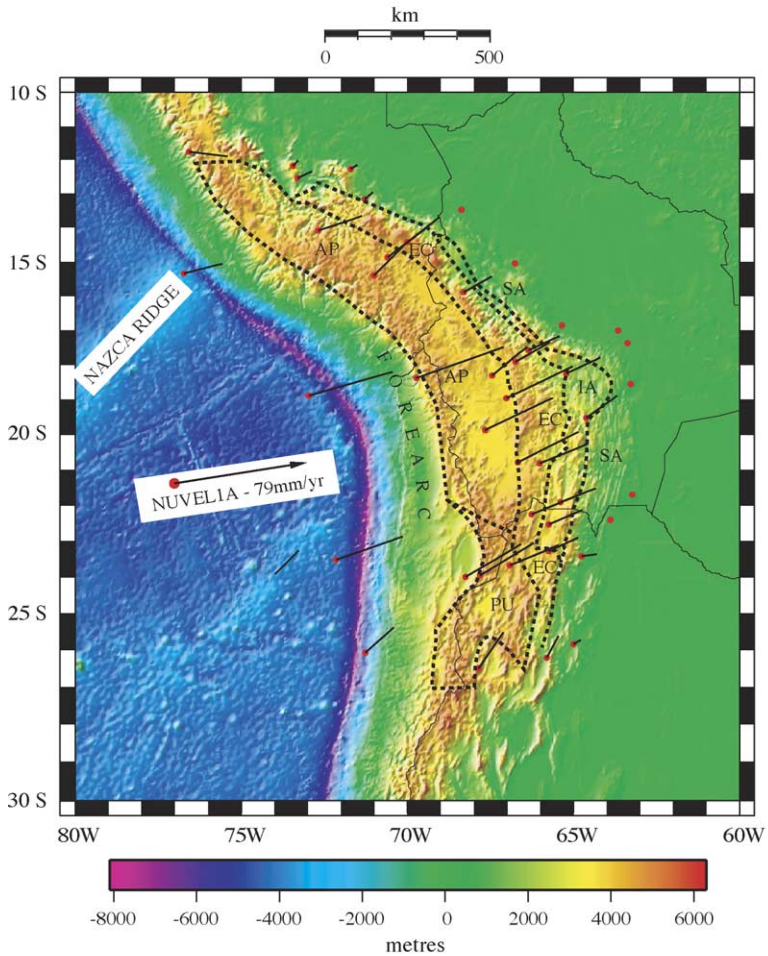

Fig. 1. Topography of the Central Andes showing the finite displacement vectors in [5] used in this study. Note the convergence of the vectors towards the axis of the bend of the Andes. The major tectonic units of the Andes are marked (AP/PU—Altiplano–Puna, EC—Eastern Cordillera, IA—Inter Andean Zone, SA—Subandes).

with the formation of an orocline [19]. We will demonstrate that three-dimensional crustal thickening calculated from the model of Kley [5] generates near identical total crustal volumes to those estimated from seismic experiments [3,4].

2. Shortening estimates and 3D method

Comparing Andean crustal thickness with amounts of crustal shortening has generally been a two-dimensional affair. Baby et al. [6] derived geometries of crustal duplexes at depth from balancing considerations and found that these structures were insufficient to fill the crustal area suggested from teleseismic estimation of Moho depths [3]. Kley and Monaldi [7], using essentially the same shortening data as this paper, compared local measured shortening to estimates based on topographic elevation–crustal thickness relationships. This approach also led to the conclusion that there was a large (~25–35%) deficit in crustal shortening-related thickening.

We use the displacement field (Fig. 1) from the plan view restoration of the Andes [5] combined in cross-section with a two-layer crustal structure (Fig. 2) to model directly the effect of shortening estimates on Andean crustal thickness. The upper crustal layer corresponds to material in the foreland fold and thrust belts lying above regional detachment horizons predicted from cross-sections and assumed to have undergone mostly brittle deformation (Fig. 1). The lower layer corresponds to crust lying below the regional detachment. Original depths to detachment have been compiled from regional restored cross-sections beneath the fold thrust belts and limited seismic data, some of it from the Plateau region [5,20–22] (Fig. 3). Our model assumes compensation of shortening in the upper layer concentrated in the eastern fold thrust belts to occur by ductile strain further west in a region bounded by the western magmatic arc and the west flank of the EC in the lower layer. This offset shortening corresponds closely to the "simple shear" concept of Andean

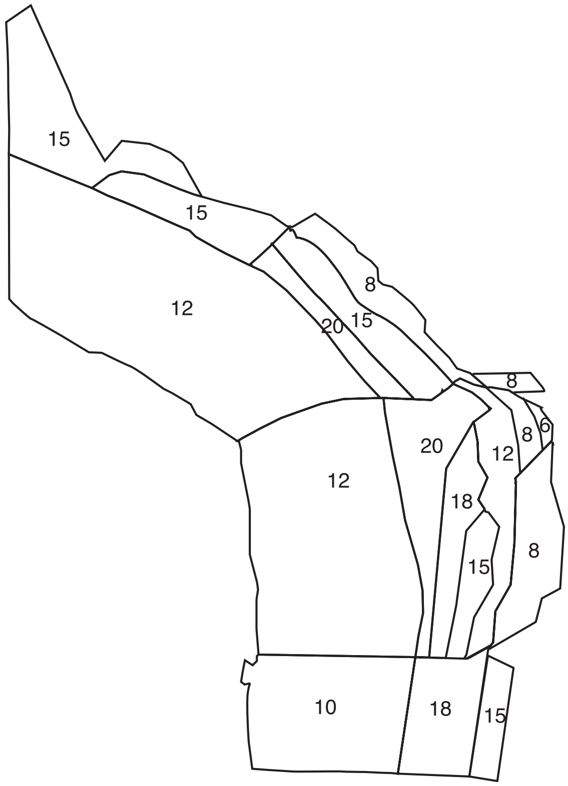

Fig. 3. Original depth to detachment (km) used for modelling crustal thickness. Zones correspond to the model in [5], and depths are estimated from cross-section data summarized therein.

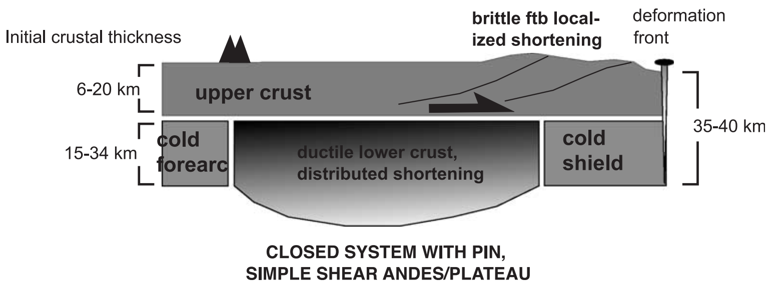

Fig. 2. Conceptual cross-section of distribution of Andean shortening between upper and lower crust in the crustal thickening model.

shortening [2,23]. We base the eastern and western limits of shortening in the lower layer on both geophysical and volcanological evidence of a region of partial melting and thermal weakening in the middle and lower crust [24–26]. Temperature modelling [27] suggests colder and stronger crust close to the subduction zone in the west and beneath the Andean fold thrust belts, where Brazilian shield material is likely to be present. We apply the coastal displacement vectors which contain total Andean shortening to the western margin of the lower crustal region, with zero displacement at its eastern margin (Fig. 4). In doing so, we are able to adhere to the simple shear Andes model [23] and geological shortening estimates at multiple points within the Cordillera simultaneously to predict their combined effects on crustal thickness. This contrasts with the more numerical approach of Yang and Liu [28] which does not adhere as directly to the field observations of shortening within the Cordillera but rather uses total shortening estimates as boundary conditions.

Tectonic thickening of the crust can be assumed to conserve volume locally. Hence, strain ellipses derived from the upper and lower crustal displacement fields (in plan view) have associated vertical "thickening" axes (Fig. 5). We use strain values of the upper crust at the scale of structural units (IA, northern, southern EC/SA) [19] to derive tectonic thickening estimates for the Andean upper crust (Fig. 4). We multiply thickening values by an initial upper crustal thickness which is the local depth to detachment (in the retro-deformed state; Fig. 3) to calculate predicted upper crustal thickness based on shortening distributions. We apply a similar procedure to the shortened zone of lower crust. Initial lower crustal thickness is calculated by subtracting depths to detachment from an assumed total crustal thickness (we show results for 35- and 40-km-thick crust) and multiplied by the thickening values derived for the five regions of lower crust in Fig. 4, while lower crust

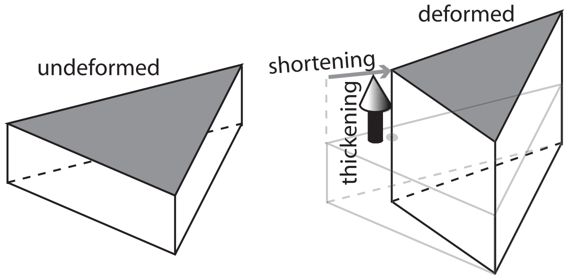

Fig. 5. Schematic diagram to illustrate a "vertical thickening axis." The volume between undeformed and deformed is conserved by allowing the deformed element to thicken by an appropriate amount.

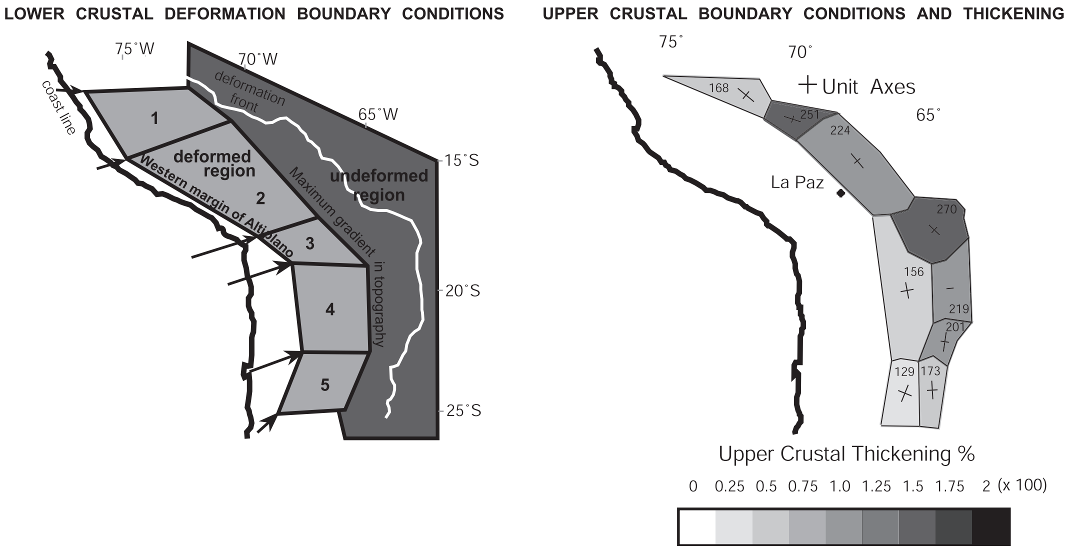

Fig. 4. Regions of lower crustal and upper crustal shortening considered in this study. Numbers on upper crustal regions represent percentage thickening experienced by the crust. Crosses represent trends of principal strain axes.

outside this region is considered to remain unthickened. We then sum the two predicted fields to derive total predicted crustal thickness after tectonic shortening. This method therefore encapsulates out of plane of cross-section motion of material and also heterogeneous (two layer) distribution of shortening with depth in contrast to cross-section only estimates.

Our initial thickness values are consistent with the modern range of global thickness estimates of "extended" and "Late Proterozoic" shield type crust [29]. The Central Andean crust shows high seismic velocities below the eastern foreland typical of shield type material due to the presence of Brazilian shield overthrust by the foreland [30]. The paired, high–low residual, isostatic gravity anomalies paralleling the western limit of the Subandes in southern Bolivia also argue for flexural support of the eastern Andes by underthrust Brazilian shield lithosphere [31]. The southern portion of the Central Andean region underwent Late Cretaceous–Early Tertiary extension evidenced by a series of rift and postrift sediments of continental and shallow marine character which extend into southern Bolivia [32,33]. Consequently, we have chosen the range of initial thickness values which best encapsulate these different situations while noting that a single value is difficult to derive for the entire region. We also note that these were the initial values assumed in previous 2D studies which predicted a shortening deficit [7].

3. Present-day crustal thickness

We test our predictions against a robust 3D crustal thickness database. Both teleseismic and seismic refraction data have been collected across the Central Andes [3,4,24,30,34,35]. Most recently, these data were processed in a three-dimensional teleseismic receiver function analysis [4], which yielded a "plan view" picture of present-day crustal thickness between 18° and 25°S, showing Moho depths ~50–80 km implying a strongly thickened crust. This showed that measured crustal thickness and elevation do not vary as linear functions of one another, interpreted as showing dominantly felsic thinner crust, while thicker crust has a deeper mafic component to it. The possibility that variations of total lithospheric thickness are responsible for the nonlinear relationship was also considered but mostly rejected based on comparisons with other regions of the earth. The base of the lithospheric mantle of the Central Andes is interpreted as being ~100 km deep. Intriguingly, this implies that regions of crustal doubling have no appreciably thicker lithosphere, which is interpreted to show delamination of the mantle lithosphere [4]. Some regions have elevation anomalies nevertheless, which suggest variations in total lithospheric thickness. The Puna plateau region, of highest average topography, sits ~2 km higher than predicted by its ~50–55-km-thick crust. This is attributed to delamination of most of the lithospheric mantle since seismic velocities of the uppermost mantle are lower beneath the Puna than the Altiplano region, and seismic attenuation is greater [36]. Thinned lithosphere beneath the Puna plateau has also been suggested based on the chemistry and isotopic composition of back-arc volcanics [37]. The Subandes have a negative elevation anomaly found to be greater than would be attributable to the effects of flexural loading, the excess due possibly to a region of increased lithospheric thickness (~120 km). We note that the SA/EC border is also considered to be the maximum eastward extent of soft, hot, deformable lower to middle crust in the thickening model presented here.

4. Comparison of real and predicted thickness

We use the 3D receiver function data and extend it with an elevation–thickness relationship for regions of no data (Fig. 6). The region covered by the receiver function data stands out as an obvious subrectangular patch in Fig. 6. Using the new data means we compare our model to a thicker present-day crust than was previously admitted [1,2,7]. Predicted thickness has been calculated on a regular grid and interpolated using the GMT [38] nearest neighbour interpolation function. Two models based on 35- and 40-km initial crustal thickness are shown in Fig. 7A and B. Their characteristics are similar, with thickest crust predicted at the axis of the bend especially beneath the EC. Thick crust is also predicted under much of the plateau. Thinner crust is found on the eastern mountain front. Subtraction of the models from the present-day data results in the difference plots of Fig. 7C and D. Blue, in this case (negative values),

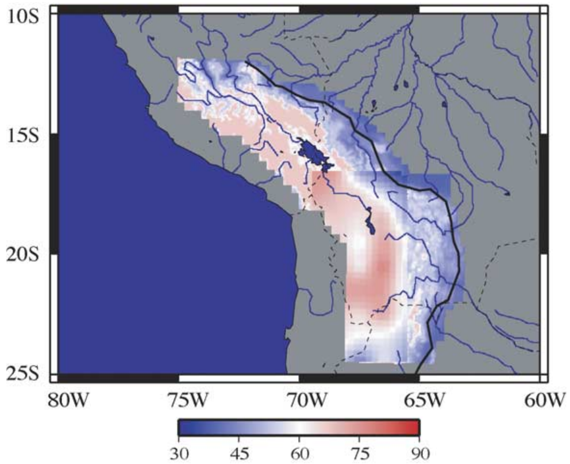

Fig. 6. Present-day crustal thickness map for the Andes based on receiver function data in [4] and a topography–thickness relationship where no receiver function data is available. Algorithm is $Thick_c$ (km)=38+8×H_{topo} (km), if 2.5 (km)≤H_{topo}; $Thick_c$ (km)=30+7.5×H_{topo} (km), if 2.5 (km)≤H_{topo}≤4(km); and $Thick_c$ km=67, if H_{topo}≥4(km). This allows a relatively thicker crust in the foreland also in accordance with receiver function data.

represents a predicted excess of material and red a predicted deficit.

Most interestingly, this method allows us to estimate the volume difference of our predictions in a manner analogous to the work of Kley and Monaldi [7]. The 40-km initial crustal thickness model predicts a ~2.7% volume excess (4.63×10^7 vs. 4.51×10^7 km^3 present-day estimate). Based on the same shortening estimates and initial thickness, 2D comparisons [7] had suggested a significant (~25–35%) volume deficit. Our estimate from a model of 35-km initial thickness gives a ~9.4% volume deficit compared to a ~30% deficit from the original 2D estimates. Hence, our 3D treatment of the original Andean shortening data suggests either no deficit in crustal volume, or that the deficit is considerably smaller than was first believed, depending on initial conditions. We note that these values do not consider the probable addition of material due to magmatism nor the removal of material due to erosion.

We now consider the predicted distribution of crustal thickness vs. that which is known to occur. Fig. 7D shows the difference with an initial 40-km crust. There is a clear excess (negative in Fig. 7) of material (blue regions) predicted in the east (maximum ~−27 km at ~65.5°W,17.8°S) and a deficit (red regions) across much of the plateau (maximum ~+25 km at ~74.7°W,11.7°S) although there is an excess of material predicted in the central part of the plateau at the latitude of the axis of the bend. It is particularly notable that a large material deficit is encountered beneath the Altiplano–Puna plateau. This was already remarked upon in 2D work [6]. Results for a 35-km initial crust are shown in Fig. 7C. This model predicts a similar although reduced thickness distribution, with no excess in the central portion of the plateau. Fig. 7C and D also shows gradient vectors calculated for the field of thickness differences, with no appreciable difference between the fields. The gradient trends strongly east–west in both the EC and SA, but there is a weaker north–south component along the axis of the Altiplano–Puna plateau. The gradient vectors could be treated as indicating how material can best be redistributed to remove thickness differences by the mechanisms discussed later in the paper.

5. Model parameters and sensitivities

The model is influenced by uncertainties in several parameters, namely, original depth to detachment, total amount of shortening (also related to original depth to detachment), and original crustal thickness. Change in predicted crustal thickness with variation in any parameter is nonlinear. Deeper average detachment depth should reduce shortening estimates, which would feed back into strain values and, hence, reduce the amount of crustal thickening. An opposite effect would be expected for shallower detachment levels. If we assumed a ±3-km variation in detachment depth, assuming an “average” detachment depth of 15 km and a very simple depth to detachment relationship, this would lead to a ~+17% to ~−20% change in shortening and an approximately similar change in “tectonic thickening” values. Such shortening variations fit quite well with the actual differences in shortening estimates between authors although these are not necessarily attributable to differing detachment levels. Apart from the effect of reducing or increasing bulk shortening estimates, a changed detachment depth will directly affect the thickening estimate even if shortening values applied are constant. However, a ±3-km depth to detachment change produces only ±~0.5% changes in total predicted crustal volume.

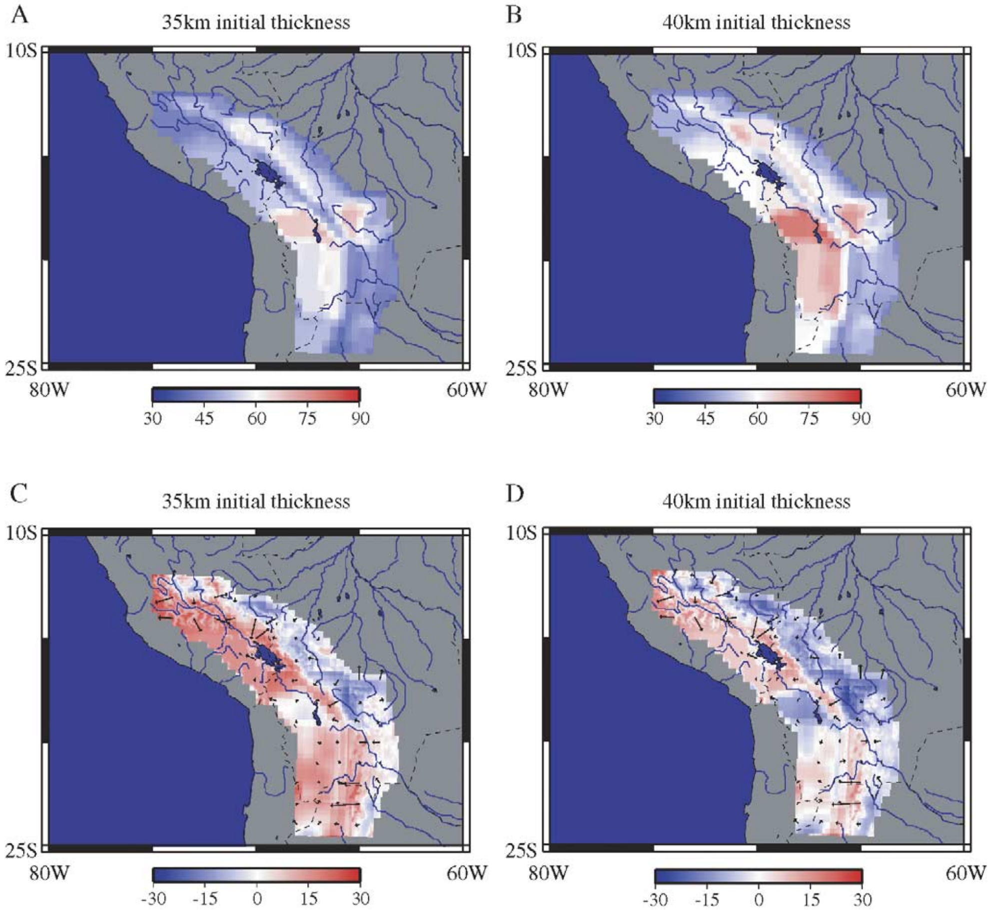

Fig. 7. (A and B) Predicted crustal thickness based on Central Andean shortening for different initial crustal thickness (35 and 40 km); (C and D) difference between measured present-day and predicted crustal thickness for different initial thickness (35 and 40 km). In panels (C and D), blue areas represent excess predicted crustal volume, red represents deficit. Gradient vectors are also shown for the difference fields.

Nevertheless, we note that this work is aimed at testing one particular set of shortening estimates for volume balance and, consequently, assumes the appropriate detachment depths for these.

A significant shortcoming of this and any other crustal thickening model is the simplifying assumption of a constant thickness initial crust everywhere. We assume this to have been the case at the beginning of major Andean shortening (~30–25 Ma) although, given the earlier tectonic history of parts of the region (for instance, south of ~20°S, the region affected by a mid-Cretaceous extension [39]), this is not likely to have been the case. Early (Eocene–early Oligocene)-shortening may also have locally affected initial crustal thickness. The change to model predictions due to heterogeneous initial crustal thickness would depend on whether significantly thinner or thicker crust coincided with the regions highest tectonic thickening. However, provided the homogeneous initial values used in the model represent a likely "average" value, these changes should be mitigated.

6. Flux of crustal material

Part of our analysis has demonstrated a near volume balance in the Central Andes but shows that the predicted distribution of material does not match the present day. We suggest that this indicates flux of crustal material throughout the evolution of the Andes although it could theoretically reflect differences in initial crustal thickness. However, given the large magnitude and short wavelength of the differences, it is unlikely that these reflect an initial, inhomogeneous crustal thickness distribution. Several mechanisms for redistributing material might be considered. Surface transfer of material by river erosion has occurred. The Altiplano has a complicated history of sedimentation. Up to 6 km of pre–early Oligocene sediments are found [13,40], the earliest with westward transport (suggesting an eastern source) but a significant portion (Potoco formation) deposited under mostly eastward transport. Late Oligocene and younger sediments with a definite eastern provenance have variable thickness. Horton et al. [40] suggests ~1–4 km although there are local occurrences (Corque syncline [1,41]) of ~5–6 km. These sediments have almost certainly been sourced from erosion of the early developing EC and therefore contributed to material transfer in our model. We would estimate this to be of the order ~3–5-km thickness from the entire EC.

There has also been a continuous redistribution of material from high parts of the Andes to the foreland (e.g., EC to SA) throughout the history of mountain building. The early foreland basin which became the SA has undergone syn-sedimentary deformation and, consequently, has no true, single, initial thickness. Material has also been transferred eastwards from the modern Andes. This process is influenced by climate variations along strike with the northern portion of the Cordillera (north of ~15°S today) undergoing the most erosion and removal of material either to the undeformed foreland of the modern Andes or bypassed to river deltas in the Atlantic. The material stored in the modern foreland can be assessed from the modern geometry of the wedge of undeformed sediment in the basin, with $\sim 1\times10^6$ km^3 stored along ~2000-km arc length of average basin width 200 km^3 and wedge thickness of 0–5 km. Added to this is material removed to river basins beyond the foreland and to the continental margins of South America. By far, the largest contribution is made by the Amazon river system, where the basin has surface area $\sim 3.6\times10^6$ km ^{2} and ~0.1 km average thickness of Cenozoic material, while the Amazon fan, which evolved since the Paleogene, has surface area of $\sim 0.4\times10^6$ km^2 with 0–10 km thickness of sediment. Provenance studies indicate that up to 50% of the sediment load of the Amazon river is derived from the Central Andes although they make up only 12% of the drainage basin [42]. Hence, a total volume of $\sim 1.2\times10^6$ km^3 may have been removed to the Amazon system. The smaller Pilcomayo/Paraguay/Parana system gives, by a similar method of estimation, ~ 0.3–0.7×10^6 km^3 of material. Thus, the volume of material eroded from the Central Andes and lost to the foreland basin, river basins, and the oceans is ~ 2.5–2.9×10^6 km^3 which is equivalent to ~5–6% of total crustal volume. This is probably a high estimate as the length of arc we are considering is only part of the Central Andes.

A second flux mechanism suggested in other mountain belts of the world [43] and the Andean Cordillera [44] is lower or mid-crustal flow in a ductile channel (so-called Poiseuille flow). In our model, substantial transfer of material (up to ~20 km thickness) over short (~100 km east–west distances and more substantial movement north–south (~500 km along strike) would be necessary. This would serve to redistribute material from the locus of maximum shortening at ~18°S. 1D diffusion calculations for the Andes [44] have estimated a viscosity of $\sim 8\times10^{18}$ Pa s to effect redistribution of material.

We estimate that the redistributive flux of excess material generated by shortening in the EC/SA into the plateau would be of the order of 0.05–0.13 km^3 year^{-1}, depending on the initial thickness of the crust and the amount of material transferred to the oceans. We base this on the volume of the blue area (excess) in Fig. 7C and D and a 25-Ma period of redistribution (excess ~ 1–3×10^6 km^3 year^{-1}). After redistribution and loss of material by erosion is accounted for, we estimate that ~60–70% of this flux would be by means of lower crustal flow. These estimates exclude the addition of material by magmatism which contribution was analysed in some detail [1]. It has been pointed out [1] that global magmatic addition rates above Mesozoic to Recent arcs are in the order of ~ 0.2–0.4×10^{-4} km^3 km^{-1} arc length year^{-1}, which is quite close to the flux rates suggested here (assuming 1000-km arc length, we find ~ 0.5–0.13×10^{-3} km^3 km^{-1} arc length year^{-1}). Similar local estimates in the Andes [45] concluded that the total contribution of magmatic addition to crustal volume was ~1.5%. This balances some of the removal of material to the foreland, river basins, and the oceans.

7. Discussion

It has been shown that the originally defined shortening deficit in the Andes may have been an artifact of two-dimensional analysis of the problem restricted to the plane of cross-sections which misses any out of plane section motion of material. This is a similar conclusion to [28]. Figs. 1 and 8 show an essential feature of the shortening model of [5], whereby material is funneled towards the axis of the bend. This adds the black-shaded material to the region bounded by the two lines marked “present edge” and is 35–40% of the grey-shaded area which is material being transported in the plane of a cross-section. This additional component of material moving along strike is ignored in studies analysing material balance in the plane of cross-section only and explains why we predict volumes very close to those found today. This demonstrates the power of attempting shortening estimates in plan view whenever possible.

We note that the shortening estimates used in this study are a compatible combination of the work of many previous authors which it was also shown [19] fit well with curvature of the Bolivian orocline, local strain patterns, and, to some degree, paleomagnetic rotations [46,47]. This model has a maximum shortening of ~275 km well below some of the new estimates proposed [12,13] and is much closer to balance than was thought based on original 2D analysis of the problem. The results presented here show that, for any material balance analysis in a mountain belt, the along strike motion of material cannot be ignored.

Including the effects of loss of material to the oceans, we still see the need for some extra shortening regardless of 3D effects. However, the amount required would be closer to the lower bounds of new estimates [11] and would not require the very high estimates [12,13], including an early Tertiary

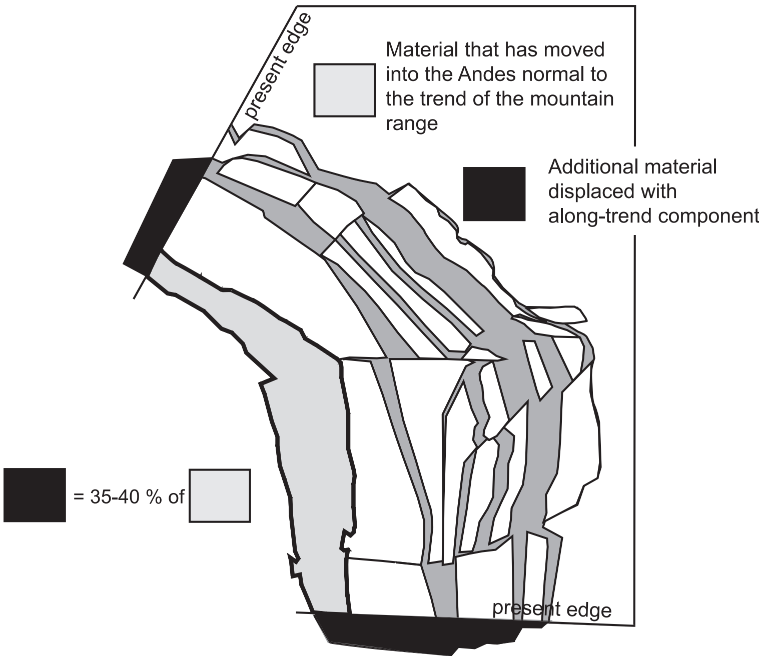

Fig. 8. The block model used to derive the displacement field of Fig. 1. Blocks represent the restored (predeformation) positions of the margin. The lines marked present edge are the present-day position of northern and southern edges of the restored model. Black-shaded region is therefore material which has moved along strike and converged towards the axis of the bend.

shortening phase of up to 200 km inferred from an interpretation of early Tertiary, sedimentary rocks in the Eastern Cordillera as representing an early, eastward migrating, foreland basin moving before a "Western Cordillera" shortening wedge. As an illustration, an additional 30 km of uniform shortening along strike assuming a 40-km initial crust would produce ~9% volume excess which would require additional removal of crust even when allowing for loss of material to ocean basins. One mechanism which might be speculated upon would be the removal of the lower crust by delamination after eclogisation. Such processes have been suggested based on magmatic evidence in the Puna region [37] and could be inferred from low seismic velocities in some places below the Altiplano [34]. It might also be argued that 40 km is an unrealistically thick initial thickness for the preshortening, Central Andean crust as this was widely at sea level in Maastrichtian–Paleocene times. In this case, the 35-km initial thickness value would be more appropriate, but it should be noted that the original shortening deficit problem was defined with respect to 35- or 40-km thick crust, and consequently, reducing the previous gap between shortening and crustal thickness by a previously ignored mechanism of along strike shortening of the Andes is significant. Hence, it is fair to conclude that some (possibly ~30–50 km in a northern "back-thrust belt" [11]) additional shortening in the Andes is required, but that the amount necessary is less than the highest of the new estimates suggest [12,13].

8. Conclusions

The "out of plane of cross-section" motion of material is very likely an essential aspect of any arcuate mountain chain. Crustal thickness estimates based on two-dimensional cross-sections will ignore this component. Our model shows that, in the case of the Central Andes, this effect could cause material equivalent to ~40% of the "in transport direction" shortening to be added due to convergent displacement patterns around the axis of the bend in the arc. A three-dimensional analysis of this shortening field consistent with many geophysical observations of the nature of the crust in the Central Andes predicts little or no deficit in crustal material and does so without major revision of earlier shortening estimates for the chain. Significant fluxes of material are also predicted which could be achieved by erosion and redeposition in the Altiplano–Puna plateau and lower crustal flow along strike of the chain. Even including the effects of significant removal of material from the Central Andes, a crustal volume excess allowing for some delamination of the lower crust can still be conceived of by allowing for limited (~30 km) additional shortening over the earlier estimates.

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