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Review Article

Gravity derived Moho for South America

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ABSTRACT

Crustal structure in South America is one of the least understood among the Earth's continental areas. Variations in crustal thickness are still poorly constrained over large portions of the continent because of scarce or unevenly distributed crustal thickness estimates throughout South America. To address this scarce and inhomogeneous data cover we explore the possibility to derive crustal thickness from satellite gravity data. In this study, we utilize the combined gravity model EIGEN-6C, which is composed of GOCE and other gravity data. The Gravity field and steady-state Ocean Circulation Explorer (GOCE) satellite has a much more uniform spatial resolution than any land-based gravity or seismic survey in South America. The gravity data inversion is for a simple two-layer model with fixed density contrast over the interface, the Moho. The method is not relying on point constraint data and assumes that all of the signal is related to topography of the Moho. Model quality can therefore be assessed by a comparison with point observations on crustal thickness. We show that for the stable part of the continent 90% of our estimates are similar, within error bounds, to seismic observations. Variations occur in active orogenic zones or regions with suspected non-standard Moho density contrasts. A comparison with seismological models shows a high correlation with the most recent model. Especially in areas where continental and global models of crustal structure have limitations in terms of wave paths or point constraints the gravity based model provides a unique continuity of crustal structure providing new insights on structure and tectonics and increase our understanding of the Earth's structure underneath South America.

Contents

1. Introduction

The crustal structure of South America is one of the least understood among the Earth's continental areas. Variations in basic but fundamental

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parameters such as crustal thickness are still poorly constrained over large portions of the continent. Estimates of crustal thickness are commonly obtained from either seismic or gravity measurements over the Earth's continents, but land-based data coverage – both seismic and gravimetric – has been traditionally scarce or, at best, unevenly distributed throughout South America. Due to restricted financial and technical means devoted to scientific purposes and local circumstances it has always been very difficult to obtain detailed information on and/or maintain networks to study the Earth's structure underneath South America. Parts of Brazil, the Andes and Venezuela have been extensively studied but the rest of the continent has been only sparsely covered with crustal thickness observations. To our knowledge, only a handful of models provide crustal thickness information on a continental scale for the South American continent (Assumpção et al., 2013–this issue; Bassin et al., 2000; Feng et al., 2004, 2007; Lloyd et al., 2010, e.g.), and these models are largely based on seismic datasets gathered from uneven distribution of seismic experiments throughout the continent. This uneven data coverage has resulted in large lateral variations in resolution and significant trade-offs between well- and poorly-resolved portions of the continent. Consequently, knowledge on South American tectonic and geodynamic processes and their relationships with and influences on crustal thickness and upper mantle structure is limited.

The Gravity field and steady-state Ocean Circulation Explorer (GOCE) satellite (launched on 17 March 2009) has a much more uniform spatial resolution than any land-based gravity or seismic survey in South America and an improved accuracy with respect to previous spaceborne gravimeters thanks to the inclusion of six accelerometers (three pairs in three orthogonal directions) (Drinkwater et al., 2003). This improved resolution and accuracy is of great interest for studies of the Earth especially in places where limited or inhomogeneous data is available, and provides a unique opportunity for improving our knowledge of basic crustal structure in places with scarce data coverage like South America (Assumpção et al., 2013).

In this study, we utilize the combined gravity model EIGEN-6C (Förste et al., 2011), which is composed of GOCE and other gravity data, to derive a model of crustal thickness variation for South America. First, crustal thickness is obtained after assuming a simple layer-over-half space model for the crust and lithospheric mantle and inverting sediment corrected Bouguer gravity anomalies based on EIGEN-6C with the 3D procedure of Parker and Oldenburg (Gómez-Ortiz and Agarwal, 2005; Oldenburg, 1974; Parker, 1973). To evaluate our gravity-based results, we compare our estimates to an independent compilation of point estimates on crustal thickness for South America developed by Assumpção et al. (2013). The evaluation exercise shows a good correlation between independent point observations and gravity-derived estimates of crustal thickness. Our model is then compared with independent continental-scale crustal thickness models based on the joint inversion of point observations and regional surface waves. The differences and similarities are used to comment on the applicability of using (satellite) gravity data for modeling of crustal thickness in areas where there are no point data or good surface wave coverage. Our results illustrate that models derived from (satellite) gravity data can provide first order constraints on crustal thickness. Especially in areas where continental and global models of crustal structure have limitations in terms of wave paths or point constraints the gravity based model provides a unique continuity of crustal structure providing new insights on structure and tectonics and increase our understanding of the Earth's structure underneath South America.

2. Material and methods

2.1. Gravity data

The crustal thickness map developed in this study is based on the inversion of a global gravity model that contains gravity gradient data from the GOCE (Gravity Field and steady-state Ocean Circulation Explorer) mission (Drinkwater et al., 2003). The GOCE satellite was launched in March 2009 and was the first of a series of Earth Explorer satellites launched by the European Space Agency (ESA), as part of its Living Planet Programme, to gather information for understanding critical Earth system variables. In particular, the GOCE satellite has the goal to map our planet's gravity field in unprecedented detail. In order to counteract the attenuation effect traditionally seen in gravity data and to amplify the gravity signal, GOCE is equipped with the first spaceborne gradiometer, thus adding unique gradient data to existing worldwide gravity models, in particular at shorter wavelengths. The gradiometer contains six proof masses capable of observing detailed local changes in gravitational acceleration in three spatial dimensions with extremely high precision. Since the gravitational signal is stronger closer to the Earth, GOCE has been designed to fly in a very low orbit of approximately 250 km which is much lower than other Earth gravity observation satellites thereby improving the signal strength.

GOCE data was chosen for this research to be used in a combined model of GOCE satellite gravity data, data from previous satellite gravity missions, radar altimetry data and terrestrial data, EIGEN-6C (Förste et al., 2011). A Bouguer corrected gravity anomaly map of the Earth (Barthelmes, 2009) was downloaded from the International Centre for Global Earth Models (ICGEM). The data is based on the classical gravity anomaly. This is defined as the magnitude of the gradient of the downward continued potential on the geoid minus the magnitude of the gradient of the normal potential on the ellipsoid (Eqs. (93) and (121)–(124) of Barthelmes (2009)). A Bouguer plate correction compensates for mass related to topography that exceeds above or below the reference surface. It is modeled by a solid slab of fixed density and infinite extent from the point of observation. This is necessary to exclude the effect of surface topography contributions in the assessment of gravity signals from the Moho. The Bouguer gravity anomaly is the classical gravity anomaly minus the attraction of the Bouguer plate. At ICGEM, it is calculated by the spherical approximation of the classical gravity anomaly minus $2\pi G\rho$ H (Eqs. (107) and (126) of Barthelmes (2009)). Their topographic heights H are calculated from the spherical harmonic digital elevation model DTM2006 used up to the same maximum degree as the gravity field model. Densities used are for $H \geq 0$ (rock) is 2.67 g/cm^3 and for $H \leq 0$ (water) is 1.67 g/cm^3.

To develop the crustal thickness map presented in this study, the Bouguer anomaly map was downloaded at a grid spacing of 0.1° from the ICGEM (International Centre for Global Earth Models) website (Fig. 1). The Bouguer anomalies were then corrected for the presence of sediments. Sediments have a lower density than the bedrock. In this sediment correction the lighter sediments were replaced with more heavy bedrock material. Sediment thickness and density information was retrieved from a global sediment thickness map (Laske and Masters, 1997) (Fig. 1) and the correction was applied in a similar way as the Bouguer correction. We used a density contrast of 0.2 g/cm^3 between the sediment basin and the surrounding bedrock. This is based on the average density value of the central layer in the digital soil map of Laske and Masters (1997) which is around 0.2 g/cm^3 less than the 2.67 g/cm^3 used for rocks in the Bouguer correction.

2.2. Inversion method

Different approaches are possible for inverting gravity data for crustal thickness. The most straightforward approach is inversion for a simple two-layer model with fixed density contrast over the interface, the Moho (e.g. Oldenburg, 1974). This method is not relying on point constraint data and assumes that all of the signal is related to topography of the interface to be modeled. A 3D approach (Li and Oldenburg, 1998) is regularly used for shallow studies but not often for modeling of the Moho discontinuity (e.g. Welford et al., 2010). To overcome the non-uniqueness inherent to this approach it is possible to do a joint inversion of gravity data with a priori information on crustal structure like seismic point observations or profiles and

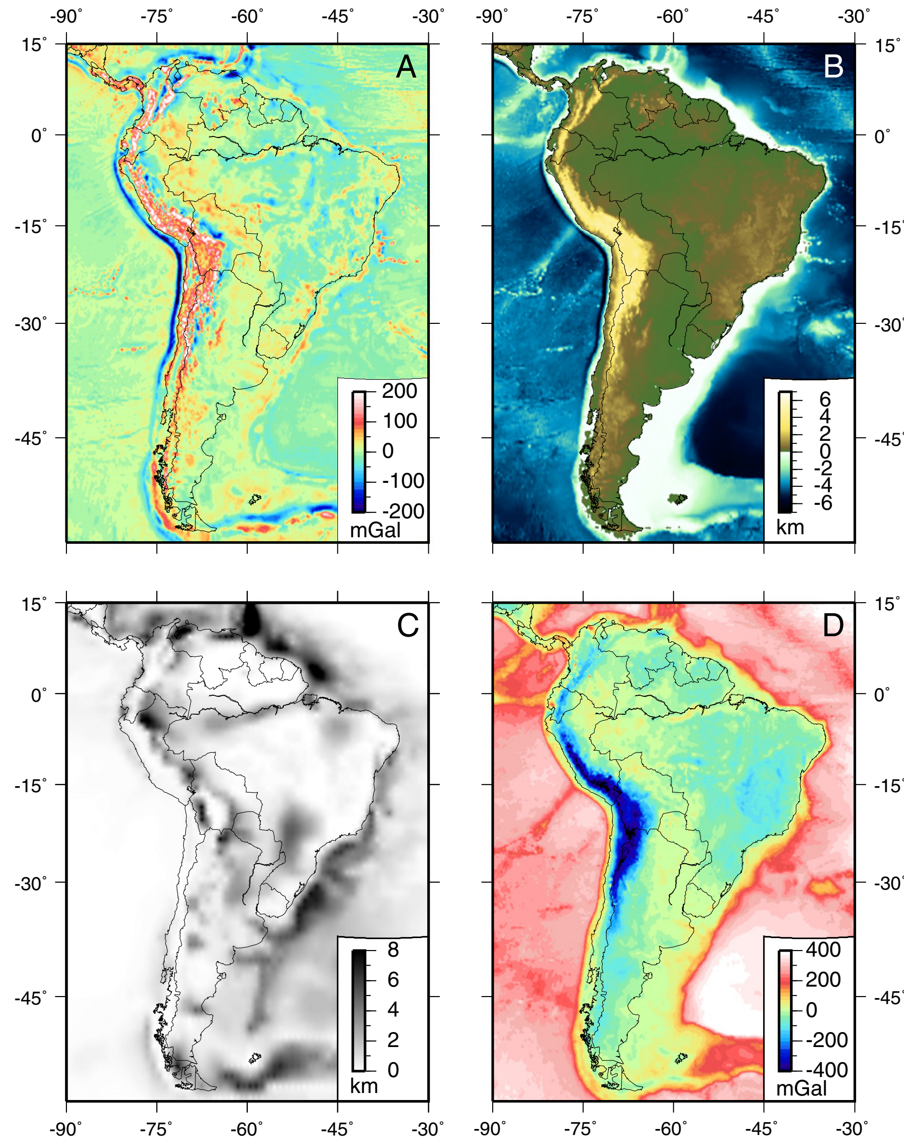

Fig. 1. Sequence of input maps in the processing. A. Free-air gravity anomaly; B. Topography from DTM2006; C. Sediment thickness for South America from (Laske and Masters, 1997); and D. The final sediment corrected Bouguer gravity anomalies which are used as input in the modeling.

lateral density variations (e.g. Schmidt et al., 2011). This method works particularly well in areas of homogeneous data cover where the constraints control the gravity inversion. This gives high accuracy for areas with point constraints but results in much higher variability for regions without constraints. This results in an uneven distribution of accuracy of the resulting output map. One way to overcome this is using a knowledge based approach. A first implementation of this approach is that Moho topography is directly linked to the causal physical process, or several processes. These processes then need to be known and well understood and the underlying assumptions, like isostatic equilibrium, need to be valid (Aitken, 2010). Second implementation would be numerical modeling in which multiple parameters are included and relations between them extensively explored. An example is the modeling by Fullea et al. (2009), who used a model with an internally consistent thermodynamic geophysical framework, where all relevant properties are functions of temperature, pressure, and composition. By simultaneously solving the heat transfer, thermodynamic, rheological, geopotential, and isostasy (local and flexural) equations, the program outputs temperature, pressure, surface heat flow, density (bulk and single phase), seismic wave velocities, geoid and gravity anomalies, elevation, and lithospheric strength for any given model. This is only possible when extensive knowledge of an area is available.

South America is a relatively poorly-studied continent so a knowledge based approach is not realistic. Furthermore, it has a spatially inhomogeneous cover of point constraints on crustal thickness (Assumpção et al., 2013). A combined inversion of constraints with gravity is therefore not recommended. If point constraints would be used in the inversion the model can be potentially improved on locations where point constraints are available. The inversion will then be forced to fit the constraints. When comparing a good fit will be observed for these locations. For locations without point constraints there is no external control on the gravity inversion, and it is not said that it is automatically correct if other places are constrained. It is then also not possible to provide a measure of the quality of the model for these regions. To keep the model as simple, balanced and non-biased as possible we have chosen not to use the constraints in the inversion. This way we show the strength of the method, without using a priori information, to provide a 1st order estimate of crustal thickness. The initial starting value for the crustal thickness is based on an average for oceanic and continental crust. This choice for this value is not subjectively chosen but is based on an exploration of the thickness–density contrast parameter space for the best fitting solution with respect to the point observations for crustal thickness.

The applied inversion method is independent of point constraint data and based on the Parker–Oldenburg iterative inversion (Oldenburg, 1974; Parker, 1973). The sediment corrected Bouguer gravity anomalies for the South American continent were modeled to obtain estimates of crustal thickness throughout the continent. We used the implementation by Gómez-Ortiz and Agarwal (2005), which results in a simple two-layer model with the Moho as the only subsurface interface. The desired data area was extended 20° to all sides and a cosine taper window was applied to the 10% outer pixels to avoid side effects during the processing. A last pre-processing step is demeaning of the gravity data. As the inversion is unstable at high frequencies (Gómez-Ortiz and Agarwal, 2005), a high-cut cosine filter was included in the inversion procedure to ensure convergence of the series. The upper boundary was set to a wavelength of approximately 200 km. This also removes intra-crustal near-surface effects which should not be attributed to Moho thickness. In the final representation a further smoothing (to a resolution of approximately 250 km) has been applied to the data for two reasons. The first reason is to make the derived model comparable to other models, like tomography based models, and secondly, to avoid spurious accuracy. The applied approach is simple, neglecting many factors like intra-crustal discontinuous structures that potentially have much larger amplitudes than Moho variations. To not over interpret the model and acknowledge that Moho related gravity anomalies are expected to be smaller and in longer wavelengths than the original data input, the smoothing has been applied. The iterative inversion process was terminated when a maximum number of 10 iterations were reached or when the difference between two successive approximations to the Moho topography was lower than 0.02 km. The computed Moho relief is then forward modeled and the resulting gravity anomaly is compared with the original input gravity anomaly.

In order to investigate the uniqueness of our crustal thickness map, we performed several inversions using a range of values for critical parameters, such as the starting Moho depth and the density contrast across the Moho interface. Since the gravity data is demeaned the starting Moho depth should also be the average of expected crustal thickness for the area under investigation. Starting Moho depth was varied between 18 and 28 km, which are reasonable bounds for combined oceanic and continental crustal thickness. The density contrast was varied between 0.25 and 0.50 g/cm^3, again in agreement with values for average crust–mantle interface which vary between 0.28 and 0.48 g/cm^3 (Bassin et al., 2000; Dziewonski and Anderson, 1981; Martinec, 1994; Sjöberg and Bagherbandi, 2011; Tenzer et al., 2012).

The final model, and corresponding starting depth and density contrast, were chosen based on a combination of criteria: (i) comparison of calculated crustal thickness with point observations, and (ii) misfit between the input gravity anomaly and the forward modeled gravity anomaly based on the computed Moho topography. Final model parameters in the inversion were 24 km for the initial starting depth and a density contrast over the Moho of 0.35 g/cm^3.

Uncertainties for the model were estimated based on crustal thickness variations observed by varying the input parameters with 0.05 g/cm^3 and with 1 and 2 km steps for the initial starting value. This results in a combined effect of, on average for the whole continent, of ± 3 km. More details and information on the spatial variability are shown in the Discussion section.

After the inversion, surface topography has been added to come to crustal thickness, rather than Moho depth, using ETOPO1 (Amante and Eakins, 2009). For clarity, we refer to crustal thickness as the total thickness of the crust from the surface to the Moho, and we use the term Moho depth to indicate the distance from sea level to the Moho.

2.3. Constraints

For validation of the gravity derived Moho depth a comprehensive compilation of 762 seismic point-constraints, 572 on-shore and 190 off-shore, on crustal thickness throughout South America (Assumpção et al., 2013) have been used. The compilation is based on crustal thickness observations from active source experiments (deep seismic refraction lines, or deep seismic reflection surveys), and receiver functions. The set of seismic point constraints includes a number of previous compilations for the South American continent (Feng et al., 2007; Lloyd et al., 2010; Pavão et al., 2012; Tassara and Echaurren, 2012) and expanded with additional point constraints from published papers, congress proceedings, theses, and unpublished monographs (see Assumpção et al. (2013), and references therein).

We observed that, in a few cases entries for the same location had been compiled from different authors and/or techniques. We removed the multiple entries based on the reliability or accuracy of the crustal thickness observation. In case both criteria above were equal the most recent result was selected. This differs from the approach followed in Assumpção et al. (2013), where multiple entries were averaged to provide a single estimate. The final database contained a total of 736 points, most of them in the Andes, eastern Brazil and northern Venezuela. Reported uncertainties for these constraints are on average ± 3 km.

2.4. South American geology

South America is a tectonically complex continent that can be regarded as a collage of several Precambrian terrains, fold belts, and intracratonic sedimentary basins to the East (the Brazilian shield), a late Proterozoic block to the south (Patagonia), and two Phanerozoic orogenic zones to the West (the Andes) and north (Caribbean) bordering the continent (Fig. 2). The Andean orogen is tectonically active and is related to the collision of the Nazca plate with the South American plate. The Brazilian shield and the Patagonian block are tectonically stable and are collectively known as the South American Platform (Almeida et al., 2000).

The South American Platform can be in turn regarded as an amalgamation of a number of Archean and Early Proterozoic cratonic nucleus of several sizes, separated by a rather continuous network of Neoproterozoic mobile belts (Cordani et al., 2000; de Brito Neves and Cordani, 1991). The cratonic blocks include the Guyana and Guaporé Shields, located to the north and south of the Amazon basin, respectively, and collectively known as the Amazonian craton, and the São Francisco craton to the east. Additional cratonic blocks have been postulated under the Paraná intracratonic basin (Cordani et al., 1984; Zalán et al., 1990), although the detailed configuration of the cratonic basement is under debate (e.g. Julià et al., 2008; Milani and Ramos, 1998).

The network of mobile belts constitutes the Brasiliano domain and is related to the building of West Gondwana during the Brasiliano/Pan-African orogeny. The Brasiliano/Pan-African orogeny was the major tectonic event affecting the platform before the opening of the South Atlantic Ocean. The later amalgamation of Pangea (Hercynian orogeny) only contributed through the accretion of a small continental mass – Patagonia – to the platform (Cordani et al., 2000). A major tectonic structure of the South American Platform is the Transbrasiliano Lineament (TBL), a 2000 km long megasuture striking in a NE–SW direction from NE Brazil to central Chile along the Brasiliano belts. It is thought to be the straightforward result of the collision between the Amazonia–West Africa and the São Francisco–Congo cratons during Neoproterozoic times (Cordani et al., 2000). Interestingly, de Oliveira and Mohriak (2003) suggested that the TBL could have also defined a zone of preexisting weakness along which an aulacogen would have developed during the splitting of West Gondwana.

The Brasiliano belts have been classified according to their lithostructural trends (de Brito Neves and Cordani, 1991) as marginal zones (external) close to, and distal zones (internal) away from, the cratonic borders. The external belts are characterized by thin-skin tectonics and reduced magmatism typical of passive margins, whereas the

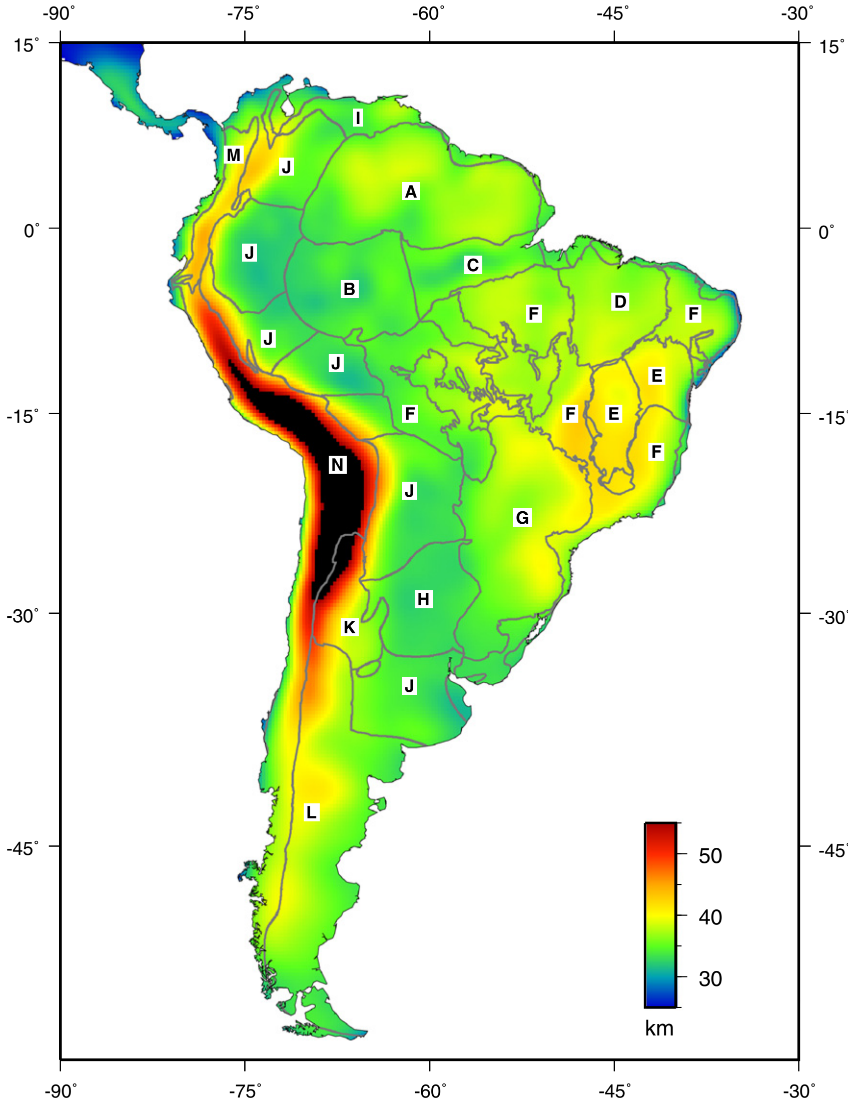

Fig. 2. Final model of crustal thickness (in km) for South America. Gray lines indicate main geological provinces modified after Schenk et al. (1997) and Almeida et al. (2000). Letters indicate the different geological provinces; A. Guyana shield, B. Solimões basin, C. Amazonas basin, D. Parnaíba basin, E. São Francisco craton, F. Brazilian shield, G. Paraná basin, H. Chaco basin, I. Guyana basin, J. Andean foreland basins, K. Familina province, L. Patagonia province, M. West–central Cordillera, and N. Andean province.

internal belts come from more varied initial tectonic settings, including magmatic arcs and associated tectonic environments, and minor cratonic (reworked) fragments (Almeida et al., 2000).

2.5. Continental crustal thickness models

Our preferred crustal thickness map will be compared with previously developed crustal thickness maps for the South American continent. In the following, we provide a brief summary of those independently developed models.

The coarsest model of crustal thickness is the South American part of the global crustal model CRUST2.0 (Bassin et al., 2000). CRUST2.0 is based on the interpolation of crustal velocity models from active-source profiling and geological estimates from terrain age and provides an independent reference against which other crustal models worldwide are usually benchmarked. Given that most parts of the continent are poorly sampled by active-source profiling, the model is largely biased towards geological estimates. Interestingly, a compilation of crustal thickness estimates in the African continent, also poorly sampled by active-source profiling, has reported little correlation between crustal thickness and terrain age (Tugume et al., 2013–this issue).

Better models of crustal thickness variation for South America are based on the joint inversion of surface-wave dispersion velocities and regional seismic waveforms with independent point constraints on crustal thickness. The dispersion velocity measurements were developed in the continental-scale surface-wave tomography study of Feng et al. (2004). In that study, fundamental-mode group velocities were obtained along more than 6000 Rayleigh-wave and 3500 Love-wave ray paths for seismic sources surrounding the continent. Rayleigh-wave dispersion velocities were measured for periods between 10 and 200 s, while Love-wave dispersion velocities were measured for periods between 20 and 70 s. Surface-wave dispersion maps were then obtained for a range of periods by tomographically inverting the dispersion curves for all the station-receiver paths using a 2° × 2° grid across the continent. The local dispersion curves for each cell were converted into models of S-velocity variation with depth through linearized, 1D inversions. However, the 1D inversions focused on mantle velocity structure and crustal structure was fixed to that predicted in the global model CRUST2.0.

To obtain models of crustal thickness variation for South America, Feng et al. (2007) developed tomographic maps of S-velocity variation by jointly inverting fundamental-mode, Rayleigh-wave group velocities measured along 5700 source-station paths (preferentially within the continent) and 1537 regional S and Rayleigh wavetrains. The joint inversion combined the surface-wave tomography scheme developed in Feng et al. (2004) with the partition waveform inversion procedure of Van Der Lee and Nolet (1997) to produce 1D velocity–depth profiles for individual cells in a Cartesian grid covering the continent. Most importantly, the 1D velocity–depth profiles were parameterized to invert for crustal thickness, so that meaningful maps of crustal thickness variation could be developed from the joint inversion. In addition, the inversion procedure also incorporated a compilation of 229 point-constraints on crustal thickness from the Automated Receiver Function Survey (Crotwell and Owens, 2005) and select temporary broadband deployments, as well as from seismic refraction and wide angle reflection profiles across the continent (see Feng et al. (2007), and references therein).

A similar model of crustal thickness variation was independently developed in Lloyd et al. (2010), also using the joint inversion procedure of Feng et al. (2007). The datasets included the 6600 fundamental-mode Rayleigh-wave dispersion curves of Feng et al. (2004), 1700 regional wavetrains from Feng et al. (2007) and Van Der Lee et al. (2001), and a new set of 225 point-constraints on crustal thickness for the continent. The set of point-constraints included part of the compilation of Feng et al. (2007) and 20 new measurements obtained from the analysis of receiver functions at newly deployed broadband stations within the Precambrian areas of Brazil. The main difference with the model of Feng et al. (2007) was that the oceanic portions of the model were accounted for through the addition of oceanic point-constraints from CRUST2.0, rather than being dismissed through the selection of pure-continental ray-paths for the dispersion curves and regional wavetrains.

The most up-to-date model of crustal thickness variation for South America based on the joint inversion of surface-wave dispersion, regional wavetrains, and point-constraints is that of Assumpção et al. (2013–this issue). Once again, the model was developed following the constrained joint inversion scheme of Feng et al. (2007). The datasets included the 5700 fundamental-mode Rayleigh-wave group velocity curves of Feng et al. (2007) augmented with 1031 new paths in the Paraná and Chaco basins (including measurements from ambient noise cross-correlation), the 1537 regional wavetrains of Feng et al. (2007), and 762 point constraints, similar to the database used in this paper for validation of the gravity derived crustal thickness model (see Section 2.3 for all details).

3. Moho topography and discussion

The topography of the Moho under South America derived from our satellite gravity inversion (GMSA12; Gravity based Moho for South America) is shown in Fig. 2 (Online available model, Appendix A). Moho topography shows a large variation from less than 6 km thickness in some ocean basins (not shown in the map) up to over 65 km in the Andes.

The central Andes (southern Peru, western Bolivia and northern Chile) show the thickest crust in the continent with everywhere a crustal thickness of 55 km or more, thinning to values of 45 km towards the southern part of the Andean province and in the West–Central Cordillera to the north. In contrast, the thinnest continental crust is found in the central part of the continent, in particular along the basins that make up the Andean foreland. Average crustal thickness for that region is below 35 km with minima around 30 km in northern Bolivia. From there eastwards the Solimões and Amazon basin show a narrow continuation of crustal thickness values below 35 km, all the way to the Atlantic Ocean.

The northern and eastern parts of the continent, the Brazilian shield, have an average crustal thickness of 40 km. Variations within the shield are nonetheless present. The Guyana Shield has a 38 km thick crust and it is thinner than the rest of the Brazilian shield where the crust is around 42 km thick. The thickest crust of the South American Platform is observed in the São Francisco craton with values around 42 km. The Parnaíba basin and Borborema province just north of it are clearly showing a thinner but homogeneous crust at 38 km crustal thickness. The Paraná basin has, on average, a crustal thickness of 40 km in the north but thins to 35 km in the southernmost tip of the basin.

The southern part of the continent, the Patagonian block, shows an average crustal thickness of 35–38 km with parts that thicken to over 40 km. Towards the southern tip of the continent, the crust thins out to around 30 km.

3.1. Validation

The GMSA12 model has been compared with point constraints on crustal thickness for South America and the oceanic part surrounding the continent. A total of 736 comparisons have been made. The point constraints have, on average, an error of ± 3 km (Assumpção et al., 2013) that, and the uncertainty related to model parameters is also around ± 3 km. There is spatial variation in this uncertainty (Fig. 3). Variance is highest in the Andes region and lowest in the regions with thinner crust. The variance in model solutions due to a change in starting thickness is 1 km for each km of change in starting depth (an almost linear relation). Variation in the starting depth is only leading to a baseline shift of the model and not to spatial variations. Variations in density contrast are stronger. An increase in density contrast of 0.05 g/cm^3 as shown in Fig. 3 will lead to a decrease in crustal thickness of, on average, ± 3 km. This effect is spatially variable due to the different Moho depths for different locations. Crustal thickness close to the starting value is less sensitive for variations in the density contrast over the Moho. Since the data have been demeaned the starting surface is relative to the average mean starting value. Deviations are calculated with respect to this mean value. That means that thickness is calculated relative to this mean value and not the Earth's surface. An increase in density contrast would bring the surface closer to the mean value, a decrease in density contrast will lead to larger variations with respect to the mean.

So any difference between data points within ± 6 km is statistically equivalent. Bearing these confidence bounds in mind, the overall agreement between the gravity-derived crustal thickness and the point constraints is fairly good. Fig. 4 shows that 70% of the data falls within ± 6 km difference. There is a very strong agreement in the oceanic part and in eastern and southern South America, with over 88% of the comparisons fall within ± 6 km. Variations are slightly larger in the Andes, with an overall agreement of around 60% but with a 5-fold increase of locations that are underestimated in GMSA12 with respect to the rest of South America. This is most likely because of the wavelength filter applied in the inversion which doesn't allow for extreme variations over very short distances. This results in an underestimation of the maximum local crustal thickness for the deepest parts in the Andean region. In the northern part of the continent, in particular the Caribbean orogenic zone in Venezuela, there is a scattered pattern of positive and negative deviations with respect to the point data. No apparent pattern is visible, with large positive deviations occurring right next to large negative deviations.

Overall the model compares well in stable and oceanic areas and has almost 90% similarity but compares less well in regions with active tectonics with complex crustal variations on a short-scale.

3.2. The Moho and its relation to the Bouguer anomaly

The basic assumption of the applied gravity method is that the sediment corrected Bouguer gravity anomaly is only due to Moho variation. To make this assumption more viable, the shortest wavelengths ($\lambda < 200$ km) have been filtered out during the inversion, which effectively removes some of the near-surface and intra-crustal small-scale variations.

Furthermore, the data has additionally been corrected for intra-crustal sedimentary basins, although whether this sediment correction is necessary is still a point of debate. Aitken et al. (2013–this issue) and Sampietro

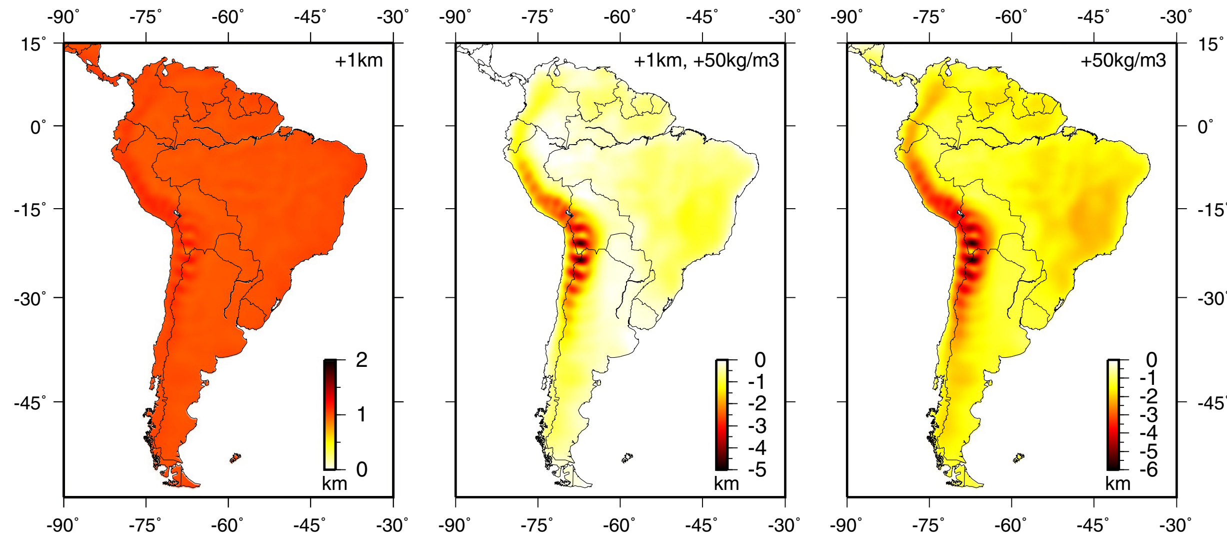

Fig. 3. Variation in crustal thickness due to variation in parameters. Two parameters can be varied which are the starting depth and the density contrast over the Moho. Each single contribution as well as the combined contribution of a change in both parameters are shown.

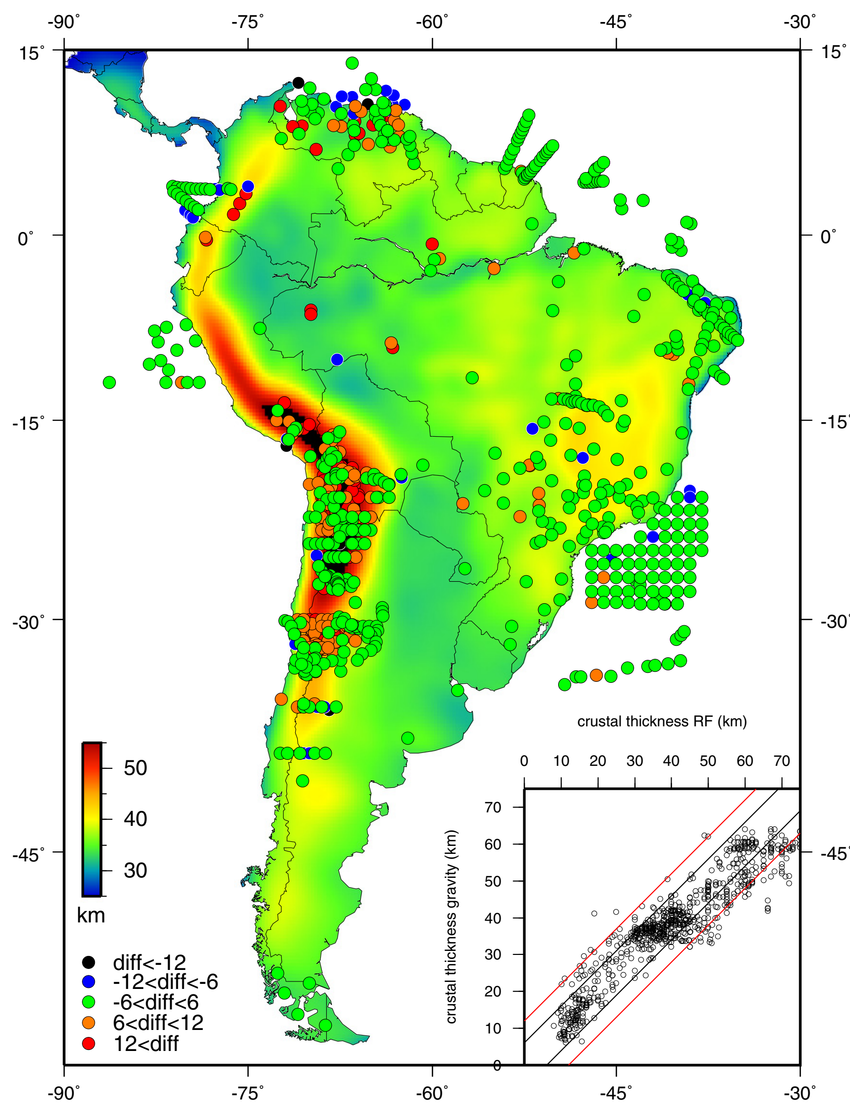

Fig. 4. Comparison of gravity derived crustal thickness with seismic point data. Deviations are defined as the difference of the seismic point observation with respect to the gravity derived estimate. Green circles are within 6 km, blue is between +6 and +12 km overestimation of the gravity model, black is over +12 km. An underestimation of −6 to −12 km is shown by orange circles and over −12 km is shown in red. The inset shows a scatterplot of misfits between seismic observations on the x-axis and gravity derived estimates on the vertical. Black line indicates 6 km, the red line 12 km deviation.

(2012), for instance, claim that the effect of sediments is negligible, but Sampietro et al. (2011) and Tugume et al. (2013–this issue) do correct for it. Interestingly, unpublished work from Barzaghi et al. (2011) for the Po area in Italy shows that when the calculated Moho signal is subtracted from the observed gravity signal a component of up to −75 mGal can remain due to sediments indicating that corrections for sediments might be necessary.

However, there will still be contributions from spatial variations in density related to different geological provinces. Furthermore, a fixed density contrast over the Moho is assumed during the inversion, which might not be accurate. As suggested by Feng et al. (2004) there are places in the crust that might have anomalously high V_s velocities in the lower crust, suggesting a corresponding increase in density and therefore a smaller density contrast across the Moho. Such variations are not accounted for in our model.

After the filtering and the sediment correction the relationship between Moho topography and Bouguer anomalies still remains. The thick crust in Eastern Brazil, for instance, correlates with high topography and low Bouguer anomalies. And while the differences are mostly less than 6 km, the thickest crust from seismic models is in the northern part of the Paraná basin, whereas in our model it is located just north of it in the Brazilian shield and the São Francisco craton which has also slightly higher elevation (Fig. 1). In the Amazon basin, GMSA12 shows an E–W oriented thin crust (along the Amazon River). This is caused by a belt of high Bouguer anomalies (Fig. 1) interpreted by Nunn and Aires (1988) as due to intracrustal volcanic load. In the western part of the Amazon and sub-Andean belt, Bouguer anomalies tend to be higher than the eastern part. The GMSA12 interprets this as a thin crust. Feng et al. (2004 Fig. 9a) suggested that this area has high V_s velocity in the lower crust. However, the Assumpção et al. (2013–this issue) model actually does indicate generally thinner crust in that area compared with the Amazon craton, which is in general agreement with GMSA12.

3.3. Comparison with other models

In the following, we highlight similarities and differences of CRUST2.0 and the surface-wave based models (see Section 2.5) in relation to GMSA12 to infer robust and poorly constrained features in the models.

Several models of crustal thickness variation have been developed for the South American continent over the past decade. These models are largely based on the continental-scale surface-wave tomography of Feng et al. (2004) and were developed by jointly inverting fundamental-mode, Rayleigh-wave, group velocities, regional wavetrains, and independent point constraints on crustal thickness (Assumpção et al., 2013–this issue; Feng et al., 2007; Lloyd et al., 2010). Logically, these models have large overlaps in data coverage and, not surprisingly, share similar large- and short-scale features throughout the continent. More interestingly, however, the models also display significant short-scale discrepancies, which probably arise from poor data coverage over large portions of the South American continent.

Fig. 5 displays our GMSA12 model, the two latest joint inversion models (Lloyd2010 (Lloyd et al., 2010) and Assumpção2012 (Assumpção et al., 2013–this issue)) described above along with a map of crustal thickness variation for South America extracted from the global model CRUST2.0 (Bassin et al., 2000). Note that the models have been plotted in the same color scheme, so that a direct comparison among them is possible. The differences between the GMSA12 and the other three models are shown in Fig. 6. Analysis is done based on the same ±6 km significance criteria. Shown are also the ±3 km deviation contour lines for indicating areas that are really similar and show over larger areas a similar trend.

A comparison between GMSA12 and the other three models reveals some similarities, but also some significant differences. There is good correlation with Assumpção2012 and CRUST2.0 on the extent and thickness of the Andes region. They all find a thick crust under the Andean Province, reaching peak values up to 70 km with CRUST2.0 even a bit thicker under southern Peru. Lloyd2010 is showing less thick crust in the southern part, covering northern Chile, with in places over 10 km thinner crust (Fig. 6). The Brazilian shield is rather uniform for all models with an average-thickness crust, 35–40 km thick, throughout the eastern Brazilian shield. It is overall slightly thicker in GMSA12 but only few places exceed 6 km deviation and those places are not consistent in location between the various models. Lloyd2010 shows the largest deviations which are located in the São Francisco Craton. The Patagonian block is slightly thicker in GSMA12 but has relatively thin crust in all models (although the block is not completely sampled in Lloyd et al. (2010) and Assumpção et al. (2013–this issue)).

A very interesting feature in GMSA12 is the belt of thin crust along the entire northern and central Andean foreland, with thickness under 35 km on average (Fig. 5). This is also partly visible in the two joint inversion models but with less spatial continuity. When compared with ray path coverage (see Fig. 3 in Lloyd et al. (2010) as an example, Assumpção et al. (2013–this issue) has added around 1000 additional paths) we see that the thin crust is confirmed in places where path coverage is good, and is missing in between. Often these paths connect two thicker parts of the model, possibly smearing the thin crust contribution leading to thicker crust on average. It is observed that this thinned crust is present throughout in the gravity based model and supported when the seismic models have good coverage. Following the argument that the gravity based model is confirmed to be fitting actual observations there is a likeliness that the tinned crust is present throughout with local variations within the thinned zone. There is very good agreement in the Chaco basin (Paraguay, northern Argentina). The thin crust in the tomographic models is mainly based on surface waves and the gravity data is providing the first independent confirmation that this thinned crust might be actually present. In places where the thin crust is imaged most clearly, like in the Chaco basin, the crust is thinner in the joint inversion models than in GMSA12. The thinning is completely absent in CRUST2.0. In fact, significant differences exist between CRUST2.0 and the other three models (e.g. a thicker crust along the Andean foreland compared to the eastern Brazilian shield).

A first thing that comes to mind is that some of the applied processing might have influenced this feature, in particular the sediment correction. That this is not the case is shown in Fig. 7. This figure shows the variation due to presence of sediments. The difference for most locations is small, only a few mGal difference due to sediment correction, on a total signal range of approximately 800 mGal between the maximum and the minimum in the original data. Maybe even more illustrative is that the regions of largest corrections, i.e. thickest sediments, are not coinciding with the regions of thinnest crust highlighted by the 35 km contour lines. The influence of sediments on the total crustal thickness is therefore considered to be minor. The applied model is very simple, we have used a constant density contrast for the sediment with respect to the surrounding bedrock. Our whole aim is to provide an estimate of crustal thickness using a very simple model that does not rely on information which is not available for most of the continent. We have therefore opted for a fixed contrast which is possibly slightly underestimating the contrast for the shallow part of sediment basins and slightly overestimating for the deeper parts. To keep the model simple we have opted for a value in between to get the average value for the density contrast as realistic as possible. Considering the relatively small impact of the sediments on the crustal thickness estimates we believe this simplistic approach has no significant impact on the derived crustal thickness.

Fig. 5 also shows that some smaller-scale features seem to persist across the several joint inversion models, such as a nucleus of thick crust (50 km) centered at 0°N and 60°W in the Guyana shield. Interestingly, Assumpção et al. (2013) also developed a crustal model based on the interpolation of point constraints, both seismic and gravimetric. In the stable part of the continent, this model is exclusively controlled by

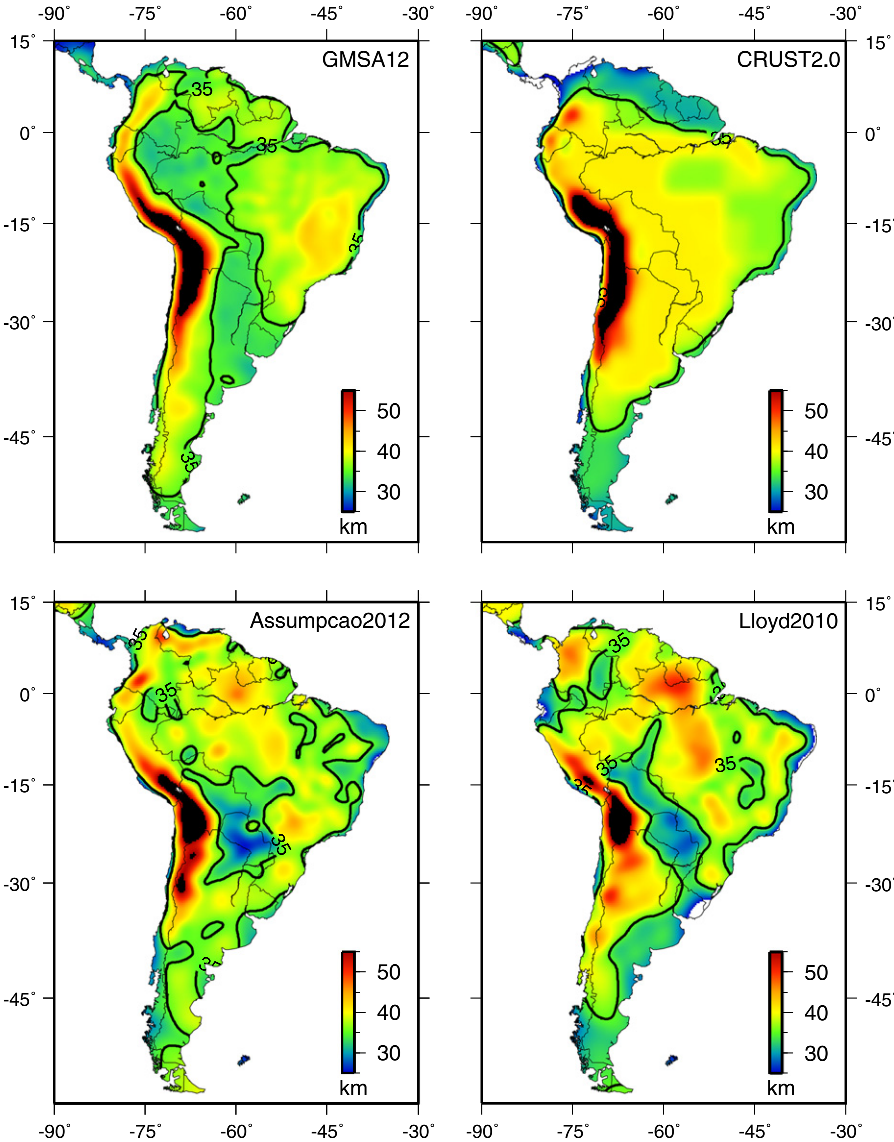

Fig. 5. Comparison between the satellite gravity derived model, GMSA12 (top left), CRUST2.0 (top right) (Bassin et al., 2000) and two seismic models, Assumpcao2012 (bottom left) (Assumpção et al., 2013–this issue), and Lloyd2010 (bottom right) (Lloyd et al., 2010). Shown contour line is at 35 km crustal thickness.

seismic point-constraints and shows that the thick crustal nucleus in the Guyana shield is due to a single point centered in the postulated nucleus. This point-constraint seems to be shared by all joint inversion models but isn't supported at all by GMSA12 which shows much thinner crust than the tomographic models. Deviations around the area of the nucleus are clearly over 6 km with Assumpção2012 and even over 12 km with Lloyd2010.

Perhaps more interestingly, some differences are also observed across the joint inversion models at these smaller scales. For instance, the Assumpção et al. (2013) model displays a second nucleus of thick crust (45–50 km) around 10°S and 65°W in the Guaporé shield, which is not observed in any other crustal model (including CRUST2.0). Once more, this seems to be due to a few point-constraints in the postulated nucleus that were not included in the other joint inversion models. The average crustal thickness throughout the Amazonian craton seems to be smaller in GMSA12 compared to the tomographic models. This is also partly seen in Feng et al. (2007) model although not as clear. These later discrepancies, however, are not clearly associated to differences in the point-constraints and are more likely due to differences in the coverage provided in the different datasets.

The thin crust along the northern border of the continent (Caribbean orogenic zone in Venezuela), as seen in GMSA12, CRUST2.0 and Lloyd2010 but not in Assumpção2012, is harder to interpret (Fig. 5). The seismic model Assumpção2012 is based on a large set of receiver function data and seismic lines that constrain a really thick crust there (40–45 km). Why this is not seen in GMSA12 and Lloyd2010 is not easily explained. For GMSA12 an explanation can be sought in the complex subsurface structure in that area with large lateral variations or a deviation in density contrast over the Moho. If the crust has a higher density than the average South American crust the crustal thickness would be underestimated. The Lloyd2010 model is reasonably consistent with GMSA12, differences exist but are small (Fig. 6). The difference between Assumpção2012 and Lloyd2010 is striking with Lloyd2010 showing a clear thinned crust through eastern Colombia and central Venezuela with thicker crust towards the east (Colombia) and west (western Venezuela). This is probably due to the lack of point constraints and very poor coverage of seismic rays near the border between South America and the Caribbean.

Another general agreement between the models is the thinning along the Atlantic coast. Near the coast, one expects thin crust due to stretching occurred during the Atlantic rifting. This is seen along

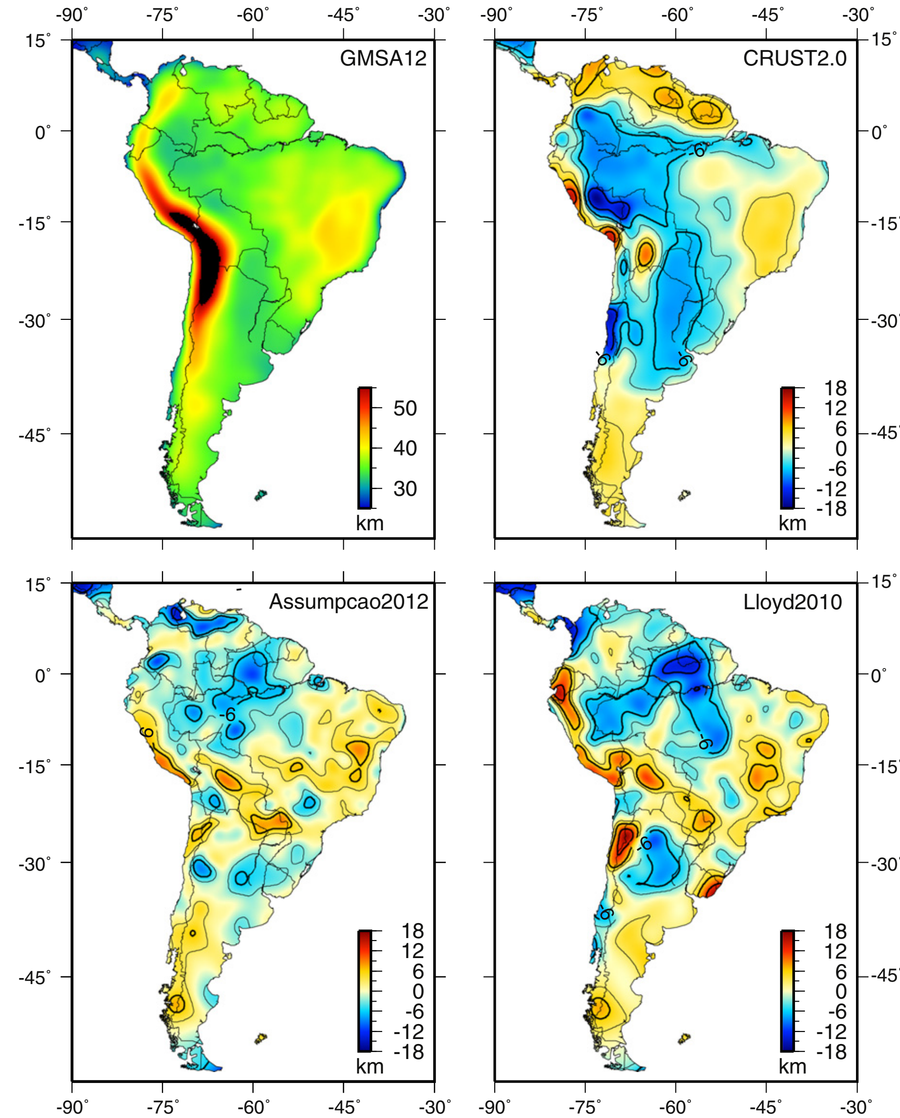

Fig. 6. Difference between the 4 models shown in Fig. 5. (top left) is the newly derived GMSA12 model, (top right) is the difference between GMSA12 and CRUST2.0, (bottom left) is the difference between GMSA12 and Assumpcao2012, and (bottom right) is the difference between GMSA12 and Lloyd2010. Shown thick contour lines are the ±6 km deviation and ±12 km deviation, thin lines indicate ±3 km deviation.

the eastern coast (roughly from 0°S to 22°S) in all models. Crust is normal near 28–30°S in both models and gets thin again along the Uruguay and La Plata (Argentina) coasts (roughly 32° to 38°S for Assumpção2012, all the way down to 45°S for GMSA12 and Lloyd2010). The degrees of thinning may be different but the qualitative behavior is the same.

Overall, the gravity-based crustal thickness model GMSA12 agrees with Assumpção2012, the best available seismic model, better than CRUST2.0 and Lloyd2010. The comparison between GMSA12, the joint inversion models and CRUST2.0 reveals that large-scale features are robustly constrained between the models but that small-scale features have a strong dependence on the set of point constraints utilized during the inversion and overall seismic coverage. This is also visible in a comparison of the point data with the various models. Not remarkably, Assumpção2012 is showing an almost 100% fit since it used all the constraints in the inversion. What is remarkable however is that GMSA12 is showing a better fit with the point data than the models of Lloyd et al. (2010) and Feng et al. (2007) (Fig. 8). Both models used part of the constraints that have been used in Assumpção2012. They both used around 230 constraints, all of which were included in our analysis and those of Assumpção et al. (2013–this issue). From the scatterplots (Fig. 8), it can be seen that both models perform less well than GMSA12 (Fig. 4). Spatially, it is evident that in the stable areas of the continent, GMSA12 is performing better, in the Andes and Caribbean border performance is similar.

Finally, significant differences exist between CRUST2.0 and the other three models (e.g. a thicker crust along the Andean foreland compared to the eastern Brazilian shield, see Fig. 6). The discrepancies between GMSA12 and the joint inversion models versus model CRUST2.0 are significant and probably result from the lack of seismic constraints of CRUST2.0 through large areas of the continent, similar to what is observed by Tugume et al. (2013–this issue) and Tedla et al. (2011) for Africa.

4. Conclusion

In this study, we utilized the combined gravity model EIGEN-6C (Förste et al., 2011) to derive a model of crustal thickness variation for South America. Crustal thickness data were obtained after inverting sediment corrected Bouguer gravity anomalies using the Parker–Oldenburg algorithm (Gómez-Ortiz and Agarwal, 2005) assuming a simple layer-over-half space model for the crust and lithospheric mantle.

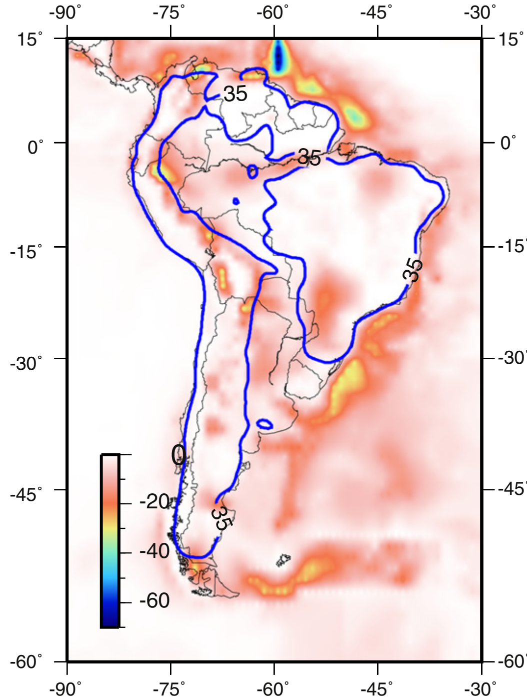

Fig. 7. Amplitude of the sediment based correction using a contrast of 200 kg/m^3. The blue line is the 35 km crustal thickness contour line (taken from Fig. 5) to indicate the area with thinner crust. The thickest sediments, and therefore the largest corrections, do not fall within the area of thin crust. For the larger part of the area with thinned crust the corrections are less than 10 mGal.

Moho topography shows a large variation from less than 6 km crustal thickness in some ocean basins up to over 65 km in the Andes. Thickest crust is found in the central Andes. On the contrary, thinnest continental crust is found along the basins that make up the Andean foreland. Average crustal thickness for that region is below 35 km with minima around 30 km in northern Bolivia. The northern and eastern parts of the continent have an average crustal thickness of 40 km with variations between 35 (Paraná basin) and 42 km (São Francisco craton). The Patagonian block shows parts that thicken to over 40 km but thins out to around 30 km on the southern tip.

Comparison of our estimates to an independent compilation of point estimates on crustal thickness for South America showed a good correlation between independent point observations and gravity-derived estimates of crustal thickness. A total of 736 comparisons have been made. Overall the model compares well in stable and oceanic areas and has almost 90% similarity for these regions but compares less well in regions with active tectonics with complex crustal variations on a short-scale like the Andes and the Caribbean orogenic zone in Venezuela.

The comparison with independent continental-scale crustal thickness models based on the joint inversion of point observations and regional surface waves and CRUST2.0 illustrate that models derived from (satellite) gravity data can provide first order constraints on crustal thickness. There is good correlation with Assumpção2012 and CRUST2.0 on the extent and thickness of the Andes region. Lloyd2010 is showing less thick crust in the southern part, covering northern Chile. The Brazilian shield is rather uniform for all models with an average-thickness crust, 35–40 km thick, throughout the eastern Brazilian shield. The Patagonian block is modeled with relatively thin crust in all models but with GSMA12 showing a slightly thicker crust than the other models.

A very interesting feature in GMSA12 is the belt of thin crust along the entire northern and central Andean foreland, with a crustal thickness under 35 km on average. This is also partly visible in the joint inversion models but with less spatial continuity. This is possibly due to the fact that there are very few seismic stations in this region and therefore very few point constraints and longer wave paths. The thin crust in the tomographic models is mainly based on surface waves and the gravity data is providing the first independent confirmation that this thinned crust might be actually present.

Thin crust along the northern border of the continent (Caribbean orogenic zone in Venezuela) is seen in GMSA12, CRUST2.0 and Lloyd2010 but not in Assumpção2012. The seismic model Assumpção2012 is based on a large set of receiver function data and seismic lines which constrain a really thick crust there (40–45 km). The Lloyd2010 model is less constrained by point observations but reasonably consistent with GMSA12. An explanation can be sought in the complex subsurface structure in that area with large lateral variations or a deviation in density contrast over the Moho. The comparison between models indicates that

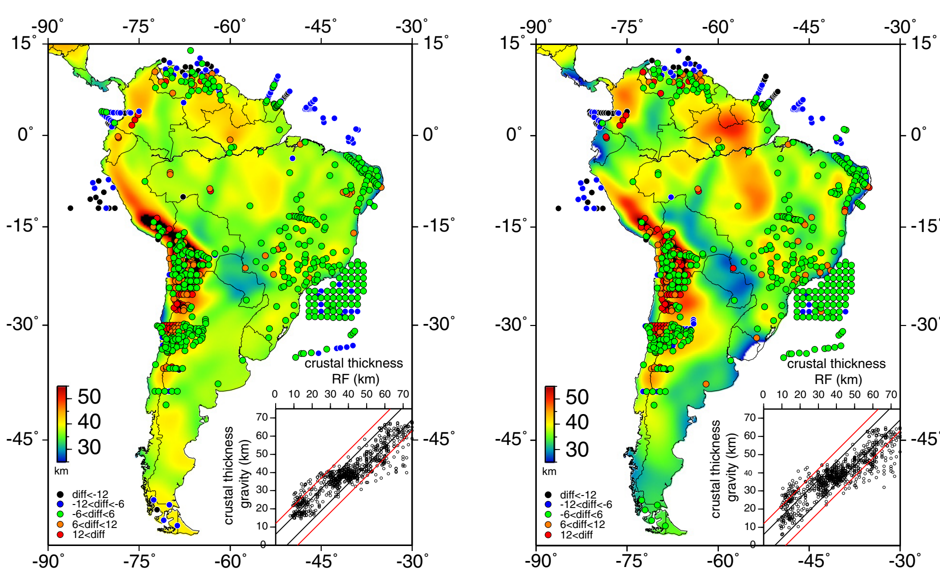

Fig. 8. Comparison of seismically derived crustal thickness with seismic point data. Deviations are defined as the difference of the seismic point observation with respect to the seismically modeled estimate of (Feng et al., 2007) (left) and (Lloyd et al., 2010) (right). Green circles are within ±6 km, blue is between +6 and +12 km overestimation of the gravity model, black is over +12 km. An underestimation of −6 to −12 km is shown by orange circles and over −12 km is shown in red. The inset shows a scatterplot of misfits between seismic observations on the x-axis and gravity derived estimates on the vertical. Black line indicates 6 km, the red line 12 km deviation.

small-scale features have a strong dependence on the set of point constraints utilized during the inversion and overall seismic coverage.

Overall, the gravity based crustal thickness model GMSA12 agrees with the model from Assumpção et al. (2013–this issue), the best available seismic model. It is predicting better than other, and older, crustal thickness models for South America. Especially in areas where continental and global models of crustal structure have limitations in terms of wave paths or point constraints, the gravity-based model provides a unique continuity of crustal structure providing new insights on structure and tectonics and increase our understanding of the Earth's structure underneath South America.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.tecto.2013.03.023.

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