Mohorovicic Discontinuity Depth Analysis Beneath North Patagonian Massif

María Laura Gómez Dacal, Claudia Tocho, and Eugenio Aragón

Abstract

The Mohorovicic discontinuity (Moho) is the surface that limits the Earth's crust and mantle. It is of paramount importance in understanding and investigating the dynamics of the Earth's interior. The GEMMA project (GOCE Exploitation for Moho Modeling and Applications), funded by the European Space Agency and Politecnico di Milano, has provided a high resolution map of the Moho surface (GEMMA Model), based on the inversion of homogeneous, well-distributed gravimetric data measured by the Steady-State Ocean Circulation Explorer (GOCE), which ensures a global coverage using gravity field. In the current paper, this Moho depth estimation (Riccardo Barzaghi, personal communication, April 20, 2012) is compared with other models based on both seismic and gravity observations, under the North Patagonian Massif (NPM). Said massif is an Argentinean plateau that stands out 500 to 700 m higher in altitude than the surrounding topography and was created by a sudden uplift without noticeable internal deformation (Aragón et al. (2011b) Upper mantle geodynamic constrains beneath the north patagonian massif, Argentina). The features described led us to analyze the crustal thickness in the area. The work describes different Moho models available in the area under study and their comparison with the GEMMA Model. The aim is to validate this well distributed, homogeneous data model in this area with sparse seismic data and check its usefulness to get more information about the Moho. According to comparisons with the different models, the crustal thickness in the study area varies between 36 and 46 km. The good agreement between the GEMMA Model and some of the other Moho models may account for the use of such model to study this little known area.

Keywords

GOCE • Mohorovicic discontinuity (Moho) • Moho models • North Patagonian Massif

1 Introduction

The Mohorovicic discontinuity is the boundary between the crust and the mantle. It is defined by seismologists as the depth at which the P-wave velocity exceeds 7.6 km/s; therefore, it depends on the density and elastic properties of crustal and mantle rocks (Lowrie 2007). The Moho plays a fundamental role in the Earth's dynamics. In particular, it helps to understand the isostatic compensation state of an area and consequently its epeirogenic movements. It also proves to be useful to construct a gravity model.

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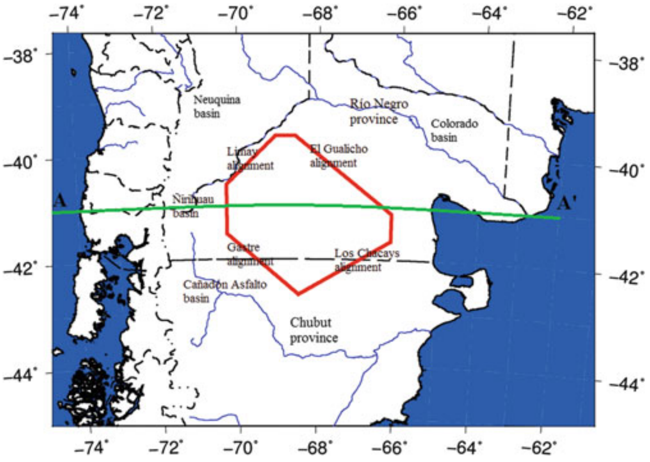

Fig. 1 Geographical location of the North patagonian massif

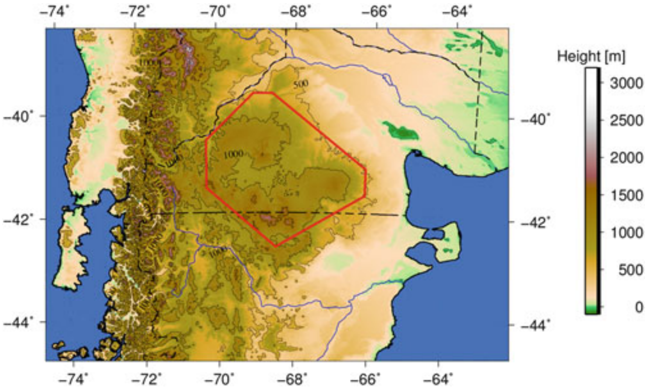

Fig. 2 Topography of the North patagonian massif and the surrounding areas

The GEMMA Model -a global, high-resolution map of the Moho using GOCE gravity satellite data- was derived by Barzaghi et al. (2014). Comparisons between this model and other Moho models are analyzed for the North Patagonian Massif both to test the GEMMA Model and to learn more about the Moho in this area. Five models are compared: two of these were created with seismic information (Feng et al. 2007; Bassin et al. 2000); others were made with a combination of both gravity and seismic techniques (Assumpção et al. 2012; Tassara and Echaurren 2012) and the last one is an inversion of gravity data of the area under study. This gravity data inversion is also presented in this work.

The North Patagonian Massif (NPM) is an Argentinean area that is sparsely studied and has interesting characteristics. Specifically, the area of study is located between the alignments Limay, Gastre, Los Chacays and Gualicho, and is called the NPM core. This area of low relief and great height constitutes a plateau that is surrounded by Neuquina, Colorado, Ñirihuau and Cañadon Asfalto basins (Aragón et al. 2011b; Fig. 1). This plateau is a 100.000 km^2, subrectangular, area that has a height of about 1,200 m above sea level and stands out 500 to 700 m higher in altitude than the surrounding topography (Aragón et al. 2010; Gómez Dacal 2012; Fig. 2).

The NPM corresponds to a morpho-structural region having a different tectonic behavior than its surrounding areas because it suffered a sudden uplift from heights below sea level to heights around 1,200 m in a brief geological time. This uplift is considered to have been generated by an epeirogenic movement because the marine sediments from the Cretaceous-Tertiary boundary lay without noticeable internal deformation at 1,100 m above sea level; however, in the surrounding areas, the sediments of the same formation are at a height between 300 and 500 m above sea level and show deformation (Aragón et al. 2010, 2011a). Such different mechanical response between the massif plateau and the surrounding back arc and the short time in which this process took place raise questions about the geodynamic behavior of the study area.

The particular features of the NPM led us to investigate the Moho and validate the GEMMA Model for this area.

2 Description of Models of Mohorovicic Discontinuity

The Moho models are mainly based on seismic or gravimetric data of an area; hence, numerous data of this kind are required to create a model. Seismic data allows to create a more accurate regional model of the Moho surface. The NPM is an area with lack of seismic data and in, consequence it is difficult to create a good regional Moho model. For this reason, global models of the Mohorovicic discontinuity seem appropriate to describe the study zone. There are many Moho models at a global scale that can be used; however in this work, the performance of the GEMMA Model (Barzaghi et al. 2014) for the study area is investigated. This model was chosen because it has been globally computed using GOCE data, thus ensuring well-distributed and homogeneous global coverage. The authors reduced the data by subtracting the contribution of the normal potential, then corrected it for the effect of topography and bathymetry and made a spherical harmonics analysis of the residual field to obtain the coefficients of the residual gravity field. After that, they related the coefficients already found to the product between Moho depth and density contrast (between mantle and crust) with a linear relationship. Taking the density contrast as a constant and equal to 630 kg/m^3 (homogeneous crust of density 2,670 kg/m^3 and a homogeneous mantle of 3,270 kg/m^3), they get the Moho depth (Sampietro and Reguzzoni 2011). The model has a resolution of 30 min. Figure 3 shows the mapping of the model in the NPM area (delimited in red) and its surroundings. It can be observed

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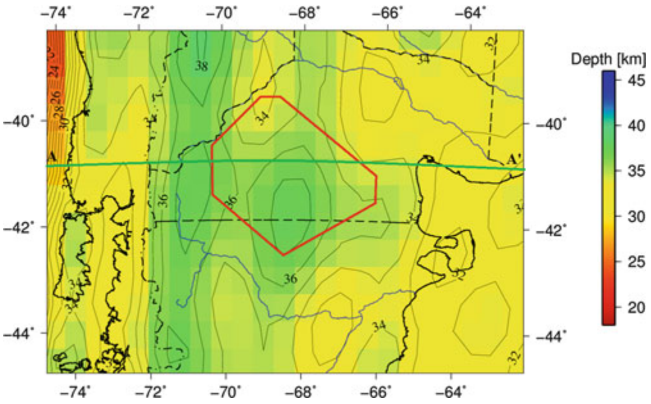

Fig. 3 GEMMA model (Barzaghi et al. 2014)

that the Moho depth varies from 34 to 36 km in the NPM area and it is thinner on its North, East and South surroundings whereas the West boundary shows the opposite.

The Global Moho model described has been compared with a set of Moho models at different scales (from global to local ones) and with different origins (based on different data and compiled with different methods) as shown in Table 1. We expect that the GEMMA Model fits correctly with these models, which constitute the only information available about the Moho surface for the interest area.

As can be observed from the figures, the Moho models for the study area have the following characteristics:

- Model A (CRUST 2.0; Fig. 4) presents a Moho depth between 36 and 40 km for the study area and it is surrounded by areas of thinner crust on the South and East boundaries and by areas of thicker crust on the other two boundaries. It should be noted that the model has a poor resolution and there are few data used for generating the model in the area under study, i.e the model is an interpolation of data available in surrounding areas. This model was chosen to make the comparison because is one of the most well-known and spread model inside the geoscience community in spite of its low resolution and it was used as the mean Moho depth for the derivation of the GEMMA Model (Reguzzoni et al. 2013).
- The Moho depth for Model B in the study zone is between 36 and 45 km and it is surrounded on the North, East and North-West boundaries by a thinner crust, on its West boundary by a thicker crust and on the South boundary there is an area with no model coverage. This can be seen in Fig. 5. There are no point estimates of the Moho depth in the NPM area to constrain this model (Fig. 5). The resolution of Model B is 2 minutes.
- According to Model C (Fig. 6), the Moho depth beneath NPM is between 32 and 38 km and in accordance with the previously described model, it is surrounded by a thinner crust on the North, East and North-West boundaries, by a thicker crust on the West boundary, and on the South boundary, there is an area with no model coverage. It is important to highlight that in the NPM area there are no point estimates of the Moho depth and there is only one point estimate near the mentioned area (Fig. 6), hence this model is mainly based on gravity data Moho estimates (from Tassara and Echaurren (2012)) for the NPM region and could be weakly defined. Nevertheless, Model C is the one with the largest database of all analyzed models.
- In Fig. 7 it can be seen that the Moho depth for Model D is between 35 and 37 km and it is surrounded by areas of thinner crust on the North, East and South boundary and by areas of thicker crust on the West boundary. Model D is the result of an adaptation of the Moho surface from a three dimensional density model of the NPM (Gómez Dacal 2012). Forward modelling was performed using the software IGMAS+ (Interactive Gravity and Magnetic Application System) and Bouguer anomalies from EGM2008, through the triangulation of sections separated 0.5°, which means a longitudinal resolution of 25 km. In the original model (Tassara and Echaurren 2012), the Moho was constrained using receiver function points and refraction profiles but there are some areas without constraints. For these regions, the Moho was shaped by fitting the intermediate wavelength of the Bouguer anomaly and under the assumption that the orogenic topography is primarily compensated by a crustal root (Tassara and Echaurren 2012). In the NPM area, the model does not have independent data to constrain the Moho surface (Fig. 7) and therefore it could be poorly defined.
- According to Model E (Fig. 8), the Moho depth beneath the NPM region is between 39 and 46 km and is surrounded by thinner crust areas on the North, East and South boundaries and by a thicker crust on the West boundary. This model was derived using Lithoflex software (Braitenberg et al. 2007), Bouguer anomalies from EGM2008 (Pavlis et al. 2012) and a cutoff wavelength of 200 km. The gravity data selected is consistent with those used in Models B and C, and the cutoff wavelength was chosen so as not to project superficial masses at Moho level in order to be consistent with the other models that show a long wavelength. The physical parameters used in the inversion were: 36 km for the reference depth and 340 kg/m^3 for the density contrast. The choice of the reference depth was based on the coincidence of several Moho models out of the NPM area; the density contrast was calculated with density values extracted from xenolithes for the lower crust and upper mantle and the upper crust values from literature values (Castro et al. 2011; Kliger 2010; Kostadinoff and Schillizi 1996; Kostadinoff and Gelós 1994). Moho depths in Model E have been obtained without taking into account the topography or any isostatic hypothesis. The

Table 1 Moho models used in this study

Model	Coverage	Description	Figure	Reference
Model A CRUST 2.0	Global.	Seismic data: reflection, refraction and receiver function studies; Specified in 2°x2° grid; Available online	Figure 4	Bassin et al. (2000) http://www.igppweb.ucsd.edu/gabi/~crust2.html
Model B	Regional model: South America.	Seismic data: joint inversion of regional S and Rayleigh waveforms and fundamental mode Rayleigh wave group velocities. There is a refraction profile at 39° South Latitude	Figure 5	Feng et al. (2007)
Model C	Regional model: South America.	Seismic data: point estimates from seismic refraction experiments, receiver function analysis, surface-wave dispersion (there is the same refraction profile as Model B and a point estimate) and gravity based estimates from Tassara and Echaurren (2012) to cover gaps in seismic information; interpolated with surface-wave tomography	Figure 6	Assumpção et al. (2012)
Model D	Regional model: Central and South Andes.	Three-dimensional density model constrained by independent data (mainly seismic; in the area, it integrates the profile of Model B): Moho surface extracted from the adaptation to the study area using *IGMAS*+ software (Götze 1978, 1984; Götze and Lahmeyer 1988; Schmidt and Götze 1998)	Figure 7	Tassara and Echaurren (2012)
Model E	Local model: NPM area.	Inversion of gravity data (Lithoflex software Braitenberg et al. 2007): Bouguer anomalies extracted from EGM2008 geopotential model (Pavlis et al. 2012)	Figure 8	——————-

standard deviations of the differences between GEMMA and Model E is ±2.57 km (Table 2).

3 Comparison of Moho Models

To evaluate the performance of the GEMMA Model (Barzaghi et al. 2014) in the study area, comparisons with other models have been made:

- The differences, in absolute value, between the GEMMA Model and the models described in Sect. 2 are depicted in Figs. 9, 10, 11, 12 and 13, respectively.
- A profile crossing the study area has been chosen to compare the different Moho models (Fig. 14). The profile is at 41° S because it crosses the middle of the North Patagonian Massif (Fig. 1).

  Crossing the NPM from West to East (from A to A'), the Moho depth varies by more than 20 km for different models, ranging from a relatively shallow depth (around 25 km), deepening down to about 40 km between 72° and 66° West longitude, and rising up again to about 35 km depth in the East.

Overall, the following characteristics can be observed:

- Model A differs significantly from the GEMMA Model with an standard deviation of 4.53 km (Fig. 9, Table 2).

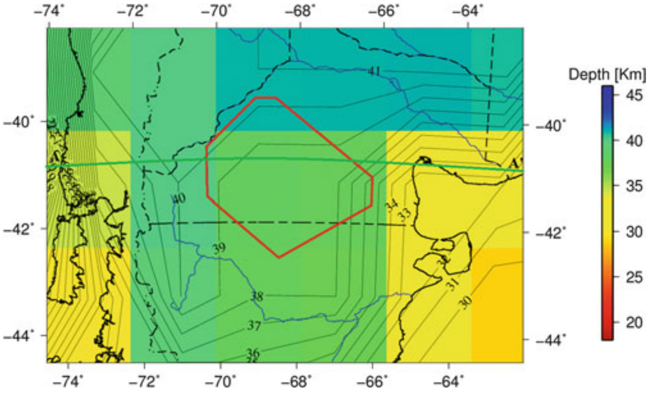

Fig. 4 Model A: CRUST 2.0 (Bassin et al. 2000)

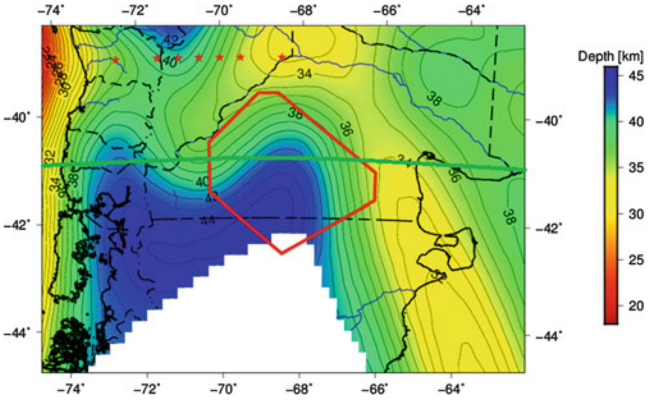

Fig. 5 Model B (Feng et al. 2007). *White area* indicates no model coverage and *red stars* constrain data

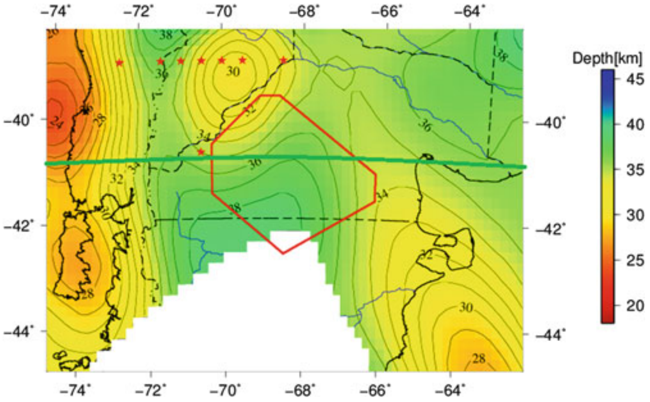

Fig. 6 Model C (Assumpção et al. 2012). *White area* indicates no model coverage and *red stars* constrain data

Nevertheless, more meaningful is the difference between the mentioned model and all the other models. The difference can be observed in Fig. 14. This fact make this model unreliable for the area. The differences between Model A and the other models could be caused by the poor resolution of Model A and, the few data in which the model was based to interpolate the Moho in the study area.

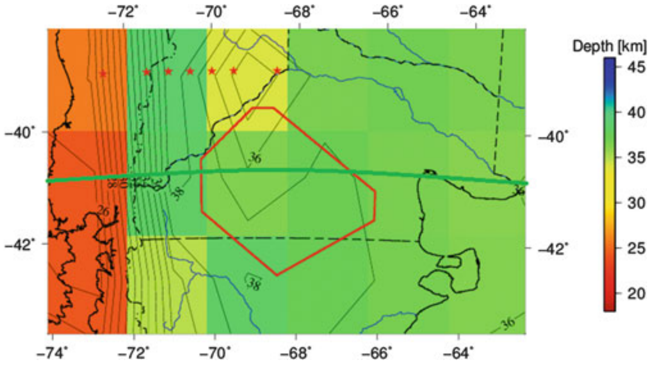

Fig. 7 Model D (Tassara and Echaurren 2012). *Red stars* indicate constrain data

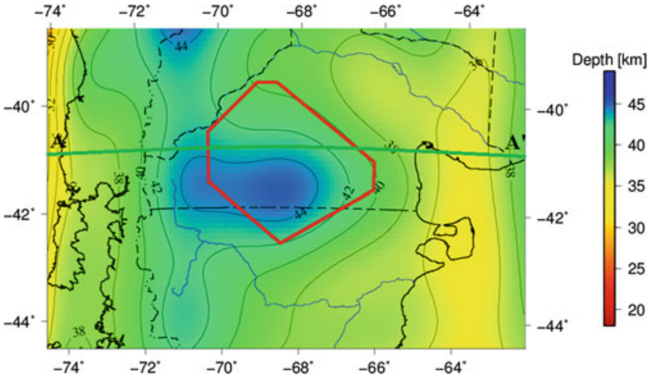

Fig. 8 Model E: made from the inversion of gravity data

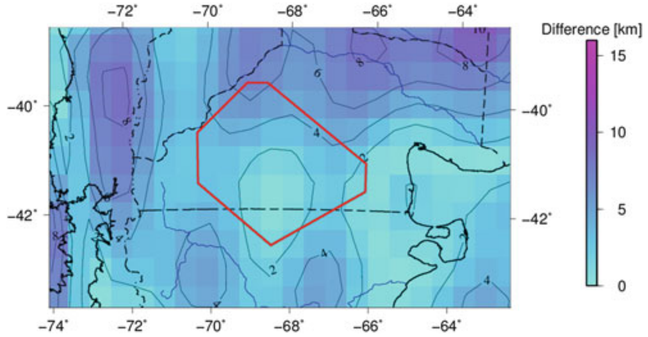

Fig. 9 Difference between the GEMMA model and model A

- Figure 10 shows that Model B differs from the GEMMA Model essentially in the NPM and the West boundary, but it is similar in the other surroundings. Figure 14 shows that Model B Moho is considerably deeper (in almost every place of the profile) than the other models, except for Model E. Model A and B are the only ones made with only seismic data; however, Model A is not worth considering as it has poor resolution.
- Figure 11 shows the opposite situation. Model C seems to be more similar to the GEMMA Model in the NPM area and different from it in the surroundings. Model

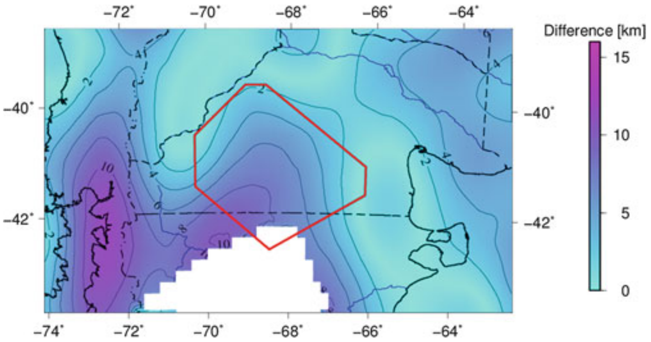

Fig. 10 Difference between GEMMA model and model B

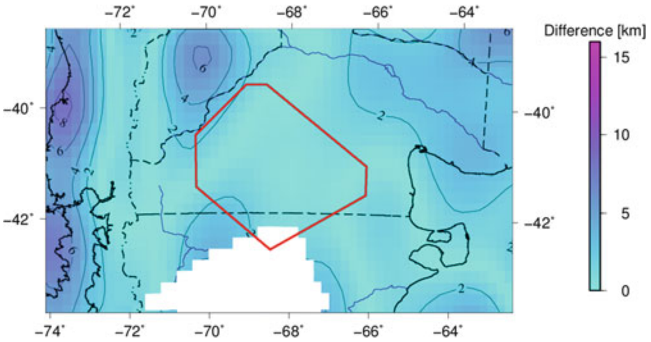

Fig. 11 Difference between the GEMMA model and model C

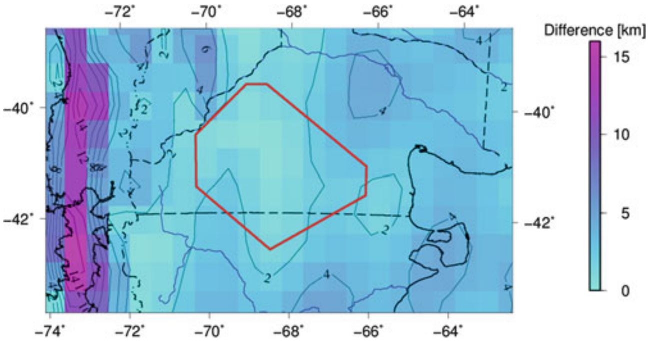

Fig. 12 Difference between the GEMMA model and model D

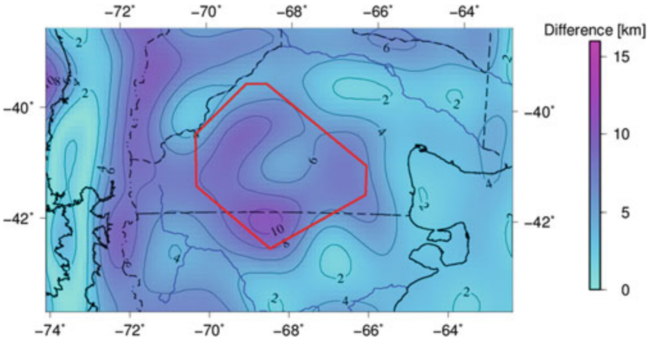

Fig. 13 Difference between the GEMMA model and model E

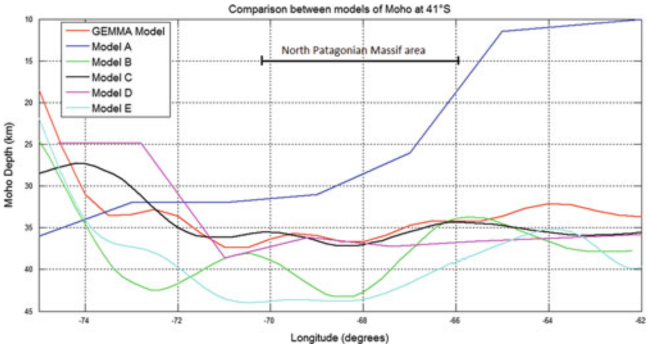

Fig. 14 Comparisons of Moho models crossing NPM along the 41°S parallel

Table 2 Standard deviations of the differences between the regional or local models and GEMMA model

Model comparison	Standard deviation [km]
Model A - GEMMA	4.53
Model B - GEMMA	3.07
Model C - GEMMA	3.08
Model D - GEMMA	6.94
Model E - GEMMA	2.56

C is the most similar to the GEMMA model (Fig. 14). This information is relevant considering that Model C is the one with the largest database. Nevertheless, it does not have any point of Moho estimate in the NPM. The similarity in the comparison between Model C and GEMMA Model in the study area can be cause by more seismic points interpolated with surface-wave tomography and complemented with the gravity-based crustal model of Tassara and Echaurren (2012). Model C includes more seismic crustal thicknesses points compared to the previous point constraints from Model B. The differences between GEMMA and Model B and C show similar error standard deviations of 3.07 and 3.08 km, respectively (Table 2).

- Model D has values similar to those of the GEMMA Model in the NPM area (Fig. 12). This could also be seen in Fig. 14. Nevertheless, the difference between this model and GEMMA Model shows the largest standard deviation of ±6.94 km as can be seen in Table 2.
- Model E has great differences with the GEMMA Model, especially in the NPM area as shown in Fig. 13. This difference can be caused by the selection of the inversion parameters. Model E values are more similar to Model B (Fig. 14).

4 Conclusions

In this study, the high resolution, homogeneous and well-distributed GEMMA Model inferred from satellite gravity observations provided by the GOCE mission (Barzaghi et al. 2014) has been compared with five other models based on seismic and/or gravity data to evaluate its quality. One of them was derived from the inversion of Bouguer gravity anomalies (Model E). The analysis has been performed on the North Patagonian Massif area (Argentina).

Most of the models show a Moho depth between 36 and 38 km (GEMMA Model and Models A, C and D) evidencing a good correlation of these models with the GEMMA Model for the area under study. Model A has poor resolution and few data to derive the model in the area of study; therefore, it is unreliable for such area. In the agreement of Models C, D and the GEMMA Model, the influence of gravity data could be observed. Models B and E show a deeper Moho discontinuity reaching 46 km. It can be caused by the different data source employed (only seismic data) in Model B, and by the more realistic density contrast of 340 kg/m^3 and the reference depth of 36 km selected for the inversion in Model E. Model C, which has been recently derived using the largest database, shows the best correlation to the GEMMA Model of all the analyzed models. All the models have discrepancies towards the West where the boundary of the continent and subduction take place.

Crustal models are useful for studies of isostasy, dynamic topography, and for the understanding of geodynamic processes at different spatial and time-scales. The study was done in a massif with no noticiable internal deformation observed; therefore, it is not expected to find any special feature in the Moho shape or depth in terms of isostasy. Nevertheless, most of the Moho models selected have shown a thickened crust below the NPM, which shows a more complex geodynamic setting than expected. This should be investigated in detail in the future.

The overall conclusion is that the model derived from GOCE data (GEMMA Model) seems to be an important contribution because it has a good agreement with some of the regional models in the North Patagonian Massif in southern Argentina. This may account for the use of such model in the NPM area.

As the GEMMA Model is a high resolution, homogeneous, well-distributed Moho model, and has shown a good correlation with the most updated regional seismic/gravity models for South America (Model C and D), at least in the NPM area, it might be used to get information about this surface in other areas with few data. On the other hand, the GOCE gravimetric model could be improved incorporating local/regional more realistic density models and seismic data.

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