Crustal thickness in the northern Andes from teleseismic pP and sS precursors

Nataly Aranda*, Marcelo Assumpção
Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo

Abstract

The crustal thickness is a very important property of the crust which is used for different purposes like understanding the crustal evolution, in geodynamic models and in modeling wave-propagation in global and regional seismic studies. In this study, we analyze the reflections from the underside of the Moho for five intermediate earthquakes occurred in the northern Andes and recorded at teleseismic distances (40°- 85°) to estimate the crustal thickness at the bounce point. The reflected phases are identified as precursors of the pP phase and sS phase and are called pmP and smS phases respectively. We find that the crustal thickness in the study area varied from 25 km to 60 km for the northern Andes. The results obtained show a crustal thickness in accordance with previous works done in this area.

Introduction

The Andean belt is constructed as a result of the subduction of the Nazca plate beneath the South American continental plate. Extended along 8000 km from Venezuela to Tierra del Fuego the Andes can be divided in three segments according to their tectonic differences: Northern (from 10°N to 4° S); central (from 4°S to 46°S) and southern Andes (south of 46°S). Hitherto crustal-thickness is well known in the southern and central Andes, where values up to 70 km have been determined, but few data is available in the northern Andes (Heit B. et al 2008). The knowledge of this property has many applications: it gives information of the crustal evolution, it is used to model wave-propagation in global and regional seismic studies, for developing surface corrections to investigate upper mantle structure, etc. (Assumpção et al. 2013).

Fromm et al. (2004), McGlashan et al. (2008), and Beck et al. (1996) estimated the crustal thickness beneath the central Andes. On the southern Andes, studies by Allmendinger et al. (1990), Regnier et al. (1994) and Gimenez et al. (2009) show the crustal thickness. Finally in the northern Andes there are few studies of the crustal thickness, some of them were done in Venezuela by Hernandez et al. (2007) and Schmitz et al. (2005). Also, Chulick et al. 2013, and Assumpção et al. 2013, did a compilation and presented a new set of contour maps including crustal thickness of South America.

Due to the high seismic activity in the Andes, it is possible to use the seismic waves to find the crustal thickness. Our study area is located in the northern Andes and the northern part of the central Andes (10° N to 8° S) which is still poorly known. Figure 1 shows the seismic data used to calculate crustal thickness in these areas used by Chulick et al. 2013, Assumpção et al. 2013 and in this work. It is possible to see that in the northern Andes there are few points with known crustal thickness. The objective of this work is to increase the data of crustal thickness in this area to have a better knowledge of the structure in northern Andes.

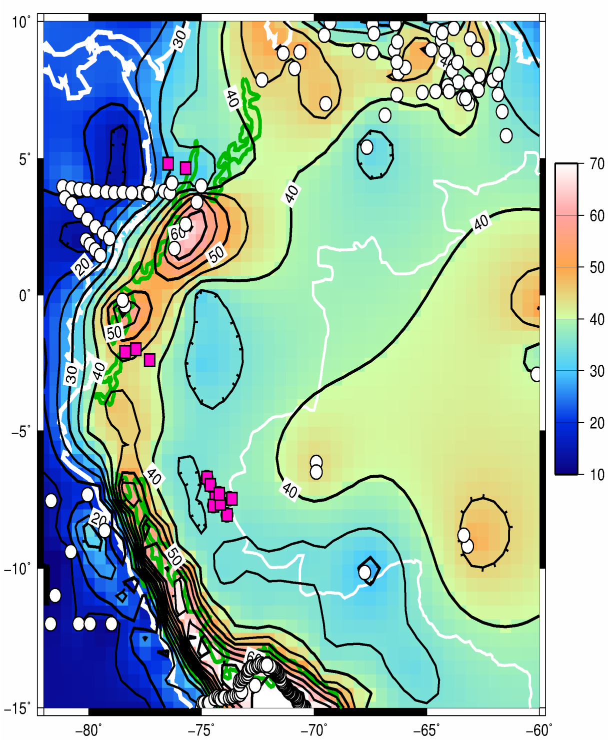

Figure 1: Crustal thickness of the study area in the northern Andes. White dots show seismic data of crustal thickness compiled by Assumpção et al. 2013 and for Chulick et al. 2013. Purple squares show the points where was calculated the crustal thickness in this work.

Method

We analyzed precursors of the pP and sS waves. For the P wave we used the vertical component seismograms (Z) and for the S waves we used both the radial (R) and transverse (T) components. The delay time between pP - pmP (or sS -smS) was converted to crustal thickness using the formula:

$$t_{pP} - t_{pmP} \approx 2h\sqrt{V_{pc}^{-2} - p^2}$$

where h is the thickness of the crust, Vpc is the velocity of the P wave in the crust (or the velocity of the S wave) and p is the ray parameter for the phases pP and pmP (or for sS and smS). The ray parameter of the pP and pmP phases were taken the same following Zhang and Lay (1993), Zandt et al. (1994) and McGlashan et al. (2008). The crustal velocity (Vpc) was the average velocity calculated by Christensen & Mooney (1995) (Vpc=6,45 km/s) similar to the one calculated by Chulick et al. 2013 (Vpc=6,435 km/s). In order to calculate the delay times between pP-pmP and sS-smS, we used the SAC (seismic analysis code) program.

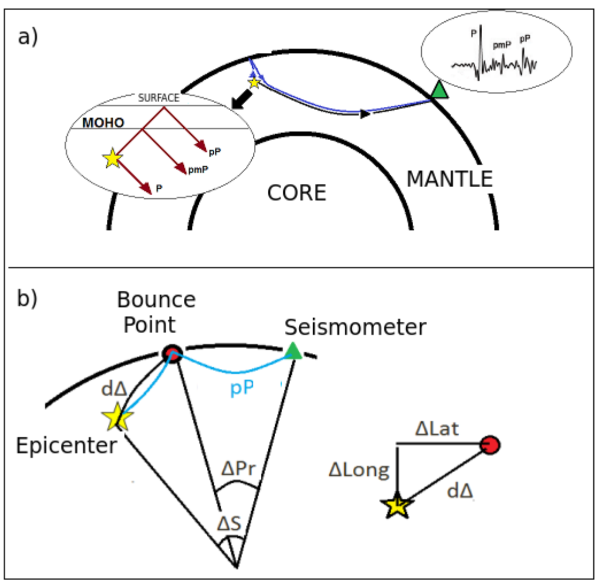

Figure 2: a) Reflection of the P wave from the underside of the Moho (pmP) and surface (pP), drawings modified from McGlashan et al. 2008. b) Bounce point localization.

For the same event, record for different stations with similar azimuth (Figure 3) we began selecting the arrival time for P, pP, S and sS phases estimated by the seismic travel time program TauPtime with the iasp91 velocity model, then we picked the pP (sS) peak and aligned at these peak and stacked to enhance the precursor pmP (smS).

The bounce points are the points where the pP waves reflect off the Earth's surface and correspond to the location of measurements for the crustal thickness, and are calculated using the great circle distance for the pP phase and the P wave originated by the reflection on the earth surface and the coordinates for the epicenter.

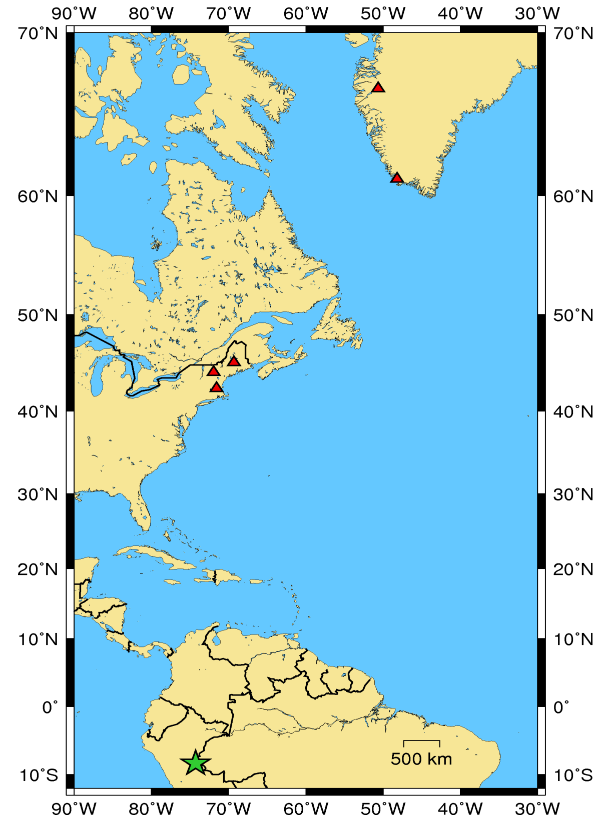

Figure 3: Example of an analyzed earthquake (green star) occurred on 2012 August 2 and the group of all stations (red triangles) with similar azimuth (~ 6°) that recorded the event.

Example

For the application of the method we must stack the seismograms with similar azimuth in order to enhance the low amplitudes of the pmP and smS precursors.

The data recorded and analyzed for the earthquake of magnitude Mw=6.1 occurred on 2012 August 8 at 74.24 W, 8.37 S at a depth of 143.3 km is shown in Figure 4 for the group with azimuth of 6°. The smS and pmP arrivals before and after stacking are also shown in this Figure.

In this example it is seen that the precursor phases are not always easily identified. For example, for pP wave in Figure 4 it is possible to see that the pmP peak is easy to identify because it is the only peak before the arrival of the pP that has the same shape of the pP phase and is the largest peak before the pP arrival. For the SH plot the smS peak is also the largest minimum peak before the sS. However, in the SV plot it is possible to see that before the arrival of the sS phase there are more than one peak with similar shape to the sS phase, but the peak selected to be the smS arrival was chosen because it is the largest peak, and the arrival time is consistent with the pmP phase.

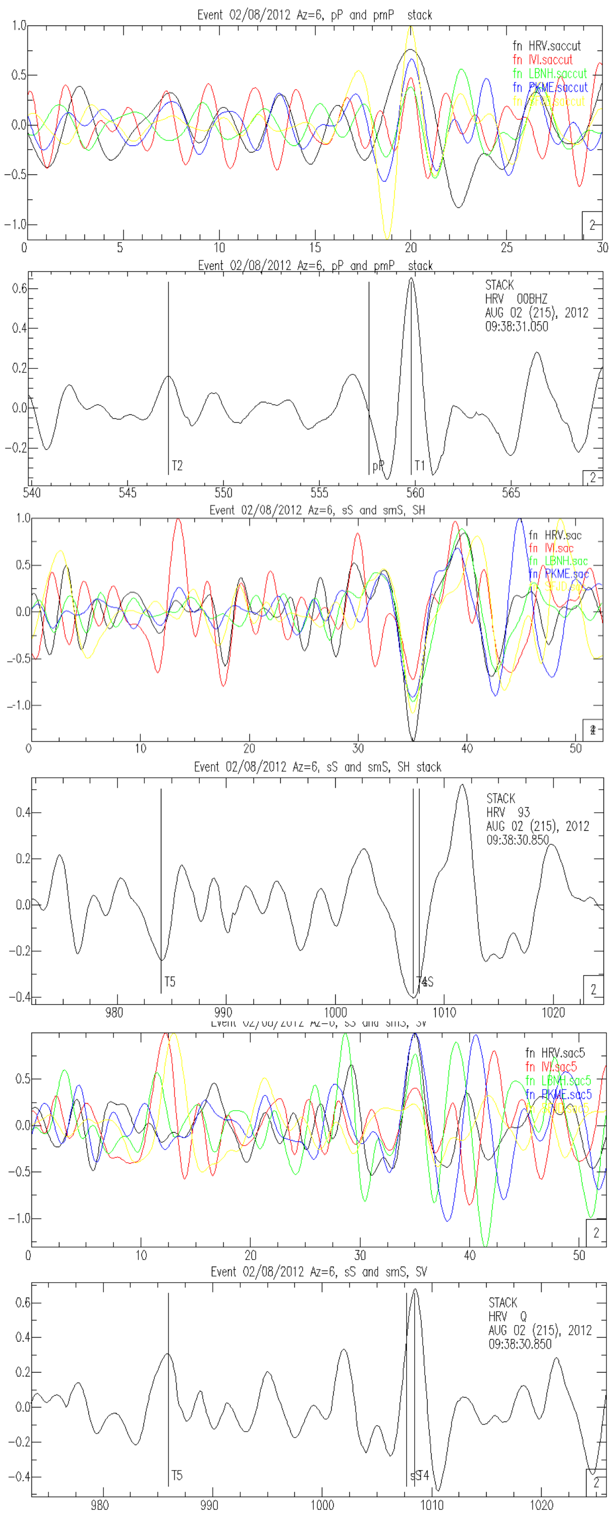

Figure 4: For each component (Z,R,T) the normalized traces are shown at the top and the stacked trace at the bottom. All traces were aligned at one peak of the pP phase (labeled "T1") and the sS phase (labeled "T4"), the T2 label is the pmP phase and the T5 labels are the smS phases. Time scale for the S waves is 1.73 the scale of the P waves. The labels "pP" and "sS" are the expected times for the IASP91 table.

Results

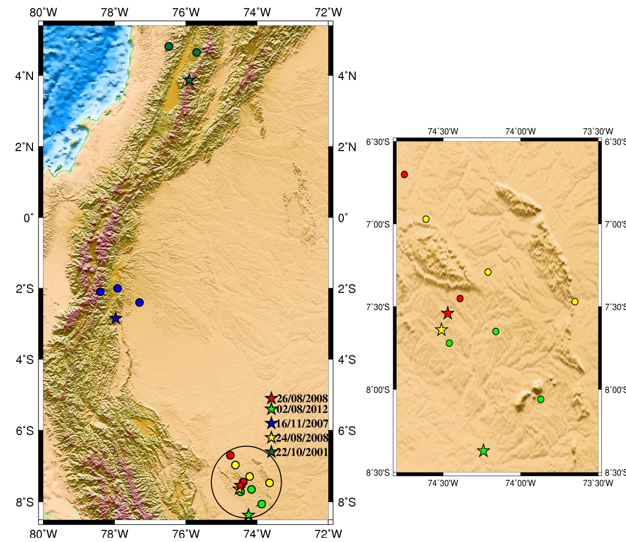

Figure 5: Left: Epicenters of all the analyzed events (stars). Circles are the bounce points where the crustal thickness was calculated for each event. Right: Zoom of the epicenters localized on the circle of left.

We analyzed five events from the northern Andes deeper than 100 km with magnitude larger than 6. (Figure 5). For all groups of similar azimuth for each event, the crustal thickness was calculated using the P wave with the vertical component and the S wave using both transverse SH and radial SV components.

Event	Crustal thickness (km)	Bounce points	Average azimuth	Number of stations
26/08/2008 (74.47 W, 7.54 S)	pmP: 39.8 ±1.2 SmSH: 35.2 ± 1.8 smSV: 42.4 ± 2.1	(74.7 W, 6.70 S)	342	10
H=152, Mw=6.2	ruidoso	(74.39 W, 7.46 S)	68	4
16/11/2007	pmP: 59.4 ± 3.5 SmSH: 49,7 ± 180 SmSV: 58,1 ± 5,4	(77.92 W, 2 S)	3	8
(77.97 W, 2.85 S)	pmP: 53.1 ±3.4 smSH: 55.9 ± 3.9 smSV: 49.6 ± 1.4	(77.3 W, 2.4 S)	56	6
H=154.7 km Mw=6.0	pmP: 45.9 ± 3.0 SmSH: 39.7 ± 1.0 smSV: 40.1 ± 1.0	(78.41 W, 2.1 S)	329	15
22/09/2001 (75.9 W, 3.87 N)	PmP: 29.1 ± 2.4 SmSH: 25.1 ± 2.7 SmSV: 29.5 ± 1.3	(76.48 W, 4.82 N)	328,8	20
H=178.6, Mw=6.2	pmP: 25.2 ± 0.5 SmSH: 37.5 ± 0.3 smSV: 32.0 ± 1.3	(75.7 W, 4.65 N)	45	7
02/08/2012 (74.24 W, 8.37 S)	pmP : 47.0±0.7 SmSH: 37,6 ± 1.7 SmSV: 40,1 ±0,8	(74.46 W, 7.72 S)	341	14
H=143.3 km	pmP: 40.9 ± 3.8 smSH: 40.2 ± 0.5 smSV: 41.5 ± 0.5	(73.87W,8.06 S)	50	10
Mw=6.1	pmP: 44.3 ± 0.2 SmSH: 47.4 ± 1,7 smSV: 48.5 ± 0.5	(74.16W,7.65 S)	6	5
24/08/2008	pmP: 38.4	(74.61 W, 6.97 S)	352	7
(74.5 W, 7.6 S)	pmP: 35.2	(73.75 W, 7.47 S)	78	4
H=147kmMw=6.8	pmP: 35.5	(74.21W, 7.29 S)	41	4

Table 1: Crustal thickness found for the five analized earthquakes using the pP and sS phases.

The crustal thicknesses measured are shown in Table 1 and all the bounce points are shown in Figure 5. To calculate the crustal thickness at the bounce points, it were assumed an average P velocity of 6.45 km s^{-1} and a relation of Vp/Vs=1,73 for the S velocity. To calculate the crustal thicknesses uncertainties it was necessary to measure the delay time between the maximum and minimum peaks of the two phases (pP-pmP and sS-smS). With these measurements we calculated the average time and then converted to crustal thickness; for the uncertainty we calculated the standard deviation for each phase.

For most of the crustal thicknesses obtained using the pP and the sS phase precursors it is possible to see that the three thicknesses (with each component) are approximately the same.

We compared our results of crustal thickness with some studies in South America by Chulick et al. 2013 and Assumpção et al. 2013. Figure 7 shows a contour map of crustal thickness of South America derived from seismic data compiled by Chulick et al. 2013, and Figure 1 shows a contour map of the crustal thickness compiled by Assumpção et al. 2013. It can be seen that there are few data in the northern Andes. Here lies the importance of this work.

Event	Bounce points	Average crustal thickness (km)	Thickness Assumpção et al. 2013 (km)	Residuals (km)
08/26/2008 (74.47 W, 7.54 S) H=152, Mw=6.2	(74.75 W, 6.70 S)	39.13 ± 3.6	35.51	3.6
11/16/2007 (77.97 W, 2.85 S) H=154.7 km Mw=6.0	(77.92 W, 2 S)	55,7 ± 5,2	46.66	9
	(77.3 W, 2.4 S)	42.4 ± 5.4	41.73	0.6
	(78.41 W, 2.1 S)	41.9 ± 3.4	46.66	-4.7
09/22/2001 (75.9 W, 3.87 N) H=178.6, Mw=6.2	(76.48 W, 4.82 N)	27.9 ± 2.4	29.59	-1.7
	(75.7 W, 4.65 N)	31.5 ± 6.1	32.19	-0.6
08/02/2012 (74.24 W, 8.37 S) H=143.3 km Mw=6.1	(74.46 W, 7.72 S)	41,5 ± 4,8	36.21	-5.3
	(73.87W,8.06 S)	40.8 ± 0.7	36.52	4.3
	(74.16W,7.65 S)	46.7 ± 2.1	37.27	9.5
08/24/2008	(74.61 W, 6.97 S)	38.4	35.9	2.5
(74.51 W, 7.64 S)	(73.75 W, 7.47 S)	35.2	37.69	-2.5
H=147 km Mw=6.8	(74.21W, 7.29 S)	35.5	37.25	-1.8

Table 2: Average crustal-thickness for each bounce point and misfit with the crustal-thickness of Assumpção et al. (2013).

In Table 2 it is presented the average crustal thickness for each bounce point, the crustal thicknesses reported by Assumpção et al (2013) and the residuals between both results. In Figure 6 there are show the residuals between both studies. The average crustal thicknesses for each bounce point was calculated by taking the average for the three phases P, SH and SV, and the uncertainty was calculated using the standard deviation between the three components.

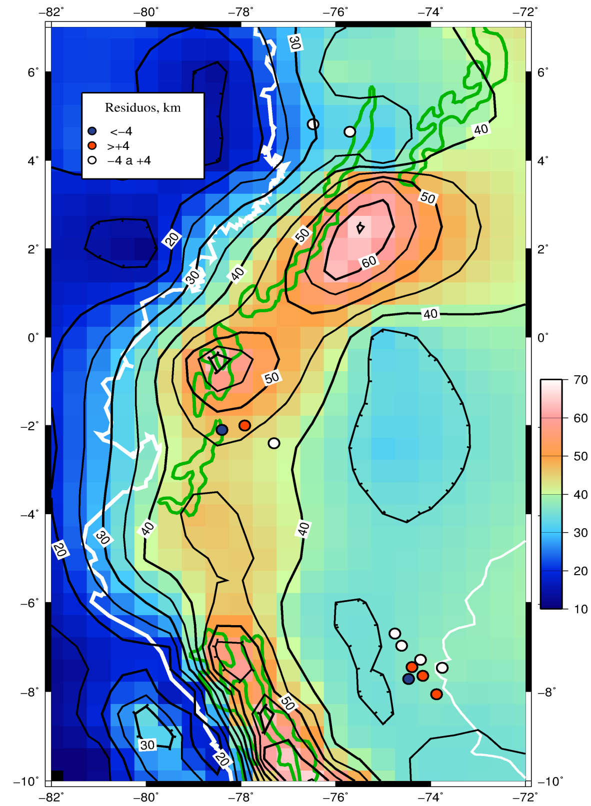

Figure 6: Residuals for crustal-thickness between the results of Assumpção et al. 2013 and this study. White circles are residuals between -4 and 4 km. Red circles mean a Moho 4 km deeper than the model. Blue circles mean the Moho is 4 km shallower than the model.

Comparing the crustal thicknesses obtained with the results of Assumpção et al. (2013), it can be seen that most of the bounce points (8 of 12) have a residual between -4 km and 4 km. Only two points show residuals > 4 km and two more show residuals < -4. These results confirm that the methodology gives results in accordance with the ones obtained by recent compilations of crustal-thickness for the area. Also, it is possible to see that the three points located on the area between -1° and -3° of latitude show residuals larger than 4 and smaller than -4 km, it is interesting that the compilations does not have direct data of crustal thickness in this area.

Conclusions

The method to identify teleseismic precursors to pP and sS for intermediate and deep earthquakes is interesting and can be applied in zones with earthquakes having magnitude larger than 6. The northern Andes is a favorable area to develop this method due to the depth of the earthquakes which are originated by the subduction of the Nazca plate beneath the South American plate.

We are getting results in areas that have not been studied previously. All the crustal thicknesses obtained here using precursors of pP and sS are in general agreement with the compilations made by Chulick et al 2013 and

Assumpção et al. 2013. Also our results helps increase the database of crutal thicknesses for the Northern Andes.

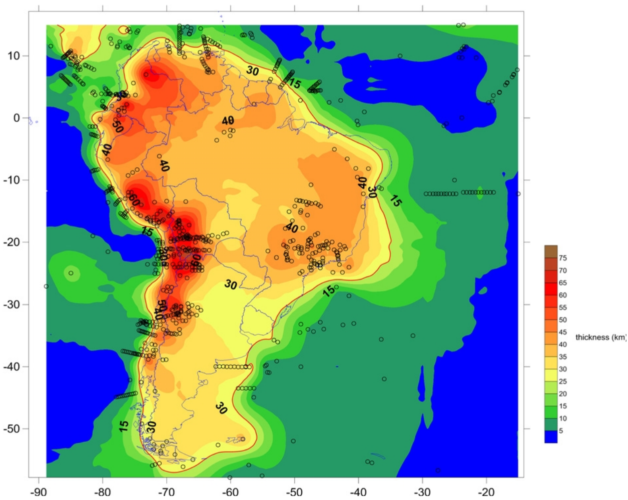

Figure 7: Contour map of crustal thickness of South America derived from seismic data taken from Chulick et al. 2013. The black dots represent seismic data profiles used in his study.

Acknowledgments

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