# Crustal thickness variations in western Venezuela from deep seismic observations

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**Abstract**

Seismic measurements were carried out in northwestern Venezuela including both, offshore and land refraction and wide angle reflection data. Seismic sections were constructed from land shots recorded on portable single channel stations as well as from airgun shots recorded by broadband seismological stations on land. Modeling of the land profile indicates the existence of a pronounced crustal thinning in the northeastern Falcón area. Additional seismic lines help to delineate the spatial distribution of the thinning area. The observations suggest that its western end occurs just west of Aracua while it opens to the east. The seismic observations discussed here support theories of diachronic opening of the Falcón Basin in an east-west fashion.

**Introduction**

Up to the present, data on crustal thickness for northern South America has been scarce (e.g. Mooney et al, 1998). In Venezuela, the first study of crustal structures was carried out in the eastern shore of Lake Maracaibo in the 1980's (Gajardo et al. 1986). Since the late 1990's deep seismic refraction experiments have been carried out, providing information on the Guayana Shield (Schmitz et al., 2002), the offshore central region (Guédez, 2003) and the Eastern Basin (Schmitz et al. 2005). Onshore observations used borehole blasts and quarry blasts as energy sources whereas offshore experiments were based on the recording of airgun shots on broadband seismological stations on land.

The present study is part of a much broader investigation currently taking place in order to study the complex plate interactions in the Caribbean-South America (CAR-SA) plate boundary zone. Such investigations make up the BOLIVAR (Broadband Ocean-Land Investigations of Venezuela and the Antilles arc Region) project funded by the NSF and the GEODINOS (Geodinámica reciente del límite norte de la placa Sudamericana) project funded by FONACIT.

This article focuses on the westernmost area of the study, involving the Falcón state and the northern part of Lara state.

**Crustal Thinning in the Falcón Basin**

The Falcón Basin in northwestern Venezuela extends over an area of some 36.000 km$^2$. Sedimentation in this basin took place during the Oligocene and the Early and Middle Miocene resulting in over 6000 m of sedimentary cover (Wheeler, 1963; Díaz de Gamero, 1977). The opening of the Falcón Basin is due to a north-northwest, south-southeast extensive regime that affected the region during the Oligocene and Lower Miocene. During the Middle Miocene sedimentation continued in the basin as a result of thermal subsidence (Audemard, 1993). Alkaline basalt intrusions and extrusions of latest Oligocene-earliest Miocene age are found in the Falcón Basin (Muessig, 1978; Muessig, 1984). These intrusions indicate that crustal thinning was associated to the opening of the basin (Muessig, 1984; Audemard, 1993).

**Method**

In the months of April and May 2004 a large-scale seismic acquisition campaign was carried out throughout northern Venezuela as part of the BOLIVAR and GEODINOS projects. Offshore reflection and refraction lines were shot off the Venezuelan coast and 4 refraction profiles were carried out on land. Airgun shots from the offshore lines were recorded on land by broadband stations of the Venezuelan Seismological Network (Guralp CMG-40T, 30s seismometers). The land profiles used chemical explosions as energy sources; two shots were fired along each profile with explosive charges of approximately 600 kg. The data discussed in this article corresponds to five offshore seismic lines and the land profile at about 70°W (Figure 1).

Receivers on land profiles were 4.5 Hz vertical geophones connected to portable single-channel REF TEK 125-01 (Texan) recorders. A total of 550 receivers were deployed with 300-500 m spacing. Shot spacing for the offshore lines was 50 m. Due to the large amount of airgun shots and the small distance between them, traces corresponding to contiguous shots were stacked together in groups of ten, rendering the seismic sections more manageable, increasing signal-to-noise ratio and reducing computing time during processing.

Offshore lines were band-pass filtered with corner frequencies of 2 and 8 Hz, whereas in the land sections corner frequencies of 2.5 and 16 Hz were used. The trace normalized sections were reduced with a reduction velocity of 6 km/s and seismic phases were correlated, particularly the Pg and PmP phases, but also other seismic phases such as intracrustal reflections and reflections from the downgoing Carribbean slab.

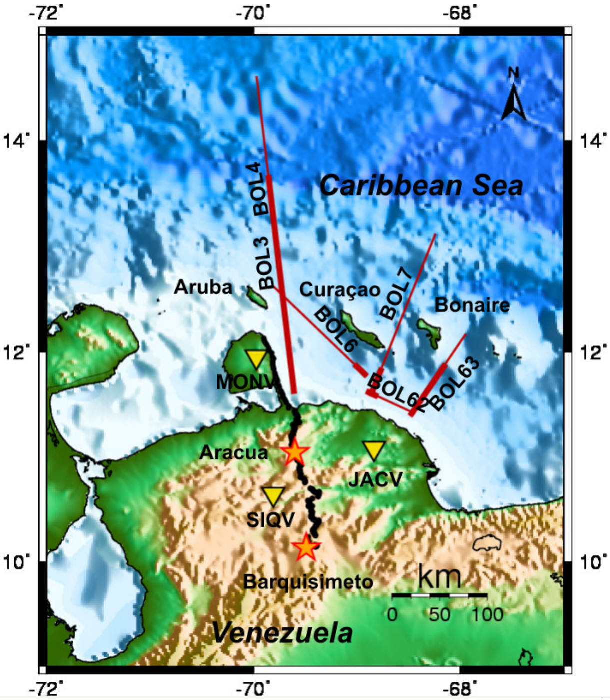


Figure 1 - Location map. Straight lines: offshore seismic reflection lines (bold segments indicate sections that were recorded by seismological stations on land) with line numbers. Inverted triangles: Stations of the Venezuelan Seismological Network used in this study with station code. Stars: Borehole blasts with shot location name. Black points: receiver positions for the land profile.

The picked travel time curves were input into the 2-D modeling software RAYINVR (Zelt and Smith, 1992), where the sections were modeled using a forward approach.

The main model was obtained from the N-S profile formed by the BOL3 line recorded in the Montecano seismological station (MONV) and the onshore refraction line (figure 1). Additional lines provided information that help to expand the model outside the 2-D domain.

**Seismic Interpretation and Modeling**

The seismic sections from the land profile, particularly the one corresponding to the Aracua shot point (figure 1) contain clear arrivals that are interpreted as belonging to the Pg and PmP phases (figure 2). In this particular case, PmP arrivals were identified south of the shot point between 100 and 50 km distance. To the north, PmP reflections were identified between 70 and 32 km distance. This travel time curves were modeled and a crustal thinning of 27 km fit the data satisfactorily (figure 3).

A seismic line constructed from airgun shots of the BOL3 line recorded by the Siquisique (SIQV) station (figure 1) was expected to be consistent with the crustal thinning due to it's proximity to the land profile. PmP arrivals were interpreted in this section between 140 and 110 km distance (figure 4). When modeled, the best data fit was obtained when no crustal thinning was considered but rather a Moho depth of 37 km (figure 5). Considering that the two profiles are separated by only approximately 25 km, this suggests that the thinning below the Falcón Basin ends directly below or only a few km west of the land profile discussed here.

Additional seismic lines constructed from airgun shots of the BOL6, BOL7 and BOL63 lines recorded by the Jacura (JACV) station (figure 1) helped track the crustal thinning east of the main line (Bezada, 2005). Modeling shows that interpreted PmP arrivals were consistent with an eastward continuation and increment in the dimensions of the structure. Further north, Moho depth was controlled by PmP reflections identified in the seismic line constructed from airgun shots recorded by the Montecano (MONV) seismological station (figure1).

**Crustal Thickness Map**

With data from all the seismic lines discussed hereto, as well as data from the previous deep refraction experiment COLM (Costa Oriental del Lago de Maracaibo; Gajardo *et al.*, 1986) as reinterpreted by Guédez (2003) a preliminary map of crustal thickness was generated using the Generic Mapping Tools software package (Wessel and Smith, 1991) (figure 6).

The map shows an overall northward reduction of crustal thickness with depth to Moho reducing from 40 to 25 km towards the north. The main feature of the map is the crustal thinning in the Falcón basin (as discussed above), where depth to Moho is reduced by approximately 10 km.

**Discussion**

Offshore and land seismic observations and the crustal thickness map derived from them indicate a thinning of the crust in northeastern Falcón. This thinning is linked to the opening of the Falcón Basin in the Oligocene and Lower Miocene (Muessig, 1984; Audemard, 1993). Seismic evidence suggests that this crustal thinning ends just west of our profile but continues eastward. Such evidence supports theories of formation of the basin that, based on stratigraphic information, propose a diachronic genesis, starting in the east and progressively moving westward (Gonzales de Juana, 1980; Audemard, 1993)

Previous gravimetric modeling of virtually the same profile (Rodríguez and Sousa, 2003) obtained similar results, with a crustal thinning occurring in largely the same geographical position but with different dimensions (crustal thickness of 20 km instead of 27 km, as shown here).

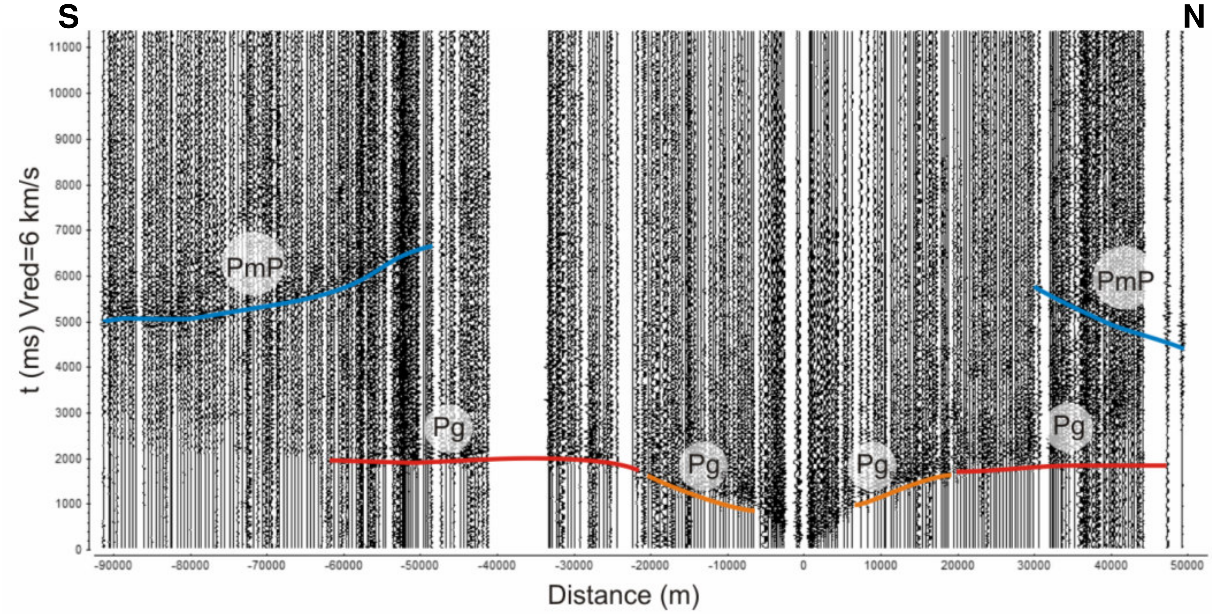


Figure 2 – Seismic section on land corresponding to the Aracua shot point. Pg arrivals are observed up to 40 km to the north and 60-70 km to the south. To the south, Moho reflections are observed between 100 and 50 km distance, whereas to the north, arrivals between 100 and 32 km are interpreted as Moho reflections. Location in figure 1.

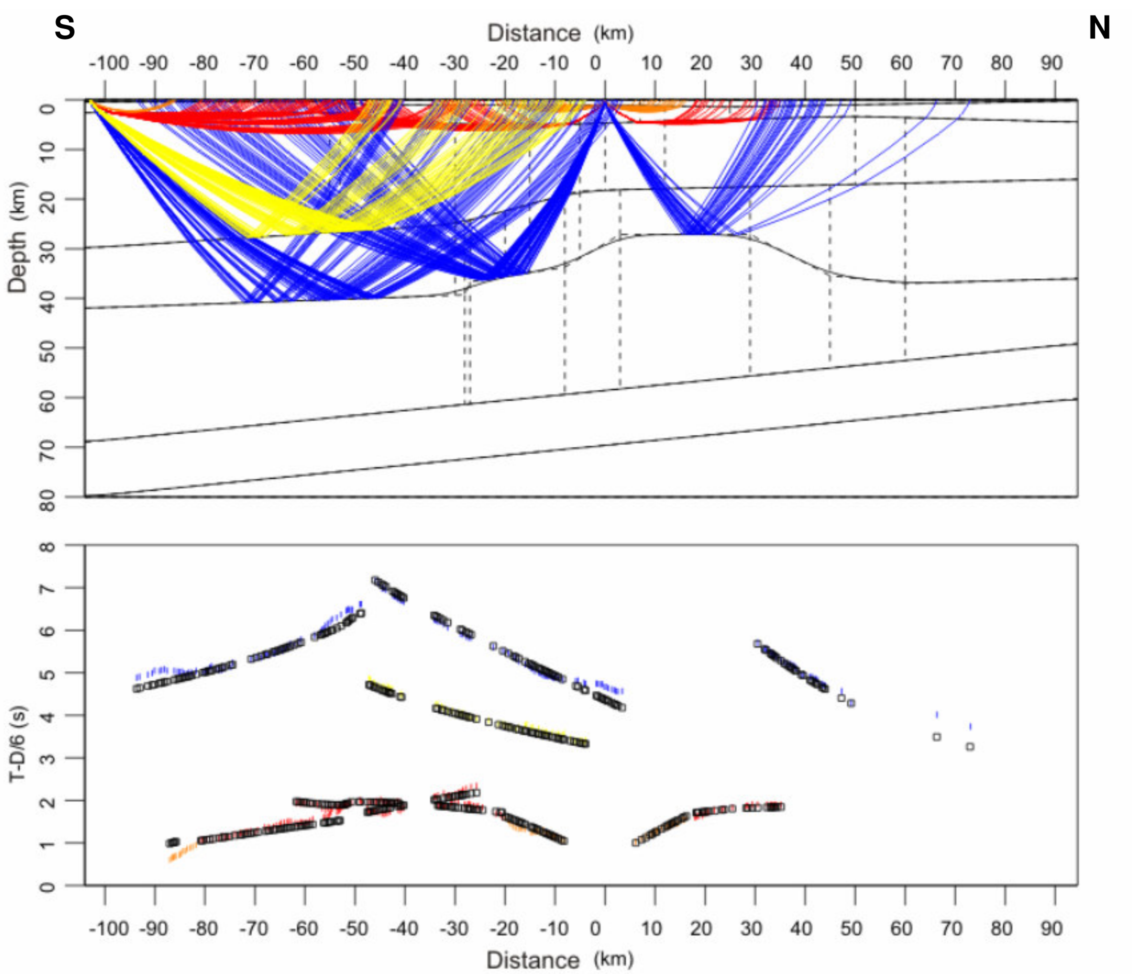


Figure 3 – Ray tracing (top) and observed (colored segments) and calculated (squares) travel times (bottom) of the land shots along profile 70°W. Model includes crustal thinning of 27 km.

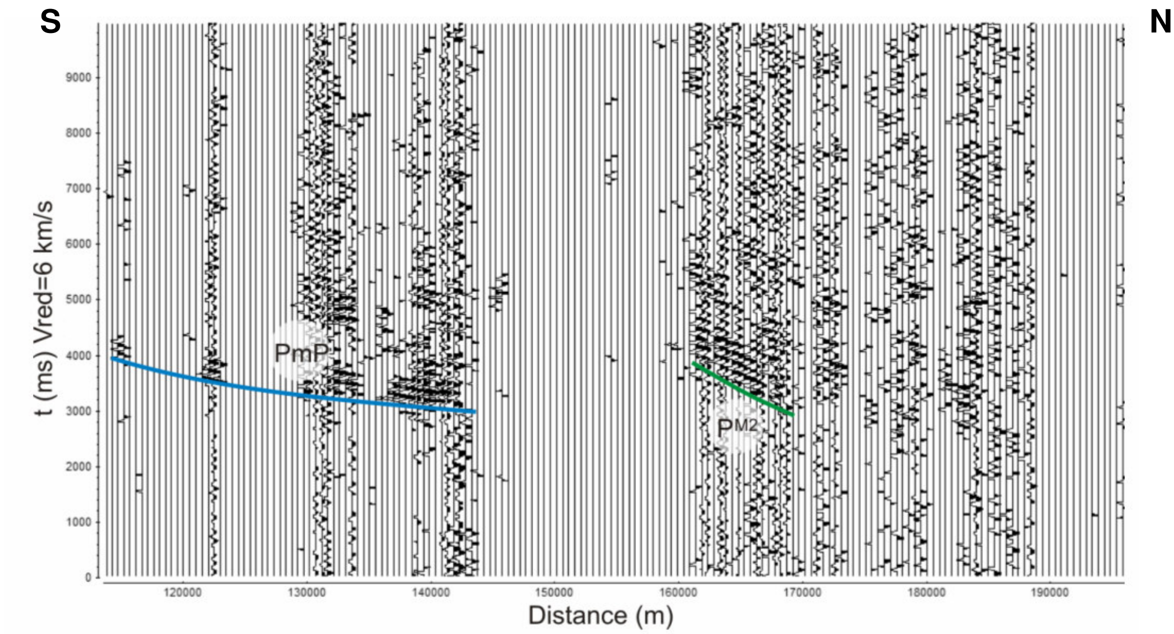


Figure 4 – Seismic section constructed from airgun shots along BOL3 line recorded by the Siquisique (SIQV) station. PmP arrivals are observed between 140 km and 110 km to the north. Location in figure 1.

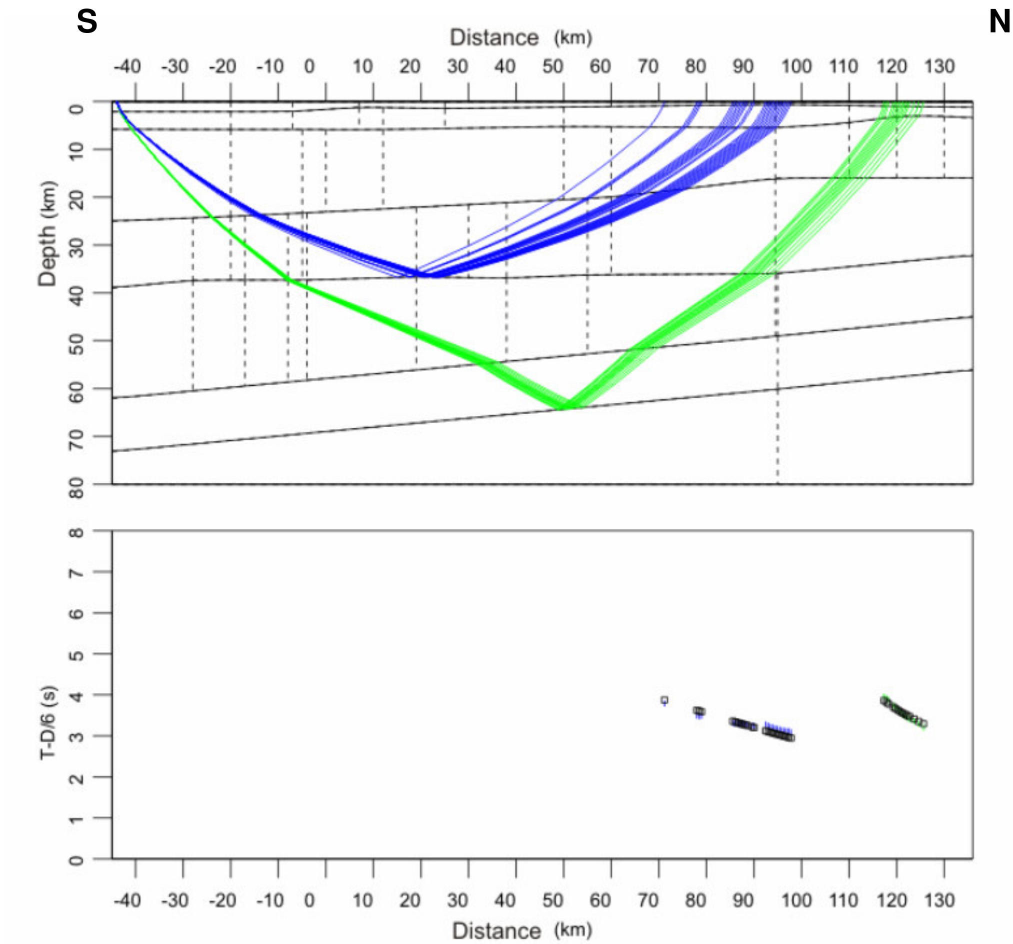


Figure 5 – Ray tracing (top) and observed (colored segments) and calculated (squares) travel times (bottom) of the recordings of line BOL3 at station SIQV. Model includes no crustal thinning but a depth to Moho of 37 km.

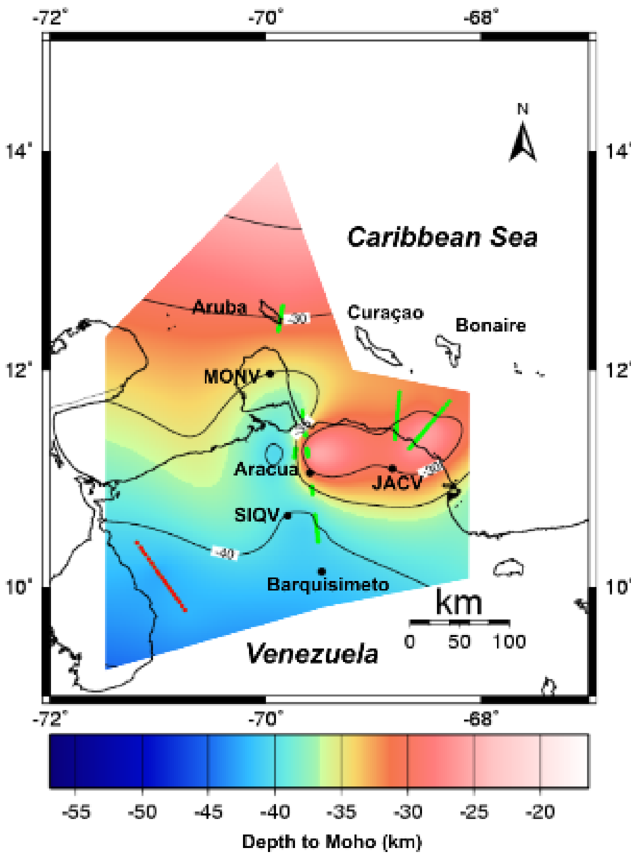


Figure 6 – Preliminary map of crustal thickness for northwestern Venezuela. Green dots indicate control points from this study. Red dots indicate control points from COLM (Gúedez, 2003).

## Conclusions

Seismic observations have shed a new light on the crustal thickness in a region where such data was not available up to the present (e. g. Mooney *et al.*, 1998). This new data, complemented with newly interpreted information (Guédez, 2003), has been used to generate a preliminary crustal thickness map for the Falcón and northern Lara area of northwestern Venezuela.

Overall, the depth to Moho shows a reduction from over 40 km in the south to approximately 25 km north of the Leeward Antilles. In northwestern Falcón, a clearly distinguishable feature is a crustal thinning where depth to Moho is reduced to approximately 27 km. The data discussed in this article suggest that this structure has an east-west trend and that its westernmost termination is located just west of Aracua. The thinned crustal area is slightly more pronounced to the east. This new evidence supports earlier theories of diachronic east-west formation of the Falcón Basin (González de Juana, 1980; Audemard, 1993)

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## References

**Audemard, Fr.**, 1993, Néotectonique, sismotectonique et aléa sismique du nord-ouest du Vénézuela (système de failles d'Oca-Ancón). PhD Thesis, Universty of Montpellier II. Montpellier, France. 369 p.

**Bezada, M.**, 2005. Modelado Bidimensional de la Corteza en la Zona de Colisión Caribe – Suramérica, Región Occidental de Venezuela (Estados Falcón y Lara). Trabajo Especial de Grado. Universidad Simón Bolívar, Venezuela.

**Diaz de Gamero, M. L.**, 1977, Estratigrafía y micropaleontología del Oligoceno y Mioceno Inferior del centro de la Cuenca de Falcón, Venezuela. Escuela de Geología y Minas, Universidad Central de Venezuela, Caracas, GEOS no 22, p. 3-60.

**Gajardo, E., Nicolle, J.L., Castejon, B. Marquez, C. y Urbáez, M.**, 1986. Modelo de corteza en la Costa Oriental del Lago de Maracaibo. III Congr. Venez. de Geofísica, Caracas, 102-111.

**Gonzalez de Juana, C. Iturralde, J. and Picard, X.**, 1980. Geología de Venezuela y de sus cuencas petrolíferas. Ediciones FONINVES, Caracas. Vol 1 407 p and Vol 2 624 p.

**Guédez, R.**, 2003. Estudio cortical en el área centro-norte y noroccidental de Venezuela a partir de datos de sísmica de refracción. Trabajo especial de grado, UCV, 124 pp.

**Mooney, W.D., Laske, G. and Masters, G.**, 1998. CRUST 5.1: A global crustal model at 5°x 5°. Journal of Geophysical Research, v. 103, p. 727-747.

**Muessig, K.**, 1978. The central Falcon igneous suite, Venezuela: Alkaline basalt intrusions of Oligocene-Miocene age. Geologie en Mijnbow, V 52(2), p 261-266.

**Muessig, K.**, 1984. Structure and cenozoic tectonics of the Falcon basin, Venezuela and adjacent areas. GSA Memoir 162, p 217-230.

**Rodríguez, J. and Sousa, J. C.**, 2003. Estudio geológico-estructural y geofísico de la sección cabo San Román-Barquisimeto, estados Falcón y Lara. Trabajo Especial de Grado. Universidad Central de Venezuela. Venezuela.

**Schmitz, M., Chalbaud, D., Castillo, J. and Izarra, C.**, 2002. The Crustal Structure of the Guayana Shield, Venezuela, from seismic refraction and gravity data. Tectonophysics, 345 (1-4), 103-118.

**Schmitz, M., Martins, A., Izarra, C., Jácome, M.I., Sánchez, J. and Rocabado, V.**, 2005. The major features of the crustal structure in north-eastern Venezuela from deep wide-angle seismic observations and gravity modelling. Tectonophysics, doi:10.1016/j.tecto.2004.12.018.

**Wessel, P., and Smith, W.H.F.**, 1991. Free software helps map and display data. EOS Trans. AGU 72, 441, 445-446.

**Wheeler, C.**, 1963. Oligocene and Lower Miocene stratigraphy of western and nothwestern Falcón Basin, Venezuela. AAPG Bulletin 47 v. 1. p 35-68.

**Zelt, C.A. and Smith, R.B.**, 1992. Seismic traveltime inversion for 2-D crustal velocity structure. Geophysical Journal International, v. 108, p.16-34.