

# SEISMIC HAZARD IN THE METROPOLITAN REGION: NEW PERSPECTIVE IN AN ANDEAN TECTONIC CONTEXT - CASE SANTIAGO OF CHILE.

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## 1 Central research question and hypothesis:

Chile is the most seismic country in the world, being witnessed earthquake that has inflicted human casualties as much as material. For that reason, it is fundamental that people in charge to design the civil structures consider on all the information possible to mitigate the possible damages due to the important seismic activity. One of the information more often used nowadays is the estimation of the seismic hazard.

The cordilleran zone of central Chile is of great strategic importance for the city of Santiago of Chile, because it is the source of hydroelectric power stations and the pipelines located in the high mountain range of central the Andes for a population of around 6 million inhabitants. More over, strategic sites of the high mountain range it is the location of the main Chilean economic resources: the Great Mining Industry.

Therefore, it is of extreme importance to properly characterize the seismic threat, enabling better estimations of the seismic hazard, in order to significantly reduce the different risks that the population of Santiago is exposed.

The seismotectonic characterization of a region consists essentially of a detailed evaluation of the seismicity and the tectonic traverse structures where the fragile and non-fragile deformation is pronounced. Historic earthquake studies, in special those that consider historical registries, allow to determine geometry of the rupture, and, through phenomenological analyses, other characteristics like focal depth, magnitude, and mechanism of the seismic rupture. The description of historical earthquakes and the system of faults in a region, along with the analysis of the present seismicity, contributes to the knowledge of the space-temporary structure of the earthquakes, enabling a better approach to the seismic threat. The determination of the laws of self-organization of earthquakes, that is to say, power laws determined by a similarity independently of the scales (Gutenberg-Richter, Omori, Hurst, etc), along with the determination of the stress regime of the region, from the analysis of the focal mechanisms of the earthquakes, permits the determination of the form and direction of the stress regime (not necessarily its amplitude). Indeed, these sismotectonic characteristics are essential to address the characterization of the seismic threat in the Santiago metropolitan region, being the core of this doctoral thesis.

## 2. Background and context (literature review)

The basic principle in any estimation of the seismic hazard is, in an ample sense, a detailed analysis of the seismicity. The sismotectonics characteristics are an integral part of this analysis, and, in the last years, have become an essential component in the characterization of the seismic hazard.

The seismicity in Chile is one of the larger ones in the world. Until beginnings of the 90s, the scientific community in Chile essentially considered for seismic threat only large events ( $M > 8.0$ ) with coastal epicenter (thrusts earthquakes). By the end of the 80s and

beginnings of the 90s, works of Kausel et al. (1992) and Campos et al. (1990), allowed to explain that several M~8 events, considered until that moment like thrust events, corresponded in fact to earthquakes of intermediate depth, opening the discussion on a new classification of the seismic events to be considered for the characterization of the seismic hazard in Chile. Later, the scientific community devoted its effort to understand and characterize crustal, less frequent events, generally with epicenter in zones practically depopulated in the country. Recently, several cortical earthquakes have occurred in Chile, for example, Chusmiza, 2001 (M=6,3) in the North zone of Chile, Curicó, 2004 (M=6,4) in the Center-South, and more recently the sismotectonic crisis of Aysén in the south of Chile, with a main event of Mw = 6,3 in April of the 2007. Amongst the important superficial events that caused damages in century XX we find the Punta Arenas, 1949 earthquake, and the Melosas, 1958, located in the cordilleran zone near Santiago, whose Mw magnitude was re-calculated recently in 6.3 (Alvarado et al, 2009). All these superficial earthquakes of important magnitude are a clear evidence of the existence of a system of active faults in the Andean sismotectonic context. In eastern Chile, this kind of superficial earthquake is not exclusive of the systems of faults associated to the formation of the Mountain range of the Andes, having also evidences of geologically active faults in the continental crust near the coastal region (Armijo et al, 1990; Herve, 1987; Naranjo, 1987). Even more, Campos et al. (2002), in a study of the Constitution-Concepcion region, found evidences clear of cortical seismic activity of this nature.

Different studies have been made in central Chile for the determination of the seismic hazard (Lomnitz, 1960; Gajardo et al, 1960; Welkner, 1964; Labbe, 1976; Barrientos, 1980; Martin, 1990; Romanoff, 1999; Silva 2007; Leyton et al, 2008), using the seismic catalogues available at the time. Barrientos (1980) was the first one to consider specifically two separated seismogenic sources (intraplate and interplate), and only recently a third seismogenic source (the cortical one) was added.

In all these studies the determination of the seismic hazard has been made using the probabilistic method of Algermissen & Perkins (1976), based on the work of Cornell (1968). The probabilistic method gives the probability of exceeding certain seismic parameter (acceleration, intensity) in a certain given period of time.

The attenuation relations show that earthquakes with magnitudes greater to 6.8 can cause great peak ground accelerations peak, up to 0.6 g in the near field. In fact, several accelerations greater to 1 g have been registered in recent earthquakes. Nevertheless, there are several uncertainties to be addressed, for example: 1) distance to the source, 2) mechanism of rupture for different earthquakes, 3) insufficient data in the near field, 4) strong dependency of the peak accelerations (rich in high frequency or short wavelengths) with respect to the heterogeneities of the propagating medium, specially affected by local geologic characteristics, and 5) the saturation of the peak accelerations in the near field (Mualchin, 1996).

Recent earthquakes in California and Japan show that the probabilistics maps of seismic risk do not give a realistic estimation to faults with long return periods. The Landers and Kobe earthquakes assumed long intervals of recurrence but nobody could predict when it would happen the next destructive earthquake. In this sense, deterministic maps give one more a more realistic estimation of the seismic danger (Mualchin, 1996).

Cases in Chile suggest that accelerations in the epicentral zone for cortical earthquakes generated in active faults are greater than the registered ones in other parts of the world (Campos et al, 2005). For example, Las Melosas, 1958 earthquake (magnitude 6,9) have been considered to produce in the Metropolitan Region accelerations between 0.7 and 1.2 g, in distances ranging from 5 and 10 km of the epicenter, and intensities of the order of VIII to IX in the epicentral area (Sepúlveda et al, 2008). This suggests the necessity to count on local studies, oriented to determine the attenuation laws for particular cases.

Recently, detailed tectonic studies of San Ramon Fault located to the East of Santiago are made in the cordilleran front; this fault system is considered active, being able to generate earthquakes with magnitudes between 6,9 and 7,4 in Santiago Metropolitan region (Armijo et al, 2009).

From the tectonic point of view, cortical earthquakes correspond to a fragile deformation of the crust as an answer to the tectonic load controlled by the process of subduction of the Nazca plate under the South American plate. These events confirm that the Andean formation and the existing system of faults in the region comprise of a tectonic process that is needed to include/understand for a correct characterization of the seismic hazard.

Tectonically, seismogenic structures displaying movement that can generate earthquakes are considered to be active geologic faults. More over, an active fault in neotectonic terms is the one that has presented/displayed movement during the present tectonic regime.

The sismotectonic analysis is a fundamental stage for an appropriate characterization of the seismic threat. The cordilleran zone forearc of Santiago, between latitudes 32.5°S and 34.5°S, show an Andean orogene with main vergence to the west (Armijo et al, 2009). Geomorphologic and geologic analyses that cover the region in study, have put in evidence new antecedent of active tectonic structures that remarkably modify the seismic hazard of the city of Santiago (Armijo et al, 2009; Rauld, 2002; Rauld et al, 2006). This one is located opposite of important active faults associated to the first Western Front of the Andean Orogene and it is located in the denominated Central Depression, which during long time was interpreted as they record in extension, limited the east and the west by normal faults (Brüggen, J.1950; Carter et al, 1965; Thiele, 1980).

One stands out in the western front, the system of San Ramon fault whose more evident morphologic expression consists of a series of escarpments of fault of type thrust-slip (inverse). The San Ramon fault, who cuts sedimentary deposits of ages Pleistocene and Holoceno throughout the edge this of Santiago, between the Mapocho and the Maipo river, constitutes an object of first order of seismic hazard, with metric slidings throughout several kilometers. This structure, has been identified recently like the main mechanism of detachment to explain the rise of the cordillerano front to a rate of sliding average of ~0.3 mm/año (Armijo et al, 2009).

More to the east, a second in front of the orogeno characterized by a second topographic step is defined upper, person in charge of high summits where important structures like the faults of Olive groves are concentrated, Black Lagoon, Chacalles-Yesillo.

### 3 METHODOLOGY

#### 3.1 1-D VELOCITY MODEL

For the cortical seismic source it is fundamental to have a data base with reliable hypocentral locations for the development of a sismotectonic study from which it is possible to find the existing relation between the presence of faults and the distribution of the seismicity is known that the typical problems associated with the location of local and regional earthquakes are the imprecision in the times of arrival, an inadequate velocity model and the consequent instabilities of the investment methods. Because the epicentral distances normally are greater than the distances between seismic stations, the hypocentral parameters cannot well be determined taking place a strong dependency between time origin and focal depth, still more complicating the later interpretation of the way how the space distribution of the seismicity is structured.

In order to calibrate a velocity model in the region, that allows to count on one better determination of the focal parameters of the cordilleran superficial seismicity, some velocity models were analyzed that have been proposed for the zone (Barrientos et al. (2004); Pardo et al, personal Communication). The SSN uses a simplified version of the model proposed by Barrientos et al (2004), allowing to create a homogenous and complete catalogue for  $M > 3.5$ . A data base with 669 events is used for the inversion of the 1D velocity structure, corresponding to the seismic superficial events (0-30 km) located between 32.5S- 34.5S and 69.5W-71.5W, registered by a minimum of 12 seismic stations of the SSN between 2000 and 2009 (a minimum of approximately 20 readings of phases P and S), and with residual less to 0.5 s (see Figure 1).

Several techniques of hypocentral location have been proposed and many depend on the type of adjustment to the stations (HypoDD method, for clusters), and of the azimuthal cover of the network of stations. In this work the use a technique proposed by Kissling (1995), based on the Velest program. This code simultaneously allows to the relocalization of hypocenters and the adjustment of the 1D velocity model by iterative processes, by means of the inversion of the arrival times, using the nonlinear ray tracing methodology. The final model consists of a series of layers of seismic velocities and stations corrections. For the solution of the problem the theory of trajectory of seismic rays (ray tracing) of the source to the receiver is used, calculating the rays direct, refracted and optionally reflected that happens through model of speeds; the inverse problem is solved using damped least square. Because the inversion is non-linear, the solution is obtained in an iterative form. Velest is not free of the main limitations found in the inversion of nonlinear problems nonlinear: there are a great variety of solutions that can satisfy the inverse problem. The solution depends on the initial model of speeds and the location of the events that initially are used for the iterative process. Velest defines a great number of control variables that must of being modified in a long process of test and error. The selection of the thickness of the different layers from the velocity model has to be made manually, because Velest does not have the possibility of changing the thicknesses of the layers automatically.

In order to analyze the goodness of fit of the velocity models and to select the initial model to use in the inversion, I selected a subgroup of 383 events of the 669, located in the cordilleran zone corresponding to the "registered events" in the mines Disputada de Las Condes and Bronces; Of these 383 events, approximately 93 correspond to

explosions. The practically exact knowledge of the hypocentral location of these events, as well as of the stations that register them, allows to the obtaining of data very precise distance-time, enabling us to introduce a information “*a priori*” like criterion of calibration of the kindness of the epicentral determination.

### 3.2 SISMOTECTONIC ANALYSIS

In this study, recent findings of active faults and the system of faults in the mountain range of Central Chile are used to carry out a sismotectonic analysis of the space distribution of the superficial cortical seismicity (< 30 km) registered by the National Seismological Service network. A new velocity model is being used, calibrated specially for the determination cortical hypocenters in the region using a window of time much greater than usually obtained of seismic campaigns of short duration (Perez et al, 2009). This allows to approach of better way the sismotectonic analysis to the light of the new antecedents contributed recently to explain the style of deformation described in this zone of the Andes.

## 4 RESULTS

From the analysis of the epicentrals locations of the earthquakes of the mine using different models from proposed velocity models for the region, are observed that the model that presents/displays less dispersion RMS corresponds to the used one by the SSN. The Figure 2 show to the location of the seismicity and the distribution of the residual ones.

The data of the explosions allowed the modeling of travel-time curves, to obtain the velocity of the halfspace, reaching an average of 6.15 km/s for P waves.

Using the velocity model of the SSN and extending the catalogue to 669 events with a minimum of 20 readings P and S corresponding to events in the cordilleran zone, it is come to relocate the hypocenters and to obtain a new model of speed using VELEST by means of a standard process of successive iterations that are producing the adjustment of the hypocenters, the correction of stations and the adjustment of the speed model. Once finalized this stage it was come to investigate the resolution of the thicknesses of the layers of the obtained velocity model. Figures 3 and 4 show the best model found in this study, the distribution of the seismic stations used and the final location of the crustal seismicity.

The kindness of the final model of found speed was verified from an analysis of Wadati using data of 10 explosions of the mine and the resolution of the focal depth of the hypocenters from readings S-P of stations located on some events was verified just. In this work 2509 cortical seismic events were relocated (depth < 30 km) for the study zone, using the data of the catalogue of the SSN. For the relocalization a 1D velocity model determined by Perez et al, 2009) was used, using VELEST by means of the propose technique by Kissling (1995). The distribution of this seismicity appears in Figure 5.

Some seismic events are located closely together, or directly, under some located seismic stations in the cordillerana zone (San Jose de Maipo (SJCH), the Melosas (LMEL), El Yeso (YECH)). With the intention of improving the determination of the depth of this cortical seismic activity, it was come to analyze times S-P of approximately of 10

events registered in the period between 2000 - 2009 for each one of those stations. The depths determined for these earthquakes vary between 9,5 -16,5 km in station SJCH, 11,2 - 17,6 km in station LMEL and 7.1-14.2 km in station YECH.

The distribution of the studied superficial cortical seismicity is organized in an approximate direction N-S, throughout two parallel strips (Figure 5). Western, organized well, homogenous and with depths between 15-25 km, located directly in the first western front of the Andean Orogene; Eastern, a wider and diffuse one, with more superficial earthquakes and a greater concentration of events in the South end, located on the second in front or higher topographic step, determined by high summits. Between both strips a little dispersed seismicity is observed.

Of this form, the distribution of the observed seismicity does not fall in contradiction with the mountain range model from a detachment level proposed by Armijo et al, 2009. The strip of western seismicity is interpreted like product of the deformation associated to the first front of the Andean Orogene, that is raised by on the central depression, and the strip of Eastern seismicity is associated to the second in front, constituent of highest summits.

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FIGURES

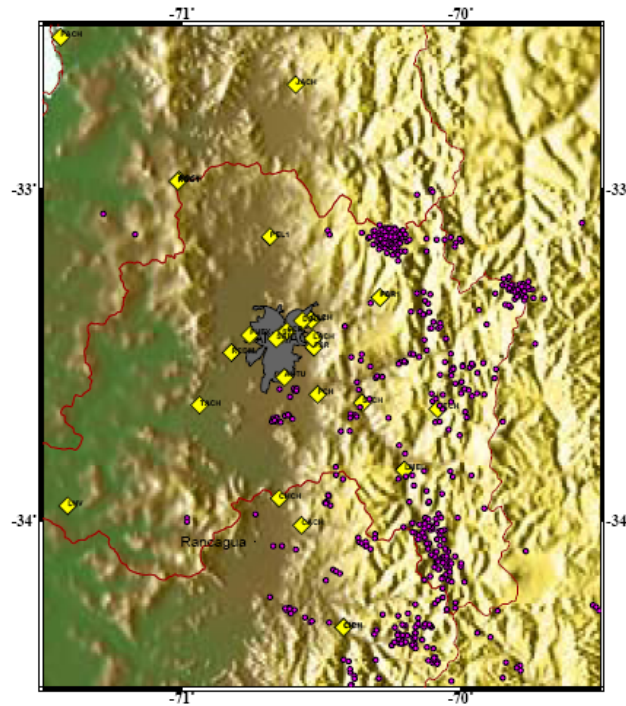
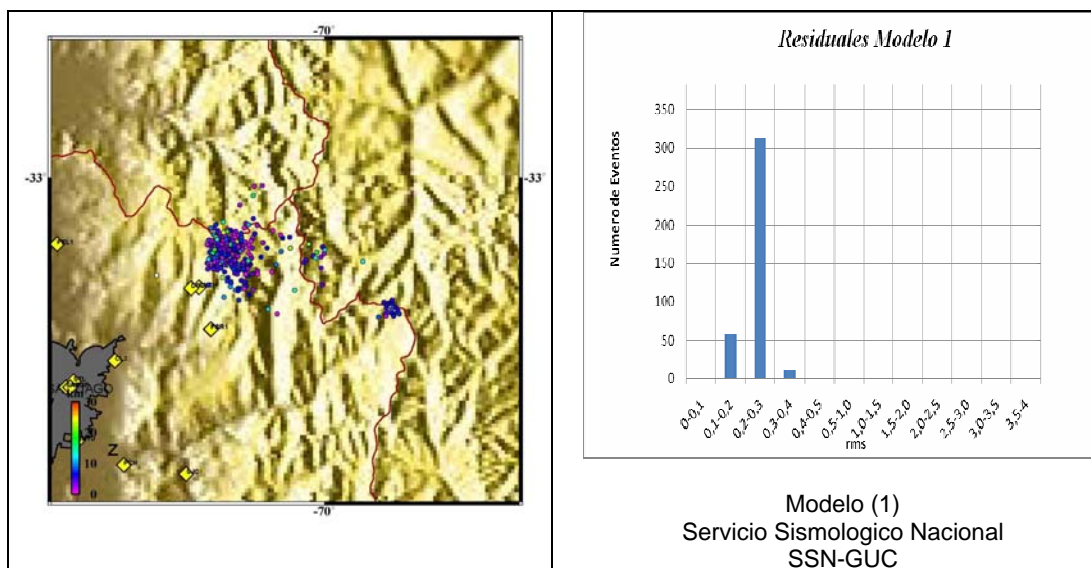


Figura 1. Initial hypocentral location of 669 events recorded by SSN cortical between 2000 and 2009. Yellow indicates the seismic stations in the magenta hypocenters located with the velocity model of the SSN



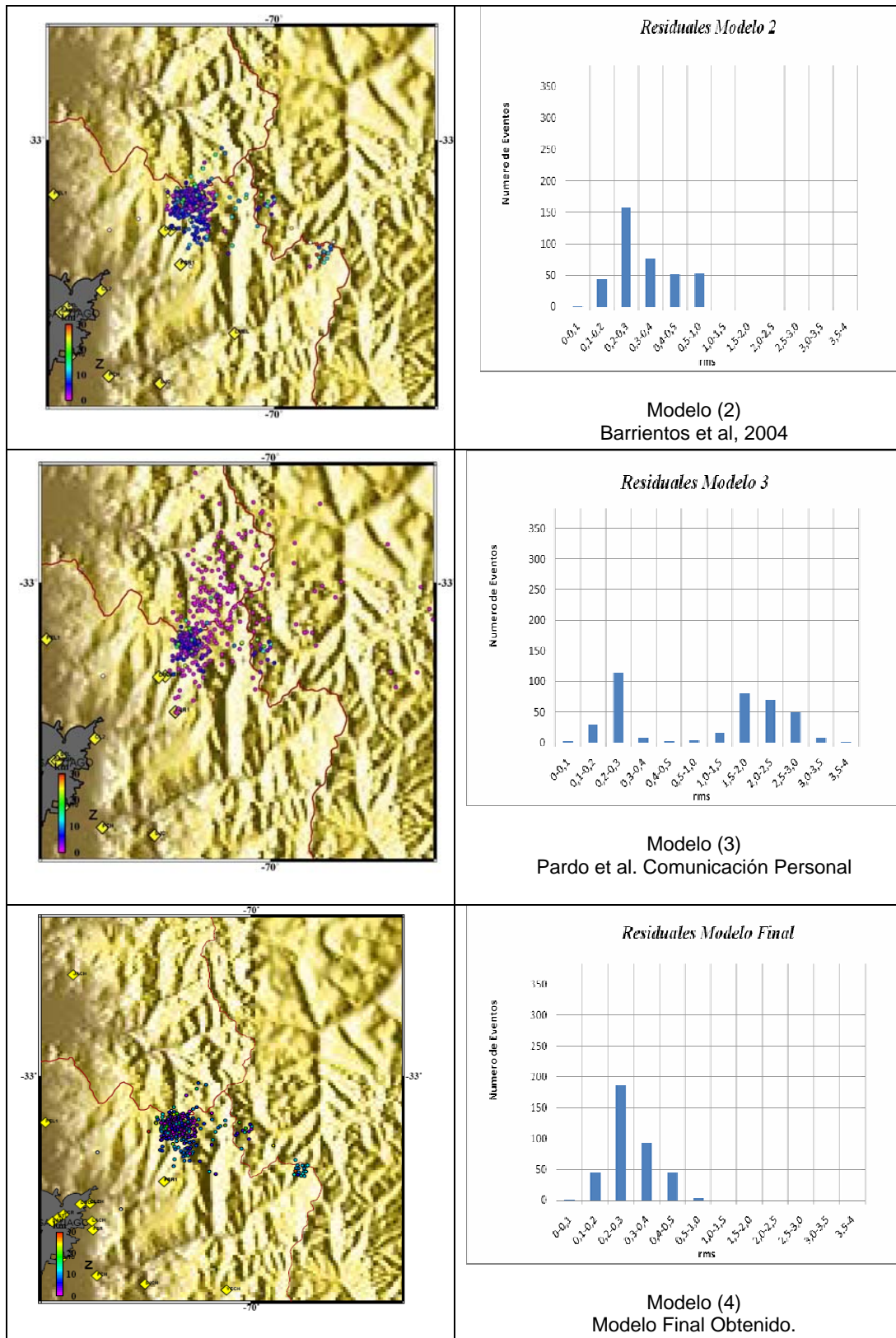


Figura 2. Hypocentral locations of the events of the Andina mine, with each of the 3 different models for the area and the final model derived from the inversion.

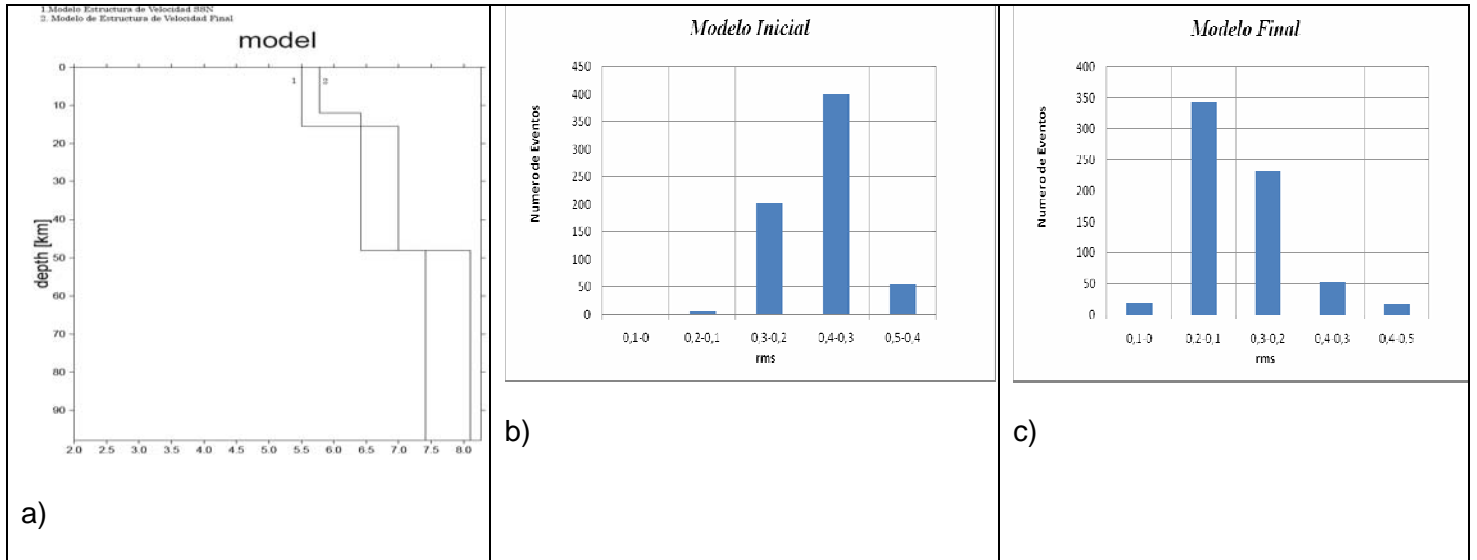


Figura 3. a) Initial velocity model (SSN) and final obtained of the inversion process. b) Residual for an average initial total of 669 events that comprise the database. c) Wastewater from the average end-end relocation of 669 events with the final velocity model.

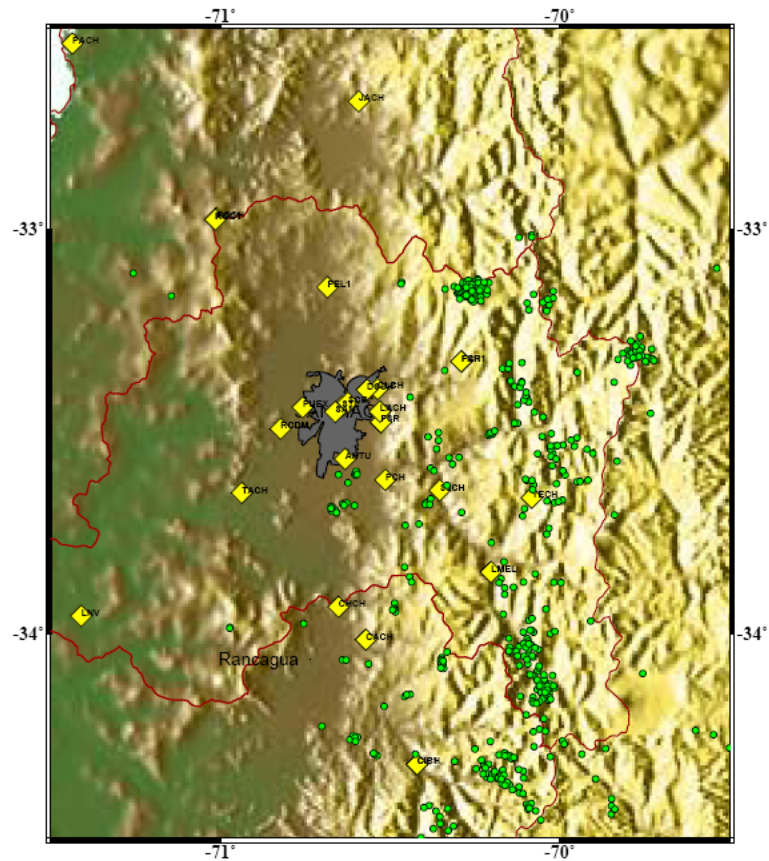


Figura 4. Final hypocentral location of 669 cortical events recorded by SSN between 2000 and 2009. Yellow indicates the seismic stations in the green hypocenters relocated with the velocity model derived from the inversion

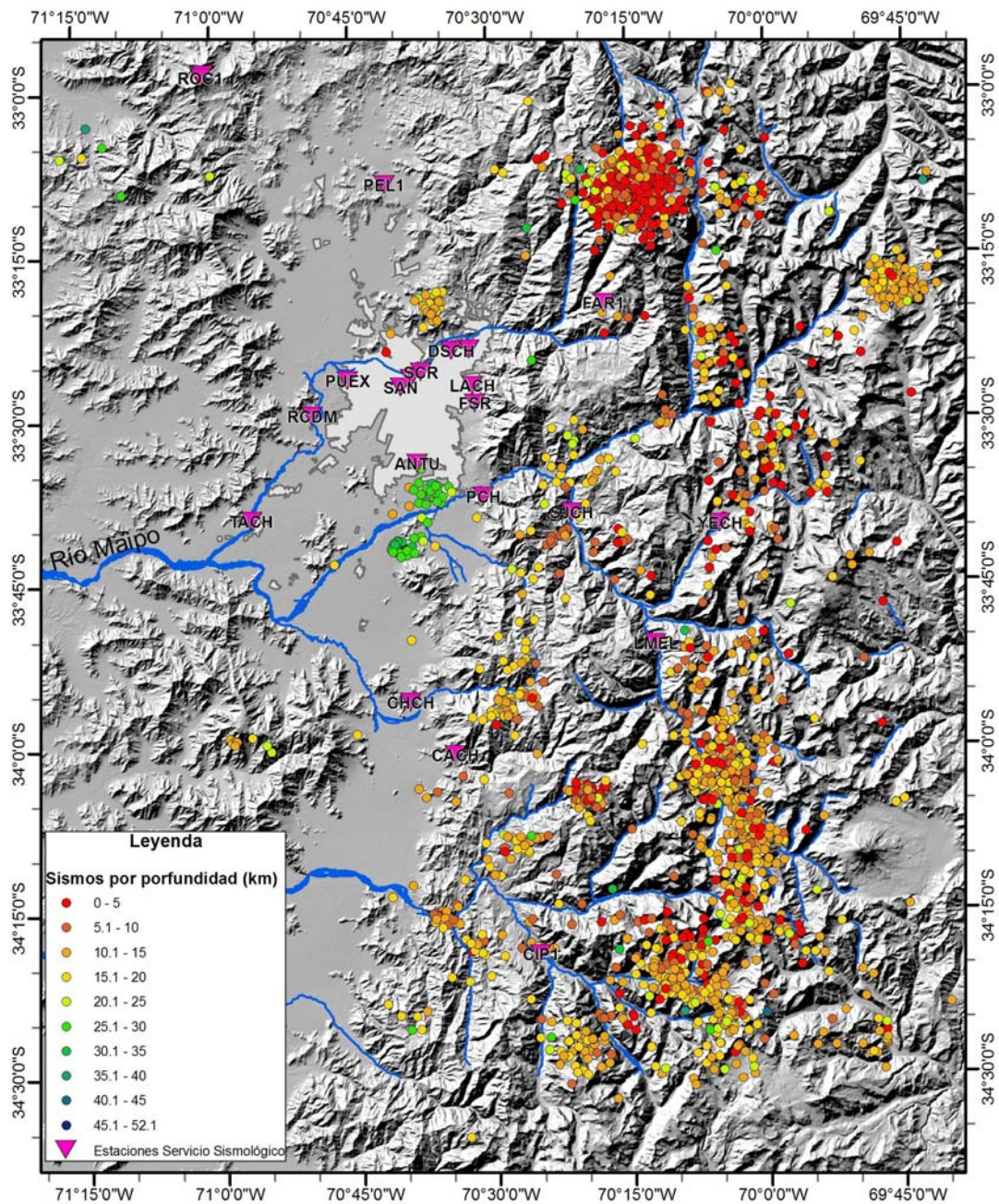


Figura 5. Hypocentral location of the 2509 final cortical events recorded by SSN between 2000 and 2009. In magenta shows the seismic stations in the colored circles hypocenters relocated with the new velocity model, where the color indicates the depth according to the scale.