Revista de la Asociación Geológica Argentina, 60 (4): 787-796 (2005)

Comparative seismic and petrographic crustal study between the Western and Eastern Sierras Pampeanas region (31ºS)

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RESUMEN. *Estudio sísmico y petrográfico cortical comparativo entre las Sierras Pampeanas Occidentales y Orientales (31ºS).* Los antiguos bloques montañosos de las Sierras Pampeanas del centro-oeste argentino constituyen una región sísmicamente activa en la zona andina de trasarco. Estos bloques de basamento cristalino afloran hasta 800 km al este de la trinchera oceánica sobre el segmento de subducción horizontal. Más de 40 sismos «sentidos», son reportados por año para esta región. La distribución de la sismicidad moderna e histórica, muestra que las Sierras Pampeanas Occidentales experimentan más sismos de mayor magnitud que las Sierras Pampeanas Orientales. Geológicamente, existen marcados contrastes en la composición litológica y estructura del basamento en ambas regiones. Un estudio sismológico reciente indica que las Sierras Pampeanas occidentales son más activas sísmicamente que las orientales, con mecanismos focales inversos que alcanzan profundidades de hasta 25 km. Las Sierras Pampeanas orientales presentan mecanismos focales inversos y de desplazamiento de rumbo con profundidades focales < 10 km. Diferentes estructuras corticales de velocidades sísmicas correspondientes a Vp 6.4 km/s, Vp/Vs ~1.80 y espesor 50 km y, Vp 6.0 km/s, Vp/Vs < 1.70 y espesor 30 km, representan a las Sierras Pampeanas occidentales y orientales, respectivamente. Estos resultados se correlacionan con la interpretación de procedencias diferentes para los terrenos del basamento de las Sierras Pampeanas occidentales y orientales. Las Sierras Pampeanas occidentales exhiben propiedades sísmicas características de una corteza oceánica máfica-ultramáfica de mayor espesor consistente con la formación de un arco de islas y cuenca de trasarco. Las orientales muestran propiedades sísmicas corticales consistentes con un mayor contenido de sílice de las rocas y con un origen más afín al de un terreno continental acrecionado.

Palabras clave: *Sierras Pampeanas, sismotectónica, corteza continental.*

ABSTRACT.The ancient Sierras Pampeanas in the central west part of Argentina are a seismically active region in the back-arc of the Andes. Their crystalline basement cored uplifts extend up to 800 km east of the oceanic trench over the flat subduction segment of the Nazca plate. Approximately 40 felt crustal earthquakes, are reported per year for this region. Historic and modern seismicity indicates that the Western Sierras Pampeanas (WSP) have more crustal earthquakes of greater-size than the Eastern Sierras Pampeanas (ESP). Remarkable changes in composition and structure also characterize the WSP and ESP basements. We have quantitatively compared both regions using seismological constrains. A recent regional study of moderate earthquakes shows reverse and thrust focal mechanisms occurring at depths down to 25 km in the WSP. In contrast, the ESP have reverse and strike-slip focal mechanisms of shallower depths (< 10 km). A seismic velocity structure of Vp 6.4 km/s, Vp/Vs ~1.80, and thickness 50 km, best represents the WSP crust. The ESP crust is characterized by Vp 6.0 km/s, Vp/Vs < 1.70, and thickness 30 km. These seismological determinations correlate with the interpretation of a different origin for the western and eastern terranes. The WSP show seismic properties indicative of a more mafic-ultramafic thick crust consistent with an oceanic island-arc and back-arc formation. The ESP show crustal seismic properties consistent with a higher silica content and with a formation by the collision of a continental terrane.

Key words: *Sierras Pampeanas, seismotectonics, continental crust.*

Introduction

One of the prominent features in the central west region of Argentina is the presence of the basement cored uplifts that make up the Sierras Pampeanas geological province (Fig. 1). Its uplift and the cessation of Andean volcanism have been correlated to the flattening of the subducted Nazca slab during the last 6-10 Ma (Kay *et al.* 1991, Ramos *et al.* 2002). The thick-skinned style of deformation in the Sierras Pampeanas markedly contrasts with the thin-skinned pattern of the fold-and-thrust belt farther west in the Precordillera (Fig. 2). Proterozoic to Paleozoic ranges of N-S trending outline this region of active tectonics (Jordan and Allmendinger 1986) with a history of destructive earthquakes that extend into central Argentina (Costa *et al*. 2000, INPRES 2005). Based on the composition and style of deformation, a division between the western and eastern Sierras Pampeanas has been observed by several authors (Caminos 1999 and references therein). Crustal earthquake distributions also show a different pattern with an intense seismic activity in the Western Sierras Pampeanas in comparison with the

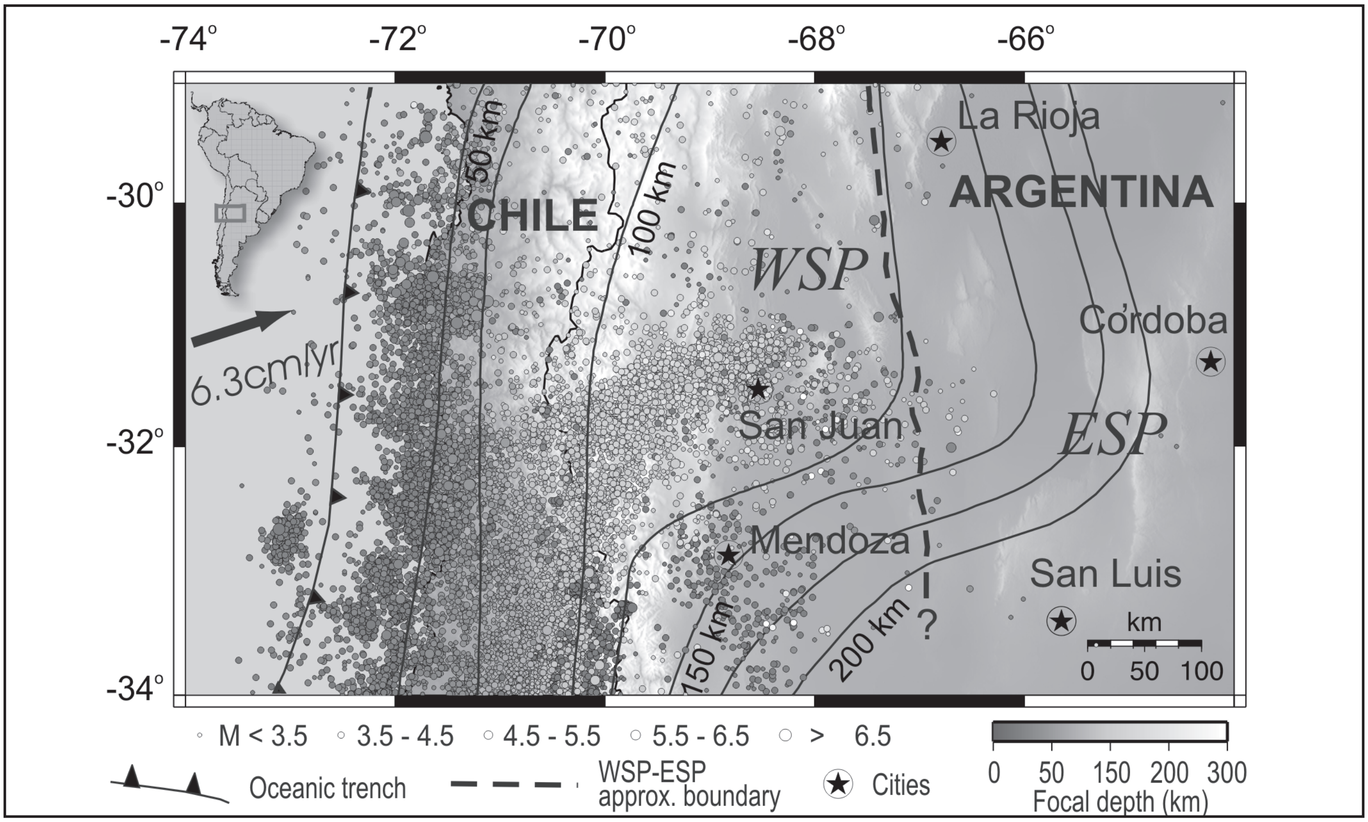


Figure 1: PDE-NEIC seismicity during the last ten years. Contours represent approximately the depth to the top of the subducted Nazca slab by Cahill and Isacks (1992). Also shown are the eastern and western Sierras Pampeanas (ESP and WSP) regions that we compare in this study.

Eastern Sierras Pampeanas (Fig. 1). In this study we present a seismological analysis that serves to quantitatively characterize the western and eastern basements of the Sierras Pampeanas crust around ~31ºS. At this latitude, the Sierras Pampeanas outcrops expose one of their most complete sections (Ramos *et al.* 2002). Our aim is to interpret the seismic results on the basis of petrological and structural properties of the exposed rocks in each crystalline basement.

Geologic setting

Geologic, petrographic, geochemical, and structural studies in the Sierras Pampeanas region have been summarized by Ramos, Miró, Bonalumi *et al*., Rapela et al., and Dalla Salda *et al*., in several chapters of the book «Geología Argentina» by Caminos (1999), which is the base for the geologic setting presented here.

The Sierras Pampeanas morphostructural unit consists of the eastern and western geological subprovinces which are a series of accreted terranes (Figs. 1 and 2). Their N-S main trending mountain blocks are separated by intervening valleys of tectonic origin with several sutures between them (Ramos *et al.* 2000). Lithologic, magmatic and tectonic associations exclude the Famatina system from this context (Fig. 2) although it was originally interpreted as part of the Eastern Sierras Pampeanas (Caminos 1979 in Miró 1999).

The Sierras Pampeanas crystalline basement terrane was developed and accreted to the western convergent margin of the Río de la Plata craton (e.g. Miró 1999 and references therein). Both the Western and Eastern Sierras Pampeanas are composed of Mesoproterozoic to Late Paleozoic metamorphic rocks and granitoid intrusions. Two main tectonic-magmatic events have been recognized during the accretionary history of the western Gondwana margin (Ramos 1994, Miró 1999): the *Pampean* orogeny during the Late Proterozoic - Early Cambrian with its tectonic-thermal climax at ~530-520 Ma, and the *Famatinian* orogeny (Middle Cambrian to Late Devonian-Early Carboniferous) with its climax at ~490-460 Ma (Rapela and Pankhurst 2001). The western and eastern terranes are separated by a ductile shear zone (Fig. 2) (Sato et al. 2003 and references therein). By Early Carboniferous the Sierras Pampeanas were already cratonized.

As mentioned above, the Eastern Sierras Pampeanas correspond to a Proterozoic orogen with one collisional event (Pampean orogenesis) close to the Precambrian-Cambrian boundary. The Pampean orogenesis is responsible for the metamorphism and magmatism that dominate in the region (Miró 1999). The Famatinian orogenic processes have practically no effect in the eastern sector. At ~31ºS the Eastern Sierras Pampeanas subprovince includes the Sierra de Pocho, Sierra Grande and Sierra Chica de Córdoba (Fig. 2). They are composed of banded schists and

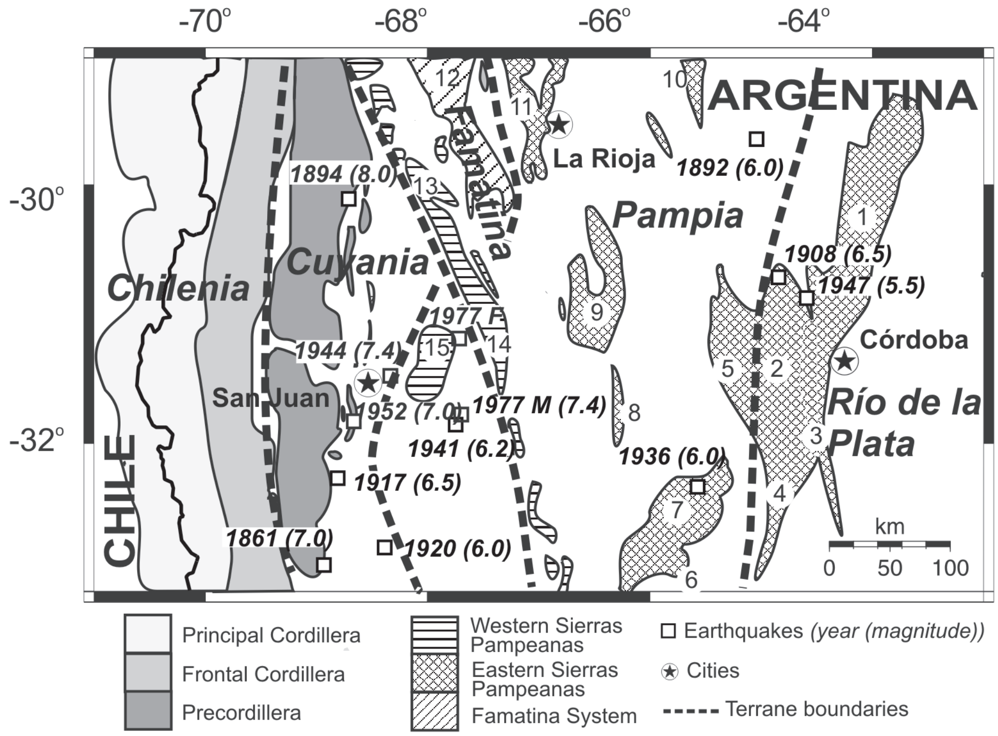


Figure 2: Main geologic provinces, terranes and historical earthquakes (references cited in the text). Key to symbols: (1) Sierra Norte de Córdoba, (2) Sierra Grande de Córdoba, (3) Sierra Chica Córdoba, (4) Sierra de Comechingones, (5) Sierra de Pocho (6) El Morro volcano, (7) Sierra de San Luis, (8) Sierra de Ulapes, (9) Sierra de Chepes, (10) Sierra Brava, (11) Sierra de Velasco, (12) Sierra de Famatina, (13) Sierra de Valle Fértil, (14) Sierra de La Huerta, (15) Sierra de Pie de Palo.

gneisses. Biotite-tonalite gneisses are the most typical rocks in the Sierras de Córdoba with subordinate marbles (mainly in the central east part), amphibolites, metaquartzites, phyllites and discontinuous N-S zones of highly serpentinized mafic-ultramafic rocks (Bonalumi *et al.* 1999). The metamorphic grade varies from greenschist to amphibolite facies, although the majority of metamorphic rocks are in the medium grade or amphibolite facies, increasing in small areas up to granulite facies with some partial melting that generates migmatitic massifs. Garnet–cordierite migmatites dominate the lithology in most of the high-grade migmatitic massifs (Gordillo 1984 in Rapela *et al*. 2002). Bonalumi *et al*. (1999) propose two environments for the Eastern Sierras Pampeanas defined by the metamorphic degree regional variation which increases from west to east with their tectonic contact coincident with a well developed ophiolitic belt. A very distinctive feature of the Eastern Sierras Pampeanas is the numerous granitic intrusions varying from small pluton to batholithic dimensions. Calc-alkaline granitoids, associated with the Proterozoic magmatic arc, intruded the metamorphic rocks. In addition, post-collision and post-tectonic granites of Early Cambrian and Silurian-Early Carboniferous ages, respectively, have been also identified (Bonalumi *et al.* 1999).

The Western Sierras Pampeanas crystalline basement is an early Paleozoic orogen with outcrops in La Rioja, San Juan, the western part of the Sierra de San Luis and other northern geographic provinces. In contrast to the eastern region, this area is characterized by the scarcity of granitoids, the absence of batholiths, and the abundance of basic-ultrabasic rocks and metacarbonate and calcosilicate sequences (Caminos 1979). Metamorphic rocks of medium to high grade and migmatites are related with the active continental margin of the Famatinian orogeny, and experienced the peak of metamorphism during the Mid-Ordovician (~466 Ma) (Rapela *et al*. 2001). The composition of the calc-alkaline intrusions of this magmatic arc varies from gabbros to tonalites and granodiorites, and ends with Late Ordovician-Early Devonian post-collision granites (Rapela *et al*. 1999).

The Western Sierras Pampeanas include the Sierra Pie de Palo which is composed of low-to-medium metamorphic rocks with an important ophiolite zone of Grenville age (~1050 Ma) whose relation with the Precordillera basement is still debated (Mc Donough *et al*. 1993, Dalla Salda *et al.* 1999, Vujovich *et al.* 2003, Galindo *et al.* 2004). Ramos *et al*. (2000) interpret the Sierra Pie de Palo as an allochthonous basement (the Cuyania terrane) amalgamated to Gondwana during the Famatinian orogeny. Ordovician metamorphism and tectonism superimposed on the Cuyania basement is well documented in the Sierra Pie de Palo as well. A proposed suture between the Pampia and Cuyania terranes lies along the western side of the Sierra Valle Fértil-La Huerta (Fig. 2) showing an intense ductile shear zone (mylonites) in good correlation with a deep crustal seismic reflection structure (Snyder *et al*. 1990, Ramos *et al*. 2000 and references therein).

Locally, Neopaleozoic continental sedimentary deposits related to glacier events (Paganzo Group) covers both the Eastern and Western Sierras Pampeanas sometimes containing pyroclastic materials from the Frontal Cordillera (Fig. 2). The basins are also affected by the Cenozoic deformation (Jordan 1995).

The most recent manifestations of volcanism around Sierra de Pocho (4.7 Ma, ~31ºS) and El Morro (2.6 Ma, ~33ºS) (Fig. 2) are interpreted as the result of the last stage in the flattening of the subducted Nazca plate during the last 5 Ma (Comínguez and Ramos 1991, Ramos 1994, Ramos *et al*. 2002).

The present structure of the Sierras Pampeanas is mainly controlled by reverse faults which tend to be horizontal at brittle-ductile transition in depth (Snyder *et al*. 1990, Comínguez and Ramos 1991, Ramos 1994, Zapata 1998). The compressional processes that uplifted the basement blocks occurred mainly in the Early Miocene. The first records of uplift correspond to the Eastern Sierras Pampeanas during Eocene times, showing reactivation of Cretaceous normal faults. The ancient weak zones are taken by the Andean faults which, in many cases, show an inversion of Cretaceous, Triassic and Neopaleozoic normal faults or even ancient structures (Precambrian or Early Paleozoic). The structural style is highly controlled by the fabric of the crystalline basement, and the faulting vergence mainly to the west with the faults parallel to the foliation (Ramos 1994, Ramos *et al*. 2000, 2002).

Crustal seismicity

The present Andean backarc crustal seismicity in the flat slab subduction segment around ~31ºS is a consequence of the compression generated by the convergence between the Nazca and South America plates at a rate of 6.3 cm/yr and azimuth ~79.5º (Fig. 1) (Kendrick *et al.* 2003). Interestingly the PDE-NEIC global catalog shows that more crustal earthquakes occur in the immediate region east of the high Andes in the Western Sierras Pampeanas than farther east in the Eastern Sierras Pampeanas (Fig. 1). Local seismic studies around San Juan have shown that teleseismic earthquake locations in this area might be affected by an offset of at least 20 km to the east (Smalley *et al*. 1993). Even considering this mislocation effect, approximately 116 earthquakes with depth < 60 km and magnitude > 4.0 have been generated in the Western Sierras Pampeanas region during the last ten years. In contrast, the Eastern Sierras Pampeanas only have a record of 27 similar events in the same period.

The historical seismicity during the last ~250 years (INPRES 2005) also shows a concentration of larger sized earthquakes in the Western Sierras Pampeanas where the most recent example occurred in 1977 in the vicinity of the Sierra Pie de Palo. Studies of its seismic source indicate that this earthquake was a multiple shock, with events of moment magnitudes 7.1 and 7.4, focal depths of 17 km and 25-30 km, respectively, and separated by 64 km and 20 s (Fig. 2) (Kadinsky-Cade 1985, Langer and Hartzell 1996). Damaging earthquakes with magnitude around 6.0 represent the larger sized earthquakes in the Eastern Sierras Pampeanas of San Luis and Córdoba (Fig. 2) (INPRES 2005).

The association of larger earthquakes with individual structures in the Sierras Pampeanas, sometimes rupturing multiple segments like the 1977 event, is difficult. However, studies in Quaternary geology have revealed recent activity along several reverse faults in both the western and eastern Sierras Pampeanas region (Costa *et al*. 2000, 2001).

Regional and local seismic studies using short period data (Regnier *et al.* 1992, Triep *et al.* 2002) and broadband seismic data (Fromm *et al.* 2004, Alvarado *et al.* 2004, 2005, Gilbert *et al*. 2005) have helped to characterize the properties of the eastern and western Sierras Pampeanas basement crust. In addition, improved crustal seismic velocity models are very useful in providing better earthquake locations and focal mechanisms of moderate-to-large earthquakes, and hence, more details of the deformation.

Full waveform modeling of broadband seismic data recorded by the Chile-Argentina Geophysical Experiment (CHARGE) network during 18 months between 2000 and 2002 provides fault plane focal mechanisms and reliable focal depths of moderate-sized crustal earthquakes and seismic velocity structure estimates between 29°S and 36°S (Alvarado *et al.* 2005). In that study, earthquake epicenter information from the Instituto Nacional de Prevención Sísmica (Argentina) and a simple crustal model were used to perform a linear least squares seismic moment tensor inversion (SMTI) for crustal Andean backarc earthquakes recorded at the CHARGE stations. The complete three-component seismic displacements were modeled at regional distances to obtain the seismic moment tensor using the method developed by Randall *et al.* (1995). The waveform modeling involved intermediate period filtering with a bandwidth of 15 - 50 s to make sure that the seismic displacements were dominated by surface waves for the earthquake sizes considered (magnitude between 3.5 and 5.2). The seismic moment tensor gives a representation of the forces acting at the seismic source. Fault plane solutions and source parameters such as seismic moment, magnitude, and focal depth were obtained from the seismic moment tensor solution. We present one example below to illustrate the method and its applications.

Regional surface waves are sensitive to the crustal seismic velocity structure. The full waveforms, filtered so that the surface waves dominate, are an effective tool to test seismic crustal models. Studies by Alvarado *et al.* (2005) have explored the SMTI results using different seismic velocity structures for the western and eastern regions (Table 1). Figure 3 shows an example for an earthquake on 18 May 2001 (event 01-138b) with epicenter in the Eastern Sierras Pampeanas (Figs. 4 and

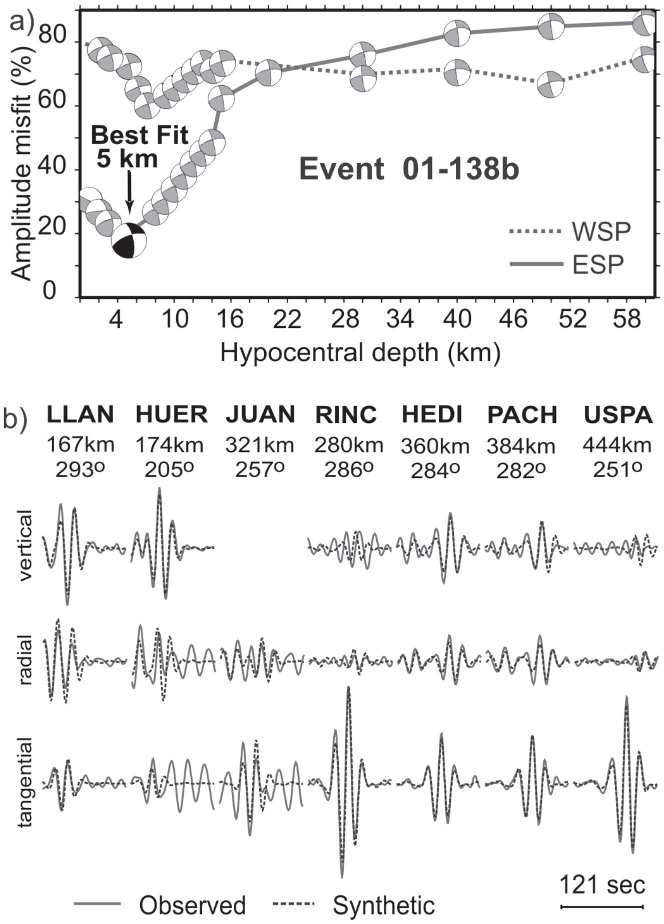


Figure 3: Results of the regional seismic moment tensor inversion (SMTI) for event 01-138b (M_w 4.3) on 18 May 2001 (see location in figures 4 and 5). **a)** Curves with focal mechanisms showing the synthetic-to-observed amplitude-misfit errors versus hypocentral depths for the Western (dashed line) and Eastern Sierras Pampeanas (solid line) velocity-structure models (Table 1). The minimum is observed at a source depth of 5 km using the ESP model. **b)** Synthetic (dashed line) and observed (solid line) waveforms for the best fit (5 km) using the Eastern Sierras Pampeanas model. Epicentral distances and azimuth of the stations used are shown below the station name.

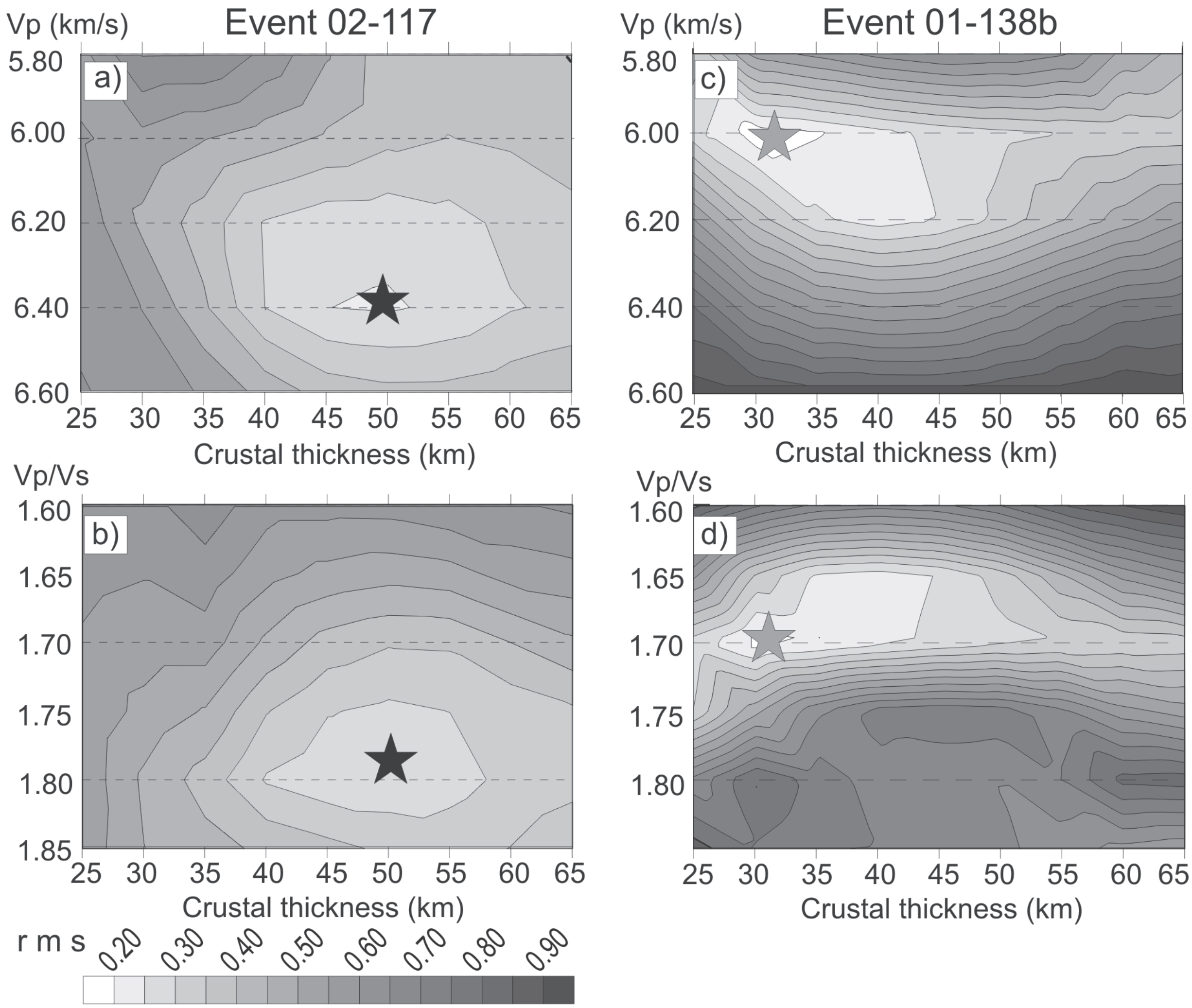
5). For this event, we modeled waveforms filtered between 15 and 30 s recorded at seven CHARGE stations (fig. 4e) for several focal depths in the 1 - 60 km range. We also tested both crustal seismic structures for the Western an Eastern Sierras Pampeanas listed in Table 1 in the SMTI for this event. The amplitude misfit between observed and synthetic seismograms is smaller for the SMTI that used the Eastern Sierras Pampeanas seismic velocity structure producing a local minimum (fitting more than 85 % of the data) at a focal depth of 5 km (Fig. 3). We obtained a strike-slip focal mechanism for this earthquake with a seismic moment of M_0 2.92 x 10^{15} Nm, magnitude M_w 4.3, focal depth 5 km, and fault plane (1) of strike 249°, dip 67° and rake 156° and fault plane (2) of strike 348°, dip 68° and rake 25°. The convention used for each fault plane solution gives the azimuth of the fault (strike), the dip of the fault considering the block located

Table 1. Crustal velocity structures for the Western and Eastern Sierras Pampeanas crust from the SMTI grid-search results (Fig. 4) by Alvarado *et al.* (2005). Both models used a half-space in the mantle of Vp 8.15 km/s, Vp/Vs 1.80 (Western Sierras Pampeanas) and 1.70 (Eastern Sierras Pampeanas), and density 3.30 (gr/cm³).

	WSP	ESP
Thickness (km)	50	32
Vp (km/s)	6.4	6.0
Vp/Vs	1.80	1.70
Density (gr/cm³)	2.85	2.85

at the right when looking at the azimuthal direction, and the rake, which is the angle of displacement measured in the fault plane from the strike direction. The focal mechanism solution does not significantly vary around the best depth (Fig. 3a). Figure 4e shows that the seismic raypaths mainly traveled in the Eastern Sierras Pampeanas from the epicenter to the CHARGE stations. Using the model proposed for the Western Sierras Pampeanas (Table 1) and the same CHARGE waveforms in the SMTI of this event, the amplitude misfit significantly increases with errors of more than 60% (fitting only 40% of the data) for the range of depths 2-10 km. However, the focal mechanism solution remains stable around the best depth using either seismic velocity structure (Fig. 3a).

A grid-search performed for the P-wave velocity (Vp), the ratio of P- to S-wave seismic velocity (Vp/Vs) fixing Vp, and the crustal thickness (th), for the crust of the Western and Eastern Sierras Pampeanas shows important differences (Alvarado *et al*. 2005). That study used an earthquake that occurred northeast of San Juan in the WSP on 27 April 2002 (event 02-117) with magnitude M_w=5.1, and the event 01-138b with magnitude M_w=4.3 discussed above (Fig. 3) with epicenter in the Eastern Sierras Pampeanas (Fig. 4). Modeling of the full waveforms recorded at CHARGE stations, that mainly traveled in the WSP for event 02-117 (see distribution of seismic stations with respect to the epicenter in Fig. 4e), were analyzed using the SMTI for a set of crustal seismic parameters. The same analysis was done for event 01-138b testing the same crustal models for raypaths traveling mainly in the Eastern Sierras Pampeanas (compare seismic raypaths for this event with those for event 02-117 in Fig. 4e). Forty-five different crustal models consisted of Vp varying from 5.8 to 6.6 km/s in steps of 0.2 km/s and thickness varying from 25 to 65 km in steps of 5 km (Figs. 4a and c) were tested. Then, 54 crustal models of Vp/Vs ratio varying in the range 1.60 - 1.85 in steps of 0.05 and the same range of crustal thicknesses were also explored using the SMTI (Figs. 4b and d). Mantle parameters remained fixed for Vp at 8.15 km/s and Vp/Vs at 1.80 (WSP) and 1.70 (ESP). Figure 4a shows a map of the SMTI minimum amplitude-misfit results from Alvarado *et al.* (2005) for the 45 crustal models for event 02-117. The best fit (> 75%) occurs around a crustal Vp of 6.4 km/s and a thickness of 50 km. However, good fits still occur for crustal Vp between 6.2 and 6.5 km/s and crustal thickness between 40 and 60 km. Fixing the crustal Vp at 6.2 km/s, the best SMTI results occur for Vp/Vs ~1.80 and crustal



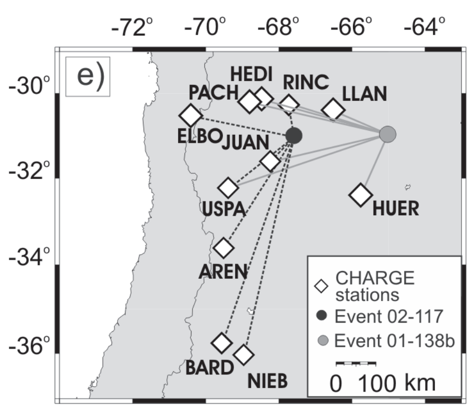


Figure 4: Grid search SMTI results obtained for events 02-117 and 01-138b (see Fig. 5 for focal mechanism and depth solutions). Stars represent the best seismic parameters for the Western and Eastern Sierras Pampeanas crust. **a)** Map of the amplitude-misfit minimum errors for each crustal Vp and crustal thickness pairs explored using event 02-117. **b)** Same as (a) but now varying Vp/Vs ratio and maintaining crustal Vp at 6.2 km/s. **c)** Map of the amplitude-misfit minimum errors for each crustal Vp and crustal thickness pairs explored using event 01-138b. **d)** Same as (c) but now varying Vp/Vs ratio and maintaining crustal Vp at 6.0 km/s. **e)** Raypaths, CHARGE seismic stations and epicenter locations used in the inversions. Note that the raypaths are mainly traveling in the Western Sierras Pampeanas for event 02-117 (black lines) and in the ESP for event 01-138b (gray lines). [modified from Alvarado *et al.* 2005]

thickness between 40 km and 57 km (Fig. 4b).

Grid-search results from Alvarado *et al.* (2005) for event 01-138b in the Eastern Sierras Pampeanas are shown in figures 4c and d. The best results (SMTI minimum amplitude-misfit) are observed for a crustal model with Vp of 6.0 km/s, Vp/Vs of 1.67 and thickness around 32 km as we show in figure 3. However good fits of more than 70% between observed and synthetic data occur for crustal models of Vp between 5.9 and 6.2 km/s, Vp/Vs in the range 1.65-1.71 and thickness between 27 and 45 km.

Discussion

Regional full waveform modeling (where surface waves dominate) of crustal earthquakes during 2000-2002 determined 14 thrust focal mechanisms in the Western Sierras Pampeanas (Fig. 5) (Alvarado *et al.* 2005). Their focal depths are between 14 and 25 km with only one exception (event 01-348 with epicenter southeast of the Sierra Pie de Palo located at a depth of 6 km). Eight earthquakes had locations in the vicinity of the Sierra Pie de Palo, which was the site of the last large earthquake (M_w 7.5) in the region in 1977 (Fig. 2) (Kadinsky-Cade 1985, Langer and Hartzell 1996). Four crustal earthquakes had epicenters in the Eastern Sierras Pampeanas, which are the first focal mechanism constraints in this region (Fig. 5). Their SMTI solutions indicate both thrust and strike-slip focal mechanism solutions. The strike-slip events are much shallower (focal depth < 10 km) than the thrust events (focal depths between 16-18 km) which is in agreement with observations for other global regions. In addition, teleseismic, regional and local seismic studies have also shown that the Western Sierras Pampeanas are much more active than the eastern region (Kadinsky-Cade 1985, Smalley *et al.* 1993, INPRES 2005). In the last 10 years, 40 felt crustal earthquakes have occurred in the Sierras Pampeanas. In this group, an average of 12 earthquakes per year with magnitude > 4.0 have been generated in the Western Sierras Pampeanas crust, whereas only three events had epicenters in the Eastern Sierras Pampeanas (Fig. 1).

Seismic studies using the CHARGE broadband data indicate different seismic velocity structures for the Western and Eastern Sierras Pampeanas basement crust. Full waveform modeling shows that the Western Sierras Pampeanas crust is best represented by a larger Vp (~6.4 km/s), a larger Vp/Vs ratio (1.80) and a greater thickness (~50 km) than these seismic parameters for the Eastern Sierras Pampeanas crust. Estimates of crustal Vp 6.0 km/s, Vp/Vs ratio 1.70, and thickness ~32 km, characterize the Eastern Sierras Pampeanas crust (Alvarado *et al*. 2005) (Fig. 4). These results are in agreement with receiver function estimates which indicate a Vp/Vs of more than 1.80 in the Western Sierras Pampeanas versus a Vp/Vs <1.75 in the eastern sector (Gilbert *et al*. 2005). The same study predicts greater crustal thickness in the Western Sierras Pampeanas than in the eastern region (Fig. 5) in good agreement with the regional waveform modeling results. Pn seismic refraction studies along the northern CHARGE transect at ~30ºS also determined a thicker crust (50 km) in the Western Sierras Pampeanas than in the eastern region (30km) (Fromm *et al*. 2004). Previous studies to locate and relocate local seismicity near San Juan have also used crustal structures composed of high P-wave velocities (*e.g.* Langer and Bollinger 1988, considered two crustal layers of Vp 6.2 and 7.3 km/s, respectively, of ~45-km total thickness). Local seismic reflection studies in the Cuyania terrane have found deep reflectors at depths of 30 km around ~32ºS (Comínguez

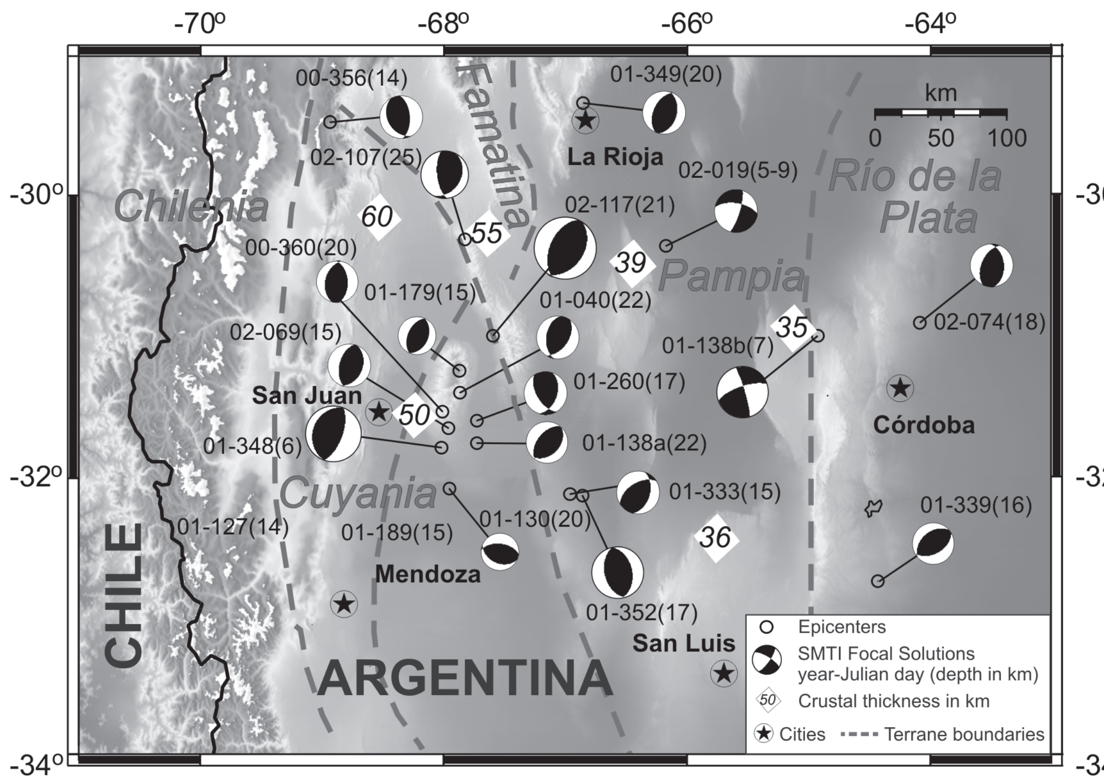


Figure 5: Results of the SMTI showing lower hemisphere projection focal mechanisms of crustal earthquakes ($3.5<M_w<5.2$) recorded by the CHARGE network. Dark quadrants are compressional motions. Observe the different distribution of the crustal seismicity and focal mechanism solutions in the Western and Eastern Sierras Pampeanas. Crustal thicknesses from receiver function analysis by Gilbert *et al.* (2005) are also shown. [modified from Alvarado *et al.,* 2005]

and Ramos 1991), and of 30-40 km to the north-northeast of the Sierra Pie de Palo (Zapata 1998). These structures have been interpreted as thrusts reactivated by collisional boundaries (Ramos 1994, Ramos *et al.* 2002) and indicate that the Moho is deeper than 30 km in the Western Sierras Pampeanas.

We find a correlation between the high crustal P-wave velocity (Vp = 6.4 km/s) with the more mafic-ultramafic composition of the Western Sierras Pampeanas. According to Christensen (1996), both the increasing metamorphic grade or the higher mafic content can explain the high Vp estimate. The high Vp/Vs ratio (Vp/Vs = 1.80 or Poisson's ratio = 0.28) compares with the global observation for the continental crust of an increasing age, which strongly maps out the mafic lower crust of shields and platforms (Zandt and Ammon 1995). We noted that these authors observed a Poisson's ratio of 0.28 ± 0.01 for the Grenville province crust in North America which is similar to our estimate in the Western Sierras Pampeanas. In this region, similar rock affinities have been attributed to the Sierra Pie de Palo lithologies (Fig. 2) of about 1.1 Ga (McDonough *et al*. 1993 Ramos *et al*. 2000, Vujovich *et al*. 2003). The presence of fluids or high pore pressure could also be responsible for the high Vp/Vs ratio (Zandt and Ammon 1995 and references therein). In this case both Vp and Vs would significantly decrease. The observed high crustal Vp, the low contrast between the crustal and upper mantle P-wave velocities from receiver function analysis (Gilbert *et al.* 2005), the high S-wave tomographic velocities below the Moho which indicate that the slab does not dehydrate until its further east penetration into the mantle (Wagner *et al.* 2005), suggest a more mafic composition (Christensen 1996, Zandt and Ammon 1995) rather than high pore pressure. Gilbert *et al.* (2005) have suggested a partial eclogitization of the lower crust in the WSP to explain the high Vp/Vs ratio and thicker crust in this region. This was previously suggested by Snyder *et al.* (1990) for a more local region around Sierra de La Huerta (Fig. 2) based on seismic reflection data. Recent studies in active continental margins also provide support that high Vp and high Vp/Vs ratio in the crust are not necessarily related to the presence of fluids and may indicate a more mafic composition (Brocher 2005). However, some water at previous stages is needed to produce the required petrological changes and hence the eclogitization but its source remains unknown.

Geologic studies indicate that the amalgamation of different terranes onto the western cratonic South America margin has been characterized by important contrasts in composition and evolution for the Western and Eastern Sierras Pampeanas (Rapela *et al*. 1999, 2002). Most of the basic-ultrabasic exposed metamorphic complexes in the Western Sierras Pampeanas have been interpreted as ancient oceanic crust preserved in ophiolitic assemblages formed in an island-arc and/or back-arc setting of Grenville age (Ramos *et al.* 2000). In contrast, the evolution of the Eastern Sierras Pampeanas has been interpreted in terms of a collision of a continental terrane (Pampia terrane) developing a continental arc. Felsic magmatism with large volume episodes is located in the inner part of the continental eastern Sierras Pampeanas crust (Rapela *et al.* 1999). The seismological results map out these compositional differences. The lower seismic Vp/Vs ratios observed from the west to the east in the Sierras Pampeanas region can be explained as an increase in the silica content of the basement terranes. A Vp/Vs ratio of 1.80 (Western Sierras Pampeanas) corresponds to lithologies with a SiO_2 content of 62% (average SiO_2 content in tonalite 61.52%) whereas a Vp/Vs of 1.70 (Eastern Sierras Pampeanas) is correlated with a 77% SiO_2 (average SiO_2 content in granite 71.30%) (Best 1982, Christensen 1996).

Finally, many more crustal earthquakes occur in the Western Sierras Pampeanas than in the eastern sector. GPS velocity vectors also show an important decay between the Western and Eastern Sierras Pampeanas (Brooks *et al.* 2003). In their simplified lithospheric Andean model, the Valle Fértil fault, which is interpreted as a suture between the Cuyania and eastern terranes by several authors (e.g. Ramos *et al*. 2000) (Figs. 2 and 5), plays an important structural control in the compression of the back-arc region. This is in agreement with the pattern of historic and modern seismicity and with the occurrence of deeper crustal thrust earthquakes of greater size in the Western Sierras Pampeanas than in the eastern sector, which also contribute to the thickening of the crust in the Western Sierras Pampeanas.

Conclusions

Seismic and petrographic properties of the Western Eastern Sierras Pampeanas basement crust, overlying the flat slab subduction zone in the south central Andean back-arc, indicate a different composition and a different style of earthquake deformation. This is consistent with the interpretation for the Western Sierras Pampeanas of a more mafic-ultramafic island arc and back-arc thick oceanic crust accreted to Gondwana. In contrast, the Eastern Sierras Pampeanas show a more felsic quartz-rich character of the rocks and a thinner crust consistent with the accretion of a continental terrane.

Acknowledgments

National Science Foundation grant EAR-9811878 supported the project CHARGE. The instruments used in the field program were provided by the PASSCAL facility of the Incorporated Research Institutions for Seismology (IRIS). We thank the Universidad Nacional de San Juan, the Instituto Nacional de Prevención Sísmica (Argentina), and the Universidad de Chile (Chile) for their support to the CHARGE project (www.geo.arizona.edu/CHARGE). We are grateful for the reviews of this article by Mario Pardo and Enrique Triep. We thank Mauro Sáez for his computer assistance. The material is based on work awarded by the National PERISHIP Dissertation Award of National Science Foundation, PERI and University of Colorado (2004), and CHEVRON-TEXACO Summer Scholarship (2005) to P. Alvarado.

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Recibido: 26 de agosto, 2005
Aceptado: 5 de diciembre, 2005