A SEISMOLOGICAL AND PETROLOGICAL CRUSTAL MODEL FOR THE SOUTHWEST OF THE SIERRA DE PIE DE PALO, PROVINCE OF SAN JUAN

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ABSTRACT

A seismic velocity analysis from teleseismic receiver functions recorded in the southwestern flank of the Sierra de Pie de Palo (Western Sierras Pampeanas, Argentina), is compared with seismic properties directly calculated from lithological composition. The seismological results show an upper layer located in the first 13 km depth. A deeper contrast in seismic velocities is found at a depth of 28 km; the petrological results indicate a composition compatible with observed greenschist and amphibolite facies mafic rocks up to this depth. The receiver function measurements at 13 km and 28 km depths could be interpreted as two potential *décollement* levels that might have favoring a mechanism to thicken the whole crust, which produces a receiver function Moho signal located at 47 km depth. In addition, the lower crust between 28 km and 47 km exhibits high seismic P-wave velocities and Vp/Vs ratio (> 1.80) that are representative of a densification consistent with upper amphibolite to granulite/ecoglite facies lithologies. Based on these results, the combined petrological and seismological analyses suggest the continuation of the same mafic-crust outcropping lithologies into the lower levels of the 47-km thickened crust, which could be part of the Pie de Palo Complex ophiolite belt or the Precordillera basement.

Palabras clave: *crustal structure, Moho, receiver functions, Sierras Pampeanas, ophiolite.*

RESUMEN

Modelo cortical sismológico y petrológico para el sudoeste de la sierra de Pie de Palo, provincia de San Juan.
Un análisis de funciones del receptor registradas en el suroeste de la sierra de Pie de Palo (Sierras Pampeanas Occidentales, Argentina), se compara con propiedades sísmicas directamente calculadas a partir de la composición litológica. Los resultados sismológicos indican una capa superior en los primeros 13 km. Otra zona de contraste entre las velocidades de ondas sísmicas, más profunda, se encuentra a unos 28 km; los resultados del análisis petrológico indican una composición compatible con rocas máficas en facies de esquistos verdes y anfibolitas hasta esa profundidad. Las observaciones de función del receptor a 13 y 28 km de profundidad podrían corresponder a dos potenciales zonas de *décollement* proporcionando un mecanismo eficiente para engrosar la corteza, la cual muestra una señal de función del receptor para el Moho a 47 km de profundidad. Además, la corteza inferior entre 28 y 47 km de profundidad exhibe velocidades elevadas de ondas P y alta relación de Vp/Vs (> 1,80), valores representativos de una densificación consistente con litologías de facies de anfibolita superior a granulita/eclogita. En base a estos resultados, el análisis petrológico y sismológico combinado sugiere la continuación en profundidad hasta los niveles inferiores de la corteza engrosada de 47 km de espesor, de las mismas litologías máficas aflorantes, las cuales podrían ser parte de la faja ofiolítica del Complejo Pie de Palo o el basamento de Precordillera.

Keywords: *estructura de corteza, Moho, función del receptor, Sierras Pampeanas, ofiolita.*

INTRODUCTION

The Sierra de Pie de Palo (~ 31.5°S-68°W) in the province of San Juan is one of the westernmost basement cored uplifts of the active Western Sierras Pampeanas in the Andean retroarc region (Fig. 1). At this latitude, the Nazca plate is subducting beneath South America nearly horizontally to the northeast (Cahill and Isacks 1992, Anderson *et al.* 2007) with a relative convergence rate of 7.5 cm/yr (DeMets *et al.* 2010). As a consequence, there is a high seismic activity at both continental crustal (< 35 km) and slab (~100 km) depths.
A seismic velocity analysis from teleseismic receiver functions recorded in the southwestern flank of the Sierra de Pie de Palo, is here compared with seismic properties directly calculated from lithological composition. This is based on the assumption that the physical properties of a rock depend on the composition and relative amounts of the various phases or minerals. The observations are combined to test for a petrological and seismic model, which includes the seismic velocity structure and Moho depth beneath the study area (Fig. 1). Thus, this paper provides new constraints on the crustal

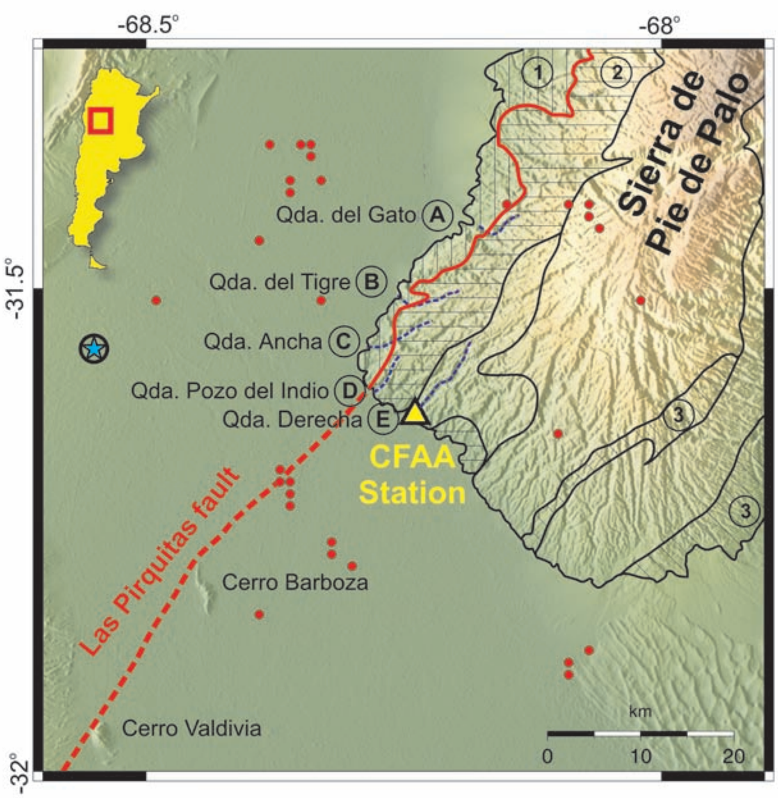

Figura 1: Region of study in the southwest of the Sierra de Pie de Palo. CFAA denotes the broadband seismic station used and the red (piercing point) dots, the incidence of coming teleseismic waves at 47 km depth (Moho depth estimation from Perarnau *et al.* 2010). Geology adapted from Chernicoff *et al.* (2009) and others therein. References: (1) Caucete Group; (2) Pie de Palo Complex including the mafic-ultramafic belt (horizontal lines); (3) Difunta Correa Sequence. (A) to (E) indicate sample locations cited in figures 4 and 5.

thickness and intracrustal velocity structure around the Sierra de Pie de Palo, and shows that geophysical evidence is consistent with the geological relationships.

GEOLOGIC SETTING

The Sierra de Pie de Palo is part of the Western Sierras Pampeanas of NW Argentina. It consists of intensely deformed polyphase metamorphic rocks belonging to three different sequences: the Pie de Palo Complex, the Difunta Correa Unit and the Caucete Group (Fig. 1).

The Pie de Palo Complex (Ramos and Vujovich 2000), interpreted as a Mesoproterozoic (1.0 to 1.2 Ga) fragment of suprasubduction zone oceanic crust, is composed of medium- to locally high-grade metamorphic rocks (Vujovich *et al.* 2004 and references therein). From west to east, it is characterized by a strongly deformed and metamorphosed mafic-ultramafic belt, intermediate to acidic *augen* orthogneisses interlayered with metasedimentary rocks (biotite-muscovite-garnet gneisses and schists), and metagraywackes and marbles. The mafic-ultramafic components represent a thrust slice of the suture zone rocks (Chernicoff *et al.* 2009 and others therein).

The Neoproterozoic (580-620 Ma) metasedimentary Difunta Correa sequence (Baldo et al 1998, Rapela *et al.* 2005) exposed in the southeastern side of the Sierra de Pie de Palo is composed mainly by calcipelite schists and para-amphibolites. This unit represents a paraautochthonous cover to the Pie de Palo Complex, and it is observed as intercalations within this complex due to tectonic imbrications (Vujovich *et al.* 2004).

The Caucete Group (Borrello 1969, Ramos and Vujovich 2000), which is exposed along the western flank of the Sierra de Pie de Palo, is a Neoproterozoic - Cambrian low-grade metasedimentary sequence comprising an association of shelf siliciclastic and carbonate rocks. On the basis of isotope data on the carbonates, the Caucete Group is considered equivalent to the Cambro - Ordovician carbonate platform of the Precordillera (Linares *et al.* 1982, Ramos *et al.* 1998, Vujovich and Kay 1998, Galindo *et al.* 2004). However, detrital zircon analysis of the Caucete Group which includes, in ascending order, the El Quemado, La Paz, El Desecho and Angacos Formations, indicate maximum depositional ages of *ca.* 550 Ma for the El Quemado Formation and *ca.* 531 Ma for the El Desecho Formation (Naipauer *et al.* 2010). The Caucete Group is structurally overlain by the Pie de Palo Complex along the first order NNE trending Las Pirquitas thrust (Vujovich and Ramos 1994, Ramos *et al.* 1996), a top-to-the-west high-strain low-angle shear zone (Fig. 1). The structural relationship between both complexes is associated with the mafic-ultramafic ophiolite belt, which has a probable continuation to deeper levels (~12 km) in the crust (Chernicoff *et al.* 2009). The Caucete Group and the Pie de Palo Complex display a shallowly east-dipping foliation that is broadly folded about a north-south axis. Recumbent isoclinal folds and sheath folds are developed within both units.

The Sierra de Pie de Palo, considered to represent the eastern extent of the Precordillera terrane or Cuyania composite terrane, has been interpreted as an allochthonous terrane of alleged Laurentian derivation (Ramos 2004 and references therein) accreted to Gondwana in Ordovician times during the Famatinian orogeny (480 - 312 Ma, Baldo *et al.* 1998). Alternatively, Finney (2007 and references therein), argue that this terrane could be para-autochthonous, and that its current position is due to strike-slip displacement along the southern Gondwana margin. According to Baldo *et al.* (1998) and Casquet *et al.* (2001), the Pie de Palo basement first underwent low pressure/temperature (P/T) type metamorphism, reaching in some places high-grade migmatitic conditions (686 ± 40 MPa, 790 ± 17 °C), comparable to the Grenvillian M_2 metamorphism of the supposed Lauren-

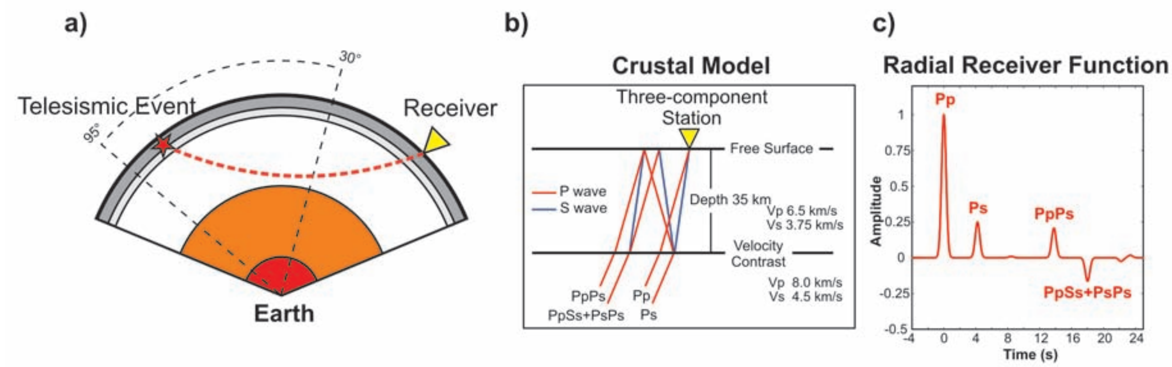

Figura 2: a) Schematic cross-section diagram showing a broadband seismic station located at an epicentral distance of 6400 km (ray parameter of 0.07) from a teleseismic earthquake. b) Example of seismic wave arrivals for a one-layer crustal model over a mantle halfspace recorded at the seismic station shown in (a). c) Synthetic radial receiver function calculated for the same model shown in (b).

tian counterpart of the terrane. The second metamorphism is of Famatinian age and took place under higher *P/T* conditions, following a clockwise P-T path (baric peak: 1300 ± 100 Mpa, 600 ± 50 °C). Vujovich and van Staal (2005) suggested that the peak of metamorphism was reached during the collisional event of the Famatinian orogeny. In addition, a retrograde metamorphic event related to mylonitization (Castro de Machuca *et al.* 2008) took place under greenschist facies conditions at *ca.* 575 ºC and < 10 kb (Baldo *et al.* 1998).

Magnetic surveys (Chernicoff *et al.* 2009) have provided geophysical evidence for the geometry of the upper crustal-scale tectonic boundary between the Grenvillian Precordillera and Pie de Palo terranes which would comprise the buried largest part of the mafic-ultramafic belt. The easterly-dipping boundary zone possibly suggest the existence of a set of synthetic east dipping, west-verging thrusts, of which only one major structure (Las Pirquitas thrust) is exposed. Structurally, the Sierra de Pie de Palo is considered as an imbricate ductile thrust system with a top-to-the-west sense of relative motion, uplifted on the Pliocene - Quaternary (Ramos and Vujovich 2000). In this process, the flattening of the Nazca plate beneath South America during the Andean orogeny (Tertiary-Quaternary) is correlated with the uplifting along reactivated high angle reverse faults of a series of crystalline basement blocks amongst which is the Sierra de Pie de Palo (Jordan *et al.* 1983, Ramos *et al.* 2002).

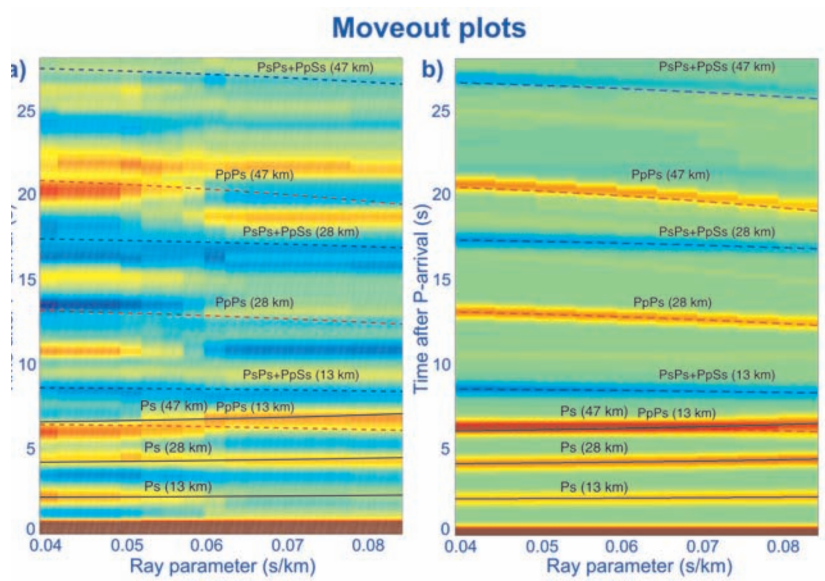

Figura 3: a) Observed receiver functions varying with epicentral distances (ray parameters). b) Synthetic receiver functions built for the crustal model constrained in this study (see Fig. 6). Note the good correlation between mid-crustal (13 km and 28 km depths) and the Moho (47 km) observed and predicted primary arrivals.

DATA, METHODOLOGY AND RESULTS

Seismic analyses

Teleseismic receiver functions are useful to estimate the crustal structure by using P-wave converted to S-wave (Ps) and other phases (PpPs and PpSs+PsPs) at discontinuities beneath a seismic station. This is accomplished assuming nearly vertical incidence of seismic waves (see piercing points in figure 1) coming from large earthquakes that occurred at far away epicentral distances of more than 3000 km or 30 degrees (Figs. 2a, b).

The results show a time series with large amplitude pulses where crustal interfaces at depth produce seismic wave phases separated in time (Langston 1979) (Fig. 2c). Different polarities and wave physical attributes are sensitive to the seismic properties of the subsurface structure.

Observed seismological data consist of high-quality P-wave teleseismic receiver functions recorded at the broadband station Coronel Fontana (CFAA, Fig. 1) located at the downstream of Quebrada Derecha. This seismic station is part of the CTBTO (Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization) global network. Receiver functions calculated from these data as a function of epicentral distances (ray parameters) are shown in the moveout plot (Fig. 3a).

The observed moveout was compared with predicted moveout curves in order to distinguish arrival of Ps phases and multiple reverberations (Fig. 2) and find values of depths and seismic velocities that have a better correlation. Thus, a full grid-search is done to estimate the best P-wave velocity (Vp), P-to-S wave velocity ratio (Vp/Vs) and depth parameters for each mid-crustal discontinuity and the Moho. Predicted moveout curves were calculated independently for a set of possible crustal models using calculated receiver functions for these models (Fig. 3b). More details about these and other receiver functions analyses using the same seismologic data and methodology can be found in Perarnau *et al.* (2010).

Petrological analyses

Ten samples of the most representative rock types belonging to the Pie de Palo Complex, were collected in the nearby area of the Coronel Fontana station and along the western flank of the Sierra de Pie de Palo to the south of the Quebrada del Gato (Fig. 1). Associations of interlayered metaquarzites, mica-quartz schists, *augen* orthogneisses, serpentinites, amphibolites and other metabasites were recognized (Figs. 4 and 5). Serpentinites and metabasic rocks have been interpreted as obducted slices of oceanic crust, probably part of an ophiolite complex formed in a suprasubduction zone setting (Vujovich *et al.* 2004 and references therein).

Petrographic analysis allowed to identify quartz-rich rocks like mica-feldspar-quartz schists (samples D2 and D3) and metaquartzite (sample D5), mica-rich rocks like epidote-quartz-biotite and garnet-bearing biotite-quartz schists (samples MIV and A34), *augen* orthogneiss (sample T13) and a variety of mafic-ultramafic rocks including amphibolites (samples D18 and NQ), epidote-chlorite-tremolite schist (sample N72) and serpentinite (sample LC2) (Figs. 4 and 5; Tables 1 and 2). Metamorphic assemblages in the metabasic lithologies hbl±act+ab+chl+ep±grt and hbl+pl±ep±grt indicate upper greenschist to amphibolite facies metamorphism (Yardley 1989).

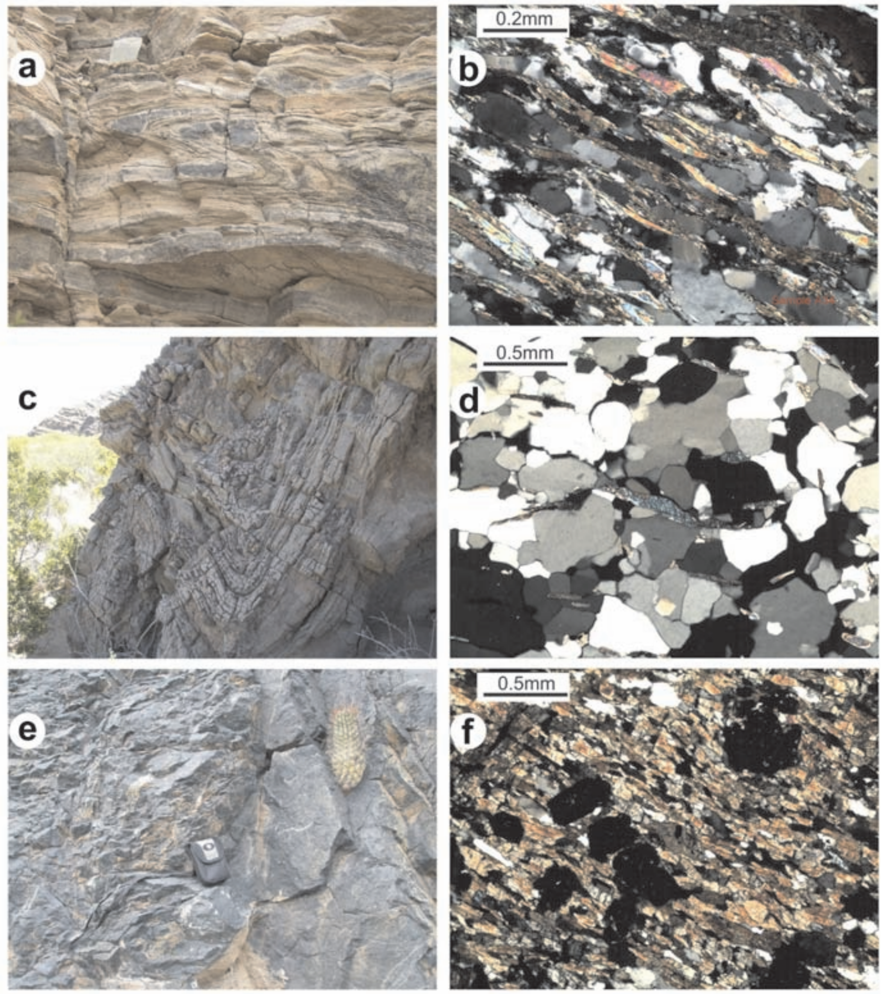

Figura 4: Outcrop views and the corresponding photomicrographs of some representative rock types analyzed in table 1. (A), (B),…indicate sample locations shown in figure 1. a-b) fsp-mca-qtz schist (C). c-d) metaquarzite (E). e-f) grt-amphibolite (E). All photomicrographs under crossed polars. Mineral abbreviations after Siivola and Schmid (2007).

Modal compositions for these rocks were obtained by conventional point counting on thin samples (≈ 900 points for each thin section) using an optical polarized microscope (see Table 1). The proportional volume of minerals in each rock sample were then calculated to be compared with a full database of rock types at a variety of high-pressure and temperature conditions using the expandable Hacker and Abers worksheet (2004). As a result, the physical and seismic properties (Vp, Vp/Vs ratio, density, among other parameters) are predicted for each rock sample assuming the metamorphic peak temperature and closure pressure at which mineral assemblages were stabilized. In this case, the estimated P-T peak metamorphic conditions of 13 kb and 600 ºC have been approximated from other studies in the Sierra de Pie de Palo by Baldo et al. (1998) and Casquet *et al.* (2001). Similar thermobarometric estimations (13.5 kb and 580 °C) were assigned to the Famatinian collision event by Vujovich and van Staal (2005). Table 1 shows markedly different estimates in calculated seismic properties due to variations in mineralogical composition of the analyzed rocks.

DISCUSSION AND CONCLUSIONS

Lateral and radial variations of physical properties (seismic velocity and density) in the Earth are primarily due to changes in mineralogy. These variations in seismic velocities and densities depend to first

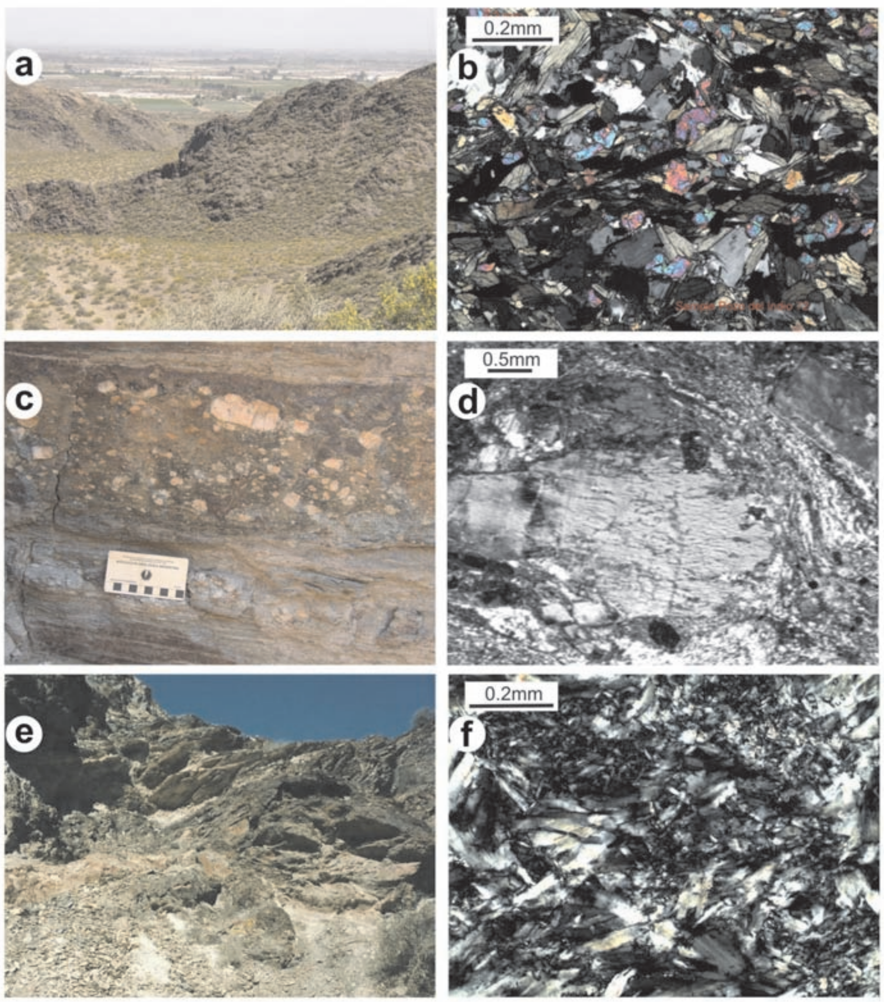

Figura 5: Outcrop views and the corresponding photomicrographs of some representative rock types analyzed in Table 1. (A), (B),…indicate sample locations shown in figure 1. a-b) ep-chl-am schist (D). c-d) *Augen* orthogneiss (B). e-f) Serpentinite mainly composed of antigorite (A). All photomicrographs under crossed polars. Mineral abbreviations after Siivola and Schmid (2007).

order, on the stable mineral assemblages and, to second order, on variations in temperature, pressure and composition. In order to interpret observed seismic radial velocities, or to predict the velocities for a starting composition, both the expected equilibrium assemblage and the physical properties of the mineral phases should be known (Anderson 1989). This study assumes that the rocks are isotropic to seismic wave propagation, but it is worth to note that in highly deformed terranes as the shallower crustal levels of the Sierra de Pie de Palo, where oriented fabrics and mylonitic rocks are widespread, the role of bulk rock anisotropy due to deformation should be taken into account in a more accurate interpretation of seismic data.

The elastic properties of minerals depend on interatomic forces and hence on bond type, bond length and packing. As minerals undergo phase changes, the ions are rearranged, increasing the length of some bonds and decreasing others. The high-temperature sequence of minerals is different from the low-temperature sequence; consequently the resulting densities and seismic velocities are also quite different. Previous broadband seismological studies at the Sierra de Pie de Palo and surrounding areas, have revealed unexpected variations in the seismic wave velocities of the upper mantle and a possible over-thickened continental crust with a complex structure that may include fault detachments and a dense lower crust (Alvarado *et al.* 2005, 2009, Gilbert *et al.* 2006, Calkins *et al.* 2006, Perarnau *et al.* 2010). These authors reported Moho depths of about 50 km in the Western Sierras Pampeanas, which is higher than the global continental crustal thickness average of 41 km (Christensen and Mooney 1995).

The seismological results in figure 6 show an upper detected layer located in the first 13 km depth with seismic velocities Vp of 5.9 km/s and Vp/Vs ratio of 1.97. Then the velocity Vp increases to a value of 6.3 km/s consistent with a Vp/Vs of 1.85. A deeper contrast in seismic velocities is found at a depth of 28 km showing a Vp of 6.7 km/s and Vp/Vs ratio of 1.81 in the deeper crustal levels. The difference in physical properties between both upper layers supports the interpretation that they truly represent different basement lithologies. These estimations are consistent with seismic observations for adjacent regions by Comínguez and Ramos (1991) and Calkins *et al.* (2006).

Studies by Vergés *et al.* (2007) propose a structural deformation model for the region with better resolution in the upper 6-km depths. In contrast, this study images clearly the discontinuities at deeper levels and thus, could be used to calibrate crustal models previously proposed by Ramos *et al.* (2002) and Vergés *et al.* (2007). It is worth to note, however, that achieved estimations have not been tested for their lateral continuation; in fact, they mainly represent a radial variation of the seismic properties in a localized portion of the southwest of the Sierra de Pie de Palo. If the same seismic velocity contrasts and mid-crust discontinuities also exist to the east beneath the Sierra de Palo or to the west in the Precordillera, is still unknown.

The seismic data obtained for the mafic-ultramafic rocks of the Pie de Palo Complex fits well with exposures of amphibolites and serpentinite rocks well exposed in the Quebrada del Gato and its surrounding areas. The petrological results predict similar seismic velocities for a composition compatible with greenschist and amphibolite facies mafic rocks up to a depth of 28 km. The deepest receiver function detected signal is constrained at

47 km depth and corresponds to the Moho. The significant increase in seismic velocities at this depth is representative of mantle composition. The lower crust between 28 km and 47 km shows velocities that are representative of a densification.

Comparisons with global observations by Christensen (1996) indicate that physical parameters for greenschist facies metabasic rocks (Vp = 6.90 km/s and Vp/Vs = 1.76 at 0.5 GPa, Christensen 1996) fit well with calculated values from amphibolites and metabasites from the Sierra de Pie de Palo (samples D18, NQ and N72) at 1.3 GPa (see Tables 1 and 2). Calculated Vp of less than 6 km/s and Vs less than 3.32 in metapelites (mica-rich schists samples MIV and A34) are lower than those proposed by Christensen (1996) for greenschist facies metapelites (Vp = 6.32 km/s Vs = 3.57 km/s at 0.5 GPa) but they maintain similar Vp/Vs ratios. Calculated Vp, and Vp/Vs in metaquartzite (sample D5), quartz-rich schists (samples D2 and D3) and granitic orthogneiss (sample T13) are lower than those proposed by Christensen (1996) for greenschist facies rocks; this is consistent with an increasing weight percent of SiO_2 for these lithologies of the Sierra de Pie de Palo compared to average global observations.

On the other hand, the serpentinite (sample LC2) supposed to be part of an ophiolite complex, has lower Vp and Vs but the highest Vp/Vs ratio of 2.20, which is in reasonable agreement with measurements in oceanic bottom rocks (Bratt and Solomon in Christensen 1996). Although it is difficult to correlate Vp or Vs estimation separately with silica content, the Vp/Vs ratio (Table 2) seems to be more sensitive to crustal composition according to Zandt and Ammon (1995). In fact, P-to-S wave velocity ratios (Vp/Vs) for averaged continental and oceanic crust compositions are estimated by Christensen (1996) to be 1.768 and 1.871, respectively. We note that the seismologic and petrological Vp/Vs values obtained in this study in the southwest of the Sierra Pie de Palo are consistent with an oceanic crustal composition at depth and/or more fractured rocks resulting in a decrease in

TABLE 1: Modal proportions and physical properties of representative rock samples from southwestern Sierra Pie de Palo.

I) Sample / Mineral (vol%)	D2	D3	D5	D18	MIV	N72	A34	T13	LC2	NQ
Quartz	42.8	47.3	93.7	13.5	33.3	17.6	34.7	30.1		10.8
Plagioclase	22.8	17.9		0.3	2.1	4.9	3.3	21.3		18.5
Microcline	11.1	3.1			0.7		21.7	17.6		
Almandine		0.8		17.1			2.6			
Tremolite						22.6				
Hornblende				54.3						62.3
Biotite	9.1	11.3	0.7	3.8	48.6	3.6	29.6	13.5		
Muscovite	10.8	15.0	5.2	0.7				11.3		
Talc									2.9	
Chlorite						22.2				
Antigorite									91.4	
Zoisite										7.9
Clinozoisite	2.7	2.5		2.2	2.3	1.6	2.1	5.9		
Epidote					12.3	16.0				
Opaques	0.8	0.3		8.2	0.7	11.5	6.1	0.5	5.7	0.5
Calcite		1.8	0.4							
Sum	100	100	100	100	100	100	100	100	100	100
P (GPa)	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
T (°C)	600	600	600	600	600	600	600	600	600	600
II) Physical properties calculated with Hashin-Shtrikman average:										
H_2O (wt%)	0.9	1.1	0.3	1.6	2.0	3.8	1.1	1.1	11.4	1.7
rho (g/cm^3)	2.80	2.83	2.74	3.51	3.15	3.19	3.08	2.83	2.75	3.09
Vp (km/s)	5.91	5.86	6.00	6.92	5.63	6.85	5.75	5.90	5.85	6.79
Vs (km/s)	3.48	3.48	3.85	3.94	3.14	3.88	3.27	3.38	2.69	3.85
K (GPa)	53	51	44	95	58	86	58	55	68	81
G (GPa)	34	34	41	55	31	48	33	32	20	46
Poissons	0.24	0.23	0.15	0.26	0.27	0.26	0.26	0.26	0.37	0.26
III) Physical properties calculated with Hashin-Shtrikman, Voigt and Reuss bounds:										
Vp H-S max	5.93	5.89	6.00	7.01	5.70	6.94	5.83	5.93	5.89	6.82
Vp H-S min	5.88	5.83	5.99	6.84	5.55	6.76	5.68	5.87	5.81	6.76
Vp Voigt	6.00	5.96	6.01	7.24	5.92	7.19	6.04	6.01	6.03	6.90
Vp Reuss	5.82	5.77	5.98	6.69	5.41	6.62	5.56	5.80	5.77	6.67
Vp VRH	5.91	5.86	6.00	6.96	5.67	6.90	5.80	5.91	5.90	6.78
Vs H-S max	3.49	3.50	3.85	3.98	3.18	3.90	3.32	3.40	2.72	3.86
Vs H-S min	3.46	3.46	3.84	3.91	3.09	3.85	3.23	3.36	2.65	3.84
Vs Voigt	3.53	3.53	3.86	4.05	3.26	3.96	3.42	3.44	2.81	3.89
Vs Reuss	3.41	3.40	3.83	3.84	2.98	3.79	3.13	3.30	2.61	3.80
Vs VRH	3.47	3.47	3.84	3.94	3.12	3.88	3.27	3.37	2.71	3.84
K H-S max	53	52	44	98	60	89	59	56	68	82
K H-S min	52	51	44	93	57	83	56	55	67	80
K Voigt	54	53	45	107	66	98	64	58	71	85
K Reuss	51	50	44	88	55	79	55	54	66	78
K VRH	53	52	44	98	60	88	60	56	69	81
G H-S max	34	35	41	56	32	49	34	33	20	46
G H-S min	33	34	40	54	30	47	32	32	19	46
G Voigt	35	35	41	58	33	50	36	33	22	47
G Reuss	33	33	40	52	28	46	30	31	19	45
G VRH	34	34	40	55	31	48	33	32	20	46

Note: VRH=Voigt-Reuss-Hill average; H-S=Hashin-Shtrikman.
(I) Modal proportions of representative rock samples from southwestern Sierra de Pie de Palo by point counting on thin sections. (II) and (III) Physical properties estimations using (II) Hashin-Shtrikman average and (III) Hashin-Shtrikman, Voigt and Reuss bounds in Hacker and Abers worksheet (2004). Counts per sample expressed as a percentage; mineral abbreviations after Siivola and Schmid (2007). Sample references: mca-fsp-qtz schists (D2, D3); metaquartzite (D5); grt-amphibolite (D18); ep-qtz-bt schist (MIV); ep-chl-tr schist (N72); grt-bearing bt-qtz schist (A34); *augen* orthogneiss (T13); serpentinite (LC2); ep-amphibolite (NQ). Peak metamorphic conditions of 1.3 GPa and 600 °C used for calculations in this study are from Baldo *et al.* (1998).

TABLE 2: A seismological and petrological crustal model for the southwest of the Sierra de Pie de Palo, Province of San Juan

Christensen 1996 (1Gpa)	QSC	QSC	QTZ	AMP	QSC	BGR	GGN	SER	BGR
Vp/Vs	1.78	1.78	1.50	1.77	1.78	1.76	1.73	2.12	1.76
σ	0.27	0.27	0.10	0.26	0.27	0.26	0.25	0.35	0.26
This study (1.3 Gpa)	**D2**	**D3**	**D5**	**D18**	**MIV**	**N72**	**T13**	**LC2**	**NQ**
Vp/Vs	1.70	1.69	1.55	1.76	1.79	1.76	1.74	2.17	1.76
σ	0.24	0.23	0.15	0.26	0.27	0.26	0.26	0.37	0.26

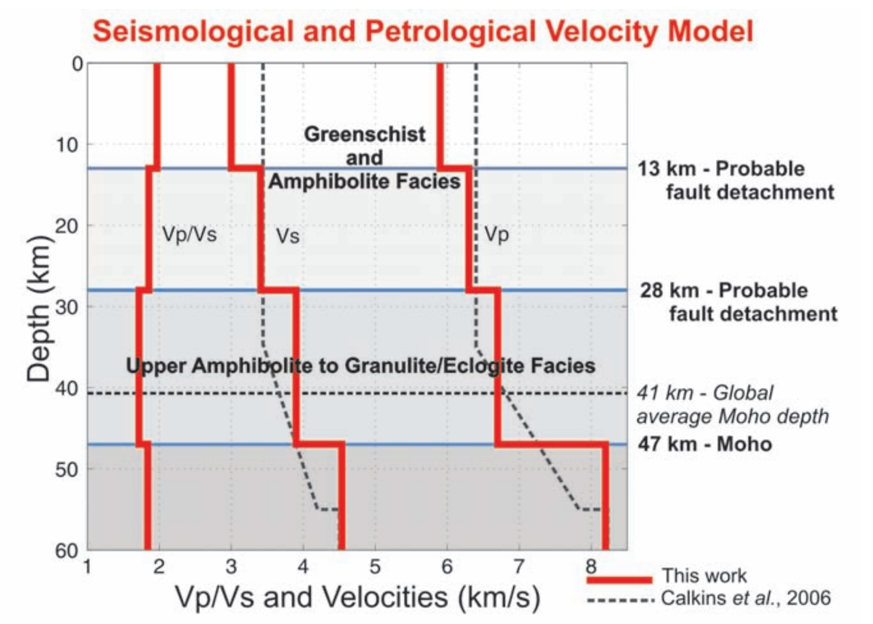

Figura 6: Proposed seismic and petrological crustal model for the southwest of the Sierra Pie de Palo. For comparison a seismic model by Calkins *et al.* (2006) in the same region and the average Moho depth in continental regions by Christensen and Mooney (1995) are also shown.

Vs and consequently higher Vp/Vs ratios. Therefore, the overall results suggest a thick 47-km crust including potential *décollement* levels at 13 km and 28 km depths. The presence of these two *décollements* might have favoring a mechanism to thicken the whole crust. The seismic parameters estimated for the lower crust of higher seismic P-wave velocity and higher density are consistent with upper amphibolite to granulite/ecoglite facies lithologies as predicted by the petrological analyses. A supposed higher abundance of eclogites at depth might significantly increase viscosity at the crustal base of the Sierra de Pie de Palo. Interestingly, garnet amphibolites exposed on the surface, show similar calculated physical parameters than those directly inferred from the seismic analysis.

Previous geophysical studies indicate magnetic anomalies that correlate with mafic and ultramafic lithologies up to depths of 12 km beneath the middle part of the Sierra de Pie de Palo (Chernicoff *et al.* 2009). The results obtained here for the combined analyses of petrological and seismological observations, suggest the continuation of the same lithologies into the lower levels of the 47-km thickened crust, which could be part of the Pie de Palo Complex ophiolite belt or Precordillera basement.

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