ACTIVE TECTONICS IN THE ARGENTINE PRECORDILLE-RA AND WESTERN SIERRAS PAMPEANAS

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ABSTRACT

The Andean foreland of western Argentina (28°S-33°S) corresponds to retroarc deformations associated with the ongoing flat subduction of the Nazca plate beneath the South American lithosphere. This region is characterized by high levels of seismic activity and crustal active faulting. To improve earthquake source identification and characterization in the San Juan region, data from seismology, structural geology and quantitative geomorphology were integrated and combined to provide a seismotectonic model. In this seismotectonic model, the Andean back-arc of western Argentina can be regarded as an obliquely converging foreland where Plio-Quaternary deformations are partitioned between strike-slip and thrust motions that are localized on the E-verging, thin-skinned Argentine Precordillera, and the W-verging thick-skinned Sierras Pampeanas, respectively. In this seismotectonic model, the Sierra Pie de Palo appears to be a key structure playing a major role in the partitioning of the Plio-Quaternary deformations.

Keywords: Seismotectonics, cosmic ray exposure dating, active faulting.

INTRODUCTION

The Andean foreland of western Argentina (Fig. 1) of San Juan and Mendoza is among the most seismically active regions in the world. Indeed, many small to moderate (M<6.4) and several large (M>6.4) earthquakes have occurred during the last century, most notably the destructive Ms = 7.4, 1944 San Juan earthquake (Instituto Nacional de Prevención Sísmica INPRÉS 1977, Alvarado and Beck 2006) and Mw = 7.4, 1977, Caucete earthquake (Kadinsky-Cade et al. 1985; Langer and Bollinger 1988) events. This seismic activity is produced by a number of crustal active faults and may result from the reactivation of ancient sutures between Paleozoic terranes (Smalley et al. 1993; Alvarado et al. 2005). In the San Juan region, most of the active structures are related to reverse compressional faulting. Nevertheless, because earthquakes on active reverse faults are not always accompanied with surface ruptures, a paleoseismological estimate of their associated seismic hazard parameters is a difficult task. To improve earthquake source identification and characterization in the San Juan region, data from seismology, structural geology and quantitative geomorphology were integrated and combined to provide a seismotectonic model (Siame et al. 2005). In this seismotectonic model, the Present-day tectonic regime is based from inversion (deviatoric stress) and moment tensor sums (strain and seismic rate of deformation) of focal mechanism solutions of moderate to large earthquakes (M = 5.0) localized along the Chilean margin and in the Andean foreland. The Neogene-Quaternary tectonic regime rely on inversion of fault plane data (deviatoric stress) and slip rates derived from geological data as well as cosmic ray exposure dating along selected active faults (e.g., Siame et al. 1997a,b, 2002). From the comparison of both Present-day and Neogene-Quaternary tectonic regimes, the Andean back-arc of western Argentina can be regarded as an obliquely converging foreland where Plio-Quaternary deformations are partitioned between strike-slip and thrust motions that are localized on the E-verging thin-skinned Argentine Precordillera and the W-verging thick-skinned Sierras Pampeanas, respectively (Siame et al. 2005). In this seismotectonic model, the Sierra Pie de Palo appears to be a key structure playing a major role in the Plio-Quaternary deformations within the Andean back-arc at about 31°S.
REGIONAL GEODYNAMIC SETTING

Along the Andes, variations in tectonic style coincide with changes in the geometry of the subducted Nazca plate (e.g., Ramos 1999 and references herein) (Fig. 1). Among those variations, high levels of crustal seismicity characterize the retroarc of the South American plate above flat-slab segments, seismic moment releases being generally 3 or 5 times greater than above 30° dipping segments (Gutscher et al. 2000).

The Andean foreland of western Argentina (28°S-33°S) corresponds to such back-arc deformation associated with the ongoing subduction of the Pampean flat-slab segment which proceeds nearly horizontally beneath the South American lithosphere for roughly 300 km at a depth of about 100 km (Cahill and Isacks 1992; Smalley et al. 1993). Coinciding with this change of the subducted Nazca plate dip (Jordan et al. 1983, Cahill and Isacks 1992), the Andean foreland domain is characterized by two opposite verging, compressional structural provinces coexisting side-by-side: the E-verging, thin-skinned Argentine Precordillera fold-and-thrust belt, and the W-verging, thick-skinned Sierras Pampeanas uplifted basement blocks (Fig. 2). In this Andean region, the flat slab geometry is attributed to the subduction of the Juan Fernandez Ridge below the South American margin (Pilger 1981), and expressed at the magmatic arc by a change in the geochemistry properties of the Neogene volcanism and a cessation of activity roughly 10 Ma ago (Kay and Abbazzi 1996). Enhanced plate coupling above a flat subduction has long been suggested to be responsible for the large-scale, thick-skinned Sierras Pampeanas basement uplifts (Jordan et al. 1983, Smalley et al. 1993). On the other hand, thermal weakness of the crust associated with eastward migration of arc magmatism as also been suggested to be responsible for thick-skinned basement uplift of the Sierras Pampeanas (Ramos et al. 2002).

Along Chilean margin (Fig. 1) and within the foreland of San Juan (Fig. 2), the Present-day tectonic regime has been investigated thanks to inversions (deviatoric stress) and moment tensor sums (strain and seismic rates of deformation) of focal mechanism solutions (Siame et al. 2005). This
The study raised the following points: (1) the slight convergence obliquity at the plate boundary is accommodated by the subduction zone itself, precluding any deformation partitioning at a lithospheric scale; (2) clockwise rotation of $\sigma_1$-axes and P-axes within the Andean foreland of western Argentina suggest that deformation partitioning may occur in the upper plate at a crustal scale; (3) comparing seismic rates of shallow deformations determined from moderate to large earthquakes localized between 22 and 36°S shows that the amount of shortening is about the same (2-4 cm/yr) between the fore-arcs of the 30° dipping slab segments and the back-arc of the flat segment. Interestingly, the trench segment corresponding to flat subduction is characterized by a much lower seismic moment release during the last 30 years. When compared to the GPS-derived velocity field (elastic strain field) for the Andean Mountains (Kendrick et al. 2003, Brook et al. 2003), it seems that the clockwise rotation of the stress and strain axes respect to the plate convergence, evidenced from both teleseismic and local focal solutions, may also be seen despite the elastic loading of the upper plate. Whether the strain partitioning suggested by both seismic data and GPS-derived velocity field is recorded at a much longer time scale than the last 30 years has been investigated through the...
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Figure 3: Structural regional map of Argentine Precordillera and western Sierras Pampeanas from Spot and Landsat image analysis (modified after Siame et al. 2005). It shows main structural sub-provinces and locates the major regional structures (dotted lines refer to either inferred or buried faults). (top) Schematic regional cross-section (CC’) at about 31°30’S latitude showing thick-skinned deformation front: Western Precordillera: modified after Cristallini and Ramos (2000); Central Precordillera: modified after von Gosen (1992); Eastern Precordillera: Zapata and Almendinger (1996); Siame et al. (2002); Structure at depth below Sierra Pie de Palo is modified according to Ramos et al. (2002) with seismicity after Régnier et al. (1992). Keys: WAP, Western Argentine Precordillera; CAP, Central Argentine Precordillera; EAP, Eastern Argentine Precordillera; ETF, El Tigre Fault; FR, Francia ramp; MB, Mataguanos Basin; UB, Ullúm Basin; NPF: North Pie de Palo Fault; TVF, Tapias-Villicüm Fault; LF, La Laja Fault; RF, Rinconada Fault; CF, Las Chacras Fault; SBF, Salinas-Berros Fault; ANF, Ampasacama-Niquizanga Fault (e.g., Siame 1998, Costa et al. 2000, Siame et al. 2002). Shaded relief from SRTM90 digital topography (e.g., Rosen et al. 2000; Far and Kobrick 2000).
analysis of the Neogene to Quaternary tectonic regimes (see section 4).

STRUCTURAL OVERVIEW OF THE ANDEAN FORELAND OF SAN JUAN AND MENDOZA (29°S-33°S)

Between 29°S and 33°S latitude, the Andean foreland of San Juan and Mendoza Provinces is characterized by three major N-trending mountainous ranges: The Cordillera Principal, the Cordillera Frontal, and the Sierras Pampeanas (Fig. 3). The Cordillera Principal was the first morphostructural unit developed after the Farallones plate break-up and is closely related to the shifting of the Andean orogenic front ever since. The associated mountain building processes ended while the Andean shortening was taking place in the Cordillera Frontal and Precordillera. The Precordillera mountain belt, which is nearly 400 km-long and roughly 80 km-wide, is a thrust-and-fold belt separated from the Cordillera Frontal by an N-S piggyback basin: the Calingasta-Iglesia Valley (Fig. 3). To the east, the Precordillera is flanked by the Bermejo foreland basin that separates the Precordillera thrust-belt from the Sierras Pampeanas, a structural province characterized by ranges uplifted above moderate to highly dipping, mostly west-verging reverse faults that root deeply into the Precambrian basement rocks (Ramos et al. 2002). The structural evolution of this region reflects the regional convergence between the Nazca and South America plates, which led to the formation of the east-verging thin-skinned Precordillera and of the west-verging thick-skinned Sierras Pampeanas, forming two opposite verging structural systems (Figs. 3 and 4) (Jordan et al. 1993, Zapata and Allmendinger 1996).

The Cordillera Frontal is the major Andean topographic feature in the studied region, and reaches elevation higher than 5000 m. This mountain belt is mainly composed of a thick Carboniferous to Triassic volcanic rocks and batholiths (Llambias and Camiños 1987), as well as significant Lower and Middle Miocene volcanic rocks (Ramos et al. 1986). During the Andean deformation, the Cordillera Frontal has apparently behaved as relatively rigid blocks, disrupted by high-angle reverse faults. Allmendinger et al. (1990) suggested that, between 29° and 31°S latitude, the Cordillera Frontal is uplifted as a ramp-anticline over a mid-crustal décollement.

The 30 km-wide Calingasta-Iglesia Valley is a piggy-back basin partly filled with Miocene sediments and andesites, and Quaternary deposits (Beer et al. 1990). The Quaternary sediments are mainly related to Pleistocene to Holocene alluvial fans (Siame et al. 1997a). In this basin, the continental strata deposited from ~16 to at least 6 Ma (Beer et al. 1990), while crustal shortening was occurring in the Cordillera Frontal and the Precordillera. This basin has been interpreted to have been passively transported above a horizontal décollement that links mid-crustal deformation beneath the Cordillera Frontal with the thin-skinned tectonics in the Precordillera (Beer et al. 1990). In the Iglesia valley, the El Tigre Fault is a 120 km-long right-lateral strike-slip fault along which geomorphic features (fan and river offsets, sagponds) and surface dislocations provide evidences for its Quaternary activity (Bastias 1985, Siame et al. 1997b, Costa et al. 2000 and references therein).

Between 30° and 32°S, the Precordillera is classically divided into three structural provinces: Western, Central, and Eastern (Ortiz and Zambrano 1981, Baldis et al. 1982). Western and Central Precordillera correspond to a mountainous topography predominantly characterized by a landscape of linear ranges and basins (Fig. 3). Reverse thrust faults bound Paleozoic ranges and narrow linear valleys filled with Neogene and Quaternary continental sediments (von Gosen 1992, Jordan et al. 1993). Western and Central AP have been described as a typical thin-skinned thrust-and-fold belt due to Neogene crustal shortening on west-dipping, imbricated structures that root down to a 10-15 km deep main décollement (Allmendinger et al. 1990, von Gosen 1992, Jordan et al. 1993, Cristallini and Ramos 1995) (Fig. 2). Formerly, the Eastern Precordillera was grouped in the Precordillera because of its geographic proximity, and mostly because Paleozoic characteristics (Ortiz and Zambrano 1981, Baldis et al. 1982). Nevertheless, since it is thrusted westwardly from the craton thanks to faults that reach mid-crustal depths, it can be attributed to the Sierras Pampeanas domain (Zapata and Allmendinger 1996, Jordan et al. 2001, Siame et al. 2002). The Central and Eastern Precordillera thus form oppositely verging thrust systems on the western and eastern side of the Ullúm-Mataquasnos-Huaco valleys (Fig. 3). Conversely to the Western and Central Precordillera, the Eastern Precordillera exhibits a drastic a-long-strike change of structural and geomorphic style at about 31°S latitude (Fig. 3). North of this latitude, the Eastern Precordillera is characterized by thick-skinned, blind thrusts and folds developed within the Neogene strata of the Bermejo valley (Zapata and Allmendinger 1996), whereas it is marked by thick-skinned emergent thrusts carrying mostly Paleozoic rocks to the south (Smalley et al. 1993, Siame et al. 2002). The location of this change in the structural style of the Eastern Precordillera coincides with the north Pie de Palo Fault (Fig. 3). In fact, it is mostly related to a major change in the basement depth from 8 to 17 km across the southern margin of the Bermejo basin (Jordan and Allmendinger 1986, Smalley et al. 1993). South of 31°S latitude, the Eastern Precordillera is bounded by one regional active thrust, the Villicúm-Pedernal thrust (Costa et al. 2000 and references therein; Siame et al. 2002). This thrust system corresponds to a 145 km-long, N20°E-trending fault that runs on the western piedmont of the Eastern Precordillera bounding Sierra de Villicúm, Sierra Chica de Zonda and Sierra de Pedernal (Fig. 3). It is characterized by a surface fault trace that clearly displaces the Quaternary deposit surfaces (Siame et al. 2002).

The Bermejo basin is a Miocene to recent foreland basin formed during the development of the Andes and Sierras Pampeanas mountains (Jordan et al. 2001). It developed firstly between 20 and approximately 7.3 Ma as a simple foreland basin adjacent to the advancing thrusts of the Western and Central Precordillera (Jordan et al. 2001). Then after a short period (1-1 Myr) of symmetrical foreland, it developed during the
last 6.5 Ma as an asymmetrical foreland associated with both thin-skinned thrusting in the Central Precordillera and thick-skinned tectonics in the Pampean basement (Jordan et al. 2001).

The Sierras Pampeanas are approximately N-trending basement block uplifts of Precambrian metamorphic rocks with topographic characteristics that consist of steep sloped sides on the faulted front and gently dipping back sides (Fig. 3). The topographical back side corresponds to a Late Palaeozoic erosional basement surface (Carignano et al. 1999). The basement blocks are separated by wide, shallow basins of unmeta-
morphosed, relatively undeformed Carboniferous and younger sediments (Salti and Gorustovitch 1984).

PRESENT-DAY SEISMO-TECTONIC REGIME

Within the Andean foreland of western Argentina, earthquake activity is characterized by two depth distributions (Fig. 2). Earthquakes with hypocentral depths at about 100 km show flat slab geometry of the Nazca plate beneath South-America (Cahill and Isacks 1992, Smalley et al. 1993, Engdahl et al. 1998), whereas earthquakes with hypocentral depth ranging from 5 to 35 km correspond to crustal seismicity between the Argentine Precordillera and the Sierras Pampeanas (Smalley et al. 1993). In this region, the crustal seismicity pattern derived from preliminary determination epicentre catalogue (USGS/NEIC) is dominated by a cluster of events centred on the Sierra Pie de Palo (Fig. 2). To efficiently interpret this pattern, we applied a gridding algorithm to the seismic event frequency distribution (Siame et al. 2005). The resulting map not only takes into account the dense N-trending ellipsoid-shaped clustering of events centred on the eastern side of the Sierra Pie de Palo, but also clearly unveils two other areas of moderate frequency located near San Juan and Mendoza cities (Fig. 4). Around San Juan city, this zone of moderate frequency corresponds to the Tulum and Matagusanos valleys, where thick-skinned active faulting has been suspected to be responsible for the Ms 7.4, 1944 San Juan earthquake (Smalley et al. 1993, Siame et al. 2002). The rest of the Precordillera is relatively aseismic, particularly north of the north Sierra Pie de Palo Fault, which is in agreement with epicentre distributions from local seismic networks (Régnier et al. 1992, Smalley et al. 1993), relocated teleseismic events (Engdahl and Villaseñor 2002), and with the location of the regional active faults (Siame et al. 2005). Within the Andean foreland of San Juan, earthquakes with Mw ≥ 4.9 provide evidence for predominantly reverse to strike-slip faulting (Fig. 2), mostly indicate E-trending shortening on ~40°-dipping faults, and have their source depths ranging from 5 to 35 km. From September 1987 to May 1988, Régnier et al. (1992) operated a digitally recording seismic network that provided a detailed view of the crustal seismicity in the area (with a maximum activity at about 25 km depth). Even if both seismicity patterns observed from teleseismic and local data are quite similar, teleseismic data are centred on the low-lying valley between Sierra Pie de Palo and Sierra de la Huerta, whereas local data cluster below Sierra Pie de Palo (Fig. 2). This slight difference in the epicentre location is most probably due to systematic differences in location obtained for the two datasets. Best-fitting deviatoric stress tensors from inversions of both teleseismic and local datasets are consistent with σ1-axes striking N95°± 2°E (Fig. 2). Moment tensor sum of the CMT solutions provide consistent results with P-axes striking N93°E (Fig. 2), parallel to the computed σ1-axes. Both inversion and moment tensor sums indicate that σ1-axes and P-axes are roughly orthogonal to the strike of the reverse faults that borders the Sierra Pie de Palo basement uplift, and consequently slightly rotated clockwise with respect to the Nazca vs. South American plates convergence trend (Fig. 2). When compared to the GPS-derived velocity field for the Andean Mountains (Kendrick et al. 1999, Kendrick et al. 2003, Brooks et al. 2003), it seems that this clockwise rotation of the stress axes does not only result from local boundary effects within the Sierras Pampeanas, as already suggested by Régnier et al. (1992), but may have a more regional significance (Siame et al. 2005).

NEOGENE TO QUATERNARY TECTONIC REGIME

STRESS REGIME FROM INVERSIONS OF FAULT SLIP-STRIAE

In order to determine the most recent states of stress within the Precordillera and westernmost Sierras Pampeanas, quantitative inversions of fault slip-vectors (striae) measured at individual in Paleozoic rocks from the Precordillera, in Mesozoic rocks from the Sierras Pampeanas, and in Neogene to Quaternary continental deposits that fill the inter-mountainous and foreland basins. Some individual sites of measurements are also located on active faults where the computed states of stress can be regarded as significant for recent stress regimes. The results of these quantitative inversions of fault slip-vectors have been presented in details in papers by Siame et al. (2002, 2005). Even if, at individual sites, some of the observed fault-slip data can be related to earlier stress states (e.g., Triassic extension in the Sierras Pampeanas), chronological relationships allowed determining the most recent set of fault-slip-vectors to determine the most recent states of stress which are discussed. The stress tensors determined using fault-slip measurements within Paleozoic and Mesozoic rocks from the Precordillera and Sierras Pampeanas are remarkably consistent with the stress tensors deduced from inversion of fault-slip data collected within the Neogene and Quaternary sediments. Compared at a regional scale, the stress regimes determined at individual sites yield a regional stress pattern that is in close agreement with the stress tensors determined using local and teleseismic focal mechanism solutions, as well as with the elastic strain field deduced from the GPS-derived velocity field (e.g., Brooks et al. 2003).

In the Precordillera, Paleozoic to Quaternary strata are involved in the deformation, which is related to the Andean (~20 Myr) structuration of the region. Since the Precordillera developed eastwardly during the last 20 Ma, the fault-slip sites determined for the Western Precordillera are most probably older than those calculated for the Central, Eastern Argentine Precordilleras and Sierras Pampeanas. In the Western and Central Precordillera, where the thrust mainly developed between 20 and 5 Ma (Jordan et al. 2001), the stress regime is dominated by σ1-axes striking parallel to that determined for the Chilean trench. In the westernmost Sierras Pampeanas and Eastern Precordillera, where the thrust initiated between 5 and 2.5 Myr, the stress regimes are dominated by N110°E-trending σ1-axes south of 31°S, whereas it is striking parallel to that determined for the Chilean trench north of 31°S (Fig. 5). When compared to the stress regime pattern to the
GPS-derived velocity field proposed by Brook et al. (2003), the stress regime pattern derived from fault slip-vector data in the Eastern Precordillera and westernmost Sierras Pampeanas, are in relative agreement. Indeed, the northern part of the San Juan foreland both $\sigma_1$-axes and GPS-derived velocity vectors strike in a direction parallel to that of the plate convergence (Fig. 5). Farther south, the comparison is not so conspicuous with GPS-derived velocity vectors striking E-W (Fig. 5). Nevertheless, GPS-derived velocity vectors seem to be also clockwise rotated, suggesting that the clockwise rotation of $\sigma_1$-axes evidenced from both focal mechanism (Present-day) and fault slip-vector (long-term) datasets may also be seen in the GPS-derived velocity field despite the upper plate elastic loading (Fig. 5).
GEOLOGICAL RATES OF DEFORMATION

Previous study (e.g., Allmendinger et al. 1990, Cristallini and Ramos 2000) have shown that Andean orogeny may have resulted in more than 90 km of shortening accommodated by the Precordillera, yielding a mean shortening rate of 5 mm/yr if integrated over the last 20 myrs. Age of shortening in the east-verging AP is relatively well-known at about 30°S (e.g., Jordan et al. 1993, Zapata and Allmendinger 1996), whereas it is less constrained at ~31°S. Near 30°S, age and amount of shortening have been estimated mostly through magnetostratigraphy and growth strata: the Western Precordillera experienced an early phase of shortening roughly 20 Ma ago (rates <5 mm/yr) followed by a period of quiescence (Jordan et al. 1993). Thrusting in the Western and Central Precordillera then resumed roughly 15 Ma ago with a period of rapid rates (15-20 mm/yr) spanning at about 10-12 Ma, followed by declining rates (Jordan et al. 1993a, Zapata and Allmendinger 1996), even though some of the easternmost thrusts may have been active throughout the Quaternary (Zapata and Allmendinger 1996, Siame 1998). Those previous studies have shown that the deformation front of the AP has experienced a total shortening of ~40 km during the last 5 Myr, implying a mean geological shortening rate of ~8 mm/yr. Regarding the Eastern Precordillera and the Bermejo Valley, they accommodated ~17 km of shortening during the last 3 Myr (Ramos et al. 2002), yielding a mean deformation rate of about 6.5 mm/yr. The amount of shortening associated with the Sierra Pie de Palo is on the order of 15 km and may have started between 5 and 3 myrs, yielding a mean shortening rate of 3-5 mm/yr (Ramos et al. 2002).

QUATERNARY RATES OF DEFORMATION FROM COSMIC RAY EXPOSURE DATING

In active tectonic studies, quantification of the tectonic forcing processes requires continuous and well-controlled chronologies of the landscape development over long-spanned time scales. Cosmic ray exposure dating methods have opened new prospects for long term surface processes analysis (e.g., Gosse and Phillips 2001). During the past decade, the cosmic ray exposure dating method provided relatively accurate estimates of the Quaternary deformation rates along active faults in the Andean Foreland of San Juan (Siame et al. 1997a, 2002).

HORIZONTAL AND VERTICAL SLIP RATES ASSOCIATED TO THE EL TIGRE FAULT

The El Tigre Fault is a 120 km-long right-lateral strike-slip fault along which geomorphic features (fan and river offsets, sag ponds) and surface disruptions demonstrate its Quaternary activity (Bastias 1985, Siame et al. 1997b). The fault is located in the Calingasta-Iglesia Valley which is a 30 km-wide piggyback basin filled with Miopliocene clastic sediments and andesites, and Quaternary deposits (Fig. 3). The El Tigre Fault trace analyzed on SPOT images extends northward from the Río San Juan to the Río Jáchal (Fig. 6), has a mean N10°E-striking, linear and discontinuous fault trace composed by 1 to 7 km-long fault strands. At the surface, this fault zone affects chiefly Tertiary and Quaternary formations as well as some Paleozoic rocks in its southern part. The fault strands are separated by stepovers, bends or relay discontinuities (Fig. 6).

The overall fault geometry may be described considering two to three main segments. The southern segment is 74 km-long, and exhibits a continuous trace, extending from 31.2°S, north of the San Juan River to ~30.9°S (Fig. 6). It is the most pronounced fault segment on SPOT satellite images where it is clearly evidenced by offset stream channels, 200-400 meters wide releasing and restraining stepovers, which are always marked by depressions and pressure ridges, respectively (Fig. 6). From 30.9°S to 30.6°S, the fault trace is also characterized by an east-facing steep slope, commonly bounded by several sag ponds on its eastern foot and by beheaded alluvial fans on its western side (Fig. 6). Southward, the fault trace vanishes within the Precordillera Paleozoic strata, and may be interpreted as the southern tip of the El Tigre Fault. On the basis of the fault trace geometry, Siame et al. (1997b) proposed to divide the southern segment of the El Tigre Fault into central and southern segments, 26 and 48 km-long, respectively. The southern segment is 46 km-long and extends as far as Rodeo city (30.2°S). Although the N10°E fault strike is preserved, this segment is composed of smaller 1 to 5 km-spaced elementary fault strands, and the surface deformation appears to be more distributed. Considering these numerous spaced fault strands, we interpreted this segment as the northern El Tigre Fault "horse-tail"-like termination (Fig. 6).

Along the southern segment of this active fault, alluvial fans skirting the western piedmont of the Precordillera are incised by a drainage network of stream channels, gullies, and ridges. Most of these geomorphic markers provide evidence for right-lateral displacements, with a maximum offset of 260±20 m cumulated during Late Quaternary. Thanks a geomorphic analysis of the alluvial fan surfaces incised by the deformed drainage network, we estimated that the channel incision took place between the abandonment of the A4 unit and the abandonment of the A3 unit (Fig. 6). Cosmic ray exposure dating of the abandoned fan surfaces allowed constraining an horizontal slip-rate for the ETF of about 1 mm/yr (0.5-2 mm/yr). Along the central segment of the El Tigre Fault, a beheaded series of alluvial fans is uplifted by pressure ridges formed within local fault strands. Cosmic ray exposure dating of these alluvial surfaces yielded a local vertical slip rate on the order of 0.3 mm/yr. The vertical and horizontal slip-rates estimated at roughly 0.3 and 1.0 mm/yr, respectively, yield a reconstructed slip-rake of about 17° for the El Tigre Fault, similar to the fault slip vector observed in a trench on the fault plane (fault plane azimuth: N17°E, dip: 78°E, stria pitch: 14°S).

VERTICAL SLIP RATE ASSOCIATED WITH THE LAST TAPIAS FAULT

The Villicum-Pedernal thrust is a 145 km-long, N20°E-trending structure that runs on the western piedmont of the Eastern Precordillera between 31°S and 32°20'Slati-
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Structural segments separated by oblique N40°E-trending fault branches define the Villicúm-Pedernal thrust. These segments are the Villicúm, the Las Tapias, and the Zonda-Pedernal segments, from north to south, respectively. Both the Villicúm and Las Tapias segments are characterized by a fault trace that clearly affects the Quaternary deposits whereas, the fault trace of Zonda-Pedernal segment is less conspicuous (Siame et al. 2002).

The Las Tapias Fault is 18 km-long and extends with the same N22°E trend between the southern Sierra de Villicúm and the northern Sierra Chica de Zonda fault branches. In the low-lying region localized between the Sierra de Villicúm and the Sierra Chica de Zonda, the Las Tapias Fault affects Quaternary alluvial deposits that overly unconformably the Neogene foreland strata and forms discontinuous and degraded west-facing scarps (Fig. 7). Minor...
Figure 7: The Las Tapias Fault. a) Structural map of the 65 km-long Quaternary segment of the Villicum-Pedernal thrust overlain on Landsat TM (after Siame et al. 2002). b) Structural map of the Las Tapias Fault shown on an aerial photograph centered on the low-lying region between Sierra de Villicum and Sierra Chica de Zonda (after Siame et al. 2002). c) Panoramic view of the Las Tapias Fault escarpment showing the three different alluvial levels. d) Map of the alluvial deposits affected by the Las Tapias Fault based on both stratigraphic relationships and surficial morphology observed in the field and on aerial photograph. The numbers refer to the minimum surface exposure ages calculated from 10Be concentrations measured in surface boulders (Siame et al. 2002). e) N110°E-striking topographic profiles constructed perpendicularly to the Las Tapias scarps (circled numbers refer to locations on d).
N40°E-trending topographic features, marked by roughly 1 m-high, and 1 to 5 km-long scarps, also affect the Quaternary deposits in the Las Tapias Fault area. These topographic features strike obliquely to the major N22°E-trending Las Tapias Fault and can be regarded as the continuation, within the Quaternary deposits, of the N40°E-trending oblique faults that affect the southern end of Sierra de Villicum. Both sets of faults at the southern Sierra de Villicum and the northern Sierra Chica de Zonda are bedding-parallel, and interpreted as flexural-slip faults.

Along strike, the Las Tapias Fault forms west facing, ~10 m-high discontinuous and degraded scarps which affect Quaternary alluvial sediments (Fig. 7). The scarps are west facing, which leads to ponding on the footwall of clastic deposits transported from Loma de Ullum. Streambeds are draining across the scarps from east to west such that the thrust scarps grown against main drainage. Nevertheless, the interaction of alluvial cutting and recurrent surface faulting has generated a strat terrace sequence that records the faulting history on the hanging wall. Stream gradients are relatively high (<8°), and recurrent faulting on the Las Tapias Fault sufficiently raised the hanging wall to produce a significant vertical downcutting. This stream incision into the up-thrown block has isolated a couple of alluvial terraces that end abruptly at the fault scarp. These terraces can be easily distinguished by their differential elevations, as well as by the difference of both incision pattern and incision degree at their surfaces (Fig. 7). The clastic source for alluvial material is the relief of Loma de Ullum, and the streams flow direction is roughly SW-NE (Fig. 7). The piedmont is still active as suggested by both a well-developed network of braided streambeds incised ~0.5 m into it, and a well-preserved surface morphology with bars and swales formed by slightly varnished abraded boulders and sub angular cobbles. In an attempt to establish absolute ages for this stratigraphically-based chronology, terrace surfaces have been sampled for cosmic ray exposure dating. Based on the cosmic ray exposure ages published by Siame et al. (2002), we propose a minimum CRE age of 1.3 ± 0.8 10Be-kyr for the piedmont surface, and best proxies for the actual abandonment ages of 6.9 ± 1.0 and 18.7 ± 2.3 10Be-kyr for the uplifted surfaces, respectively (Fig. 7).

The displaced alluvial deposits geometry with respect to the fault scarps has been studied to estimate the uplift rate for the hanging wall of the Las Tapias Fault. Indeed, the uplifted terraces result from episodic fault incision into the up-thrown block of the Las Tapias Fault. The vertical separation between the projections of these terraces, measured at the inferred fault plane may thus provide a first approximation of the vertical component of fault displacement. To constrain the vertical component of fault displacement, three topographic profiles have been surveyed perpendicular to the fault trace (Fig. 7). The scarps bounding A2 and A3 terraces have been constructed through time by repeated faulting on the Las Tapias Fault. Since topographic profiles provide constraints on minimum vertical displacement between the geomorphic surfaces and 10Be cosmic ray exposure ages provide lower limits for time elapsed since surface abandonment, these data allow estimating lower limits for the long-term uplift rate. All together, these estimates yield to a mean uplift and shortening rate of 0.7 ± 0.3 mm/yr and 0.8 ± 0.5 mm/yr, respectively (Siame et al. 2002, 2005). This shortening rate is consistent with the ~1 mm/yr shortening rate determined further north over the past 3 Myr by Zapata and Allmendinger (1996) across Eastern Precordillera and Bermejo basin individual structures.

THE ROLE OF THE SIERRA PIE DE PALO

Within the structural context of the Andean back-arc at about 31°S, the Sierra Pie de Palo appears to play a key role in the partitioning of the Plio-Quaternary deformations. Located in the westernmost Sierras Pampeanas, the Sierra Pie de Palo is roughly NNE-striking. It forms an 80 km-long and 35-40 km-wide, ellipsoidal shape that reaches elevation as high as 3162 m (Fig. 3 and Fig. 5). This mountain range is an actively growing basement fold (e.g., Ramos et al. 2002) associated with an important seismotectonic activity (Fig. 4). In this area, evidences of Quaternary active deformation are found along the eastern and northern borders of the Sierra Pie de Palo as well as along the western borders of the Sierra de Valle Fertil and Sierra de la Huerta (Fig. 8) (Costa et al. 2000, Siame et al. 2002, Siame et al. 2005). With a dissymmetrical arch-like shape (Fig. 4), its topography is characterized by steep-sloped sides on the eastern and northern fronts and western and southern gently dipping back sides (Fig. 4). The surface envelope of Sierra Pie de Palo corresponds to an inherited, Late Paleozoic erosional surface (Carignano et al. 1999) affecting in Precambrian metamorphic rocks. Since, geologic evidence indicates that the range was covered by Late Pliocene distal synorogenic deposits derived from the Precordillera (Ramos and Vujovich 2000), the deformation associated with the growth of the Sierra Pie de Palo may have started between 5 and 3 Myr (Ramos et al. 2002). The eastern and western flanks of the Sierra Pie de Palo are characterized by east-dipping and west-dipping Pliocene strata, respectively, indicating that the surface structure of Pie de Palo is characterized by a basement fold (Ramos et al. 2002). This basement structure passively folded the Pliocene strata and the unconformity that separates them from the basement, in a similar way than other Sierras Pampeanas (Garcia and George 2004). Based on that, Ramos et al. (2002) proposed that the structure is controlled by a basement wedge detached at about 15-20 km depth (Fig. 3), according to the crustal seismicity provided by a local network (Régnier et al. 1992). In this context, the role of the Niquizanga Fault (ANF) is still unclear. Indeed, at depth this fault may correspond to a west-dipping, thick-skinned reverse structure that most probably ruptured during the 1977 Caucete earthquake (Kadinsky-Cade et al. 1985, Langer and Bollinger 1988). However, it produced very little surface ruptures, suggesting that this fault is mostly buried. Indeed, along the eastern flank of Sierra Pie de Palo, the Pliocene beds are dipping to the east, and near Niquizanga, those strata are slightly folded and unaffected by the fault (V. Ramos, persomm. comm.). To explain these observa-
tions, Ramos et al. (2002) have proposed that east-dipping faults along the eastern border of Sierra Pie de Palo might be related to W-verging, thick-skinned fault propagation associated to the Sierra de la Huerta and Sierra Valle Fértil. However, such a W-verging thick-skinned propagation would necessary have produced a significant relief instead of the subsiding Bermejo valley. To our opinion, even if buried along most of its length, an E-verging, Niquizanga Fault system should be regarded as the structure responsible for the dissymmetrical, long-wave length shape of the surface envelope of the Sierra Pie de Palo (Fig. 3).

To evaluate the degree of tectonic activity around the Sierra Pie de Palo, some geomorphic lines of evidence can be drawn from the study of the drainage network. Indeed, even if the lithological and climatic conditions (semi-arid climate) contributed to a good preservation of its surface envelope, the Sierra Pie de Palo is dissected by fluvial incision. Moreover, taking into account that the lithological conditions are fairly constant throughout the whole area, any active tectonic perturbation should thus be discriminated using the geomorphic indices associated to the drainage network that dissects the Sierra Pie de Palo. Among those geomorphic indices, the hypsometric integral value, related to the degree of dissection of a given landscape, is commonly used to discriminate between tectonically active and inactive regions (Strahler 1952). Indeed, high values of the hypsometric integral (i.e., values close to 1) indicate youthful topographies whereas intermediate to low values (i.e., values close to 0) are related to more matured and dissected landscapes. In the Sierra Pie de Palo, one can consider that the hypsometric integral value of a given drainage basin is directly related to its degree of tectonic activity. The figure 8 presents a map of the drainage basins together with the hypsometric integral values calculated using the SRTM90 digital topography (e.g., Rosen et al., 2000, Far and Kobrick, 2000). This morphometric approach unveils that the drainage basins with high values of hypsometric integral are preferentially located along the northern and eastern borders of the Sierra Pie de Palo. Moreover, along the eastern border, the drainage basins show rectilinear shapes that correlate the seismicity frequency (see above), and the steep slope that characterizes this side of the Sierra Pie de Palo. Considering these combined observations, and the November 23, 1977, Caucete, earthquake sequence (Kadinsky-Cade et al., 1985, Langer and Bollinger, 1988), it appears that the eastern and northern flanks of the Sierra Pie de Palo are probably among the most active zones in the area.

DISCUSSION OF A SEISMOTECTONIC MODEL FOR THE ANDEAN FORELAND OF SAN JUAN AND MENDOZA

The Andean back-arc of western Argentina can be regarded as an obliquely converging foreland where Plio-Quaternary deformations are partitioned between strike-slip and
thrust motions that are localized on the E-verging thin-skinned Argentine Precordillera and the W-verging thick-skinned Sierras Pampeanas, respectively. In this partitioning model the El Tigre Fault, Eastern Precordillera and western Sierras Pampeanas faults play important roles. The El Tigre Fault geometry and segmentation is tightly associated with the geometry of the Precordillera ranges. Indeed, slight variations of strike in the Precordillera range appear to parallel the El Tigre Fault geometry and discontinuities (Siame et al. 1997b). For example, the southern termination of the El Tigre Fault coincides with the Precordillera ranges bending from N160°E to N10°E close to Rio San Juan. Along its northern segment, the El Tigre Fault steps westwardly, playing as a horst-tail termination, coinciding to another orientation change of the Precordillera ranges (Fig. 5). Among others, these observations lead Siame et al. (1997b) to propose that the El Tigre Fault may correspond to a crustal-scale strike-slip fault, closely related to the Precordillera fold-and-thrust belt. In this Plio-Quaternary transpressive system, the El Tigre Fault should accommodate the dextral strike-slip component while the Eastern Precordillera-Pampeana thrusts should accommodate N110°E-trending shortening (Fig. 5). Indeed, if one assumes that the convergence obliquity is regionally accommodated by the El Tigre Fault, Quaternary slip-rates estimated thanks to cosmic ray exposure dating (~1 mm/yr) imply that 3-8 mm/yr of shortening have to be accommodated throughout the Eastern Precordillera-Pampeana system in a N110°E-trending direction (Fig. 5). Interestingly, this direction corresponds to the orientation of the σ1-axes computed from both focal mechanism (Present-day) and fault kinematic (long-term) datasets within the Eastern Precordillera and westernmost Sierras Pampeanas. This direction also coincides with the trend of the North Pie de Palo Fault that marks the northern limit of the growing Sierra Pie de Palo (Fig. 3), and corresponds to a regional structure playing a major role regarding the seismicity distribution pattern (Fig. 2 and Fig. 4). In our partitioning model, the estimated range of Quaternary shortening rates (3-8 mm/yr) is in close agreement with the geological rates estimated from crustal balancing studies (e.g., Allmendinger et al. 1990, Cristallini and Ramos 2000). Since this range of shortening rates has to be distributed over several active thrusts, it is also consistent with a minimum shortening rate of 0.8 ± 0.5 mm/yr determined for the Las Tapias Fault of the Eastern Precordillera south of 31°S over the Holocene period (Siame et al. 2002). Even if one argued as to the degree to which the GPS data are accurate, these data suggest that, south of 31°S, 7-9 mm/yr of E-trending shortening have to be accommodated between the Calingasta Valley and Sierra Pie de Palo, with about 4 mm/yr between Eastern Precordillera and Sierra Pie de Palo (Brook et al. 2003). Those GPS-derived shortening estimates are thus slightly higher than the long-term geological and Quaternary rates. Moreover, north of 31°S, GPS data suggest that only 2-3 mm/yr are accommodated between the western Precordillera and the Sierra Valle Fértil, with less than 1 mm/yr within the Bermejo valley. GPS data thus seem to confirm that most of the Present-day tectonic activity is concentrated south of 31°S, in the Sierra Pie de Palo area. In this context, the shortening rate estimated from seismic moment tensor sum appears to be one order of magnitude greater (3-4 cm/yr) than those estimated above from the GPS-derived velocity field (Siame et al. 2002, 2005). This high rate of co-seismic shortening strongly suggests that the November 23, 1977, Caucete, earthquake sequence may have released the elastic deformation accumulated in this region, the high discrepancy with GPS-derived and geological shortening rates being much probably due to the too short-spanned time window. South of 31°S, the regional compressional stress regime is dominated by N110 ± 10°E-trending σ1-axis perpendicular to the trend of the Sierra Pie de Palo, and parallel to the trend of the north Pie de Palo Fault (Fig. 5). In this context, the process of basement uplift that exhumed the Sierra Pie de Palo has most probably triggered the regional clockwise reorientation of the compressional axes, observed at the long-term (fault striae) and short-term (seismicity) time windows. This may have started 5-3 Myr ago, that is to say since the Sierra Pie de Palo is actively growing.

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