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TECTONOPHYSICS
Tectonophysics 434 (2007) 81 – 92
www.elsevier.com/locate/tecto

Kinematic variations across Eastern Cordillera at 24°S (Central Andes): Tectonic and magmatic implications

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Received 18 November 2005; received in revised form 29 November 2006; accepted 4 February 2007
Available online 14 February 2007

Abstract

The Eastern Cordillera (Central Andes, ∼24°S) consists of a basement-involved thrust system, resulting from Miocene–Quaternary eastward migrating compression, separating the Puna plateau from the Santa Barbara System foreland. The inferred Tertiary strains arising from shortening in the Eastern Cordillera and Santa Barbara System are similar, higher than in the Puna. Slip data collected on the major ∼N–S trending faults of Eastern Cordillera show a westward progression from dip-slip (contraction) to dextral and sinistral motions. This, consistently with established tectonic models, may result from partitioning due to the oblique Mio-Quaternary underthrusting of the Brazilian Shield north of 24°S. This strain partitioning has three main implications. (1) As the dextral and sinistral shear in the Eastern Cordillera are ∼62% and 29% of the compressive strain respectively, the Eastern Cordillera results more strained than Santa Barbara System foreland, contrary to previous estimates. (2) The partitioning in the Eastern Cordillera may find its counterpart in that to the west of the Central Andes, giving a possible structural symmetry to the Central Andes. (3) The easternmost N–S strike-slip structures in the Eastern Cordillera coincide with the easternmost Mio-Pliocene magmatic centres in the Central Andes, at ∼24°S. Provided that, further to the east, the crust is partially molten, the absence of magmatic centres may be explained by the presence of pure compressive structures in this portion of the Eastern Cordillera.

Keywords: Compressional tectonics; Strike-slip faulting; Strain partitioning; Central Andes; Eastern Cordillera

1. Introduction

To understand the overall strain distribution within an orogen it is crucial to define: (a) its style of deformation, (b) the relationships with its geodynamic context and (c) if magma is available, the structural control on the rise and emplacement of magma.

The style of deformation of an orogen is given by the geometry and kinematics of its major structures, as those accommodating most displacement. In obliquely convergent settings, the deformation may also induce, in addition to compressional systems, strike-slip and even extensional structures, usually resulting from strain partitioning or back-arc extension (e.g. Taylor and Karner, 1983; Malinverno and Ryan, 1986; Woodcock, 1986). The evaluation of the predominant structural style (extensional, strike-slip or contractional) within the

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0040-1951/$ - see front matter
doi:10.1016/j.tecto.2007.02.001

orogen permits, in turn, to infer the relationships with the surrounding tectonic setting (as due to back arc extension, oblique or orthogonal convergence). Magma is another important geodynamic indicator, as it may give additional information, especially in convergent settings, about the structures that control its rise and emplacement. Our knowledge on the tectonic setting of volcanoes within orogens is still limited to few studies on specific areas (e.g. Nakamura, 1977; Tibaldi, 1992; Sato, 1994; Lara et al., 2004). Conversely, the more abundant studies on eroded plutons in orogens have shown that magma is here commonly intruded along localized extensional areas induced by the activity of strike-slip structures, resulting from strain partitioning during oblique convergence (Busby-Spera and Saleeby, 1990; Glazner, 1991; Tikoff and Teyssier, 1992; Tobisch and Cruden, 1995; Tikoff and de Saint Blanquat, 1997; De Saint Blanquat et al., 1998; Wilson and Grocott, 1999).

In this context, the Central Andes, resulting from the moderately oblique convergence between the Nazca and South American plates, provide a suitable study area to evaluate these relationships between the local structure, the tectonic setting and magmatism. Magmatic activity accompanies the polyphased build-up of the Central Andean orogen (De Silva, 1989), mainly focusing along the volcanic arc and NW–SE structures, extending to considerable distances (up to ~300 km) to the east of the arc, on the Puna Plateau and the Eastern Cordillera. The anomalous location of these latter volcanoes, in such an off-arc position, poses serious questions about their tectonic control and the origin of the magma.

In order to better understand (a) the type of deformation of the Eastern Cordillera and (b) its control on off-arc magmatism (with an overall transverse orientation), structural field work was carried out along the major fault systems of the Eastern Cordillera. The collected data highlight the role of Mio-Quaternary partitioning due to the oblique underthrusting of the Brazilian Shield.

2. Geologic and tectonic setting

The Central Andes underwent a complex tectonic history, at least since the Eocene (e.g. Arriagada et al., 2003), mainly controlled by the rate and direction of convergence between the South America and the Nazca plates; the post-Eocene convergence has been characterized by an overall moderate obliquity, with dextral motion south of the Arica-Santa Cruz bend (e.g. Pardo-Casas and Molnar, 1987; Dewey and Lamb, 1992; Somoza, 1998; Hindle and Kley, 2002).

The eastern portion of the Central Andes, at ~24°S, is characterized by the ~N–S trending Eastern Cordillera, between the Puna plateau (thickened axis of the orogen, mean elevation ~4000 m), to the west and the Santa Barbara System foreland, to the east (Fig. 1; Omarini and Götze, 1991; Allmendinger and Zapata, 2000; Gerbault et al., 2005). The Eastern Cordillera, from 23°S to 26°S, is characterized by a basement-involved thrust system, developed, with an eastward migration, during Miocene–Quaternary time (Marrett et al., 1994; Reynolds et al., 2000; Riller et al., 2001; Mon et al., 2005). It mainly consists of Late Precambrian–Lower Palaeozoic and Cretaceous–Tertiary sedimentary rocks, even though igneous Palaeozoic and Tertiary rocks are present (Turner and Mon, 1979).

Major ~N–S trending faults have been active during the mid-Miocene to Quaternary build up of the Eastern Cordillera, and responsible for the present

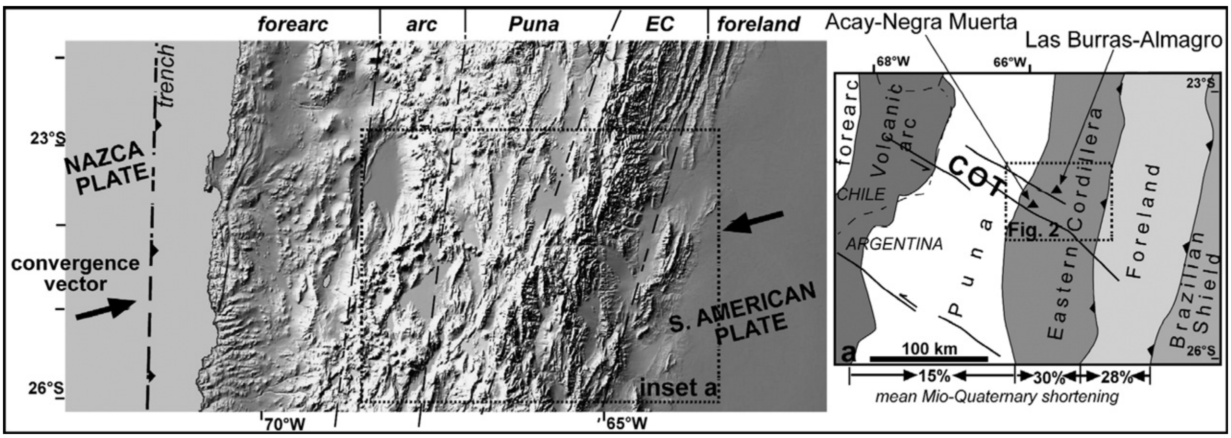

Fig. 1. DEM image of Central Andes, showing the main structural units. Inset a: general setting of the eastern Central Andes at 24°S. EC = Eastern Cordillera.

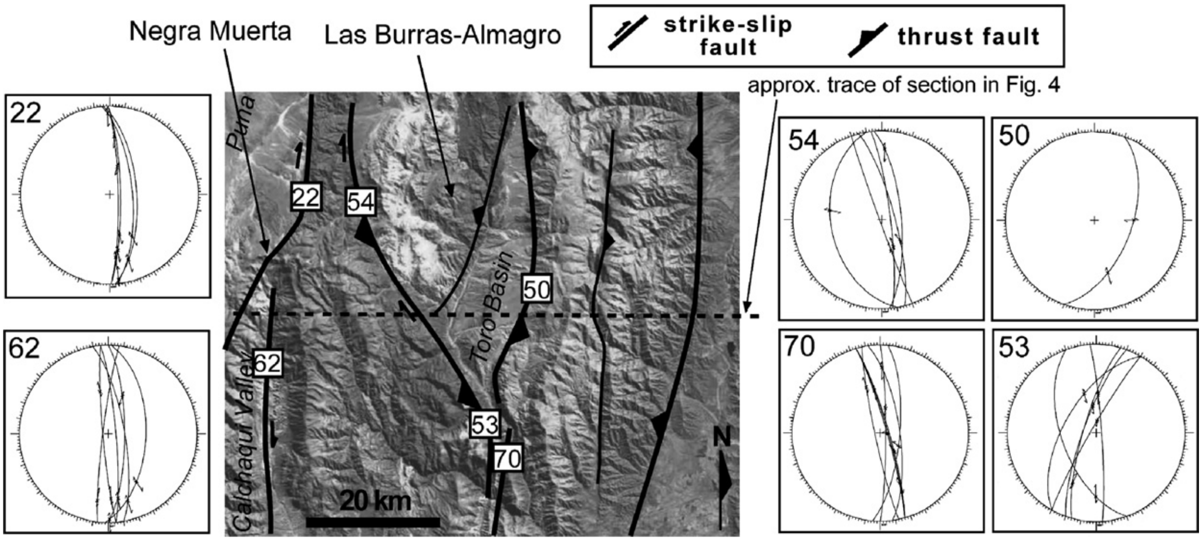

Fig. 2. Landsat satellite image of Eastern Cordillera at ~24°S, showing its main fault zones, the measurement sites (numbered) and the related stereographic representation of the ~N–S faults.

morphology, characterized by ~N–S trending ridges (Marrett et al., 1994). These faults, with a significant amount of shortening, have been interpreted as the main thrust systems accommodating the polyphased (Marrett and Strecker, 2000) contraction (Drozdzewski and Mon, 1999; Strecker and Marrett, 1999; Reynolds et al., 2000). In particular, the area of the Eastern Cordillera at ~24°S underwent two main phases of deformation, with WNW–ESE and, subsequently, WSW–ENE compression (Marrett and Strecker, 2000). The transition between these two phases possibly occurred in Pliocene, with the variation in the direction and rate of the absolute motion of South America Plate (Marrett et al., 1994; Marrett and Strecker, 2000).

Despite the eastward migration of the compression, the estimated amounts of Tertiary shortening from the Puna to the Santa Barbara System do not show an evident eastward decrease. In fact, total Tertiary shortening in the Eastern Cordillera, at ~24°S, is estimated at 25–35% (Drozdzewski and Mon, 1999; Coutand et al., 2001), similar to the 25–30% of Tertiary shortening for the Santa Barbara System foreland (Kley et al., 1999; Kley and Monaldi, 1999, 2002) and higher than the 15% of Tertiary shortening of the Puna plateau (Coutand et al., 2001) (Fig. 1). Different Late Tertiary structural styles are present in these units. While the Santa Barbara System, at ~24°S and to the south, is dominated by thick-skinned Mio-Quaternary pure compression (Cahill et al., 1992; Allmendinger and Gubbels, 1996; Kley and Monaldi, 1999), the Plio-Quaternary evolution of the Puna plateau is mostly characterized by N–S dextral faults (Cladouhos et al., 1994).

The Eastern Cordillera, at ~24°S, is also characterized by magmatic products associated with the convergence of the Nazca and South American plates. In fact, magmatism in the Central Andes at ~24°S is focused along the N–S trending volcanic arc and, to the east, along NW–SE trending structures (Viramonte et al., 1984; Viramonte and Petrinovic, 1990; Riller et al., 2001). The longest of these NW–SE structures, the Calama-Olocapato-El Toro (COT), extends for more than 300 km to the east of the arc (Fig. 1). Its presence within the Eastern Cordillera is highlighted by NW–SE lineaments, corresponding to sinistral faults on the field (Matteini et al., 2005a) and by the NW–SE alignment of Miocene magmatic centres (Matteini et al., 2002a,b). The most important centres in the Eastern Cordillera are the plutonic complexes of Las Burras and Acay (13–14 Ma) and the volcanics of Almagro and Negra Muerta (6–7 Ma) (Fig. 1, inset; Riller et al., 2001; Matteini et al., 2005a,b; Hauser et al., 2005; Petrinovic et al., 2005). Geochemical and geophysical data suggest widespread partial melting in the mid-lower crust of Central Andes; this may be responsible, focusing into crustal-scale discontinuities, such as the COT, for the magmatism observed to the east of the arc (Matteini et al., 2002a,b; ANCORP, 2003; Heit et al., 2005; Tassara, 2005).

3. Methodology

Field work has been used to collect 36 sets of fault slip data across the Eastern Cordillera, in the area between the Toro Basin (to the east) and the Puna plateau (to the west) at ~24°S, along the major ~N–S trending faults (thick lines; Fig. 2). These in fact form zones of intense brittle deformation, focusing most of the bulk strain in the Eastern Cordillera and separating larger areas with moderate or negligible deformation (Fig. 2). Besides the sites of field measures, we have identified these structures from remote sensing analysis (satellite images and aerophotos, Fig. 2) and compared their extent and geologic features in existing geologic maps (Cladouhos et al., 1994; Marrett et al., 1994; Strecker and Marrett, 1999; Marrett and Strecker, 2000; Coutand et al., 2001).

The timing of fault movements has not been directly dated. Even though the faults are found in Late Precambrian (metasedimentary Puncoviscana Formation) to Oligocene sedimentary deposits, we assume that their formation and activity are restricted to the build up of the Eastern Cordillera, from late Miocene to Quaternary. This assumption is consistent with previous studies (Marrett et al., 1994; Marrett and Strecker, 2000).

The slip data have been obtained from the identification and measurement of the slickenlines on the fault planes. These consisted of striations, sometimes associated with mineral fibers. Their measurement involved the determination of the pitch and possible sense of motion. The latter was determined considering the presence and orientation of micro- and meso-indicators (such as stylolites, extension fractures, Riedel shears, steps and chatter marks) on the fault plane.

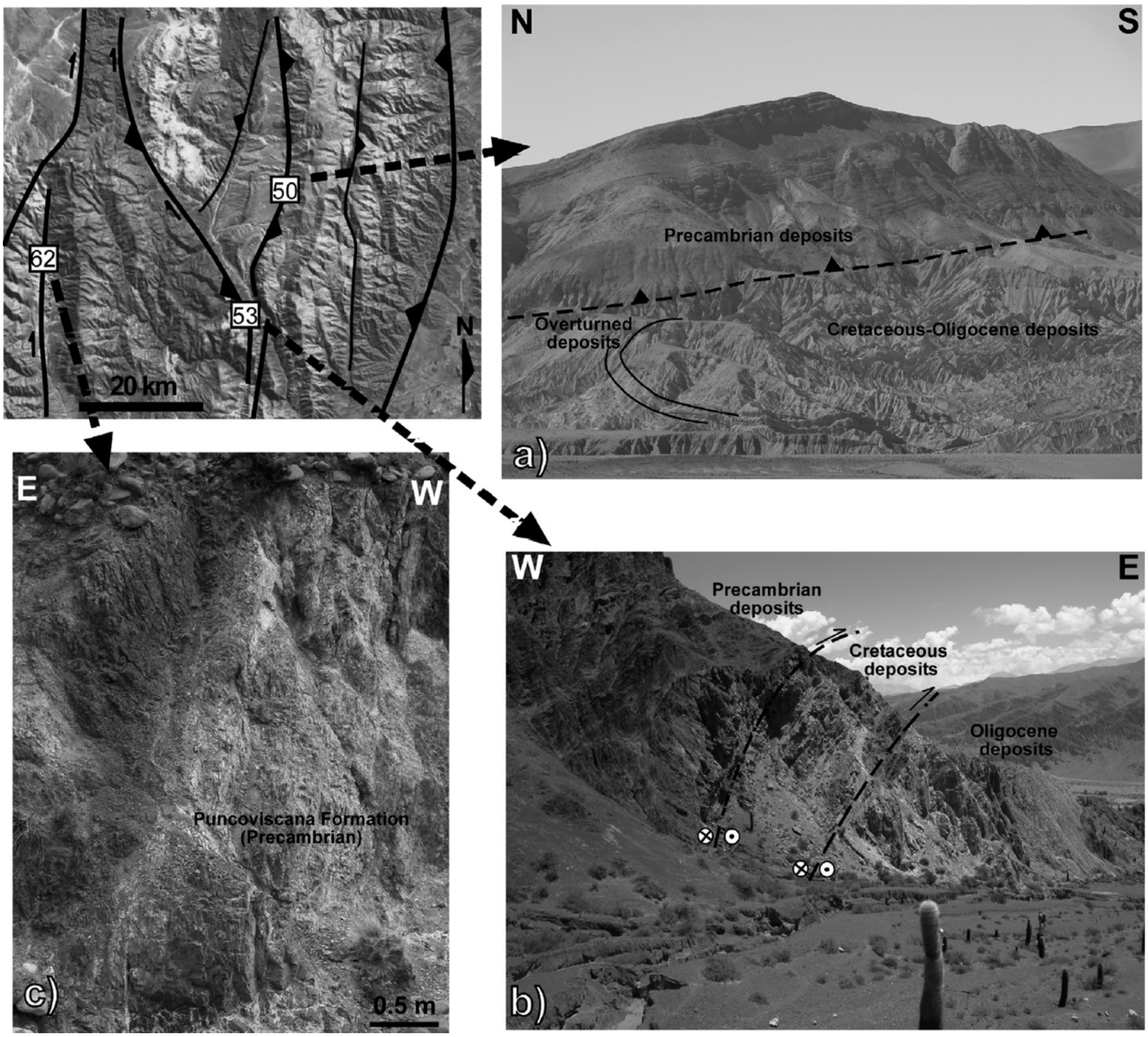

Fig. 3. Examples of major N–S trending fault zones across the Eastern Cordillera. (a) Thrust front outcropping at measure site 50; (b) transpressive fault zone outcropping at measure site 53; (c) intense deformation associated with N–S dextral faults at site 62.

The slip data are derived from the pitch of the slickenlines, that is the angle which a fabric makes to the strike direction. Pitch values range from 0° to 180°; these correspond to pure strike-slip motions, whereas pitches = 90° correspond to pure dip-slip motions; it is anticipated that all the recognized dip-slip faults are thrusts. Therefore, the pitch values quantify any component of orthogonal and lateral shear on the faults across the Eastern Cordillera.

4. Results

The general geometric and kinematic features of the studied ~N–S trending faults, as well as their location, are shown in Fig. 2. Despite the overall similar trend and morphological expression, these fault zones show significant differences, briefly summarized here. The Toro Basin is a thrust-bounded basin (Fig. 2); the fault zone on its eastern border, the Gòlgota thrust (Marrett et al., 1994), consists of a shallow E-dipping thrust, juxtaposing the Precambrian Puncoviscana Formation with the Oligocene deposits (Fig. 3a). The latter are overturned, forming a syncline in the foot-wall, whereas the Puncoviscana in the hanging-wall forms a thrust-related frontal anticline. The south-western Toro Basin is bordered by the Solà thrust (Marrett et al., 1994); despite its clear contractional component, this is characterized by high angle, W-dipping transpressive faults, juxtaposing the Puncoviscana Formation (forming a major syncline in the hanging-wall) on the Cretaceous and Oligocene deposits (foot-wall; Fig. 3b). Further to the west, a N–S fault zone controls the development of the N–S Calchaqui Valley immediately to the east of the Puna border (Figs. 2 and 3). This, characterized by a narrow deformed area within the valley axis made up of Puncoviscana, consists of several subvertical splays, with predominant strike-slip component. Despite the lack of a strong contractional component, the fault zone is marked by intense cataclastic breccia. These features suggest a broad westward increase of the strike-slip component along the major faults across the Eastern Cordillera.

Table 1
Main parameters of the collected fault slip data

Strike (°)	Dip (°)	Pitch (°)	Kinematics	Site
20	55	78	R	50
20	55	130	S+R	50
344	83	50	D+R	70
168	85	135	D+R	70
344	84	88	R	70
5	72	100	R	70
344	82	109	R	70
360	85	67	R	70
200	78	112	R	53
210	60	115	R	53
196	78	38	D	53
210	85	104	R	53
356	85	55	R+D	53
158	58	35	D	53
160	88	60	D	54
170	42	110	R	54
353	82	115	R	54
355	72	25	U	54
345	78	113	U	54
356	65	153	D	22
356	65	175	D	22
355	69	10	D	22
355	69	130	R+S	22
359	80	143	D	22
359	80	157	D	22
359	82	150	S	22
359	82	35	D	22
359	82	43	R	22
2	55	132	U	62
2	55	175	U	62
360	75	35	U	62
175	85	28	D	62
175	85	130	U	62
355	83	152	U	62
350	75	157	D	62
187	85	25	U	62

R = reverse or thrust fault; S = sinistral fault; D = dextral fault; U = undefined kinematics.

To better define the kinematics of these major faults, as well as of the remaining ones in this portion of the Eastern Cordillera (shown in Fig. 2), we collected fault slip data. Thirty-six slip data were measured along the major ~N–S trending faults across the Eastern Cordillera, at ~24°S (Table 1). Since the measurements were conducted on faults with an overall N–S (N05° ± 25°) direction (Fig. 2), the strike variations of the faults are considered, to a first approximation, negligible in evaluating the pitch variations across the Eastern Cordillera.

The pitch variations across the Eastern Cordillera (Fig. 4) are projected along an E–W section (Fig. 2), accordingly with the sense of shear of the fault. The horizontal sense of shear is dextral for 18 faults, sinistral for 10 faults and unknown for 8 faults. The data were collected over an E–W distance ~60 km, corresponding to ~3/4 of the ~80 km wide the Eastern Cordillera at ~24°S (Figs. 2 and 4). The slip data show that, in general, the highest and lowest pitch values occur to the west of the area, whereas the intermediate pitch values occur to the east. Therefore, the major faults progressively vary from almost pure horizontal shear at the western front of the Eastern Cordillera, to almost pure compression at the eastern border, defining a progressive westward increase in the strike-slip component.

The more abundant pitches indicating dextral motions have a significantly better correlation (R = 0.75) than those indicating sinistral motions (R = 0.58) (Fig. 4). These best fit values have been obtained grouping separately the dextral and sinistral faults and considering the departure of their pitch value from the pure dip-slip motion (90°) towards the pure dextral and sinistral motions respectively. The mean variation of the pitch of the better correlated dextral faults with distance is ~50° over ~60 km, that is ~0.8°/km, whereas that of the worse correlated sinistral faults is ~25° over ~60 km, that is ~0.4°/km (Fig. 4).

5. Discussion

The implication of the data of Fig. 4 may be limited by their moderate correlation and amount. We believe that the degree of correlation is significant enough to investigate to which extent it has tectonic implications. We also believe that the limited fault slip data, having been collected along the major fault zones of the Eastern Cordillera, may be representative of its overall tectonic evolution, at least along an E–W section. Therefore, taking into account for these limitations, a plausible mechanism is here proposed for the data distribution of Fig. 4. Further investigations may confirm the possible importance of this mechanism in the frame of the tectonic evolution of the eastern Central Andes.

As far as the age of the observed deformation is concerned, the studied faults have been active during the build up of the Eastern Cordillera (mid-Miocene–Present) (Fig. 2; Marrett et al., 1994). Precise age determinations are not available; however, established tectonic models for this part of the Andes (Cladouhos et al., 1994; Marrett et al., 1994; Marrett and Strecker, 2000; Hilley and Strecker, 2005) suggest more detailed indirect insights on the timing of deformation. While the component of shortening along the N–S faults can be related to an overall ~E–W compression from Miocene to Present, the strike-slip component should be related to deviations from the ~E–W direction of compression. The most important change in these deviations occurred between 10 and 2 Ma (Cladouhos et al., 1994; Marrett

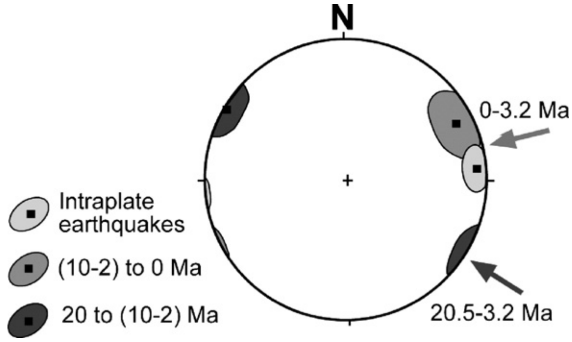

Fig. 5. Stereographic comparison of maximum compression directions from 20.5 Ma to sometime between 10 and 2 Ma, and from sometime between 10 and 2 Ma to 0 Ma. This figure results from the merging of different data sets, as incremental shortening axes, intraplate earthquakes and absolute motion azimuths for South America Plate (Marrett and Allmendinger, 1990; Cladouhos et al., 1994; Marrett et al., 1994; Marrett and Strecker, 2000); squares = shortening axes; ellipses = 95% confidence limits. See Marrett and Strecker (2000) for further details and assumptions.

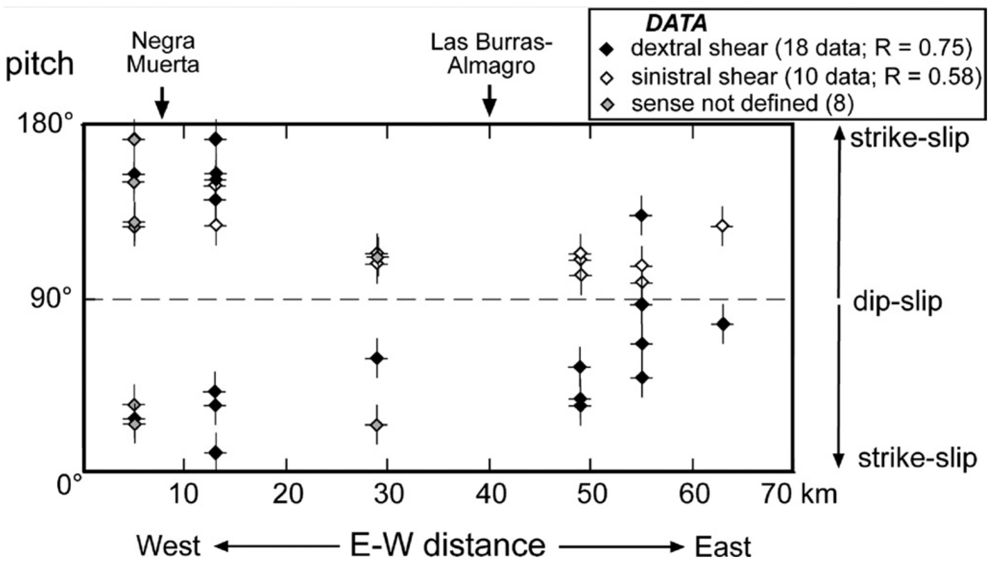

Fig. 4. Variation of the pitch angle of the major ~N–S faults in the Eastern Cordillera. The data have been collected along an ideal E–W section at ~24°S (see sites in Fig. 2).

et al., 1994; Marrett and Strecker, 2000). In fact, before 10 Ma (according to Cladouhos et al., 1994), or before 3.2 Ma (accordingly to Marrett and Strecker, 2000), or even ~2 Ma (accordingly to Marrett et al., 1994), the possible overall direction of regional compression was ~WNW–ESE (Fig. 5). Subsequently, sometime between 10 and 2 Ma, the possible direction of compression became ~WSW–ENE, as a result of plate motion reorganization (Fig. 5; Marrett and Strecker, 2000). This variation, regarding the direction (from WNW-ESE to WSW-ENE) and rate (increase) of the absolute motion of the South American Plate (Marrett and Strecker, 2000), permits an indirect dating of the faults with a predominant strike-slip component. In fact, the sinistral component of the ~N–S faults may be related to the WNW–ESE compression, active between 20.5 and sometime between 10 and 2 Ma; similarly, the dextral component of the ~N–S faults may be related to the later WSW–ENE compression, active from sometime between 10 and 2 Ma until Present (Fig. 5; Marrett and Strecker, 2000, and references therein).

Similarly to these stress changes, reflecting variations in the absolute motion of South American Plate (Marrett and Strecker, 2000), the kinematic variations across the Eastern Cordillera may be related to plate motion readjustments. Since the westward transition from dip-slip to strike-slip motions occurs in the eastern Andes, it is unlikely that this results from the moderately oblique convergence between the Nazca and South American plates, on the western part of the Andes (Fig. 1). In fact, oblique convergence has been occurring, from Miocene, also behind the Andes (Marrett and Strecker, 2000), resulting in the underthrusting of the Brazilian Shield, well evident north of 24°S (Fig. 5; e.g. Allmendinger and Gubbels, 1996; Whitman et al., 1996). Our data may be interpreted in the frame of a progressive transition from the compression in Santa Barbara System foreland (Cahill et al., 1992; Whitman et al., 1996; Kley and Monaldi, 1999) to the late Miocene–Quaternary N–S dextral shear in the Puna (Cladouhos et al., 1994).

This suggests that the kinematic variations across the Eastern Cordillera, and at a broader scale from Puna to Santa Barbara System, represent the transition in the partitioning of the strain in the eastern portion of the Central Andes at ~24°S, as a result of the oblique convergence of the Brazilian Shield. A similar process was proposed for the late Miocene–Quaternary N–S dextral faults on Puna, at 22°S (Cladouhos et al., 1994). The partitioning into strike-slip (to the west) and thrust (to the east) faults has also been recognized in the Central Andes, during the Late Cenozoic, at 16°S (Lamb and Hoke, 1997) and, during the Quaternary, at 18°S (Dewey and Lamb, 1992). Therefore, despite the fact that our data are limited to a transect at 24°S, the repartition of the deformation into strike-slip and thrust faults seems widespread, from Miocene to Present, at the back of much of the Central Andes.

The partitioning at 24°S has three main implications, considered below.

1) It shows that, despite the similar amount of bulk contraction in the Eastern Cordillera and in Santa Barbara System, the former is affected by an additional strain deriving from the strike-slip component. As regards the dextral shear, this is estimated extrapolating the mean gradient of 0.8°/km to the 80 km wide Eastern Cordillera at 24°S, resulting in an overall westward increase in the dextral shear by ~64°. Since this increase is broadly linear (Fig. 4), its mean value (32°) can be applied across the entire Eastern Cordillera. The 25–35% of overall shortening C in the Eastern Cordillera corresponds to 34±9 km (Drozdzewski and Mon, 1999; Coutand et al., 2001). Knowing the pitch angle variation of the dextral faults/distance ratio (0.8°/km) and the overall shortening C (34±9 km), the mean percentage of dextral shear D across the Eastern Cordillera can be estimated as a function of C:

$$D = C\tan 32° = 21 \pm 5\text{km}$$

This estimate is based on the likely assumption that both the dextral and the contractional deformation across the Eastern Cordillera develops in the same time frame and tectonic setting. In this context, the dextral shear in the Eastern Cordillera is 21/34 (corresponding to ~62%) of the pure shortening. The same procedure is used to evaluate the sinistral shear, with a gradient of 0.4°/km over 80 km, giving an overall westward increase of ~32°. Similarly, the mean percentage of sinistral shear S across the Eastern Cordillera can be estimated as

$$S = C\tan 16° = 10 \pm 5\text{km}$$

corresponding to ~29% of the pure shortening.

These calculations imply that, despite of the similar amount of shortening in the Eastern Cordillera and Santa Barbara System, the former underwent a larger strain, due to the strike-slip component. In fact, in the Eastern Cordillera, our results are consistent with a dextral and sinistral shear ~62% and ~29% of the total shortening respectively (Fig. 6); in Santa Barbara System foreland, previous data suggest 25–30% of Tertiary shortening, without evidence of significant strike-slip faulting (Kley and Monaldi, 1999; Kley et al.,

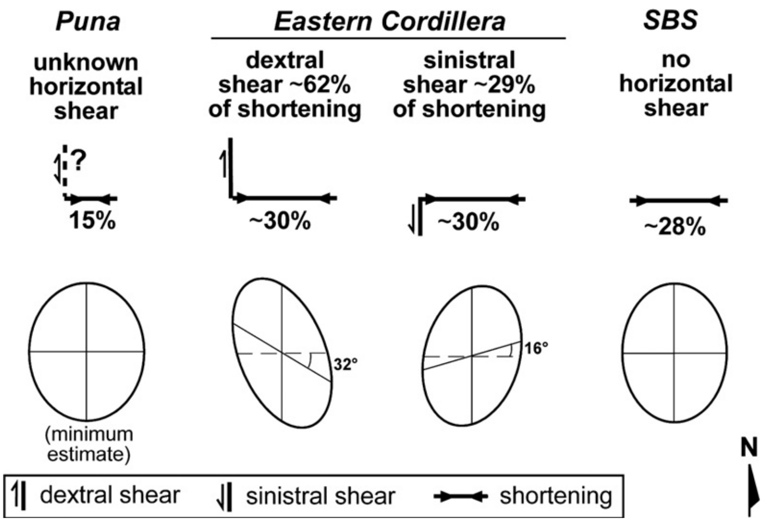

Fig. 6. Estimated mean shortening and horizontal shear in Puna, Eastern Cordillera (EC) and Santa Barbara System (SBS) during Mio-Quaternary. Lower part of the figure reports the estimated strain ellipses for the 3 areas.

1999). Similar results have been found in the Central Andes of Bolivia (Hindle et al., 2005). As regards the strain in Puna, the moderate Cenozoic shortening (15%) recognized here (Coutand et al., 2001) may similarly consist of a minor part of the total strain, which is mostly due to the predominant strike-slip activity (Cladouhos et al., 1994).

Therefore, the strains considering only the contractional component in this eastern part of the Andes may prove unrealistic to define any eastward increase or consistency of the deformation. In fact, taking into account also for the strike-slip component, it appears that most of the strain focused in the Eastern Cordillera (Fig. 6). However, since the exact amount of strike-slip component in Puna is unknown, it cannot be excluded that this eastern part of the Andes underwent progressively larger strains westwards. In fact, considering the overall eastward migration of the deformation in the eastern Central Andes, the overall tendency in decreasing the shortening westwards may be accompanied by the increase in horizontal shear (Fig. 6).

2) The partitioning related to the dextral faults to the east of the Central Andes may have its counterpart to the west, at the Andes front (Fig. 7). It is in fact commonly accepted that the front of the Andes has been undergoing slip partitioning as a result of the moderate oblique convergence (~15°) between the Nazca and South American plates (e.g. Pardo-Casas and Molnar, 1987; Dewey and Lamb, 1992; Lavenu and Cembrano, 1999; Cembrano et al., 2002); this usually results in an overall compression on the trench side and strike-slip shear on the arc side. Evidence of thrusts and dextral faults parallel to the margin suggesting partitioning has been found at ~20°S (Farìas et al., 2005). However, evidence for a partitioning at the Andes front, between 21° and 25°S, is very limited (Scheuber and Reutter, 1992; Victor et al., 2004) and, if present, is probably masked or complicated by widespread extension (Fig. 7; Gonzalez et al., 2003; Von Huene and Ranero, 2003). Therefore, the precise definition of any Mio-Quaternary strain partitioning to the west of the Andes at ~24°S may appear speculative. Nevertheless, even if accompanied by significant extension, mainly due to the gravitational collapse of the accretionary wedge (Von Huene and Ranero, 2003), a relevant contraction must be present at depth towards the trench side (Pritchard et al., 2006, and references therein). Similarly, the well-defined and straight lineaments cutting through the present volcanic arc (Reutter et al., 1991; Scheuber and Reutter, 1992; Reijs and McClay, 2003) suggest that intra-arc strike-slip fault zones may exist in this portion of Andes. These considerations suggest that, despite the lack of strong evidence, strain partitioning is plausible to the west of the Andes, even at ~24°S.

If this proves true, a general across-strike symmetry in the style of deformation of the most recent history (starting sometime between 10 to 2 Ma) of the Central Andes may be inferred. This results in an overall pure compression at the sides of the orogen and horizontal shear in its inner portion.

3) The Central Andes is characterized, to the back of the volcanic arc, by widespread magmatism focused

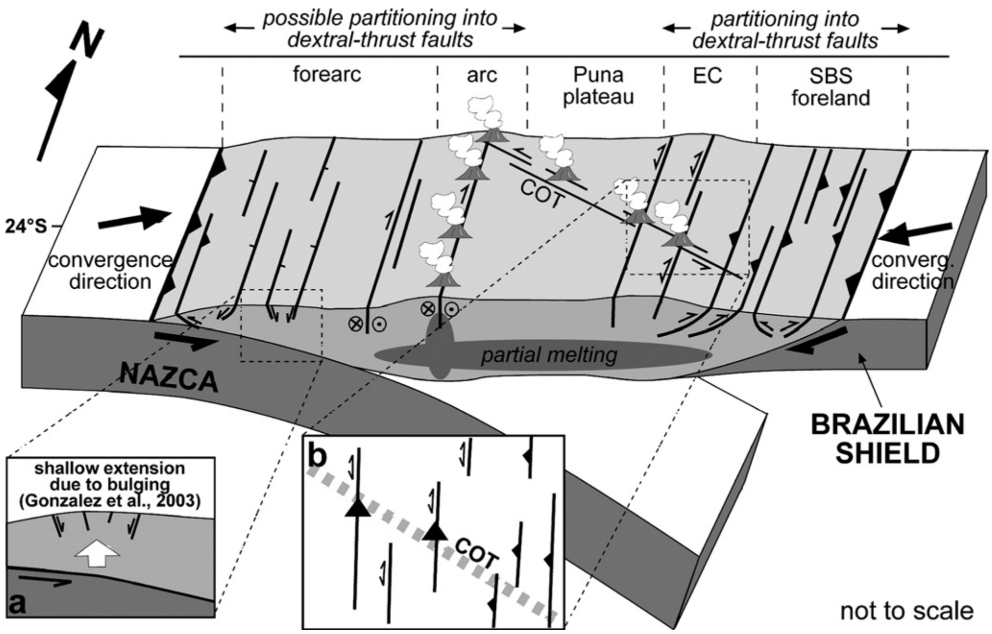

Fig. 7. Schematic structural model of the Central Andes at ~24°S. Possible strain partitioning at both sides gives a structural symmetry (strike-slip+thrust faults) to the orogen. Shallow extension at the front of the Andes results from bulging due to deeper compression (inset a; Gonzalez et al., 2003). Magmatic activity along the COT is observed in correspondence with the easternmost N–S strike-slip faults in the Eastern Cordillera (inset b). Black triangles in inset b represent the Negra Muerta and Las Burras-Almagro magmatic complexes. EC=Eastern Cordillera; SBS=Santa Barbara System.

along NW–SE transverse structures, as the Calama-Olocapato-El Toro system (COT; Fig. 1). The easternmost magmatic centres (Negra Muerta-Acay, Las Burras-Almagro; Fig. 1) along the COT within the Andean orogen are located in the Eastern Cordillera, between 200 and 300 km to the east of the arc. These centres are, at a broad scale, NW–SE aligned and located in proximity to NW–SE sinistral faults, showing an overall relationship with the COT. However, detailed field investigations suggest that most of the magmatic activity is locally focused along releasing bends induced by the activity of N–S strike-slip faults (Matteini et al., 2005a). The location of the easternmost magmatic centre, Las Burras-Almagro (upper arrow in Fig. 4) suggests that the area is characterized by an overall transpressive setting, where strike-slip faults may still form, even though probably smaller than the major faults across the Eastern Cordillera. This is consistent with field observations, at the ~14 Ma Las Burras-Almagro magmatic centre: here several N–S strike-slip faults, forming a composite fault zone with a total length ~20 km, are associated with magmatic activity (Matteini et al., 2005a). This suggests that the Las Burras-Almagro magmatic centre is located in correspondence with the eastward limit of the N–S strike-slip faults within the Eastern Cordillera (Fig. 7, inset b). To the east, where the horizontal shear fades, turning into almost pure contraction, significant magmatic activity is lacking.

The lack of magmatism to the east of Las Burras-Almagro may be related (a) to the effective lack of magma at depth or (b) to the local structural setting, which hinders the shallow rise and extrusion of magma below the easternmost part of the Eastern Cordillera. Since several evidence highlights the widespread presence of molten zones below the Eastern Cordillera (Fig. 7; Lamb and Hoke, 1997; Pope and Willett, 1998; Yuan et al., 2000; Riller et al., 2001), it is possible that the absence of magmatic centres to the east of Las Burras-Almagro may be explained by the observed pure contraction. Pure contraction alone may not necessarily hinder the shallow rise and extrusion of magma. In fact, the extrusion of magma in purely convergent settings has been previously documented in NE Japan (Acocella et al., 2005) and Ecuador (Tibaldi, 2005). However, in both cases, the shallow rise of magma largely occurs along the volcanic arc, as a result of the ascent of melts from the subducting slab; therefore, volcanic activity appears largely magma-driven. Conversely, the fact that in the Eastern Cordillera the rise of restricted volumes of magma is scattered at a significant distance from the arc suggests that regional tectonics may play a more significant role in controlling its ascent and emplacement. In this context, the widespread presence of active compressional structures may definitively limit the extrusion of the moderate batches of magma present at depth. Therefore, it appears that the observed variation in the structural style across the Eastern Cordillera plays an important role in explaining the lack of magma to the east of Las Burras-Almagro. The occurrence of the magmatic centres along the N–S strike-slip faults in the Eastern Cordillera suggests that, in an overall transpressive context, the rise and emplacement of magma are largely controlled by the strike-slip structures.

6. Conclusions

The possible strain partitioning found across the Eastern Cordillera, at the back of the Central Andes at 24°S, has three main implications.

1) Since the dextral and sinistral shear in the Eastern Cordillera are ~62% and ~29% of the compressive strain, respectively, the Eastern Cordillera results more strained than Santa Barbara System foreland, contrary to previous estimates.
2) The partitioning to the east of the Central Andes may find its counterpart in that possibly occurring to the west, giving an overall structural symmetry to the Central Andes at ~24°S.
3) The easternmost N–S strike-slip structures in the Eastern Cordillera coincide with the easternmost Miocene magmatic centres in the Central Andes, at ~24°S. Provided that, further to the east, the crust is partially molten, the absence of magmatic centres may be explained by the presence of pure contractional structures in this portion of the Eastern Cordillera.

Acknowledgements

R. Allmendinger, J. Cembrano, J. Kley and M Sandiford provided useful comments. This work has been carried out in the frame of the scientific convention between the universities of Pisa (Italy) and Salta (Argentina) and was supported by the COINICET-CIUNSA (Salta-University, Argentina) and MIUR-PRIN2003 Project (2003041444_002, R. Mazzuoli coordinator).

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