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The Southern Central Andes vertical axis tectonic rotations: relations with the deformation pattern

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ABSTRACT. Along the Central Andes a pattern of vertical axis tectonic rotations has been paleomagnetically identified. Such rotations are counterclockwise north of Arica Deflection (~19°S) and clockwise to the south. Different hypothesis and models have been proposed to explain the Central Andean Rotation Pattern (CARP). However, the CARP is a subject of ongoing debate. Recently, the quantity, quality, and geographic distribution of paleomagnetic data have expanded greatly. Such expansion has been accompanied by an increase in the knowledge of the deformation periods in the Andes, allowing a more detailed analysis of the temporal and spatial distribution of the detected rotations. We compiled and analyzed the available Cenozoic paleomagnetic data for the region extending between 19° and 27.5°S. The results suggest the possible existence of different rotational domains with distinct characteristics. We propose that in the Southern Central Andes, a close correlation would exist between the style and the temporal and spatial pattern of deformation and the amount of recorded vertical axis rotations. However, in order to further investigate such relationship, new paleomagnetic studies are necessary, particularly in the Eastern Cordillera domain, in Paleogene rocks cropping out in the Altiplano-Puna and in Neogene rocks of the forearc.

Keywords: Southern Central Andes, Paleomagnetic data, Deformation, Rotational domain, Cenozoic.

RESUMEN. Rotaciones tectónicas según ejes verticales en los Andes Centrales del Sur: relaciones con el patrón de deformación. En los Andes Centrales se ha identificado un patrón de rotaciones tectónicas según ejes verticales a través de estudios paleomagnéticos. Dichas rotaciones son en sentido antihorario al norte del codo de Arica (~19°S) y en sentido horario hacia el sur. Distintos autores han propuesto diferentes hipótesis y modelos para tratar de explicar el Patrón de Rotaciones de los Andes Centrales (PRAC). Sin embargo, el PRAC sigue siendo objeto de debate. Recientemente, la cantidad, calidad y la distribución geográfica de los datos paleomagnéticos ha aumentado de manera notable. Dicho incremento ha sido acompañado por un importante progreso del conocimiento de los períodos de deformación en los Andes, permitiendo un análisis más detallado de la distribución espacial y temporal de las rotaciones detectadas. En este trabajo se recopilan y analizan los datos paleomagnéticos cenozoicos disponibles para la región que se extiende entre los 19° y los 27,5°S. Los resultados obtenidos sugieren la posible existencia de distintos dominios rotacionales con diferentes características. Aparentemente existe una estrecha correlación entre el estilo y el patrón espacial y temporal de deformación y la magnitud de las rotaciones según ejes verticales. Sin embargo, para investigar de manera más detallada dicha relación, es necesario disponer de un mayor número de datos paleomagnéticos. Especialmente, deberían llevarse a cabo nuevos estudios paleomagnéticos de rocas paleógenas del Altiplano-Puna, de rocas paleógenas y neógenas de la Cordillera Oriental y de rocas neógenas del norte de Chile.

Palabras clave: Andes Centrales del Sur, Datos paleomagnéticos, Deformación, Dominios rotacionales, Cenozoico.

1. Introduction

Along the Central Andes a pattern of vertical axis tectonic rotations has been paleomagnetically identified (*e.g.,* Isacks, 1988; Beck, 1988; Dewey and Lamb, 1992; Somoza *et al.,* 1996). This Central Andean Rotation Pattern (CARP, Somoza *et al.,* 1996) is characterized by counterclockwise block rotations north of Arica Deflection (~19°S) (Gephart's symmetry plane; Gephart, 1994) and clockwise rotations to the south. Different hypothesis and models have been proposed to explain the CARP. Isacks (1988) presented a regional oroclinal model, suggesting that an ancient curvature of the margin was enhanced to accommodate along-strike gradient of Neogene horizontal-shortening in the eastern part of the Central Andes. However, Arriagada *et al.* (2008a) ran a 2-D map view restoration experiment using first-order constraints on the magnitude and age of shortening and rotations in the Central Andes, and concluded that the Arica Deflection formed during the Eocene-Oligocene as a consequence of differential shortening focused in the Eastern Cordillera. According to these authors, Neogene shortening in the sub-Andean zone only slightly enhanced the orogenic curvature of the Central Andes. Alternatively, models suggesting the existence of local block rotations in response to distributed shear have also been proposed (*e.g.,* Beck, 1988; Dewey and Lamb, 1992; Somoza *et al.,* 1996; Beck, 1998). Such distributed shear would result from partitioning of the oblique convergence vector between the Nazca and South American plates into coast parallel and perpendicular components. In such models, the Arica Deflection is considered a primary feature of the Andean chain. Somoza *et al.* (1996), while agreeing with the local block rotations model, proposed partitioning of the convergence vector into components perpendicular and parallel to ancient structural trends. Some authors (Beck *et al.,* 1994; Butler *et al.,* 1995) developed models which combine oroclinal bending and local block rotations, then each locality would record a local amount of rotation plus a regional (orocline related) rotation. Domino-style models that relate the rotations detected in northern Chile to observable faults in the forearc have also been published (*e.g.*, Forsythe and Chisholm, 1994; Randall *et al.,* 1996; Taylor *et al.,* 1998; Abels and Bischoff, 1999). However, Arriagada *et al.* (2003) found clockwise tectonic rotations of up to 65° within the forearc domain (Antofagasta region), which would have occurred mainly during the Incaic orogenic event of Eocene-Early Oligocene age. Taylor *et al.* (2005) also noted that many of the rotations detected in the forearc of northern Chile are particularly large and appear to record a rotational event older than those observed elsewhere in the Central Andes. They argued that such data define a domain marked by large clockwise crustal rotations related to late Paleocene-Early Eocene highly oblique convergence.

Most of the models developed to explain the CARP are of regional character (*e.g.,* Isacks, 1988; Beck, 1988; Beck *et al.,* 1994; Butler *et al.,* 1995) and do not consider the possible existence of different rotational domains in the Central Andes. Local models have also been proposed, but they are focused in the forearc (*e.g.,* Forsythe and Chisholm, 1994; Taylor *et al.,* 1998; Abels and Bischoff, 1999; Arriagada *et al.*, 2003; Taylor *et al.*, 2005). Recently, the quantity, quality, and geographic distribution of paleomagnetic data have expanded greatly (Richards *et al.,* 2004; Prezzi *et al.,* 2004; Arriagada *et al.,* 2006; Roperch *et al.,* 2006; Taylor *et al.,* 2007; Barke and Lamb, 2007; Arriagada *et al.,* 2008b; Maffione *et al.*, 2009). The increased paleomagnetic data set has been accompanied by an increase in the current knowledge of the deformation periods in the Andes (*e.g.*, Oncken *et al.,* 2006; Ege *et al.,* 2007; Hongn *et al.,* 2007; Barnes and Ehlers, 2009), allowing a more detailed analysis of the temporal and spatial distribution of the detected rotations. Considering all what has previously been mentioned, the major goal of our work is to further investigate the possible existence of different rotational domains with distinct characteristics, and their correlations with the deformation pattern and morphotectonic units identified in the Central Andes. Taking into account the scarce number of deformation and exhumation studies available for the Northern Central Andes (specially north of 19°) (*e.g.,* Barnes and Ehlers, 2009), we compiled the available cenozoic paleomagnetic data for the region extending between 19° and 27.5°S (Southern Central Andes).

2. Geologic setting

From W to E, the southern Central Andes can be divided into forearc, magmatic arc and backarc, which include different morphotectonic units (*e.g.,* Jordan *et al.*, 1983; Mpodozis and Ramos, 1990; Allmendinger *et al.*, 1997; Kley *et al.*, 1997). The forearc comprises the Coastal Cordillera, the Longitudinal Valley, the Chilean Precordillera and the Preandean depression. The magmatic arc is represented by the Western Cordillera (Fig. 1). The backarc consists of: the Bolivian Altiplano, the Puna, the Eastern Cordillera, the Subandean Ranges, the Santa Bárbara System and the Chaco foreland (Fig. 1).

The Coastal Cordillera is mainly built up by Jurassic to Lower Cretaceous basaltic to andesitic volcanic and plutonic rocks (Mpodozis and Ramos, 1990). The Chilean Precordillera consists of Paleozoic basement, Mesozoic and Cenozoic sedimentary and volcanic rocks, together with Upper Cretaceous to Paleogene plutons (*e.g.,* Scheuber *et al.,* 1994). The present day magmatic arc is represented by the Western Cordillera. Note that the magmatic arc of the Central Andes has been displaced to the east (~200 km) since the Early Jurassic, from the Coastal Cordillera to the Western Cordillera, defining four successive arc systems

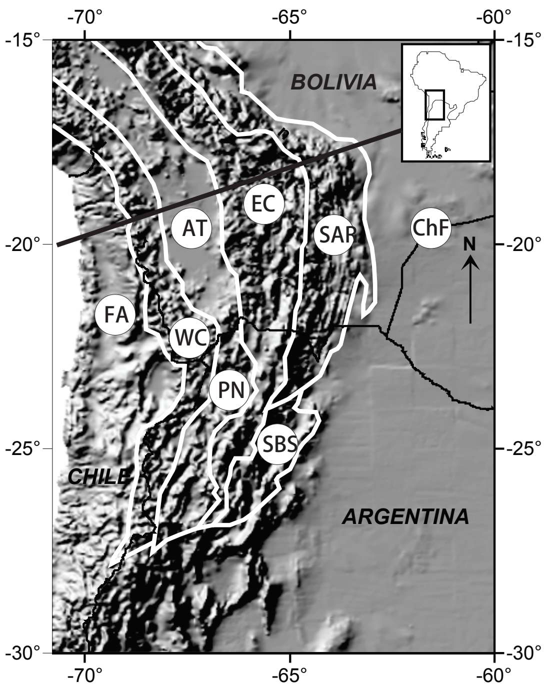


FIG. 1. Shaded relief topography (GTOPO30 digital elevation model) showing the different morphotectonic units identified in the Central Andes. Inset shows the study area with relation to South America. **FA:** forearc; **WC:** Western Cordillera; **AT:** Altiplano; **PN:** Puna; **EC:** Eastern Cordillera; **SAR:** Subandean Ranges; **SBS:** Santa Bárbara System; **ChF:** Chaco Foreland; **Bold black line:** Gephart's symmetry plane (Gephart, 1994).

(*e.g.,* Coira *et al.,* 1982; Scheuber *et al.,* 1994). The Altiplano-Puna plateau is a wide intramountainous basin with Mesozoic-Cenozoic sedimentary infill reaching thicknesses of up to 10 km (*e.g.,* Jordan *et al.,* 1983). The plateau overlies a 30° east-dipping segment of the subducted Nazca plate; north of 12°S and south of 28°S the slab is dipping gently and an internally drained plateau is absent (*e.g.,* Jordan *et al.,* 1983; Isacks, 1988), with absence of recent volcanic activity, while in the region of steep slab dip, basaltic-andesitic-dacitic volcanism is active along the arc, with local volcanic buildings present within the plateau. The volcanic arc and local volcanic centres have been active from Miocene to present time (*e.g.,* Stern, 2004; Schurr and Rietbrock, 2004). Since the Late Miocene an ignimbrite flare-up produced a major volcanic province, the Altiplano-Puna Volcanic Complex (de Silva, 1989; Coira *et al.,* 1993). The Altiplano-Puna is bounded by the Western Cordillera to the west and by the tectonic highlands of the Eastern Cordillera to the east. The Eastern Cordillera is mainly composed of Precambrian to Paleozoic rocks, covered by Cretaceous and Cenozoic sediments (*e.g.,* Giese *et al.*, 1999). Deformation began in the Late Eocene in the Eastern Cordillera (see below) and later in the Altiplano-Puna plateau. Contractional deformation going on since the Miocene, generated a fold-thrust belt system in the back arc region of the Central Andes, now represented by the Subandean Ranges and the Santa Bárbara System. The Subandean Ranges are a thin skinned fold and thrust belt, while the Santa Bárbara System is a thick skinned thrust belt (*e.g.*, Kley *et al.,* 1999).

Shortening in the Central Andes began in the Late Cretaceous at the present-day forearc (Arriagada *et al.*, 2003; Somoza and Zaffarana, 2008; Somoza, 2008) where deformation persisted till the Eocene (Incaic event). During the Eocene shortening propagated to the Eastern Cordillera (Oncken *et al.,* 2006; Hongn *et al.,* 2007). The following stage, occurring between 29 and 20 Ma, affected the whole Altiplano, the entire Eastern Cordillera, and expanded shortening southwards into the Puna domain (Oncken *et al.,* 2006; and references therein). In the period between 19 and 8 Ma, deformation increased in the Puna, slowed down in the Altiplano and began in the eastern flank of the plateau. In the final period (7-0 Ma) the Subandean fold and thrust belt developed (Oncken *et al.,* 2006). It propagated eastwards, somewhat discontinuously (Echavarría *et al.,* 2003).

Opposing models for surface uplift history of the Altiplano-Puna have been proposed, including: **1.** a rapid and recent rise whereby ~2.5 km of elevation was obtained between ~10-6 Ma (*e.g.,* Garzione *et al.*, 2006) and **2.** a slow and steady rise inferred to be commensurate with deformation that began between ~60-40 Ma (*e.g.,* McQuarrie *et al.*, 2005). Barnes and Ehlers (2009) evaluated both uplift models by synthesizing observations of the Altiplano-Puna lithosphere, the deformation history, sedimentation, exhumation, magmatism, uplift and fluvial incision. They concluded that the slow and steady uplift model is most consistent with available constraints. The rapid uplift model may be an overestimate, while a more protracted Cenozoic uplift history is tenable (Barnes and Ehlers, 2009).

3. Tectonic analysis

3.1. Paleomagnetic data

In order to achieve a better understanding of the CARP we have gathered the available Cenozoic paleomagnetic data for the Southern Central Andes (between 19° and 27.5°S) (Tables 1 and 2). We did not consider the data from the southeastern margin of the Puna (*e.g.*, Aubry *et al.,* 1996) as such rotations have been related to the Tucumán Transfer Zone (Jordan *et al.,* 1983; Allmendinger *et al.,* 1983; de Urreiztieta *et al.,* 1996). Transfer zones can give rise to large local components of rotation making the detection of possible regional ones difficult.

Reliability criteria have not been applied to the data. Beck (1998) applied his own reliability criteria to the paleomagnetic poles from the Central Andes and classified them into five different categories. He determined that there was no significant difference between the results obtained from all the data or only his best categories (IV and V). Rotations have been determined by comparing observed and expected directions (Demarest, 1983) derived from the reference mean paleopoles calculated by Besse and Courtillot (2002) (Tables 1 and 2). Each reference paleopole was used in accordance with the age of the magnetization of each Andean paleomagnetic data. It is important to mention that Taylor *et al.* (2005) highlighted that no major difference in the pattern of rotations for the past 100 My arose when using global data sets (Besse and Courtillot, 2002) or dominantly South American data (Lamb and Randall, 2001) as reference.

The Cenozoic Central Andean paleomagnetic data are divided here into two age groups (for the Neogene and Paleogene) (Tables 1 and 2, respectively). The spatial distribution, sense, and amount of rotations for the CARP are shown in figure 2. In general, Neogene data show a larger number of insignificant rotations than Paleogene data. Rotations are considered insignificant when the correspondent confidence interval is larger than the rotation value (*e.g.,* 08±15°). Most Paleogene data in figure 2 arise from northern Chile (forearc zone), while most Neogene data correspond to southern Bolivia and northwestern Argentina (Western Cordillera to Subandean Ranges, Fig. 2). As previously documented by other authors (*e.g.*, Prezzi and Alonso, 2002), it can be observed that rotations recorded in Paleogene rocks are conspicuously larger than the ones recorded by Neogene rocks. No correlations are found between latitude of sampling sites and amount of rotation within each morphotectonic unit. In order to further investigate possible relationships between age and amount of rotation, we plotted the age of magnetization *versus* the amount of rotation (with the corresponding confidence intervals) for the different morphotectonic units (Fig. 3). In the case of the forearc, Neogene rotations are not significant, while rocks older than 50 Ma record rotations remarkably larger than those reported by 25-50 Ma rocks. The few data available from the Eastern Cordillera appear to present an analogous pattern, with rocks older than 40 Ma showing larger rotation than Neogene rocks. On the other hand, Paleogene and Neogene rotations detected in the Altiplano-Puna are of similar amount and comparable to Neogene rotations registered in the Eastern Cordillera and the Subandean Ranges (Table 1) (Figs. 3 and 4). Only one Neogene sampled zone in the Altiplano (Roperch *et al.,* 2000) and one Paleogene sampled area in the Puna (Prezzi and Alonso, 2002) exhibit large rotation (~40°) (Tables 1 and 2). Roperch *et al.* (2000) proposed that the large rotation showed by Lower Miocene Rondal volcanics reflects just local conditions, related to activity in both the San Vicente thrust and the Pululus fault zone, two tectonic features surrounding the Rondal locality. Prezzi and Alonso (2002) sampled a narrow stripe (~1.5 km wide and 6 km long) of the Salta Group (Cretaceous-Eocene) (Marquillas *et al.,* 1993), which is longitudinally bounded by two faults (Alonso, 1986), suggesting that the large rotation detected is of local origin.

TABLE 1. NEOGENE VERTICAL AXIS ROTATIONS PALEOMAGNETICALLY DETECTED IN THE CENTRAL ANDES.

	Zone	Age M	Location Latitude °S	Longitud °W	R±ΔR	Reference
Quehua, Bolivia	AP	10	19.9	67	18 ± 9.4°	MacFadden *et al.* (1995)
North Uyuni, Bolivia	AP	20	20	67	2.8 ± 18.1°	Roperch *et al.* (2000)
Altiplano volcanics and intrusions, Bolivia	AP	10	20.1	67.5	12.5 ± 13.9°	Lamb (2001)
Lipez Sediments, Bolivia	AP	20	21.8	66.5	10.8 ± 17.7°	Roperch *et al.* (2000)
Lipez Rondal volcanics, Bolivia	AP	20	21.8	66.5	40.3 ± 12.2°	Roperch *et al.* (2000)
Los Frailes, Bolivia	EC	7	19.5	66.3	9.9 ± 7.7°	Barke *et al.* (2007)
Inchasi, Bolivia	EC	5	19.7	65.3	-1.1 ± 5.6°	MacFadden *et al.* (1993)
Camargo Syncline, Bolivia	EC	25	21.75	65.2	6.3 ± 4.7°	Lamb (2001)
Cerdas, Bolivia	EC	16	21.8	66.3	12.4 ± 8.1°	MacFadden *et al.* (1995)
Quebrada Honda, Bolivia	EC	13	22	65.5	19.9 ± 5.6°	MacFadden *et al.* (1990)
Laguna de Pozuelos Basin, Argentina	EC	12	22.4	66	7.6 ± 7.8°	Prezzi *et al.* (2004)
Miomará Fm., Argentina	EC	10	23	65.38	15.1 ± 19.3°	Maffione *et al.* (2009)
Río Yacones, Argentina	EC	8	24.6	65.5	24.1 ± 27.2°	Viramonte *et al.* (1994)
Azapa, Perú	FA	25	19.1	70.1	-1.4 ± 9.1°	Roperch *et al.* (2006)
Río Loa, Chile	FA	11	22	68.5	2.8 ± 11.6°	Somoza *et al.* (1999)
Lower El Loa Fm., Chile	FA	20	22.4	68.4	4.5 ± 7°	Somoza and Tomlinson (2002b)
Upper El Loa Fm., Chile	FA	10	22.5	69.1	-1.6 ± 5.2°	Somoza and Tomlinson (2002b)
Paciencia Group, Chile	FA	25	22.8	68.4	25.7 ± 12.1°	Hartley *et al.* (1992)
M01, Chile	FA	10	27.2	71	-5.7 ± 5.4°	Arriagada *et al.* (2006)
Upper Miocene ignimbrites, Argentina	PU	10	22.5	66.7	-0.3 ± 9.5°	Somoza *et al.* (1996)
San Juan de Oro Basin, Argentina	PU	13	22.5	66.5	5.2 ± 6.5°	Prezzi *et al.* (2004)
Morro Blanco, Argentina	PU	10	23	66.5	-0.9 ± 4.8°	Prezzi and Alonso (2002)
Loma Blanca Mine, Argentina	PU	7	23.1	66.4	12.7 ± 9°	Prezzi and Alonso (2002)
Chorrillos, Argentina	PU	10	24.3	66.4	19.3 ± 12.4°	Coutand *et al.* (1999)
Siete Curvas, Argentina	PU	24	24.6	67.1	14.3 ± 4.5°	Prezzi and Vilas (1998)
Juncal Grande, Argentina	PU	12	25.8	67.6	3.0 ± 7.4°	Prezzi (2001)
Monteagudo, Bolivia	SA	25	19.95	63.9	8 ± 6.9°	Lamb (2001)
Ingre, Bolivia	SA	25	20.73	63.85	14 ± 18.3°	Lamb (2001)
Río Salado, Bolivia	SA	25	21.25	64.3	4.2 ± 11.5°	Lamb (2001)
Bermejo, Bolivia	SA	25	22.4	64.5	38 ± 21.6°	Lamb (2001)
La Porcelana, Argentina	SA	7	22.9	64.2	14.8 ± 6.6°	Reynolds *et al.* (2000)

Zone indicates morphotectonic unit: **AP:** Altiplano; **EC:** Eastern Cordillera; **FA:** forearc; **PU:** Puna; **SA:** Subandean Ranges. Age indicates the approximate age of the magnetization. Location indicates the geographic coordinates of the respective sampling area. **R±ΔR** are rotation (clockwise positive) and confidence interval in direction space (Demarest, 1983) using as reference the paleopoles determined by Besse and Courtillot (2002).

3.2. Structural development

Deformation along the Central Andes occurred during various periods of shortening and plateau development. Oncken *et al.* (2006) compiled sources that described in detail the age relationships between growth deposits and structures based on stratigraphic and structural analysis, isotopic age dating, fission track analysis, and estimates of the duration of shortening based thereon. Figure 5 summarizes the current knowledge of deformation periods in the Southern Central Andes in three maps which show

TABLE 2. PALEOGENE VERTICAL AXIS ROTATIONS PALEOMAGNETICALLY DETECTED IN THE CENTRAL ANDES.

	Zone	Age Ma	Location Latitude °S	Longitud °W	R ± ΔR	Reference
El Molino Fm., Maicoma, Bolivia	AP	70	19,7	67	0.0 ± 10°	Richards *et al.* (2004)
El Molino Fm., Chita, Bolivia	AP	70	20,1	66,9	-12.0 ± 9.5°	Richards *et al.* (2004)
Santa Lucía Fm., Maragua, Bolivia	EC	60	19,1	65,4	17.9 ± 6.0°	Richards *et al.* (2004)
El Molino Fm., La Palca, Bolivia	EC	70	19,5	65,8	43 ± 5.8°	Richards *et al.* (2004)
Santa Lucía Fm., Otaví, Bolivia	EC	60	20,1	65,2	0.2 ± 9.1°	Richards *et al.* (2004)
Santa Lucía Fm., Camargo North, Bolivia	EC	60	20,6	65,2	24.2 ± 8.9°	Richards *et al.* (2004)
Potoco (Camargo) Fm., Camargo, Bolivia	EC	50	20,8	65,2	26.5 ± 7.2°	Richards *et al.* (2004)
Cachi-Cerro Tintín, Argentina	EC	40	25,1	66,1	42.3 ± 4.3°	Coutand *et al.* (1999)
Moreta/Candado Fms, Argentina	EC	30	22,7	65,6	30.1 ± 23.9°	Maffione *et al.* (2009)
Camiña, Perú	FA	50	19	69,45	4.3 ± 18.5°	Roperch *et al.* (2006)
Purilactis Fm., Chile	FA	70	22,5	68,45	41.8 ± 5.1°	Somoza and Tomlinson (2002b)
San Pedro Fm., Chile	FA	30	22,66	68,17	12.1 ± 7.6°	Somoza and Tomlinson (2002b)
Purilactis Group, Chile	FA	70	22,7	68,3	51.3 ± 9.2°	Hartley *et al.* (1992)
Cinchado Fm and Intrusives, Chile	FA	60	23,1	69,2	37.7 ± 12.2°	Arriagada *et al.* (2003)
Totola Fm., Chile	FA	60	23,2	68,6	46.6 ± 12.5°	Arriagada *et al.* (2000)
Lican/Totola Fm., Chile	FA	60	23,3	69,7	62.8 ± 8.8°	Arriagada *et al.* (2000)
Cinchado Fm and Intrusives, Chile	FA	60	23,4	69,2	43.8 ± 9.1°	Arriagada *et al.* (2003)
CV3, Chile	FA	60	25,12	69,75	37.1 ± 10.7°	Arriagada *et al.* (2006)
Chile-Alemania Fm., Catalina, Chile	FA	50	25,2	69,7	39.8 ± 9.8°	Dupont-Nivet *et al.* (1996)
CV4, Chile	FA	60	25,78	69,5	27.9 ± 11.7°	Arriagada *et al.* (2006)
Chile-Alemania Fm., Q. Juncal, Chile	FA	50	25,8	69,5	27.4 ± 18.4°	Dupont-Nivet *et al.* (1996)
Cerro Valiente (central domain), Chile	FA	60	26,35	69,4	50.0 ± 12.7°	Randall *et al.* (2001)
J13, Chile	FA	35	26,48	69,43	23.9 ± 5.4°	Arriagada *et al.* (2006)
PD2, Chile	FA	50	26,55	69,29	0.7 ± 32.2°	Arriagada *et al.* (2006)
P6, Chile	FA	40	26,66	69,42	-0.8 ± 10.1°	Arriagada *et al.* (2006)
P1, Chile	FA	60	26,67	69,56	-7.3 ± 21.6°	Arriagada *et al.* (2006)
P3, Chile	FA	55	26,76	69,74	34.9 ± 23.0°	Arriagada *et al.* (2006)
P2, Chile	FA	70	26,8	69,61	-0.9 ± 17.5°	Arriagada *et al.* (2006)
Copiapina Grannitic Pluton, Chile	FA	50	26,8	69,9	37.8 ± 9.4°	Taylor *et al.* (2007)
Copiapina Grannitic Pluton, Chile	FA	66	26,8	69,9	51.3 ± 11.3°	Taylor *et al.* (2007)
P7, Chile	FA	60	26,89	69,49	48.1 ± 15.8°	Arriagada *et al.* (2006)
CV2, Chile	FA	60	26,97	69,99	41.8 ± 17.3°	Arriagada *et al.* (2006)
Cerrillos Fm., Q. Cóndores, Chile	FA	55	27,33	70,2	42.9 ± 6.3°	Taylor *et al.* (2007)
Cabeza de Vaca Pluton, Chile	FA	62	27,5	70,1	35.8 ± 8.4°	Taylor *et al.* (2007)
Cerrillos Fm., Carrizalillo, Chile	FA	55	27,57	70,18	55.8 ± 6.8°	Taylor *et al.* (2007)
Coranzulí, Argentina	PU	52	23,1	66,4	44.5 ± 10.2°	Prezzi and Alonso (2002)
Lower Pozuelos Fm., Argentina	PU	30	24,7	67,2	1.2 ± 7.5°	Coutand *et al.* (1999)
Quiñoas Fm., Antofalla, Argentina	PU	30	25,5	68	13.3 ± 8.1°	Arriagada *et al.* (2008b)

Zone indicates morphotectonic unit: **AP**: Altiplano; **EC:** Eastern Cordillera; **FA** forearc; **PU** Puna. Age indicates the approximate age of the magnetization. Location indicates the geographic coordinates of the respective sampling area. R±ΔR are rotation (clockwise positive) and confidence interval in direction space (Demarest, 1983) using as reference the paleopoles determined by Besse and Courtillot (2002).

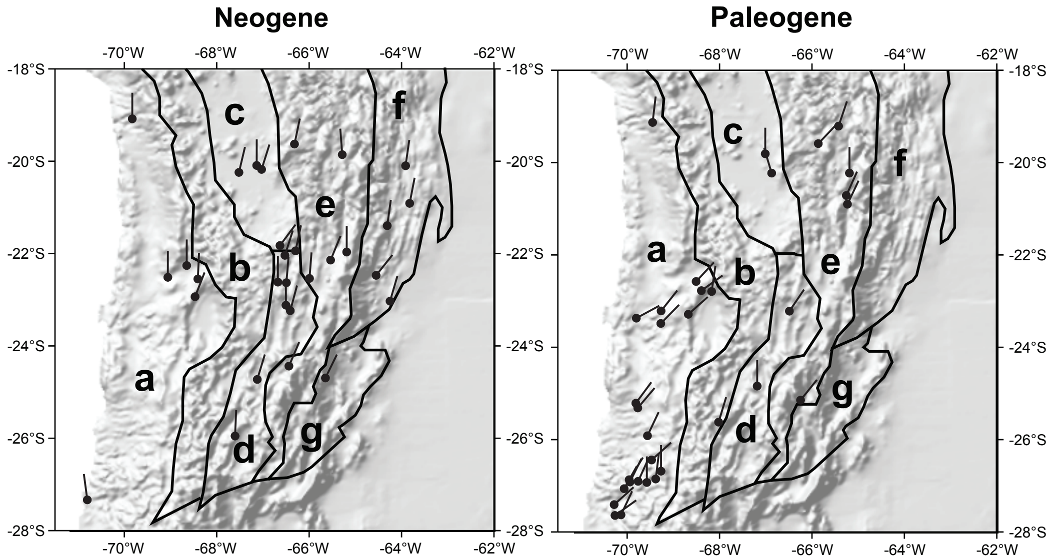
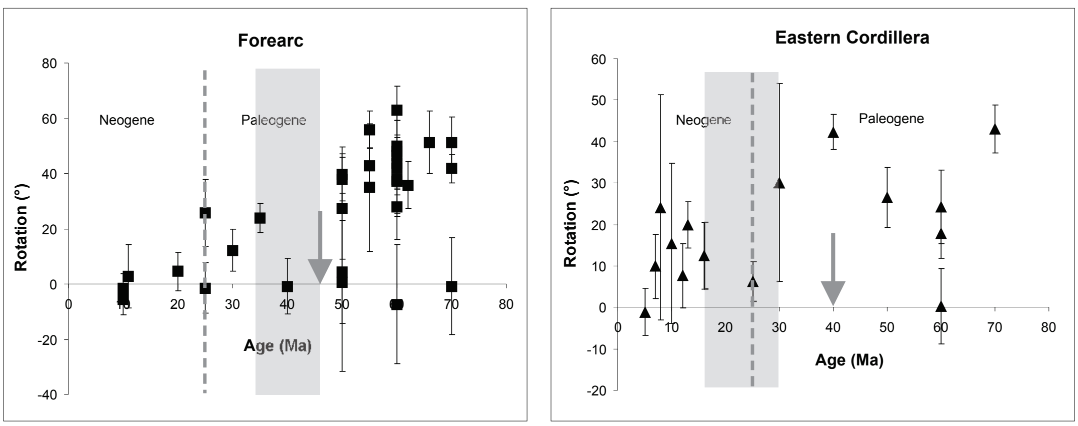


FIG. 2. Shaded relief topography (GTOPO30 digital elevation model) showing the spatial distribution, sense, and amount of rotations paleomagnetically detected along the Southern Central Andes. Circles show sampling areas, rotations are indicated by black lines. **a.** forearc; **b.** Western Cordillera; **c.** Altiplano; **d.** Puna; **e.** Eastern Cordillera; **f.** Subandean Ranges; **g.** Santa Bárbara System.



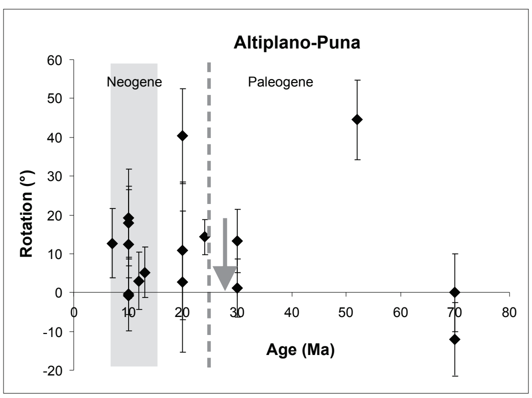


FIG. 3. Age of magnetization *versus* recorded rotation (with the corresponding confidence intervals) for the different morphotectonic units. **Gray dashed line:** indicates Neogene-Paleogene limit; **gray arrow:** indicates onset of deformation; **light gray shaded zone:** indicates period of maximum shortening rate (Oncken *et al.,* 2006). The data plotted comes from Tables 1 and 2.

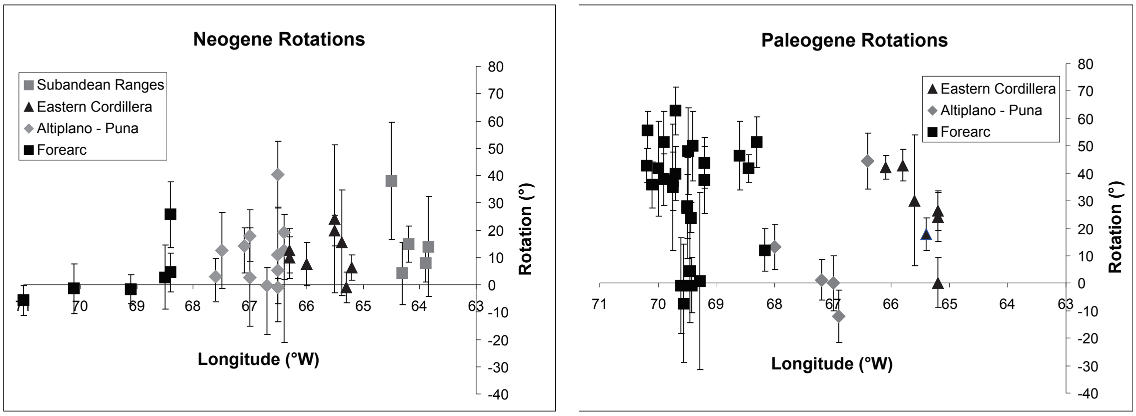


FIG. 4. Longitude of sampled area *versus* recorded rotation (with the corresponding confidence intervals) for Neogene and Paleogene paleomagnetic data. The data plotted comes from Tables 1 and 2.

different time windows (Deformation Data Bank in Oncken *et al.,* 2006; Ege *et al.,* 2007; Hongn *et al.,* 2007; Somoza, 2008; Somoza and Zaffarana, 2008). Such maps depict an evolution with an initial stage (60-30 Ma) involving only two domains of shortening, one in the Chilean Precordillera and the other in the Eastern Cordillera. This stage includes a main period of transpressional deformation, the Incaic event. The next stage of shortening (29-12 Ma) propagated through the entire orogen (Western Cordillera, Altiplano, Puna, Eastern Cordillera and Santa Bárbara System); only the Subandean Ranges remained unaffected (Fig. 5). During the final period (11-0 Ma) deformation ceased in the Altiplano and northern Puna, continued in the still active southern Puna and shifted to the eastern flank of the plateau, with the development of the Subandean Ranges fold and thrust belt. This low resolution image of deformation was complemented by a detailed analysis of shortening across the plateau at 21°S±1° by Oncken *et al.* (2006). They used the available data on horizontal shortening (*e.g.*, Kley and Monaldi, 2002; Echavarría *et al.,* 2003; Elger *et al.,* 2005) and recently published ages from synkinematic growth deposits and unconformities (*e.g.*, Horton, 2005; Ege, 2004). They collected such data for all individual structures building each morphotectonic unit of the Southern Central Andes. These authors considered the results from 21°S as representative for the entire plateau between 15 and 23°S for fluctuations over long time spans (>5-10 My), as smaller fluctuations may reflect local variations in the activity of individual structures along strike. Oncken *et al.* (2006) documented that significant Cenozoic deformation began in the Chilean Precordillera at ~46 Ma and was active until ~35 Ma. They identified two main stages of shortening across the Altiplano, one in the Oligocene (between ~35-30 and ~25-20 Ma) (Barnes and Ehlers, 2009) and the other in the Middle to Late Miocene (between 20 and 10 Ma), with maximum shortening rates between 15 and 8 Ma. In contrast to this evolution, the Eastern Cordillera deformed over a longer time span, starting at 40 Ma. Deformation spread from its center to the flanks, with maximum shortening rates between ~33-30 and ~20-17 Ma (Barnes and Ehlers, 2009). Deformation in the Eastern Cordillera almost ceased between 12 and 8 Ma, with the formation of the San Juan de Oro surface and the initiation of the Subandean fold and thrust belt (Gubbels *et al.,* 1993; Somoza *et al.,* 2002; Somoza and Tomlinson, 2002a; Oncken *et al.,* 2006). In coincidence with these observations, Arriagada *et al.* (2008a) noted that Incaic deformation concentrated along the Chilean Precordillera and the Eastern Cordillera of southern Bolivia and northwestern Argentina. Deformation in the Chilean Precordillera began in the Late Cretaceous and peaked between ~45 and ~32 Ma, while shortening in the Eastern Cordillera occurred mainly in the Paleogene-Early Miocene, starting at ~45-40 Ma (Arriagada *et al.*, 2008a).

Variations in Nazca and South America relative motions during the Cenozoic have been suggested to exert a primary influence on the deformation pattern of the Central Andes (*e.g.,* Somoza, 1998). Several authors (*e.g.,* Pardo-Casas and Molnar,

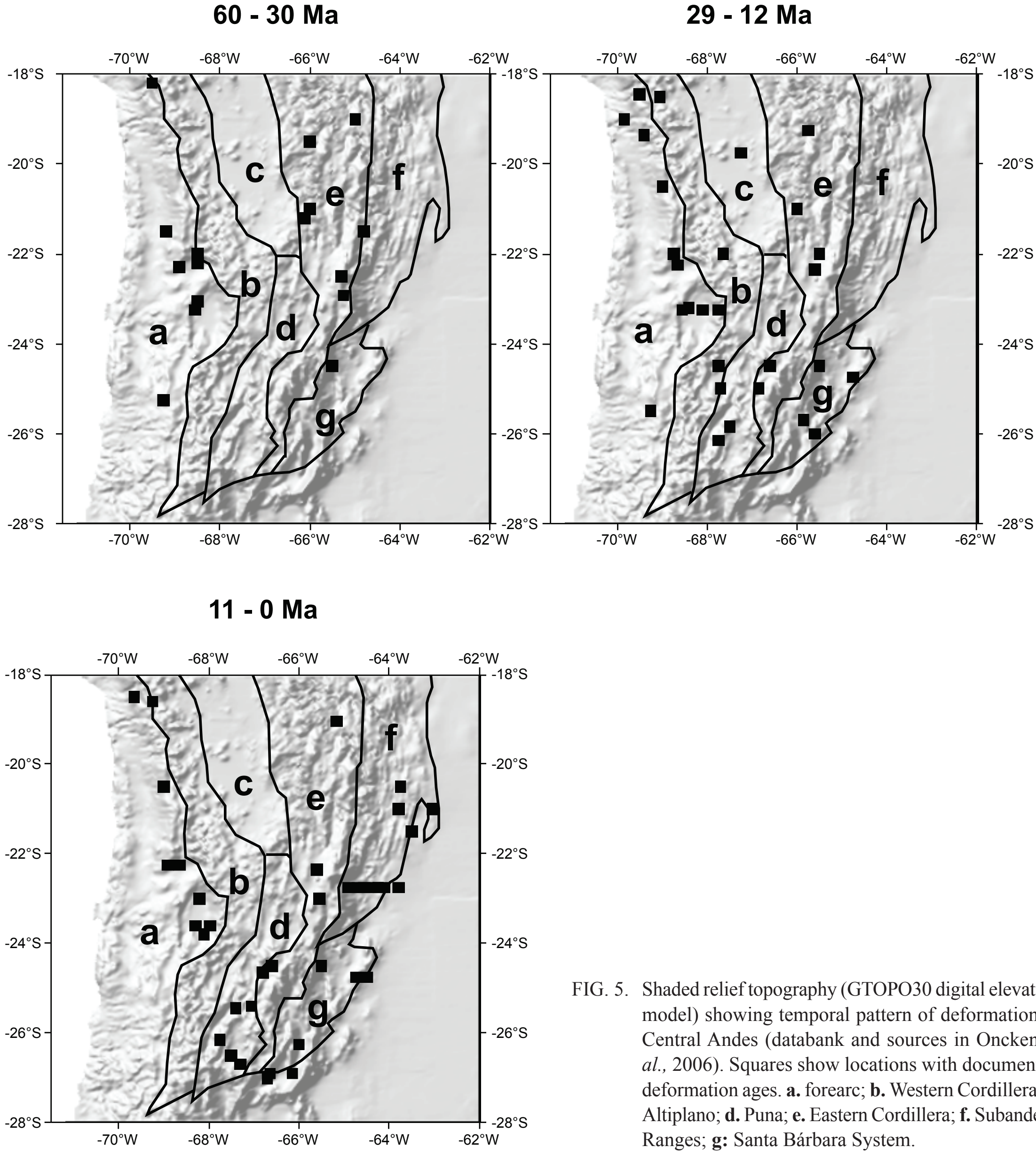


FIG. 5. Shaded relief topography (GTOPO30 digital elevation model) showing temporal pattern of deformation in Central Andes (databank and sources in Oncken *et al.,* 2006). Squares show locations with documented deformation ages. **a.** forearc; **b.** Western Cordillera; **c.** Altiplano; **d.** Puna; **e.** Eastern Cordillera; **f.** Subandean Ranges; **g:** Santa Bárbara System.

1987; Somoza, 1998; Sdrolias and Müller, 2006) determined the existence of two periods of rapid convergence (~15 cm/yr) during the Cenozoic: between ~55 and 40 Ma and between ~28 and 10 Ma. They also noted that convergence was dextral and moderately oblique in Chile (~40° at 22°S) during the Early Cenozoic between ~50 and 28 Ma. At ~28 Ma a change to roughly E-W direction took place; a further change between ~20 and 16 Ma was observed, but it could reflect problems with the reconstruction for the Farallon-Pacific pair or accommodation of a major plate reorganization in the southeast Pacific (Somoza, 1998). Oncken *et al.* (2006) performed a time series analysis of various features of the Central Andes. They correlated the plate kinematic parameters with the evolution of shortening in the upper plate and observed that neither the convergence rate between Nazca and South America, nor convergence obliquity seemed to be related to the evolution of the shortening rate in the Central Andes. Oncken *et al.* (2006) proposed that only a weak correlation between an increased shortening rate and enhanced convergence rate may exist for the initial stage of deformation. However, onset of deformation both in the Chilean Precordillera and in the Eastern Cordillera took place during the period of Early Cenozoic oblique convergence (~50-28 Ma), which is contemporaneous with the Incaic transpressional event (Arriagada *et al.*, (2008a). On the other hand, deformation in the Altiplano began later, when convergence was ~E-W.

This temporal distribution of deformation across the Southern Central Andes would provide an explanation for the large rotations registered during the Paleogene in the forearc and the Eastern Cordillera. Rotations in rocks older than 50 Ma from northern Chile are larger (typically between 30° and 60°) (Fig. 3). Taylor *et al.* (2005) proposed that they would be related to the period of maximum obliquity of Farallón-South America plate convergence. They determined that the data define an anomalous domain, where markedly large rotations seem to predate rotations registered elsewhere in the Central Andes. Paleogene Eastern Cordillera data appear to define another domain of large rotations (typically between 25° and 40°). Such rotations are detected in rocks carrying magnetizations older than 40 Ma (Fig. 3). The large rotations detected in rocks older than 50 Ma from the northern Chile domain predate the onset of deformation in the Chilean Precordillera proposed by Oncken *et al.* (2006) (~46 Ma), whereas those detected in the Eastern Cordillera may have initiated in concert with deformation in that region (~40 Ma). These temporal relationships would suggest that in northern Chile and Eastern Cordillera, Paleogene rocks would have been exposed to longer and/or more intense periods of transpressional deformation, and consequently would have undergone larger rotations than those of the Neogene (Fig. 3). The existence of more intense Paleogene deformation in the Eastern Cordillera is supported by the results of the 2-D map view model developed by Arriagada *et al.* (2008a). Arriagada *et al.* (2008a) stated that the large magnitude of the CARP is better explained if a largest amount of shortening in the Central Andes is considered during the Eocene-Oligocene, with the Incaic event of deformation being important in the Chilean Precordillera, but with major shortening concentrated along the Eastern Cordillera. The exhumation history summarized by Barnes and Ehlers (2009) for the Central Andes supports the existence of longer periods of deformation in northern Chile and Eastern Cordillera. In convergent orogens exhumation histories are assumed to be a proxy for deformation, by considering that the onset of the recorded, rapid erosional exhumation is a signature of the deformation that generates the topography and relief necessary to produce such erosion (Barnes and Ehlers, 2009). Barnes and Ehlers (2009) proposed that exhumation in the Chilean Precordillera began in the Paleocene to mid-Eocene (~60-40 Ma), with exhumation also recorded in the mid-Miocene (~15 Ma). The Eastern Cordillera experienced two phases of exhumation; in Bolivia, during the Late Eocene-Oligocene (~45-40 to ~20 Ma) and Middle-Late Miocene to Recent (~15 to 0 Ma), and in Argentina, during the Middle Eocene-Oligocene (~50 to 30 Ma) and Early Miocene (23 to 15 Ma) (Barnes and Ehlers, 2009). On the other hand, in the Altiplano-Puna, where deformation began later (~at 29 Ma) during E-W convergence, and maximum shortening rates were attained between 15 and 8 Ma, Paleogene and Neogene rocks recorded rotations of similar amount (~10°) (Fig. 3). This can be interpreted in terms that, in the Altiplano-Puna, Paleogene and Neogene rocks would have been exposed to deformation periods of similar duration and/or intensity or were exposed to a unique Neogene period of deformation, with minor strike slip component. Regarding exhumation, in the Altiplano-Puna it began in the Earliest Oligocene (~30 Ma) and continued locally into the Middle-Late Miocene (~18 Ma) or into the Late Miocene-Early Pliocene (~5 Ma) (Barnes and Ehlers, 2009).

In order to further investigate the above proposed correlation between the temporal and spatial pattern of deformation and the amount of recorded vertical axis rotations, each data set corresponding to the different morphotectonic units (forearc, Altiplano-Puna and Eastern Cordillera) was analyzed applying the circular von Mises distribution (von Mises, 1918). The choice of the circular theoretical distribution to be used is not very important for small natural samples of geological orientations, considering that one distribution may converge towards another, as extreme values of their parameters are considered (Borradaile, 2003). The von Mises distribution is a continuous probability distribution on the circle. It may be thought of as a close approximation to the wrapped normal distribution, which is the circular analogue of the normal distribution. The von Mises distribution is more mathematically tractable than the wrapped normal distribution and is the preferred distribution for many applications (Borradaile, 2003). Furthermore, documentation and tests are more developed for this distribution (Borradaile, 2003). It is used in applications of directional statistics, where a distribution of angles is found which is the result of the addition of many small independent angular deviations, such as grain orientation in a granular material. This distribution has two parameters: θ is the mean paleomagnetic direction and k indicates the dispersion of the data. θ is a measure of location (the distribution is clustered around θ), k is a measure of concentration. If k is zero, the distribution is uniform, and for small k, it is close to uniform. If k is large, the distribution becomes very concentrated about the angle θ with k being a measure of such concentration.

In our statistical analysis, for each morphotectonic unit, we calculated the parameters θ_n and k_n and θ_p and k_p corresponding to rotations recorded by Neogene and Paleogene rocks respectively (Table 3). Then, the statistical test of Watson (1983) was used for each morphotectonic unit to determine if both data sets (Neogene and Paleogene rotations) have a common mean direction, *i.e.,* if they come from the same or from different populations (Table 3). The Neogene parameters for the forearc are: θ_n= 3.97° and k_n=31.7. The Paleogene parameters for the forearc are: θ_p= 32.83° and k_p=9.07. The mean of the Paleogene rotations is considerably larger than the mean of the Neogene rotations. Moreover, the Paleogene rotations show more dispersion than the Neogene rotations. At 95% confidence level, the Paleogene and Neogene data have distinct mean directions, indicating that they would come from different populations (Table 3). In the case of the Eastern Cordillera, the Neogene parameters are: θ_n= 11.81° and k_n=58.79, while the Paleogene parameters are: θ_p= 26.39° and k_p=17.81. The mean of the Paleogene data is considerably larger than the mean of the Neogene data. Again, the Paleogene data show more dispersion than the Neogene data. The same statistical test (Watson, 1983) was applied, resulting that at 95% confidence level, the Paleogene and Neogene rotations have distinct mean directions, indicating that they would come from different populations (Table 3). For the Altiplano-Puna, the Neogene parameters are: θ_n= 11.39° and k_n=38.04, while the Paleogene parameters are: θ_p= 9.06° and k_p=9.06. Both means are similar, with Paleogene data showing more dispersion than Neogene data. At 95% confidence level, the test of Watson (1983) indicates that the Paleogene and Neogene rotations have the same mean directions, demonstrating that they come from the same population (Table 3).

TABLE 3. VON MISES (1918) PARAMETERS AND WATSON (1983) STATISTICAL TEST FOR EACH MORPHOTECTONIC UNIT AND FOR EACH TIME PERIOD CONSIDERED.

	θ	*k*	R	Watson (1983) statistical test	χ^2 (95%)
Forearc					
Neogene	3.97°	31.7	0.9842	1.6875	0.8231
Paleogene	32.83°	9.07	0.9449		
Eastern Cordillera					
Neogene	11.81°	58.79	0.9915	0.8613	0.8231
Paleogene	26.39°	17.81	0.9719		
Altiplano-Puna					
Neogene	11.39°	38.04	0.9822	0.0115	0.8231
Paleogene	9.06°	9.06	0.9447		

R indicates the corresponding resultant vector. Watson (1983) statistical test indicates the corresponding value of such test.
χ^2 (95%) indicates the corresponding value of the chi-squared distribution at 95% confidence level.

Recapitulating, our statistical analysis indicates that Paleogene and Neogene rocks cropping out in the forearc recorded vertical axis tectonic rotations which belong to different data populations. The same result was obtained for the Eastern Cordillera rotations. On the other hand, in the case of the Altiplano-Puna, Paleogene and Neogene rocks recorded vertical axis tectonic rotations which come from the same data population. These results might indicate that the rotations detected during different time spans in distinct morphotectonic units would respond to the style and spatial and temporal pattern of deformation. That is to say, our results agree with the existence of different rotational domains and would suggest that along the Southern Central Andes a close correlation would exist between the different deformation periods and the amount of recorded vertical axis rotations. However, in order to further investigate such relationship, new paleomagnetic data are necessary. Particularly, in the Eastern Cordillera domain the scarce number of available paleomagnetic data and the large confidence interval of many of the recorded rotations, impose an important drawback to the robustness of our analysis. Likewise, new paleomagnetic data of Paleogene rocks cropping out in the Altiplano-Puna are required to further validate our interpretations. Neogene rocks of the forearc should also be sampled, considering the limited number of data available. Such new paleomagnetic data would permit to gain a deeper insight into the issue of Neogene *versus* Paleogene deformation and vertical axis tectonic rotations. In addition, detailed structural studies should also be conducted to achieve a better knowledge of the relations between vertical axis tectonic rotations and amount of shortening, timing, style of deformation and structural trends in the Central Andes.

4. Conclusions

The compilation and analysis of the Southern Central Andes Cenozoic paleomagnetic data permit to conclude that:

a. Paleogene and Neogene rotations detected in the Altiplano-Puna would be of similar amount and comparable to Neogene rotations registered in the Eastern Cordillera and the Subandean Ranges.

b. Rotations registered by Paleogene data in northern Chile and Eastern Cordillera are larger than the ones recorded by Neogene rocks in these regions and elsewhere.

c. In northern Chile and Eastern Cordillera, Paleogene rocks would have been exposed either or both to longer and/or more intense periods of transpressional deformation, and consequently would have undergone larger rotation than Neogene rocks.

d. In the Altiplano-Puna, Paleogene and Neogene rocks would have been exposed to deformation periods of similar duration and/or intensity with minor strike slip component and accordingly depict similar amount of rotation.

e. In the Southern Central Andes, a close correlation would exist between the style and the temporal and spatial activity of deformation and the amount of recorded vertical axis rotations.

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