



THE SOUTHERN CENTRAL ANDES VERTICAL AXIS TECTONIC ROTATIONS: RELATIONS WITH THE DEFORMATION PATTERN

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Resumen

En los Andes Centrales se ha identificado un patrón de rotaciones tectónicas (PRAC) según ejes verticales a través de estudios paleomagnéticos. Diferentes hipótesis han sido propuestas tratando de explicar el PRAC, sin embargo el debate continúa. Recientemente, la cantidad, calidad y 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, 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 existencia de distintos dominios rotacionales con diferentes características. En particular, las rocas paleógenas del norte de Chile y de la Cordillera Oriental habrían registrado rotaciones grandes. Aparentemente existe una estrecha correlación entre el patrón espacial y temporal de deformación y la magnitud de las rotaciones según ejes verticales. Sin embargo, para profundizar en la investigación de dicha correlación nuevos estudios paleomagnéticos son necesarios, especialmente en el dominio de la Cordillera Oriental, en rocas paleógenas aflorantes en el Altiplano-Puna y en rocas neógenas del antearco.

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.



Introduction

Along the Central Andes a pattern of vertical axis tectonic rotations has been paleomagnetically identified (*e.g.* Isacks, 1988; Beck, 1988). This Central Andean Rotation Pattern (CARP, Somoza *et al.*, 1996) is characterized by counterclockwise block rotations north of Arica Deflection ($\sim 19^\circ$ S) 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. Alternatively, models suggesting the existence of local block rotations in response to distributed shear have also been proposed (*e.g.* Beck, 1988; Somoza *et al.*, 1996). 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. Some authors (*e.g.* 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.* 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; 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.* 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 (*e.g.* 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; 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).

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). Rotations have been determined by comparing observed and expected directions (Demarest, 1983) derived from the reference mean paleopoles calculated by Besse and Courtillot (2002). The cenozoic Central Andean paleomagnetic data are divided here into two age groups (for the Neogene and Paleogene). The spatial distribution, sense, and amount of rotations for the CARP are shown in Figure 1. In general, neogene data show a larger number of insignificant rotations than paleogene data. Most paleogene data in Figure 1 arise from northern Chile (forearc zone), while most neogene data correspond to southern Bolivia and northwestern Argentina (Western Cordillera to Subandean Ranges, Figure 1). 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. In order to further investigate possible relationships between age and amount of rotation, we plotted the age of magnetization vs. the amount of rotation (with the corresponding confidence intervals) for the different morphotectonic units (Figure 2). 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 (Figure 2).

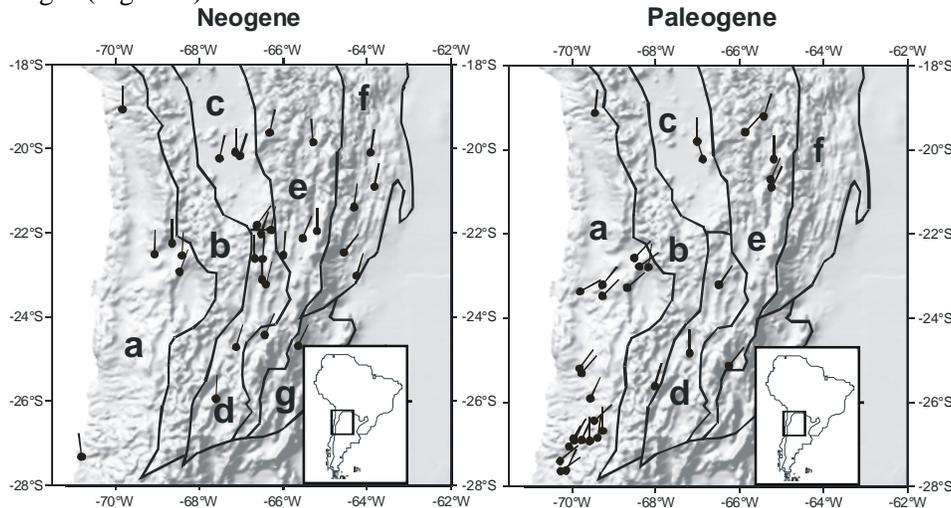


Figure 1: Shaded relief topography (GTOPO30 digital elevation model) showing the spatial distribution, sense, and amount of rotations paleomagnetically detected along the Southern Central Andes. Circles show sampling areas, rotations are indicated by black lines, a: forearc, b: Western Cordillera, c: Altiplano, d: Puna, e: Eastern Cordillera, f: Subandean Ranges, g: Santa Bárbara System.

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. Oncken *et al.* (2006) proposed 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. 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 $21^{\circ}\text{S} \pm 1^{\circ}$ by Oncken *et al.* (2006). They used the available data on horizontal shortening and recently published ages from synkinematic growth deposits and unconformities. 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 (Oncken *et al.*, 2006). In coincidence with these observations, Arriagada *et al.* (2008) 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.*, 2008).

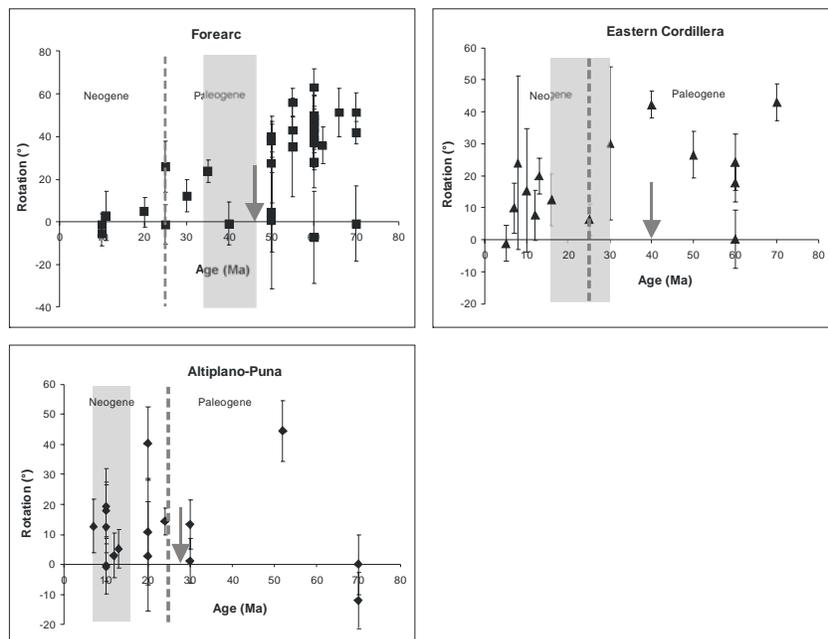


Figure 2: Age of magnetization vs. recorded rotation (with the corresponding confidence intervals) for the different morphotectonic units. Gray dashed line: indicates Neogene-Paleogene limit, gray arrow: indicates onset of deformation, light gray shaded zone: indicates period of maximum shortening rate (Oncken *et al.*, 2006).

Analysis and conclusions

The 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°) (Figure 2). 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 (Figure 2). 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 (Figure 2). 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.* (2008). Arriagada *et al.* (2008) 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. 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 Eo-Oligocene (~45-40 to ~20 Ma) and mid-late Miocene to recent (~ 15 to 0 Ma), and in Argentina, during the mid Eo-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°) (Figure 2). 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 mid-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 von Mises distribution is a continuous probability distribution on the circle. This distribution has two parameters: $\bar{\theta}$ is the mean paleomagnetic direction and k indicates the dispersion of the data. In our statistical analysis, for each morphotectonic unit, we calculated the parameters $\bar{\theta}_n$ and k_n and $\bar{\theta}_p$ and k_p corresponding to rotations recorded by neogene and paleogene rocks respectively. 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. The neogene parameters for the forearc are: $\bar{\theta}_n= 3.97^\circ$ and $k_n=31.7$. The paleogene parameters for the forearc are: $\bar{\theta}_p= 32.83^\circ$ and $k_p=9.07$. At 95% confidence level, the paleogene and neogene data have distinct mean directions, indicating that they would come from different populations. In the case of the Eastern Cordillera, the neogene parameters are: $\bar{\theta}_n= 11.81^\circ$ and $k_n=58.79$, while the paleogene parameters are: $\bar{\theta}_p= 26.39^\circ$ and $k_p=17.81$. 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. For the Altiplano-Puna, the neogene parameters are: $\bar{\theta}_n= 11.39^\circ$ and $k_n=38.04$, while the paleogene parameters are: $\bar{\theta}_p= 9.06^\circ$ and $k_p=9.06$. 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.

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 vs. 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.

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