Paleomagnetism in the Precordillera of northern Chile (22°30’S): implications for the history of tectonic rotations in the Central Andes

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Abstract

Widespread clockwise rotations in Mesozoic and Lower Tertiary rocks of northern Chile have been interpreted as the sum of two rotational events separated in time: an early rotation related to local deformation plus a late rotation related to wholesale rotation of northern Chile linked to Late Cenozoic oroclinal bending in the Central Andes. In this paper we report new paleomagnetic data from Cretaceous, upper Oligocene and Miocene sedimentary rocks in the Precordillera of northern Chile. The results suggest that all these rocks acquired their remanence at or close to the time of deposition. The lack of rotation in undeformed lower Miocene strata clearly indicates that clockwise rotations found in underlying, faulted and folded Cretaceous rocks were completed before the Late Cenozoic. Results from nearby localities in deformed upper Oligocene strata would argue for little (<5°) rotation since the late Oligocene. Data from widely separated Miocene localities covering an area of about 5000 km² in the Calama basin strongly suggest that northern Chile did not undergo significant wholesale rotation during the Late Cenozoic. This, together with previous paleomagnetic evidence against Neogene rigid-body-like rotation of the southern Peruvian forearc, suggests that the curved shape of the Central Andean forearc was not significantly enhanced during the Late Cenozoic. By inference, all of the rotation in most Mesozoic and Lower Tertiary rocks of northern Chile was accomplished in the Cretaceous and/or Early Cenozoic, when the locus of deformation in the Central Andes was localized in the present forearc region. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Central Andes; paleomagnetism; rotation; Chile; Precordillera

1. Introduction

Paleomagnetic studies in northern Chile have shown the common presence of clockwise rotations in Mesozoic and Lower Tertiary rocks [1–8]. Although there is general agreement that these rotations constitute an important component of the regional deformation, their origin remains poorly understood and is a matter of ongoing debate (e.g. [9–11]). A major unknown is the relative contributions of local block rotations and...
large-scale processes, such as oroclinal bending, in the end product rotation record. During the Cretaceous and Paleogene, northern Chile was the focus of arc magmatism and deformation, which included local block rotations [2,4,5,7,8]. However, in the Late Cenozoic, deformation in northern Chile was relatively minor and instead major crustal deformation occurred behind the arc, in the foreland belt of Bolivia and northwest Argentina. It has been suggested that northern Chile in the Late Cenozoic experienced a wholesale clockwise rotation to accommodate southward decreasing Neogene shortening in the eastern foreland belt of the orogen [12]. This has led many workers to suggest that the paleomagnetically observed rotations are the sum of an early, Cretaceous and/or Paleogene component due to local deformation, and a later, Neogene component related to passive clockwise rotation of the entire region (e.g. [9–14]). Constraining the timing of rotations is therefore important for understanding the influences of local and orogen-scale deformational events in the tectonic evolution of northern Chile in particular and of the Central Andes in general.

Based on paleomagnetic constraints, we show that clockwise tectonic rotations observed in Cretaceous rocks from the Cordillera de Domeyko (Fig. 1) were completed before the deposition of lower Miocene rocks. This result is incompatible with the hypothesis of significant wholesale rotation of northern Chile during the Late Cenozoic, and suggests that rotations detected in rocks from the modern Central Andean backarc are related to causes other than Late Cenozoic rotational bending.

2. Tectonic setting and regional geology

Upper Paleozoic to Triassic volcanoplutonic complexes constitute the main pre-Andean (pre-Jurassic) outcrops in the Precordillera of northern Chile [15]. The Mesozoic and Cenozoic Andean cycle was linked to three distinct tectono-magmatic episodes which young episodically eastward [16–18]. During the Jurassic and Early Cretaceous, arc magmatism was located along the coast of Chile and backarc extension prevailed in the area of the Cordillera de Domeyko [16]. The first important episode of contractional deformation occurred during the Late Cretaceous [19], after which the magmatic arc developed in the Precordillera itself, immediately west of the Cordillera de Domeyko, and continued there through to the early Oligocene [17,18]. Contractional deformation in northern Chile culminated with the widespread Incaic orogenic phase in the middle Eocene [18,20,21]. In the Miocene magmatic activity again shifted eastward to its present position along the Chilean international border, and deformation became concentrated in Bolivia and northwest Argentina (i.e. the present backarc region).

Most sampling for this study was performed in the northern part of two morphotectonic units of northern Chile: the Cordillera de Domeyko and the Cordillera de la Sal (Fig. 1, see also [22]). The Cordillera de Domeyko is a ~60 km wide, N–S oriented range mainly composed of fault bounded blocks of Paleozoic rock [20]. A thick succession...
of Cretaceous to Eocene rocks (Purilactis Formation and other units [7,23]) is in fault contact with the Paleozoic along the eastern border of the range. Stratigraphic relations and radiometric data constrain the deformation in the Cordillera de Domeyko to the Eocene [7,20,23]. The Cordillera de la Sal is a narrow (5–10 km wide), SSW–NNE trending foldbelt located to the east of the Cordillera de Domeyko, in the Salar de Atacama depression [24] (see Fig. 1 for location). The stratigraphy of this range is dominated by the upper Oligocene–lower Miocene Tambores and San Pedro formations [24,25]. These units overlie with angular unconformity the Cretaceous to Eocene succession on the east side of the Cordillera de Domeyko, and are in turn unconformably over-

Fig. 2. The northern part of Cordillera de Domeyko and Cordillera de la Sal showing sampling locations. U1, U2, and U3 in the legend depict the main angular unconformities in the area. U3 is present only in the Salar de Atacama basin, whereas U2 corresponds to the regional Incaic orogenic phase. Black squares and triangle show location of sites of Arriagada et al. [7] and Hartley et al. [2] respectively. Magnetostratigraphic sections of Kape [40] are located in Rio Grande and Quebrada Tambores (QT).
laid by upper Miocene ignimbrites and gravels in the study area (Fig. 2), and by 17 ± 2 Ma lavas 7 km to the northeast of the village of Rio Grande [22]. These relations suggest that the first deformation affecting the Tambores and San Pedro formations occurred at or close to the early Miocene. Northwest of the Salar de Atacama basin, the faulted and folded rocks of the Cordillera de Domeyko are overlain by gently west-dipping Miocene strata of the El Loa Formation, which constitute part of the Calama basin fill [26,27]. Farther to the northwest, widespread flat-lying and largely unfaulted upper Miocene and Pliocene strata and ignimbrites in the Calama basin (Fig. 1) indicate that deformation in this region was minor and localized during much of the Late Cenozoic [28,29].

3. Paleomagnetic study

3.1. Methods

Most samples were collected from Cretaceous and lower Miocene rocks in the western border of Cerros de Tuina (Fig. 2), and farther east from upper Oligocene strata in the Salar de Atacama basin. Each paleomagnetic site for the upper Oligocene and lower Miocene rocks involves four or more samples taken from a single (or several adjacent) bed(s), in this way the paleomagnetic mean directions for each formation were obtained by averaging site-mean directions. Cretaceous rocks were sampled in three localities, in each of which we took one to three samples from several stratigraphic horizons along a continuous section. In this case the time-averaged direction for each section was obtained after averaging their single-stratigraphic-level paleomagnetic directions. This latter procedure was also followed when sampling two sections of upper Miocene–Pliocene strata west of Calama (Fig. 1). Almost all the samples were oriented using magnetic and solar compasses, both methods yielding similar values. Geographical coordinates and basic structural information for the sampling locations are given in Table 1.

Specimens from all samples were subjected to progressive thermal and/or alternating field (AF) demagnetization. Results were analyzed using principal component analysis [30], components showing a maximum angular deviation (MAD) > 10° were rejected from further study. The bulk magnetic mineralogy of some Cretaceous samples was explored by observing both hysteresis loops and acquisition of isothermal remanent magnetization. Rotations, inclination flattening, and their confidence intervals (Table 2), were calculated in direction space [31,32].

3.2. Reference poles

Whenever possible we used reference poles from stable South America. Paleomagnetic poles from other plates were transferred to South American coordinates in order to resolve time intervals for which autochthonous paleopoles are not available. The reference poles in the footnote of Table 2 are those required according to the magnetization ages we interpret for the rocks involved in this study. Those of Cenozoic age are compromise solutions to resolve the lack of a complete apparent polar wander (APW) curve for South America.

An early Miocene (ca. 20 Ma) paleopole for the African plate was calculated by combining the entries M4, P19, M5, and P22 in Ubangoh et al. [33]. The result was transferred to South America using the anomaly 6 reconstruction of Cande et al. [34]. An Oligocene (≈30 Ma) pole position was obtained by transferring to South American coordinates the ca. 30 Ma North American paleopole reported by Diehl et al. [35]. This transfer was achieved using a 30 Ma reconstruction interpolated from the rotations listed by Müller and Smith [36]. A Late Cretaceous (ca. 75 Ma) paleopole was calculated by averaging three 85–70 Ma pole positions from Brazilian alkaline complexes [37] and a 80–65 Ma paleomagnetic pole from basalts in Patagonia [38].

3.3. Sampling

Ninety-nine fine-grained paleomagnetic samples from two sections of palustrine carbonate facies in the upper part of the El Loa Formation were
taken near Quebrada Opache, 15 km west-southwest of Calama (Fig. 1). Fifty-four samples from 28 decimeter-scale thick beds were taken from a gently southeast dipping, 22 m thick section (PH section). Forty-five samples from 16 decimeter-scale thick beds were collected from a subhorizontal, 27 m thick section (BB section). In both these sections at least two samples were taken from each bed studied. Laser fusion $^{40}$Ar/$^{39}$Ar dating on biotites from an ash in the lower part of the palustrine section yielded an age of 5.76 ± 0.10 Ma [26].

Fine- to medium-grained, reddish to brown sandstones of the Cretaceous Purilactis Formation were drilled at three localities on the western border of the Cerros de Tuina (Fig. 2), where the formation crops out in the footwall blocks of Eocene reverse faults. The sampled stratigraphic

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Paleomagnetic results</th>
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<tbody>
<tr>
<td><strong>Upper El Loa Formation (upper Miocene–Pliocene)</strong></td>
<td></td>
</tr>
<tr>
<td>PH$^a$</td>
<td>22°28.7′</td>
</tr>
<tr>
<td>BB</td>
<td>22°30.0′</td>
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<tr>
<td>Mean$^b$</td>
<td>18 beds</td>
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<td><strong>Lower El Loa Formation (lower Miocene)</strong></td>
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<tr>
<td>YA1</td>
<td>22°23.7′</td>
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<td>YA2</td>
<td>22°23.7′</td>
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<tr>
<td>YA3</td>
<td>22°23.6′</td>
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<td>22°23.5′</td>
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<td>TN1</td>
<td>22°28.5′</td>
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<tr>
<td>TN2</td>
<td>22°28.5′</td>
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<tr>
<td>TN3</td>
<td>22°28.4′</td>
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<tr>
<td>Mean$^b$</td>
<td>9 sites</td>
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<tr>
<td><strong>San Pedro Formation (upper Oligocene)</strong></td>
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</tr>
<tr>
<td>PN1</td>
<td>22°38.9′</td>
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<tr>
<td>PN2$^a$</td>
<td>22°38.9′</td>
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<td>PN3</td>
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<td>Mean$^b$</td>
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<td><strong>Purilactis Formation (Cretaceous) at Cerros de Tuina</strong></td>
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<tr>
<td>PRA-E</td>
<td>22°30.9′</td>
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<tr>
<td>PRA-W</td>
<td>22°30.9′</td>
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<tr>
<td>Mean$^b$</td>
<td>10 beds</td>
</tr>
<tr>
<td>PR97</td>
<td>22°28.6′</td>
</tr>
<tr>
<td>PR99</td>
<td>22°31.2′</td>
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Lat., Long.: site or section location; n (N/n): number of samples for the site (number of stratigraphic levels/number of samples for the section) involved in statistics; Decl. G, Incl. G: declination and inclination of paleomagnetic vector in geographical coordinates; $\alpha_{95}$: cone of 95% confidence level around mean direction [46]; $k$: precision parameter [46]; BP: strike and dip of bedding plane, with strike in degrees to the East and dip measured 90° clockwise from strike; Decl. S, Incl. S: declination and inclination referred to paleohorizontal after applying BP values.

$^a$ Mean direction involves normal and reversed polarities.

$^b$ Structurally corrected directions from the preceding sites (or single beds) are averaged. The result is given as normal polarity vector.

on biotites from an ash in the lower part of the palustrine section yielded an age of 5.76 ± 0.10 Ma [26].

Fine- to medium-grained, reddish to brown sandstones of the Cretaceous Purilactis Formation were drilled at three localities on the western border of the Cerros de Tuina (Fig. 2), where the formation crops out in the footwall blocks of Eocene reverse faults. The sampled stratigraphic
packages have thicknesses of 20, 40, and 80 m in locations PRA (36 samples from 10 beds), PR97 (19 samples from 17 beds), and PR99 (26 samples from nine beds), respectively. Samples from location PRA came from both limbs of a decameter-scale, open anticline. In Table 1 we have listed results from the east (PRA-E) and west (PRA-W) limbs separately.

Unconformably overlying pre-Tertiary rocks and Eocene structures on the western border of the Cerros de Tuina lies a ~150 m thick succession of conglomerates and reddish to tan sandstones, siltstones, and mudstones constituting the lower part of the El Loa Formation. Seventy-eight samples were taken from nine sites in Quebrada Yalqui (sites YA1–YA4 in Fig. 2), Quebrada del Yeso (sites YA5 and YA6), and Quebrada Tuina (sites TN1–TN3). In these cases each site comprises stratigraphically closely spaced fine-grained beds which are separated from the next site by metric to decametric packages of coarse-grained layers. $^{40}$Ar/$^{39}$Ar dating on biotites from a stratiﬁcally located 10 m above site YA6 gave an age of 19.62 ± 0.36 Ma [26], placing the sampled strata in the lower Miocene. The outcrops of the Cretaceous (PR97 section) and lower Miocene (TN sites) rocks in Quebrada Tuina have physical continuity, allowing us to constrain the rotation history for two separate periods of time for a single structural block.

About 30 km to the southeast of the preceding locations we took 53 samples (10 sites, PN in Fig. 2) from mudstones and siltstones of playa-lake deposits of the San Pedro Formation. Each site comprises four to eight samples taken from one to three successive, meter to decimeter thick beds. Sites PN1–PN7 are located in the village of Rio Grande (Fig. 2), whereas samples of sites PN8–PN10 belong to outcrops on both sides of the Grande river at San Bartolo. The unit dips toward the northwest in both zones, and the integrated sampling covers about 150 m of stratigraphic section. K–Ar dating on tuffs in the San Pedro Formation have given ages ranging from 25 to 28 Ma (upper Oligocene) [22,25].

3.4. Results

3.4.1. Upper El Loa Formation (PH and BB sections)

Natural remanent magnetization (NRM) intensities ranged from 0.3 to 35 mA/m. Sixty samples showed either unstable behavior during demagnetization or poor statistical deﬁnition of the remanence and were rejected from further study. Thirty-nine samples from 18 stratigraphic levels (15 from section PH, and three from section BB) showed a high unblocking temperature and moderate coercivity component of magnetization, with magnetite being the likely carrier (Fig. 3a). At least three polarity zones are present in section PH (from bottom to top: N-R-N), and two polar-

| Rock unit (label) | Ref. pole (Ma) | $R \pm \Delta R$ | $F \pm \Delta F$
|-------------------|---------------|----------------|----------------|
| Upper El Loa Fm. (PH+BB) | 10 | $-3.5 \pm 6.6$ | $6.0 \pm 5.6$
| Lower El Loa Fm. (TN+YA) | 20 | $-0.4 \pm 6.8$ | $6.9 \pm 5.5$
| San Pedro Fm. (PN) | 30 | $5.4 \pm 7.8$ | $12.0 \pm 8.3$
| Purilactis Fm. (PRA) | 75 | $38.0 \pm 7.3$ | $12.0 \pm 6.5$
| Purilactis Fm. (PR97) | 75 | $39.5 \pm 5.5$ | $9.3 \pm 5.2$
| Purilactis Fm. (PR99) | 75 | $44.5 \pm 5.9$ | $6.0 \pm 5.5$
| Purilactis Fm. (PRA) | 115 | $27.1 \pm 6.9$ | $2.0 \pm 6.7$
| Purilactis Fm. (PR97) | 115 | $28.6 \pm 5.0$ | $-0.7 \pm 5.4$
| Purilactis Fm. (PR99) | 115 | $33.6 \pm 5.4$ | $-4.0 \pm 5.5$

$^{1}$'Label' is the code used to identify the sites or locations in Table 1. 'Ref. pole' is the reference pole used to compare the datum; 10 Ma: 87.4°S, 339.2°E, $\alpha_{05} = 5.1^\circ$ [43]; 20 Ma: 84.5°S, 294.7°E, $\alpha_{05} = 2.4^\circ$ (see Section 3.2); 30 Ma: 82°S, 297°E, $\alpha_{05} = 4.5^\circ$ (see Section 3.2); 75 Ma: 80.6°S, 344.2°E, $\alpha_{05} = 4.4^\circ$ (see Section 3.2); 115 Ma: 87°S, 159°E, $\alpha_{05} = 3.8^\circ$ [47]. $R$ is rotation (positive is clockwise); $F$ is inclination flattening (positive denotes shallower than expected); $\Delta R$ and $\Delta F$ are 95% confidence level of $R$ and $F$, respectively.
ity zones in section BB, where only directions from the reversed zone are suitable for tectonic analysis. The tilt-corrected directions from 18 beds yield a positive, class C reversal test [39]. The formation-mean direction is indistinguishable from the expected late Miocene direction at the sampling locality (Table 2), indicating these rocks did not undergo vertical axis rotation.

3.4.2. Lower El Loa Formation (YA and TN sites)

The intensity of NRM ranged from 10 to 100 mA/m. A component of magnetization directed to the origin was observed in most samples after removal of a soft magnetization coincident with the present-day field (Fig. 3b). Maximum unblocking temperatures in the range of 570–600°C and nearly complete demagnetization at 60–80 mT suggest that magnetite is the main carrier of the remanence. Normal and reversed polarities found in nine sites give a positive, class C reversal test [39]. Comparison with the expected early Miocene magnetic field reveals that these rocks did not undergo tectonic rotation (Fig. 3d).

3.4.3. San Pedro Formation (PN sites)

The intensity of NRM in rocks from this unit ranged from 15 to 60 mA/m. Samples from one site did not yield coherent results and were re-
jected from further study. A shallow, northward directed component of magnetization was isolated in the remaining sites. In some of them this component has maximum unblocking temperatures of about 580°C and median destructive fields of ca. 25–35 mT (e.g. specimen PN44FX in Fig. 3c), consistent with magnetite as the principal carrier. However, thermal and AF demagnetization indicated an important contribution of hematite in other sites (e.g. specimen PN14T in Fig. 3c), in some cases constituting the main carrier of remanence (e.g. specimen PN1T in Fig. 3c).

The structural attitudes in the sampling sites are not sufficiently different to apply a statistically significant tilt test. However, the inclination of the time-averaged direction is very shallow in field coordinates (11°), but it becomes comparable with that of the expected inclination when restored to the paleohorizontal (Fig. 3d). This strongly suggests that the isolated remanence is pre-tilting, and probably primary in origin. Although almost all the sampled beds show normal polarities (Table 1), the stratigraphic thickness covered by sampling (~150 m) is enough to argue that PSV must be acceptably averaged out. The unit-mean direction is not very different from the expected direction, the main discrepancy residing in its lower inclination (Fig. 3d, Table 2) which could be a result of post-depositional compaction. The small declination anomaly (5° clockwise) is not statistically significant, although its sense is coherent with the regional tendency in the southern Central Andes.

The formation-mean direction we obtained (Table 1) is almost identical to those computed by Kape [40] from mostly fine-grained rocks of this unit at Rio Grande and Quebrada Tambores (~20 km SW of Rio Grande, Fig. 2). In contrast, Hartley et al. [2] obtained different, highly dispersed results from coarse- to medium-grained sandstones in Rio Grande. We favor our data and those of Kape, both comprising fine-grained rocks, as the best determination of the late Oligocene magnetic field in the area. These three results are tightly clustered, suggesting the possibility of a small (~5°), barely significant rotation affecting the sampled San Pedro strata. Nevertheless, it must be taken into account that accurate determination of small rotation is precluded by uncertainties in the definition of the South American APW.

3.4.4. Purilactis Formation (PRA, PR97 and PR99 localities)

The intensity of NRM ranged from 10 to 30 mA/m. Rock magnetism results and high stability to AF suggest that hematite is almost the only carrier of remanence in these samples. Thermal demagnetization isolated a well-defined (MAD < 5°) component of magnetization of normal polarity in all the samples. Bulk magnetic susceptibility decreased progressively during thermal treatment, typically reaching 80% (65%) of the initial value after heating at 450°C (650°C). The NRM of samples from the eastern limb of the anticline at locality PRA (PRA-E section) is almost entirely constituted by a single component showing an unblocking temperature spectrum from 620°C to more than 680°C (Fig. 4a). Most samples from sections PR97, PR99, and PRA-W carry a component of magnetization which unblocks over a range of temperatures distributed between ca. 300°C to as high as 660°C (Fig. 4b,c). A positive fold test [41] is observed after unfolding the PRA anticline. This, and the improved clustering shown by the three location mean directions after their restoration to the paleohorizontal (Fig. 4e), strongly indicates that the isolated components are pre-tilting, and probably of Cretaceous age.

In some cases (most cases in the PR99 section) the trajectory of the thermally distributed component did not trend toward the origin (e.g. Fig. 4b,d), revealing the presence of an additional component. This behavior does not correlate with the susceptibility changes mentioned above. A clear resolution of this higher temperature component was difficult due to a combination of factors such as its relatively low intensity (probably <10% of the NRM) and its partial overlap with the thermally distributed component. Nevertheless, its direction was acceptably defined in three samples of the PR99 section (e.g. specimen PR68TX in Fig. 4d), and was assumed to be coincident with stable endpoints observed between 650 and ca. 680°C in another four samples of this
The mean direction of this high temperature magnetization is very close (slightly shallower) to the thermally distributed component, suggesting it is also pre-tilting. Since both the components present in location PR99 support the same tectonic interpretation, only the values derived from the statistically better defined thermally distributed component are used in the tectonic interpretations below.

Mpodozis et al. [23] suggested that the Purilactis Formation was deposited during the Cretaceous Normal Superchron (see also [7]), which agrees with the exclusive presence of normal polarities observed in this study. The Cretaceous reference poles in Table 2 imply a significant southward drift of South America during the Cretaceous Superchron. The lack of precise dating of the Purilactis Formation means that the appropriate reference pole is either the 115 Ma or $V_{75}$ Ma paleopole in Table 2, or a pole position located midway between them. Nevertheless, results in Table 2 indicate that, irrespective of the reference pole used, these rocks underwent fairly uniform, moderate magnitude clockwise vertical axis rotations. It is worth noting that the paleomagnetic inclinations of the locality means fit better with the mid-Cretaceous expected direction.

3.4.5. Summary and tectonic significance of results

Time-averaged paleomagnetic directions from upper Miocene–Pliocene rocks in Quebrada Opache and lower Miocene strata west of Cerros de Tuina are concordant with expected paleofields. These results, together with recently reported evidence of no rotation in an upper middle Miocene section at Lasana [29] (see Fig. 1 for location), strongly suggest that the Calama basin did not undergo vertical axis rotation during the Late Cenozoic.

The results from upper Oligocene strata of the San Pedro Formation would argue for little rotation since the late Oligocene. The origin of any small rotation in these rocks could be related to the early Miocene closure of the basin by contractional deformation [2]. In any case, the upper temporal bound for rotation in this part of the Cordillera de la Sal is late Miocene, as dictated by unrotated upper Miocene ignimbrites that unconformably rest on the San Pedro strata at San Bartolo [29].
Previous paleomagnetic studies in Cretaceous to Paleocene rocks along the eastern border of the Cordillera de Domeyko have detected clockwise rotations, varying from 20° to 65° [2,7] (see Figs. 1 and 2 for location of their sampling sites). Our results show the occurrence of clockwise rotations in faulted and folded Cretaceous rocks along the western border of Cerros de Tuina, indicating that the rotational deformation is not restricted to the eastern border of the Cordillera de Domeyko but likely also affected the blocks of Paleozoic rock farther west, in the core of the range. The lack of rotation in lower Miocene rocks that unconformably overlie Cretaceous and older units in the Cerros de Tuina suggests that rotations here, and perhaps elsewhere in the region, were completed entirely before the Late Cenozoic. We suggest that the bulk of rotation in most localities from the Cordillera de Domeyko region is related to the Incaic orogenic phase (Eocene). Nevertheless, a small amount of younger rotation could have been superimposed in those localities affected by the early Miocene? contractual deformation of the San Pedro basin.

4. Implications for the timing of tectonic rotations

Both the structural and topographic trends in the Central Andes encompass the curved shape of the South American continental margin. Albeit the topography is largely a product of Late Cenozoic mountain building [12], the structural trends result from a protracted Mesozoic-Cenozoic tectonic evolution, characterized by the progressive migration of both the magmatic foci and the deformation front toward the foreland (e.g. [16,42]). The first contractual events of the Andean Cycle occurred in both northern Chile and the coastal areas of southern Peru (i.e. the present forearc) during Cretaceous to Eocene times. By then, most areas in the modern backarc functioned as a foreland basin to the developing orogen, although important Paleogene deformation seems to have occurred locally in Bolivia as well. By the Late Cenozoic, the locus of contractional deformation shifted eastward to Bolivia and northwest Argentina, whereas the deformation in the modern forearc was localized and of much lesser magnitude. The oroclinal model of Isacks [12] proposes that along strike variation in the amount of Neogene crustal shortening (with a maximum in Bolivia) increased the seaward concavity of the continental margin. In this way, his model predicts a wholesale counterclockwise rotation of the Peruvian forearc and a blocklike clockwise rotation of most of northern Chile. In contrast, our paleomagnetic data from the Calama basin indicate that an area of about 5000 km² in the Precordillera of northern Chile did not undergo paleomagnetically detectable rotation during the Late Cenozoic, providing evidence against wholesale rotation of northern Chile during this time interval. This, together with the presence of unrotated Upper Tertiary localities in the southern Peruvian forearc and in northernmost Chile [43,44], strongly suggests that the curvature of the continental margin did not undergo observable modification by rotation and oroclinal bending during the Late Cenozoic. Since any large-scale rotation in the eastern part of the orogen should have been recorded in the western areas (see Fig. 12 in Kley [45]), the lack of significant bending in the forearc implies that the external belt in Bolivia has not undergone rotational bending either. Consequently, all of the paleomagnetically observed rotation in rocks from the modern backarc should reflect the amount of local rotational deformation in areas of variable extent [29,44].

Structurally constrained paleomagnetic studies in Mesozoic and Lower Tertiary rocks from northern Chile have shown that Cretaceous and/or Early Cenozoic deformation in the sampling areas provoked vertical axis rotations [2,4,5,7,8,10]. Our results demonstrate unambiguously that rotations in folded and faulted Cretaceous rocks of the Cerros de Tuina were completed before deposition of practically undeformed lower Miocene strata. The perspective that the forearc did not undergo significant wholesale rotation during the Late Cenozoic suggests that most of the paleomagnetically detected rotations from Mesozoic and Lower Tertiary rocks in this region may be interpreted exclusively in terms of pre-Miocene rotational deformation. This, and the
discussion above, favors the contention that significant vertical axis rotations in most areas of the orogen would have locked when local deformation shut down [29,43,44]. In this context, most time-averaged paleomagnetic directions from Central Andean rocks may indicate the sense and amount of rotation related to upper crustal deformation at the sampling locality.

5. Conclusions

Paleomagnetic results from the studied sector of the Precordillera of northern Chile demonstrate that vertical axis rotations of faulted and folded Cretaceous rocks were accomplished prior to the deposition of undeformed and unrotated lower Miocene strata. Additionally, results from neighboring localities in deformed upper Oligocene strata would reflect only a very small (~5°) rotation since the late Oligocene.

Available paleomagnetic data from the Neogene Calama basin indicate that no significant wholesale rotation of northern Chile occurred during the Late Cenozoic. This, coupled with paleomagnetic data from the southern Peruvian forearc, suggests that the curvature of the Central Andean forearc has not been significantly enhanced during the Neogene.

From the above it is inferred that the bulk of rotation observed in most Mesozoic and Lower Tertiary rocks of the present Central Andean forearc was accomplished before the Late Cenozoic, when this region was the main locus of deformation in the orogen. Nevertheless, some small component of rotation may have been added to those few areas of the forearc showing Late Cenozoic deformation. Likewise, the modern Central Andean backarc has been the main locus of Late Cenozoic deformation and hence also the main locus of Late Cenozoic rotations as well.

Most paleomagnetic results in the Central Andes would indicate the amount of rotation that occurred during upper crustal deformation at the sampling locality, and accordingly may show all the spatial and temporal variations that crustal deformation in the orogen shows. In the long term, the principal locus of rotational deformation has migrated episodically eastward through time, in concert with the overall eastward shift of the locus of deformation in the Central Andes.

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