Central Andean rotation pattern: Evidence from paleomagnetic rotations of an anomalous domain in the forearc of northern Chile

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ABSTRACT

We have reanalyzed the pattern of paleomagnetically detected rotations in the central Andes (the central Andean rotation pattern) in order to investigate the temporal and spatial distributions of rotations. The dominant pattern of rotation is well known with counterclockwise rotations in the northern Andes (clockwise in the southern Andes) linked to Neogene orogenesis and shortening. However, much of the rotation in the forearc of northern Chile (23–30°S) is distinctly anomalous because of markedly high rotations that appear to predate rotations observed elsewhere in the central Andes. We argue that the data define a domain located in the forearc of northern Chile marked by major (>25°) clockwise crustal rotations related to late Paleocene–early Eocene highly oblique convergence. This rather diffuse and cryptic deformation style accommodated strong shortening perpendicular to the Andean margin by vertical axis rotations rather than by conventional fold-thrust belts or transpressional fault systems.

Keywords: rotation, Andes, convergence, obliquity, timing, Chile.

INTRODUCTION

The conspicuously arcuate nature of the central Andes led to the orocline hypothesis (Carey, 1955), in which a straight Andean mountain chain underwent postorogenic bending by rigid rotation. Early paleomagnetic studies revealed opposing rotations in northern and southern limbs and hence supported the Carey-type oroclinal model. In a seminal paper, Isacks (1988) linked plateau creation and rotation of the orocline limbs to along-strike differential shortening of the orogen caused by subduction at a preexisting, albeit less curved, bend in the margin. This model, with maximum shortening at the hinge, decreasing to both northwest and south, envisages rotation of the forearc and margin in an essentially passive manner with shortening concentrated in the retroarc. The model predicted maximum rotations of 10° counterclockwise north and 25° clockwise south of the bend, dependent on shortening and thermal inputs. The limited paleomagnetic database supported this hypothesis in that observed and predicted rotations coincided. Given the paucity of data, little thought was given to the potential for variation in the age of rotation. Recently, the quantity, quality, and geographic distribution of paleomagnetic data have expanded greatly (Arriagada et al., 2003b; Prezzi and Alonso, 2002; Rousse et al., 2003) and the hypothesis is referred to as the central Andean rotation pattern.

The increased paleomagnetic data set (Data Repository Table DR1[1]) has been accompanied by an increase in shortening estimates from balanced cross sections, and crustal and map area balancing (Kley, 1999; McQuarrie, 2002). Along-orogen differential shortening remains the likeliest driver of Neogene rotation and uplift. However, rotations in pre-Neogene units in the forearc region greatly exceed predicted rotations from Neogene shortening estimates alone (Kley, 1999). This is most notable in northern Chile, and it is this anomaly which we focus upon here, suggesting that it defines a discrete forearc domain in northern Chile with rotation that is linked to an older collisional event rather than Neogene uplift per se.

CENTRAL ANDEAN ROTATION PATTERN AND NEOGENE DEFORMATION

Rotations were determined by comparing observed and expected directions derived from synthetic reference poles (Besse and Courtillot, 2002). Previously there has been debate over reference pole choice; we found that there is no major difference in the pattern of rotations for the past 100 m.y. when using global data sets (Besse and Courtillot, 2002) or dominantly South American data (Lamb and Randall, 2001). Differences become more pronounced in Early Cretaceous–Jurassic reference directions. The central Andean rotation pattern data are here divided into three age groups (Neogene, Paleogene, and Mesozoic) based on the unit or magnetization ages given by the original authors (Figs. 1A, 1C).

The Neogene data (here <25 Ma) are almost all located within the present arc to retroarc. Rotations are relatively small, locally variable (kilometer scale), but consistent with identified shortening gradients and local structures that provide an adequate explanation of the variability (Lamb, 2001; Riller and Oncken, 2003). At the scale of the central Andes (Fig. 1A), the collected data, despite local variability, show a smooth change of rotation with latitude. This trend is fitted with a simple polynomial function and compared with the predicted rotations derived from structural estimates (Kley, 1999). It is clear, with some exceptions that we surmise to be unresolved problems in the structurally derived estimates, that the data sets are in reasonable agreement (Fig. 1B). This implies that the paleomagnetic data, viewed at a regional scale, provide insight into the long-term mountain-building processes in the Neogene. Furthermore, the data imply that north of 23°S, Neogene rotation of the Chilean forearc region should not exceed ~8° clockwise. Only at 22–23°S are there paleomagnetic data of suitable age for comparison, and these record no discernible rotation (Arriagada et al., 2003b; Somoza et al., 1999; Somoza and Tomlinson, 2002a); however, the predicted rotation is at the limit of detection. Further studies need to clarify whether this lack of rotation is an artifact or a real discrepancy in predicted forearc rotation. South of 23°S no suitable forearc units have been studied. Given the data (Fig. 1A), it is therefore necessary to consider, at the large scale, that this part of the forearc may have rotated passively by a maximum of ~18° during the Neogene (Fig. 1A). In a numerical analysis of shortening, rotation, and distributed fault-bound blocks, Arriagada et al. (2003a) reached a similar conclusion as to the maximum likely rotation. Other estimates of the Neogene rotation, based on strike change and shortening, invoking a megakink geometry involving NW-SE structures, suggest ~11° of clockwise rotation in the forearc between 23° and 29°S, with no rotation to the north (Somoza and Tomlinson, 2002b).

The pre-Neogene record of rotations (Fig. 1C) shows a distinct anomaly with respect to the Neogene data set (Fig. 1A). The majority of these data are located in the forearc of

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[1] GSA Data Repository item 2005154, Table DR1, supporting data as an Excel spreadsheet of paleomagnetic data for the Andes, is available online at www.geosociety.org/pubs/ft2005.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

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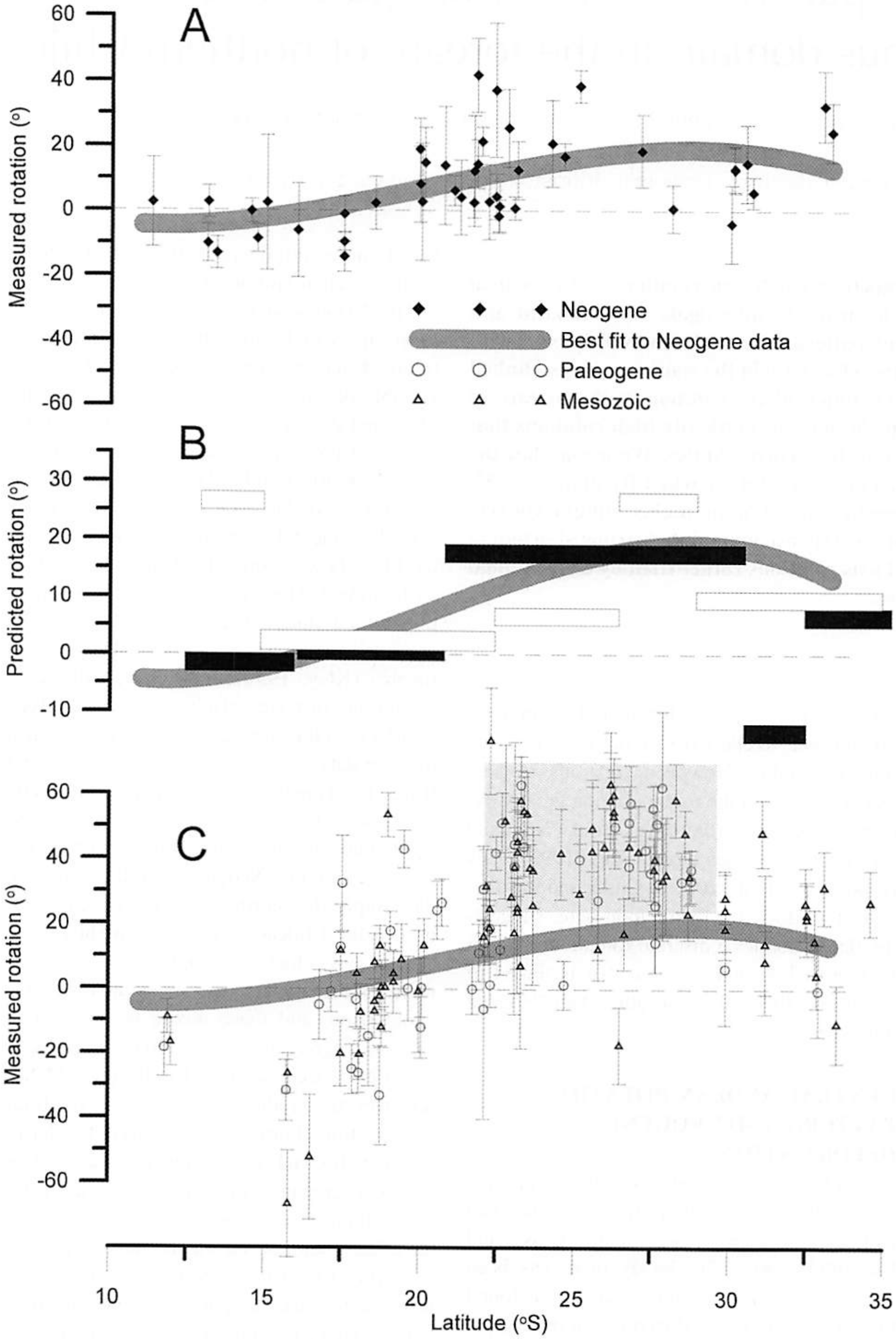

Figure 1. Central Andean rotation pattern. Paleomagnetically observed rotations, calculated from 10 m.y. interval reference poles (Besse and Courtillot, 2002), against latitude. A: Neogene data fitted with third-order polynomial trend line. B: Neogene trend line vs. structural derived rotations from balanced cross sections (white) and crustal area balancing (black) (Kley, 1999). C: Paleogene and Mesozoic data vs. Neogene trend line.

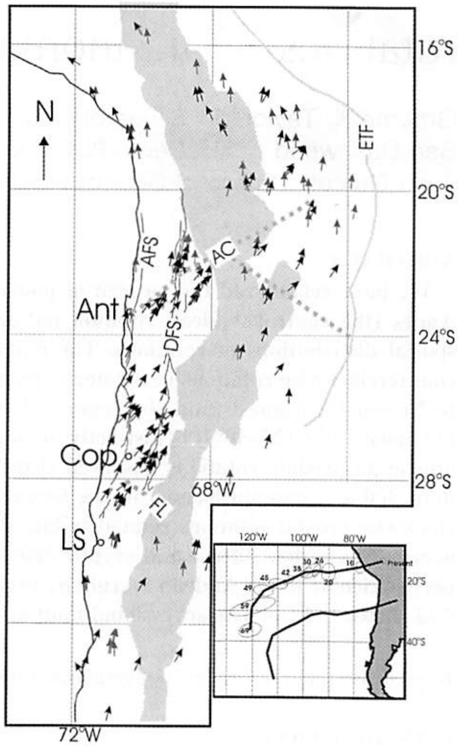

Figure 2. Geographical distribution of rotations. Also shown: Eastern thrust front (ETF), Atacama (AFS) and Domeyko (DFS) fault systems, Antofagasta-Calama (AC) and Fortuna (FL) lineaments, and Antofagasta (Ant), Copiapó (Cop), and La Serena (LS) cities. Rotations in black are statistically significant; those in gray are not. Inset: Nazca–South America convergence (Pardo-Casas and Molnar, 1987); ages in Ma.

northern Chile and southern Peru. In the northern limb (north of 18°S) data are sparse, and it is difficult to determine their consistency with the Neogene data set. Recently it was argued that rotation in the Peruvian forearc was accomplished between 10 and 8 Ma during uplift, and explains rotations observed in both Mesozoic and Tertiary units (Rousse et al., 2003).

In marked contrast to Peru, the Chilean forearc region (~23°–29°S) (Fig. 1C) exhibits consistently large (30°–45°) clockwise rotations (Arriagada et al., 2003b; Fernández et al., 2000; Randall et al., 1996, 2001; Riley et al., 1993; Taylor et al., 2002). Clearly these rotations are not in accord with shortening predictions or observed younger rotations in the retroarc (Figs. 1A, 1B). Instead these rotations demarcate a 700-km-long domain characterized by large-magnitude clockwise rotation, the timing of which clearly predates Neogene orogenesis.

GEOGRAPHIC LIMITS OF THE DOMAIN

The northern limit at 22–23°S is defined by a sharp reduction in rotations close to the NE-trending Antofagasta-Calama lineament, north of which, although data are sparse, rotations diminish rapidly (Arriagada et al., 2003b; Goguitchaichvili et al., 2003; Fig. 2). This lineament is the southernmost of a series of deep-seated, NE-trending dextral structures that influenced the geological evolution of the craton and its margins (Jacques, 2003). It is also close to a major change in shortening across the Andes at a suspected former bend in the orogen (McQuarrie, 2002) and a significant change in basement inferred from gravity studies. Directly to the east, major changes in topography, structural style, and magmatism in the retroarc are linked to a NW crustal lineament (Allmendinger et al., 1997). The southern limit of the domain at 29°–30°S is marked by rapidly diminishing rotations becoming insignificant south and east of La Serena. We have yet to identify a causative structure, but note the marked kink in regional strike from

NNE-SSW to N-S at these latitudes; this and similar deflections have been suggested as a possible locus for a change in rotations.

The eastern boundary of the domain is difficult to define, having two possible options that have a profound difference in their significance for the timing of rotation. The more obvious, and initially appealing option, is that this boundary is marked by the orogen-parallel, dominantly sinistral, strike-slip to transpressional, middle to late Eocene Domeyko fault system, noted for its major copper porphyries and inferred to be a deep-seated fundamental fault system (Fig. 2). Along the length of the system, rotations are variable with both exceptionally large and small rotations associated with blocks within the system (Arriagada et al., 2000, 2003b; Fernández et al., 2000; Randall et al., 2001). It could be argued that this might typify the bounding master fault for a region recording major rotations. In such a case, the rotations would appear to be linked to significant middle Eocene to early Oligocene deformation in northern Chile (Tomlinson and Blanco, 1997). The alternative option is that the boundary of the rotated area is somewhere to the east of the Domeyko fault system covered by the products of the Neogene to recent arcs. This scenario may be supported on the grounds that substantial clockwise rotations have been identified to the east of the main strands of the Domeyko fault system (Arriagada et al., 2003b; Randall et al., 2001; R. Fernández, 2004, personal commun.). In this case, variable rotations, with counterclockwise rotations being kinematically favored in a sinistral fault system, associated with the Domeyko fault system would be superimposed upon and overprint the widespread clockwise rotations in the domain. This would imply a pre–42–40 Ma cause for the major rotations, as discussed here.

AGE OF ROTATION WITHIN THE DOMAIN

The Andean subduction boundary in northern Chile consists of a series of arcs that young episodically eastward, showing limited spatial and temporal overlap, except with the immediately preceding arc. This poses problems for determining the age of paleomagnetic rotations in that units older, younger, and, if possible, synchronous with the rotation event are normally sampled to constrain the rotation over time. Here it is necessary to look at the data set as a whole for first-order variations.

Given the rotation, spatial, and age data available (Figs. 1C, 2, and 3), there is no systematic difference between rotations recorded by Mesozoic and Paleocene units within the domain. This therefore imposes a lower bound on the age of rotation, ca. 60 Ma. The variation in rotation magnitude (Figs. 2 and 3) appears to be a consequence of proximity to the Domeyko fault system. In contrast, the older but equally important Atacama fault system has no notable effect on the rotations (Randall et al., 1996), which have similar magnitudes to the east and west. There is, however, a marked trend (Fig. 3) in decreasing rotation between 60 and 40 Ma, although the individual magnetization ages and consequent rotations are relatively weakly constrained, as several of the studies yielded remagnetizations. Nonetheless the gross trend suggests this was the main period of rotation in the domain and that rotation probably accumulated over a relatively prolonged ~15 m.y. period. Further studies of temporally well constrained magnetizations and rotations are needed to fully support this hypothesis.

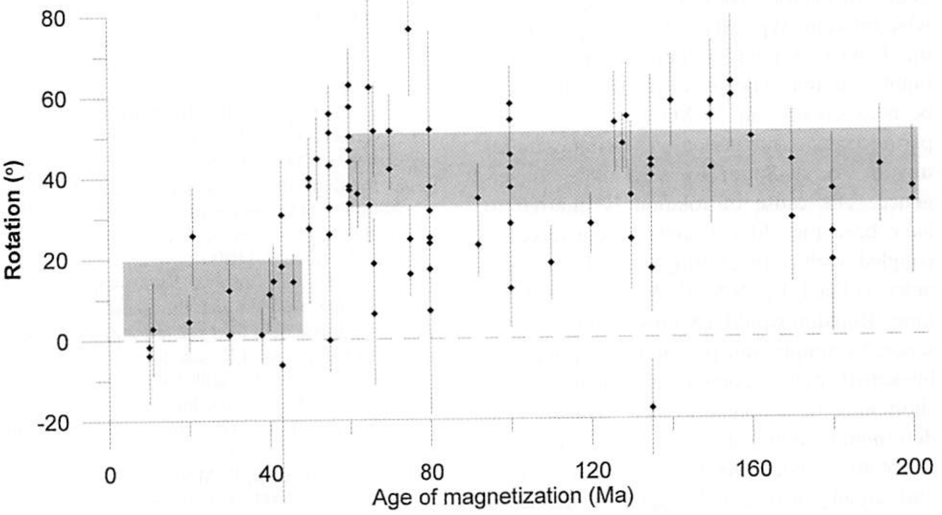

Figure 3. Paleogene to Mesozoic rotations between 22° and 30°S in northern Chile plotted against given age. Note distinct change in values between ca. 60 and 40 Ma.

DISCUSSION

The geographic distribution and magnitude of the rotations imply that they would have been driven by large-scale forces affecting the plate margin. The suggested 60–40 Ma period for the rotations coincides with a period of marked convergence obliquity between the Nazca and South American plates (Pardo-Casas and Molnar, 1987) (up to 49 Ma), after which convergence would have been much closer to orthogonal (Fig. 2). After 49 Ma the convergence rate increased substantially and is compatible with more discrete transpression typified by the later activity of the Domeyko fault system.

Throughout the southern half of the domain, the ubiquitous presence of NW- to NNW-trending sinistral brittle faults has been linked to clockwise rotations (Abels and Bischoff, 1999; Grocott and Taylor, 2002; Randall et al., 1996; Taylor et al., 1998). These structures, part of long-lived sinistral lineaments that can be traced throughout much of this part of South America, have been repeatedly reactivated, controlling basin formation, granite emplacement, and fault relay zones (Jacques, 2003; Salfity, 1985). Within the domain, the youngest documented expression of these structures is southeast of Copiapó, where the Fortuna lineament cuts and delimits the southern boundary of an extensive Paleocene to mid-Eocene caldera field (Rivera and Falcón, 2000). The timing and geographic coincidence suggest that the obliquity of convergence as a driving mechanism, coupled with these preexisting structures, producing a strong crustal anisotropy, was the dominant cause of clockwise rotation in the domain. If correct, the Domeyko fault system represents not the controlling structure, or the eastern limit of the rotations, but rather the system into which transpression became more highly localized and discretely partitioned as convergence became more direct.

CONCLUSIONS

Neogene paleomagnetic rotations in the central Andes are consistent with those predicted by shortening estimates. Simple analysis suggests a maximum of ~18° (~10°) clockwise rotation of the southern (northern) limb based on studies in the arc to retroarc region. While paleomagnetic evidence suggests that the Peruvian forearc deformed passively and rotation occurred during the period 10–8 Ma, the evidence for Neogene rotation of the Chilean part of the forearc is ambiguous, with Oligocene–Miocene strata in the north recording no discernible rotation.

Jurassic to Eocene rocks in northern Chile (22°–29°S) normally record rotations that greatly exceed any prediction of passive Neogene forearc rotation due to uplift and/or orocline formation. They instead record clockwise rotations typically ≥30°, except close to the Domeyko fault system, where they are highly variable. The age of rotation appears to be between 60 and 40 Ma and is linked, in part at least, to the period of maximum obliquity of Nazca–South America plate convergence. The cause of rotation is inferred to have been the oblique angle of convergence coupled with a preexisting crustal heterogeneity defined by NW-NNW–trending structures. Rotation would have been caused, in essence, by simple transpressional coupling in a bookshelf style accommodating margin-wide shortening in a nonpartitioned manner. This deformation, dominated by vertical axis crustal rotations extending over a broad area, is both areally diffuse and cryptic, in the sense that it is not expressed by conventional strain partitioning into margin-parallel and margin-perpendicular structures. The onset of mid-Eocene deformation in northern Chile was marked by the development of the Domeyko fault system, which overprinted earlier rotations and the NW structures to some extent. Rotations would have been, perhaps, more localized along the fault system and deformation more concentrated into a narrower belt along the system. We note the coincidence of the southern boundary of the identified domain with other features in the Andes, such as the change from thin- to thick-skinned thrust belts of the Sierra Pampeanas, the steep to flat slab transition, and volcanic to nonvolcanic zones. Clearly the connection between this domain, which may have become strain hardened during rotational deformation, and such features needs to be investigated.

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REFERENCES CITED

Abels, A., and Bischoff, L., 1999, Clockwise block rotations in northern Chile: Indications for a large-scale domino mechanism during the middle-late Eocene: Geology, v. 27, p. 751–754.

Allmendinger, R., Jordan, T., Kay, S.M., and Isacks, B., 1997, The evolution of the Altiplano-Puna Plateau of the central Andes: Annual Review of Earth and Planetary Sciences, v. 25, p. 139–174.

Arriagada, C., Roperch, P., and Mpodozis, C., 2000, Clockwise block rotations along the eastern border of the Cordillera de Domeyko, northern Chile (22°45′–23°30′S): Tectonophysics, v. 326, p. 153–171.

Arriagada, C., Roperch, P., and Cobbold, P.R., 2003a, Rotaciones tectonicas y origen del oroclino Boliviano: (2) restauracion numerica de la deformacion y un modelo evolutivo de la curvatura oroclinal, 10th Congreso Geologico Chileno: Concepcion, Universidad de Concepcion, 6 p.

Arriagada, C., Roperch, P., Mpodozis, C., Dupont-Nivet, G., Cobbold, P.R., Chauvin, A., and Cortés, J., 2003b, Paleogene clockwise tectonic rotations in the forearc of central Andes, Antofagasta region, northern Chile: Journal of Geophysical Research, v. 108, no. B1, 2032, doi: 10.1029/2001JB001598.

Besse, J., and Courtillot, V., 2002, Apparent and true polar wander and the geometry of the geomagnetic field over the last 200 Myr.: Journal of Geophysical Research, v. 107, no. B11, 2300, doi: 10.1029/2000JB000050.

Carey, S.W., 1955, The orocline concept in geotectonics: Royal Society of Tasmania Papers and Proceedings, v. 89, p. 255–288.

Fernández, R., Roperch, P., Mpodozis, C., and Tomlinson, A., 2000, Paleomagnetismo y rotaciones tectonicas en la Cordillera de Domeyko, entre los 26 y 27 S, Region de Atacama, Chile: IX Congreso Geologico Chileno, Actas, v. 2, p. 562–566.

Goguitchaichvili, A., Alva-Valdivia, L.M., and Urrutia-Fucugauchi, J., 2003, Paleomagnetism and rock magnetism of the Jurassic La Negra Formation, northern Chile: Implications for tectonics and volcanic stratigraphy: International Geology Review, v. 45, p. 563–573.

Grocott, J., and Taylor, G.K., 2002, Magmatic arc fault systems, deformation partitioning and emplacement of granitic complexes in the Coastal Cordillera, north Chilean Andes (25°30′S to 27°00′S): Geological Society [London] Journal, v. 159, p. 425–442.

Isacks, B., 1988, Uplift of the central Andean plateau and bending of the Bolivian orocline: Journal of Geophysical Research, v. 93, p. 3211–3231.

Jacques, J.M., 2003, A tectonostratigraphic synthesis of the sub-Andean basins: Inferences on the position of South American intraplate accommodation zones and their control on South Atlantic opening: Geological Society [London] Journal, v. 160, p. 703–717.

Kley, J., 1999, Geologic and geometric constraints on a kinematic model of the Bolivian orocline: Journal of South American Earth Sciences, v. 12, p. 221–235.

Lamb, S., 2001, Vertical axis rotation in the Bolivian orocline, South America, 2. Kinematic and dynamical implications: Journal of Geophysical Research, v. 106, p. 26,633–26,653.

Lamb, S.H., and Randall, D.E., 2001, Deriving palaeomagnetic poles from independently assessed inclination and declination data: Implications for South American poles since 120 Ma: Geophysical Journal International, v. 146, p. 349–370.

McQuarrie, N., 2002, Initial plate geometry, shortening variations, and evolution of the Bolivian orocline: Geology, v. 30, p. 867–870.

Pardo-Casas, F., and Molnar, P., 1987, Relative motion of the Nazca (Farallon) and South American plates since Late Cretaceous time: Tectonics, v. 6, p. 233–248.

Prezzi, C.B., and Alonso, R.N., 2002, New palaeomagnetic data from the northern Argentine Puna: Central Andes rotation pattern reanalyzed: Journal of Geophysical Research, v. 107, no. B2, 2041, doi: 10.1029/2001JB000225.

Randall, D.E., Taylor, G.K., and Grocott, J., 1996, Major crustal rotations in the Andean margin: Paleomagnetic results from the Coastal Cordillera of northern Chile: Journal of Geophysical Research, v. 101, p. 15,783–15,798.

Randall, D.E., Tomlinson, A., and Taylor, G.K., 2001, Paleomagnetically defined rotations from the Precordillera of northern Chile: Evidence of localized in situ fault-controlled rotations: Tectonics, v. 20, p. 235–254.

Riley, P., Beck, M.E., Burmester, R., Mpodozis, C., and García, A., 1993, Paleomagnetic evidence for vertical-axis block rotation from the Mesozoic of north-central Chile: Journal of Geophysical Research, v. 98, p. 8321–8333.

Riller, U., and Oncken, O., 2003, Growth of the central Andean Plateau by tectonic segmentation is controlled by the gradient in crustal shortening: Journal of Geology, v. 111, p. 367–384.

Rivera, O.M., and Falcón, M.F., 2000, Calderas tipo colapso-resurgentes del Tercario inferior en la Pre-Cordillera de la Region de Atacama: Emplazamiento de complejos volcano-plutonicos en las cuencas volcano-tectonicas extensionales Hornitos y Indio Muerto: IX Congreso Geologico Chileno, v. 2, p. 67–71.

Rousse, S., Gilder, S., Farber, D., McNulty, B., Patriat, P., Torres, V., and Sempere, T., 2003, Paleomagnetic tracking of mountain building in the Peruvian Andes since 10 Ma: Tectonics, v. 22, doi: 10.1029/2003TC001508.

Salfity, J.A., 1985, Lineamientos transversales al rumbo andino en el noroeste Argentino: IV Congreso Geologico Chileno, v. 2, p. 119–137.

Somoza, R., and Tomlinson, A., 2002a, Paleomagnetism in the Precordillera of northern Chile (22°30′S): Implications for the history of tectonic rotations in the central Andes: Earth and Planetary Science Letters, v. 194, p. 369–381.

Somoza, R., and Tomlinson, A.J., 2002b, Los Andes centrales del sur durante el Neógeno: Observaciones e hipótesis sobre la cinemática horizontal: XV Congreso Geológico Argentino, v. 1, p. 82–87.

Somoza, R., Singer, S., and Tomlinson, A., 1999, Paleomagnetic study of upper Miocene rocks from northern Chile: Implications for the origin of late Miocene–recent tectonic rotations in the southern central Andes: Journal of Geophysical Research, v. 104, p. 22,923–22,936.

Taylor, G.K., Grocott, J., Pope, A., and Randall, D.E., 1998, Mesozoic fault systems, deformation and fault block rotation in the Andean forearc: A crustal scale strike-slip duplex in the Coastal Cordillera of northern Chile: Tectonophysics, v. 299, p. 93–109.

Taylor, G.K., Gipson, M., and Grocott, J., 2002, New palaeomagnetic results from the Coastal Cordillera/Precordillera boundary northern Chile: Implications for plate margin deformation, 5th International Symposium on Andean Geodynamics, Volume 1: Colleques & Seminaires: Toulouse, France, Institut de Recherche pour le Développement, p. 633–636.

Tomlinson, A., and Blanco, N., 1997, Structural evolution and displacement history of the West fault system, Precordillera, Chile: Part 1. Synmineral history: VIII Congreso Geológico de Chile, Actas, v. 3, p. 1873–1877.

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