Clockwise block rotations in northern Chile: Indications for a large-scale domino mechanism during the middle-late Eocene

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ABSTRACT

The Andean deformational pattern of the northern Chilean Precordillera between 26°30′ and 27°00′S suggests significant influence of an orogen-oblique (northwest-trending) pre-Andean basement structure. The left-lateral reactivation of this structure and the associated deformation can be explained by clockwise vertical-axis rotations of forearc-wide crustal blocks during the middle-late Eocene (ca. 39 ± 3 Ma) induced by the coupling stress due to oblique northeastward subduction of the oceanic Farallon plate beneath the South American continent. The compressive stress at the leading edges of the blocks may have been accommodated 200 km away from the Peru-Chile trench in what is now the Precordillera, where the magmatic arc was then located. The postulated large-scale domino mechanism explains the paleomagnetically observed in situ block rotations, as well as the orientation, segmentation, and shear sense of major structural elements within large parts of the present forearc in northern Chile.

INTRODUCTION

A growing paleomagnetic database for the Coastal Cordillera and Central Valley of northern Chile (Fig. 1) indicates clockwise-rotated declinations that are significantly larger than for other segments of the active margin of southern South America, incompatible with models that consider solely large-scale oroclinal bending (for discussion see Somoza, 1994; Beck et al., 1994). Therefore, it is thought that in addition to oroclinal bending and differential shortening, in situ rotations of crustal blocks around subvertical axes are responsible for the discordant paleomagnetic declinations. For the region considered here (Fig. 2), these rotations have usually been attributed to left-lateral transpression during the Mesozoic, induced by oblique convergence with south-southeast–directed subduction (e.g., Forsythe and Chisholm, 1994; Randall et al., 1996; Taylor et al., 1998a). The suggested mechanisms do not, however, take into account investigations from the Precordillera that revealed the same sense of rotation (e.g., Riley et al., 1993), nor are they temporally compatible with the results of Roperch et al. (1997) and Taylor et al. (1998b) that point to the Tertiary as the period of major rotation.

On the basis of field studies in the Chilean Precordillera between 26°30′ and 27°00′S, coupled with remote-sensing (Landsat thematic mapper, aerial photographs) analyses and a reinterpretation of previously published data, we propose a deformation mechanism that explains the anomalous declinations by clockwise rotation of elongated, very large crustal blocks that moved in a domino manner about subvertical axes. We suggest that (1) these blocks are bounded by pre-Andean, northwest-trending zones of structural weakness at deep- to mid-crustal levels, (2) these zones were reactivated as wrench faults in a left-lateral sense, and (3) the resulting pervasive movements were induced by a dextral transpressive tectonic regime that prevailed during the late Eocene due to subduction to the northeast. The model emphasizes the significance of the pre-Andean setting for the Andean orogeny in northern Chile.

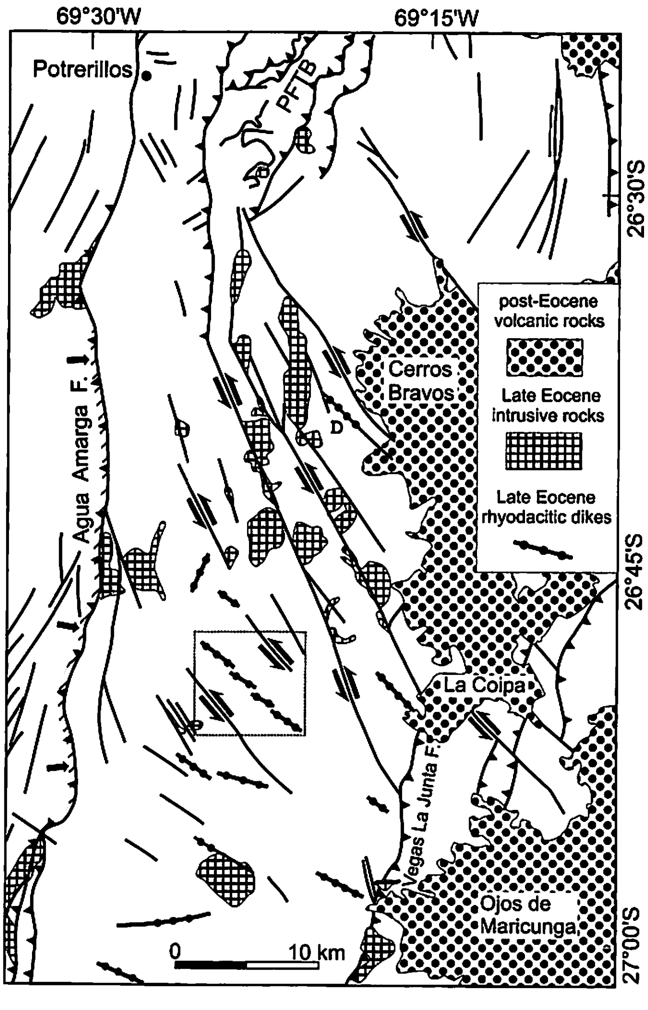

Figure 1. Overview geologic map of Chilean Precordillera near 26°45′S showing major structural elements active during middle-late Eocene, and distribution of lithological units referred to in text (only intrusions affected by major faults are shown). Box encloses en echelon dike indicating sinistral shearing during emplacement. Arrows point to limestone outcrop along trace of Agua Amarga thrust. D—dated rhyodacitic dike. PFTB—Potrerillos fold and thrust belt (after Cornejo et al. [1993] and our mapping).

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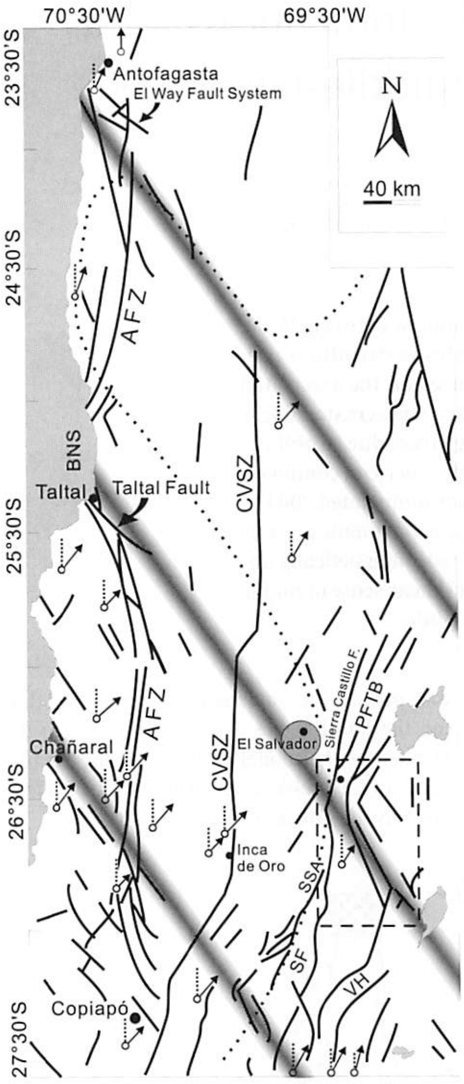

Figure 2. Outline map of northern Chilean forearc between 23°30′ and 27°30′S. Location of Figure 1 is shown by dashed box. Also shown are proposed deep-seated discontinuities (shaded lines) and rough outline (dotted) of region elevated ~2400 m above sea level west of Precordillera referred to in text. Gray circle represents El Salvador caldera. AFZ—Atacama fault zone, CVSZ—Central Valley shear zone, BNS—Bahía de Nuestra Señora, SF—Sierra Fraga, SSA—Sierra San Andrés, VH—El Varillar–El Hielo basement uplift, PTFB—Potrerillos fold and thrust belt. Mean paleomagnetic rotations are modified from Roperch et al. (1997) and Taylor et al. (1998b).

STUDY AREA

In the Chilean Precordillera between 26°30′ and 27°00′S is a set of as much as 35-km-long, steeply dipping faults that strike north-northwest, i.e., oblique to the general northward trend of the Precordillera (Fig. 1). The age of movement along these faults is constrained by overlying undisturbed Oligocene-Miocene extrusive rocks of the Cerros Bravos and La Coipa volcanic complexes (ca. 26–22 Ma), whereas crosscutting relationships with dated intrusive rocks indicate movement during the middle Eocene between ca. 42 and 39 Ma (Cornejo and Mpodozis, 1994; Cornejo et al., 1993). Kinematic analyses of these north-northwest–trending faults reveal both a component of normal dip slip (maximum ~500 m) and a more significant component of left-lateral strike-slip displacement. In addition to small-scale indicators of left-lateral movement (Cornejo et al., 1993), map-scale cutoffs of concordant lithological contacts indicate large displacements, as much as ~3.5 km, on individual faults. Field relationships show that dip slip essentially postdated strike slip, which we interpret as the result of collapse after overall contractional deformation in the magmatic arc. The regional stress field is expected to have changed between 36 and 32 Ma (latest shortening in the region; Cornejo et al., 1997) and 26 Ma (undisturbed Cerros Bravos–La Coipa volcanic rocks). The north-northwest–trending faults merge northward with thrusts (Fig. 1) of the Potrerillos fold and thrust belt, the formation of which is also attributed to the middle-late Eocene (Cornejo et al., 1993). To the south, the structural pattern suggests that the north-northwest–trending faults merge with reverse faults, although the actual intersections are covered by post-Eocene volcanic rocks. These reverse faults separate a broad Paleozoic basement uplift from Mesozoic rocks. The best-exposed example is the Vegas La Junta fault, which continues uninterrupted from the La Coipa area southward to beyond 27°S (Mercado, 1982). A minimum age for movement on this fault is fixed by undisturbed overlying Miocene Atacama gravels.

A widespread rhyodacitic dike swarm is present in the transitional area between the domain of north-northwest–trending faults and the reverse faults to the south (Fig. 1). With few exceptions, the orientation of the dikes varies between 040° and 060°. In one case, the en echelon segments of a single dike, traceable over 9 km, indicate emplacement during regional left-lateral shear strain. Another dike of the swarm, which intruded along a north-northwest–trending fault farther north, was dated as 39.3 Ma (Cornejo et al., 1993). Provided that the en echelon-segmented dike has a similar age, this date gives a constraint for the time of bulk deformation.

To the west, the domain of north-northwest–trending faults is limited by the 30°–70°W dipping Agua Amarga fault, which places Mesozoic upon Paleogene rocks (Fig. 1). Activity on this fault is bracketed by displaced intrusions dated between 47 and 44 Ma (Cornejo et al., 1993) and undisplaced Miocene Atacama gravels. The thrusting movement was favored by stratiform, incompetent lithologies, as indicated by a narrow, upthrust limestone sequence following the fault trace for ~40 km. In addition to our observation that no kinematic indicators for lateral movements occur along the Agua Amarga fault, this characteristic suggests that it is a purely contractional structure without significant strike-slip movements. To the north, the Agua Amarga fault probably continues into the Sierra Castillo fault, which represents the western limit of the Potrerillos fold and thrust belt, but the potential connection is obscured over ~6 km by Miocene Atacama gravels. This subvertical (Cornejo et al., 1993) or 60°–80°E dipping fault (Perello and Müller, 1984; Olson, 1989) separates Mesozoic volcanic rocks on the west from uplifted Permian granitoids on the east. Thus the vertical offset sense and the dip direction of the Sierra Castillo fault are markedly different from those features of the Agua Amarga fault, and we agree with Cornejo et al. (1993) that their dissimilarity is the result of different amounts of vertical thickening and uplift in their adjacent eastern hinterlands. Just as for the Agua Amarga fault, despite relatively detailed mapping, no clear kinematic indicators for lateral movements along the Sierra Castillo fault have been documented (Perello and Müller, 1984; Cornejo et al., 1993). To the south the Agua Amarga fault grades into the eastern periphery of the complexly deformed Sierra San Andrés–Sierra Fraga region (Fig. 2), where at least two compressional periods are recognized (Cisternas and Vincente, 1976; Mpodozis and Allmendinger, 1993). The available constraints for the timing of these periods do not preclude a late Eocene age for the younger period, which here may include left-lateral displacements along the La Ternera fault system (Mpodozis and Allmendinger, 1993).

Collectively, these structural and geochronologic characteristics suggest that the main structural features in the Precordillera, at least between 26°00′S and 27°15′S, are kinematically linked and were active during the middle-late Eocene. Furthermore, they require an explanation without recourse to major strike-slip movements along margin-parallel faults.

PREEXISTING STRUCTURE

The domain of north-northwest–trending faults is best explained by the reactivation of a preexisting basement structure during the Eocene orogeny (Fig. 2). Its presence is indicated by the following observations. (1) The thickness of Upper Triassic and Jurassic sedimentary rocks increases significantly from south to north across it (Prinz et al., 1994). Furthermore, the spatial distribution of the Triassic facies, which is typical for active rifting, suggests a horst and graben situation with a boundary being congruent with the domain of north-northwest–trending faults (Suarez and Bell, 1992; Suarez et al., 1995). (2) On the basis of $^{87}Sr/^{86}Sr$ ratios of an extensive sample suite, Mpodozis et al. (1995) proposed that the domain of north-northwest–trending faults marks the boundary between two fundamentally different basement provinces, possibly separating two accreted Paleozoic terranes. (3) To the northwest of Potrerillos, a hypothesized extension of the structure coincides with a major gap in the Atacama fault zone at the Bahía de Nuestra Señora (Fig. 2). At this location, an ~7–8 km left-lateral offset of the Atacama fault zone along the west-northwest–trending Taltal fault is evident (e.g., Naranjo and Puig, 1984). Brown et al. (1993) considered the Taltal fault to be part of a brittle fault set that offset ductilely deformed parts of the Atacama fault zone left laterally ~70 km in a north-northwest direction. Crosscutting relationships allow a post-Cretaceous timing for this movement.

DEFORMATION MECHANISM

Plate tectonic reconstructions indicate a relatively rapid, approximately northeastward subduction of the oceanic Farallon plate beneath the South American continent during the late Eocene, thereby inducing an overall dextral transpressive tectonic regime in the arc and forearc (e.g., Scheuber and Reutter, 1992). This prerequisite, together with the outlined deformational patterns and the evidence for a preexisting basement structure, suggests the following mechanism to explain the clockwise rotations documented by paleomagnetic investigations. The oblique coupling stress at the subduction interface triggered rotation of large, crustal blocks via a domino mechanism, favored by approximately northwest-trending zones of structural weakness in the pre-Andean basement (Figs. 2 and 3). Shortening by thrusting and reverse faulting occurred at the leading edges of the blocks in the Precordillera, where the magmatic arc was situated during that time. The increased geothermal gradient led to a thermally weakened crust and favored the uplift of basement ridges surrounded by folded sequences of their Mesozoic to Cenozoic cover (Scheuber and Reutter, 1992). Shortening of the trailing edges of the blocks in the Coastal Cordillera may be indicated by regional uplift and widespread strike-slip overprinting of older faults. The bulk finite shortening axis also rotated clockwise (Fig. 3), and led to the frequent north-northeast to northeast trend of contractional structures in the Precordillera south of 25°S (Fig. 2; e.g., Sierra Fraga). When the deformation reached the eastern limit of the thermally weakened crust, further rotation was impeded. Faults that developed during late stages of the orogeny, e.g., presumably the Sierra Castillo fault and Agua Amarga fault, are therefore margin parallel and represent purely contractional features without a significant strike-slip component. The preexisting strength differences of the regional rheology associated with the margin oblique Triassic-Jurassic basin and range structures were potentially capable of hampering extensive strike-slip movements along the margin-parallel faults (Beck et al., 1993). Displacements between the rotating blocks were accomplished in the upper crust by brittle deformation, dominantly by left-lateral displacements along approximately northwest-trending faults. The long north-northwest–trending faults in the area acted as a transfer-relay fault zone that transmitted the shortening strain between the Potrerillos fold and thrust belt in the north and the Paleozoic basement uplift in the south.

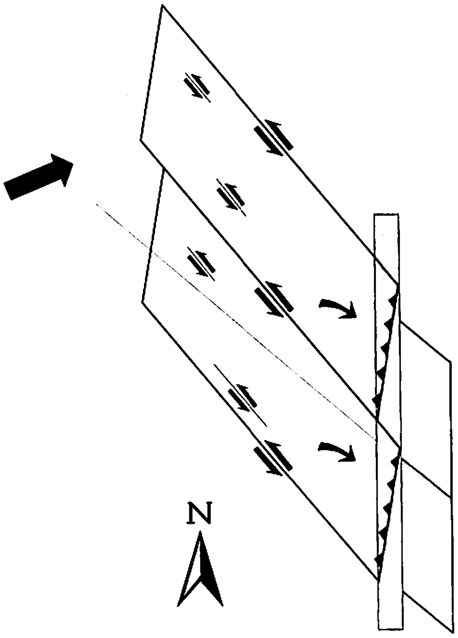

Figure 3. Postulated block-rotation mechanism. Dextral transpression causes clockwise rotation, inducing left-lateral offset between blocks and orogen-oblique tectonic transport. Contractional structures are developed at leading edges of blocks in thermally weakened magmatic arc (shaded). Movement is accompanied by pervasive fracturing of uppermost brittle crust in forearc.

OTHER NORTHWEST-TRENDING STRUCTURES

The paleomagnetic results indicate clockwise rotation of very large regions of northern Chile and suggest, if the outlined model is correct, the existence of further northwest-trending major discontinuities (Fig. 2). From southeast of Chañaral on the coast to as far south as the Argentine border at 28°S, a northwest-trending thickness anomaly in the Upper Triassic–Jurassic sedimentary section (Prinz et al., 1994) is coincident with a region of dominantly northwest-trending brittle faults with a left-lateral sense of displacement. These faults displace 106 Ma intrusive rocks and represent the youngest known active structures in the Coastal Cordillera of this area (e.g., Randall et al., 1996). To the north, another discontinuity is suggested along the prolongation of the left-lateral Culampajá lineament (Salfity, 1985), from the Argentine Puna northwestward across the Chilean Precordillera, possibly as far as the El Way fault system that cuts the Atacama fault zone south of Antofagasta. The Central Valley shear zone, as defined by Randall et al. (1996), loses its distinct gravity signature when it intersects this feature (Herrmann and Zeil, 1989), which is also coincident with the northern limit of an unusual northwest-trending elevated region west of the Precordillera (Fig. 2; cf., Isacks, 1988, Plate I).

DISCUSSION AND CONCLUSIONS

The proposal that the Andean orogeny in Chile was influenced by northwest-trending pre-Andean structures is not new (e.g., Sylvester and Linke, 1993), but their importance for Andean kinematics has probably been underestimated. None of the proposed discontinuities are well exposed as a continuous feature, but appear only as dispersed brittle faults, mainly in the Coastal Cordillera and the Precordillera. Their less distinct appearance in the Central Valley may be due to covering by post-Eocene sedimentary deposits, whereas the adjacent ranges have been relatively uplifted since the Miocene, leading to erosion and exhumation of deeper stratigraphic levels; the different exposure is also a primary feature. For example, in and around the El Salvador caldera, no significant northwest-trending faults are present, although this exposed Paleocene structure is situated upon a supposed discontinuity (Fig. 2). However, in contrast to the Precordillera to the east, this region was not actively uplifted during the middle-late Eocene, and the pre-middle Eocene volcanic rocks were originally much thicker in the Central Valley in comparison to those in the Precordillera (Olson, 1989; Comejo et al., 1993). Therefore, faults formed by reactivation of a deep-seated pre-Andean structure may not have propagated to the surface in this area. The porphyry copper deposit of El Salvador inside the caldera, however, is associated with middle Eocene (44–41 Ma) intrusions, and inside the open-pit mine a northwest-trending structural fabric largely controls and cuts through all units of the porphyry complex (Cornejo et al., 1997).

Another complicating factor is that the movement will internally deform and split crustal units of the proposed size into smaller blocks on many scales, depending on several localized factors. This variability is indicated by (1) the paleomagnetic data that show spatially unsystematic clockwise rotation magnitudes that differ by at least 30° and (2) the widespread distribution of the approximately northwest-trending faults in the forearc (e.g., Herrmann and Zeil, 1989; Randall et al., 1996).

We conclude that (1) the middle-late Eocene arc and forearc of the northern Chilean active margin were simultaneously deformed, and (2) the reactivation of the proposed deep-seated discontinuities during transpression led to a pervasive brittle deformation of the upper forearc crust that was not just a passive sliver between the coupled subduction interface and the more ductilely deformed magmatic arc. The suggested mechanism integrates many recent geologic phe-

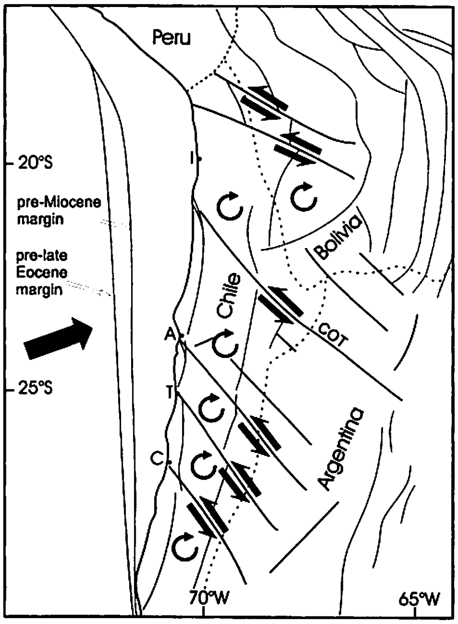

Figure 4. Sketch of hypothetical mechanism in southern central Andes contributing to clockwise rotation of paleomagnetically observed declinations in pre-Neogene rocks (simplified and modified after Baby et al. [1992] and Salfity [1985]; COT—Calama–Olacapato–El Toro lineament, I—Iquique, A—Antofagasta, T—Taltal, C—Chañaral).

nomena in the forearc of northern Chile and reflects their strong mutual dependence, although it is, by nature, too simple on a local scale. The process may be of more widespread significance than suggested here; another repeatedly active, northwest-trending trans-Andean structure with left-lateral offsets has long been suggested farther north crossing the Precordillera at Calama, the Calama–Olacapato–El Toro lineament (Fig. 4; e.g., Schreiber and Schwab, 1991).

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REFERENCES CITED

Baby, P., Sempere, T., Oller, J., and Hérail, G., 1992, Evidence for major shortening on the eastern edge of the Bolivian Altiplano: The Calazaya nappe: Tectonophysics, v. 205, p. 155–169.

Beck, M. E., Jr., Rojas, C., and Cembrano, J., 1993, On the nature of buttressing in margin-parallel strike-slip fault systems: Geology, v. 21, p. 755–758.

Beck, M. E., Jr., Burmester, R. R., Drake, R. E., and Riley, P. D., 1994, A tale of two continents: Some tectonic contrasts between the central Andes and the North American Cordillera, as illustrated by their paleomagnetic signatures: Tectonics, v. 13, p. 215–224.

Brown, M., Diaz, F., and Grocott, J., 1993, Displacement history of the Atacama fault system 25°00′S–27°00′S, northern Chile: Geological Society of America Bulletin, v. 105, p. 1165–1174.

Cisternas, M. E., and Vincente, J.-C., 1976, Estudio geológico del sector de Las Vegas de San Andrés: Congreso Geológico Chileno, 1st, Santiago de Chile, Actas, p. A.227–A.252.

Cornejo, P., and Mpodozis, C., 1994, Estrato volcanoes y domos coalescentes del Oligoceno Superior-Mioceno Inferior en la Franja de Maricunga: Los sistemas Cerros Bravos-Esperanza y La Coipa: Congreso Geológico Chileno, 7th, Concepción, Actas, p. 13–17.

Cornejo, P., Mpodozis, C., Ramirez, C., and Tomlinson, A. J., 1993, Estudio geológico de la región de Portrerillos y El Salvador (26°–27° Lat. S): Santiago de Chile, Sernageomin-Codelco, Informe registrado, v. 1, 250 p.

Cornejo, P., Tosdal, R. M., Mpodozis, C., Tomlinson, A. J., Rivera, O., and Fanning, C. M., 1997, El Salvador, Chile porphyry copper deposit revisited: Geologic and geochronologic framework: International Geology Review, v. 39, p. 22–54.

Forsythe, R., and Chisholm, L., 1994, Paleomagnetic and structural constraints on rotations in the north Chilean coast ranges: Journal of South American Earth Sciences, v. 7, p. 279–294.

Herrmann, R., and Zeil, W., 1989, Tectonics and volcanism in the north Chilean Longitudinal Valley (24°30′–25°15′S): Zentralblatt für Geologie und Paläontologie, Teil 1, v. 5/6, p. 1065–1073.

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

Mercado, M., 1982, Carta geológica de Chile, Hoja Laguna del Negro Francisco, Región de Atacama, no. 56: Santiago de Chile, Servicio Nacional de Geologia y Mineria, 1 sheet, scale 1:100000, 73 p.

Mpodozis, C., and Allmendinger, R. W., 1993, Extensional tectonics, Cretaceous Andes, northern Chile (27°S): Geological Society of America Bulletin, v. 105, p. 1462–1477.

Mpodozis, C., Cornejo, P., Kay, S. M., and Tittler, A., 1995, La Franja de Maricunga: Síntesis de la evolutión del Frente Volcánico Oligoceno-Mioceno de la zone sur de los Andes Centrales: Revista Geológica de Chile, v. 21, p. 273–313.

Naranjo, J. A., and Puig, A., 1984, Carta geológica de Chile, Hojas Taltal y Chañaral, nos. 62–63: Santiago de Chile, Servicio Nacional de Geología y Mineria, 1 sheet, scale 1:250000, 140 p.

Olson, S. F., 1989, The stratigraphic and structural setting of the Potrerillos porphyry copper district, northern Chile: Revista Geológica de Chile, v. 16, p. 3–29.

Perello, J., and Müller, G., 1984, El horst de Sierra Castillo en la Cordillera de Domeyko, al occidente del Salar de Pedernales: Sus fallas limites Barrancas y Sierra Castillo: Comunicaciones, v. 34, p. 47–55.

Prinz, P., Wilke, H.-G., and Hillebrandt, A. V., 1994, Sediment accumulation and subsidence history in the Mesozoic marginal basin of northern Chile, *in* Reutter, K.-J., et al., eds., Tectonics of the southern central Andes: Berlin, Springer, p. 219–232.

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.

Riley, P. D., Beck, M. E., Jr., and Burmester, R. F., 1993, Paleomagnetic evidence of vertical axis block rotations from the Mesozoic of northern Chile: Journal of Geophysical Research, v. 98, p. 8321–8333.

Roperch, P., Dupont-Nivet, G., and Pinto, L., 1997, Rotaciónes tectonicas en el norte de Chile: Congreso Geológico Chileno, 8th, Antofagasta, Actas, p. 241–245.

Salfity, J. A., 1985, Lineamentos transversales al rumbo andino en el noroeste Argentino: Congreso Geológico Chileno, 4th, Antofagasta, Actas, p. 119–137.

Scheuber, E., and Reutter, K.-J., 1992, Magmatic arc tectonics in the Central Andes between 21° and 25°S: Tectonophysics, v. 205, p. 127–140.

Schreiber, U., and Schwab, K., 1991, Geochemistry of Quaternary shoshonitic lavas related to the Calama-Olacapato–El Toro lineament, NW Argentina: Journal of South American Earth Sciences, v. 4, p. 73–85.

Somoza, R., 1994, South American reference pole for the mid-Cretaceous: Further constraints in the interpretation of Andean paleomagnetic data: Geology, v. 22, p. 933–936.

Suarez, M., and Bell, C. M., 1992, Triassic rift-related sedimentary basins in northern Chile (24°–29°S): Journal of South American Earth Sciences, v. 6, p. 109–121.

Suarez, M., Bell, C. M., and Hutter, T., 1995, Lower Triassic lacustrine sediments in La Coipa area, Atacama, Chile: Journal of South American Earth Sciences, v. 8, p. 9–15.

Sylvester, H., and Linke, M., 1993, Structural control of intrusions and hydrothermal alteration zones by intersecting fault systems in the Cretaceous magmatic arc of the southern central Andes at 27°S, III. region, Chile: Zentralblatt für Geologie und Paläontologie, Teil 1, v. 1/2, p. 361–376.

Taylor, G. K., Grocott, J., Pope, A., and Randall, D. E., 1998a, 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., Paulton, C., Selby, T., and Grocott, J., 1998b, Paleomagnetism and block rotations in northern Chile: New results from the Inca de Oro region and their implications: Andean Geoscience Workshop, 3rd, Plymouth, UK; Programme and Abstracts, 1 p.

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