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Paleomagnetism of Permo-Triassic and Cretaceous rocks from the Antofagasta region, northern Chile

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ABSTRACT

New paleomagnetic data from Permo-Triassic and Late Cretaceous rocks yield a consistent trend of vertical-axis-tectonic-rotations which are consistent with the Central Andean Rotation Pattern (CARP). However, three sites in the Tuina Formation and one site in the Purilactis Group record large rotations (80°). These mayor rotations are probably due to dextral-transpressive deformation occurring in close relation with the Incaic tectonic phase. Consequently, it is possible to infer that previous tectonic phases Peruvian and K-T would not have produced significant tectonic rotations in the area.

1. Introduction

The central Andes, a noncollisional orogeny, are a prime example of oroclinal bending (Isacks, 1988), the idea that mountain ranges form initially in a linear geometry and then are bent into their more highly curved configuration (Carey, 1955). The "Bolivian Orocline" is the change in trend of the Andes from NW to N near 18°S. The origin of the Bolivian Orocline has traditionally been studied with paleomagnetic data (e.g., Arriagada et al., 2003, 2006a, 2008; Beck, 1987; Coutand et al., 1999; Lamb, 2001; McFadden, 1990; Roperch and Carlier, 1992; Scanlan and Turner, 1992; Somoza and Tomlinson, 2002). Counterclockwise rotations with respect to stable South America are found along the Peruvian margin (Heki et al., 1984, 1985; May and Butler, 1985; Roperch and Carlier, 1992; Roperch et al., 2011) while clockwise rotations characterize the Chilean margin (Forsythe et al., 1987; Hartley et al., 1992a; Riley et al., 1993; Roperch et al., 1997). This pattern of tectonic rotations is usually called Central Andean Rotation Pattern (CARP) (Beck, 2004; Taylor et al., 2005; Roperch et al., 2006; Arriagada et al., 2008).

Mountain building in the Central Andes occurred mainly during the Cenozoic and this is the reason why paleomagnetic studies along the margin of northern Chile and Peru have been focused on essentially Jurassic, Cretaceous and Tertiary units (Fig. 1). While there are numerous paleomagnetic studies in Paleozoic rocks of the Argentinan Andes (Geuna and Ecosteguy, 2004), few studies have been reported for the Paleozoic-Triassic basement in the Andes of Northern Chile (Jesinkey et al., 1987). However, in the study of Jesinkey et al. (1987) there is no paleomagnetic data on Tertiary rocks to test the rotation history of this area.

In the present contribution, we will present paleomagnetic results from the Permo-Triassic Tuina Formation in an area where Cretaceous and Tertiary red beds have already been studied (Hartley et al., 1992a; Arriagada et al., 2000; Somoza and Tomlinson, 2002; Arriagada et al., 2003).

2. Tectonic setting

The oldest rocks found here correspond to a succession of andesitic lavas, tuffs and sandstones (Tuina Formation) deposited in a continental, volcanic environment (Mundaca, 1982). Continental sedimentary rocks of Albian to Maastrichtian-Danian age (Tonel,

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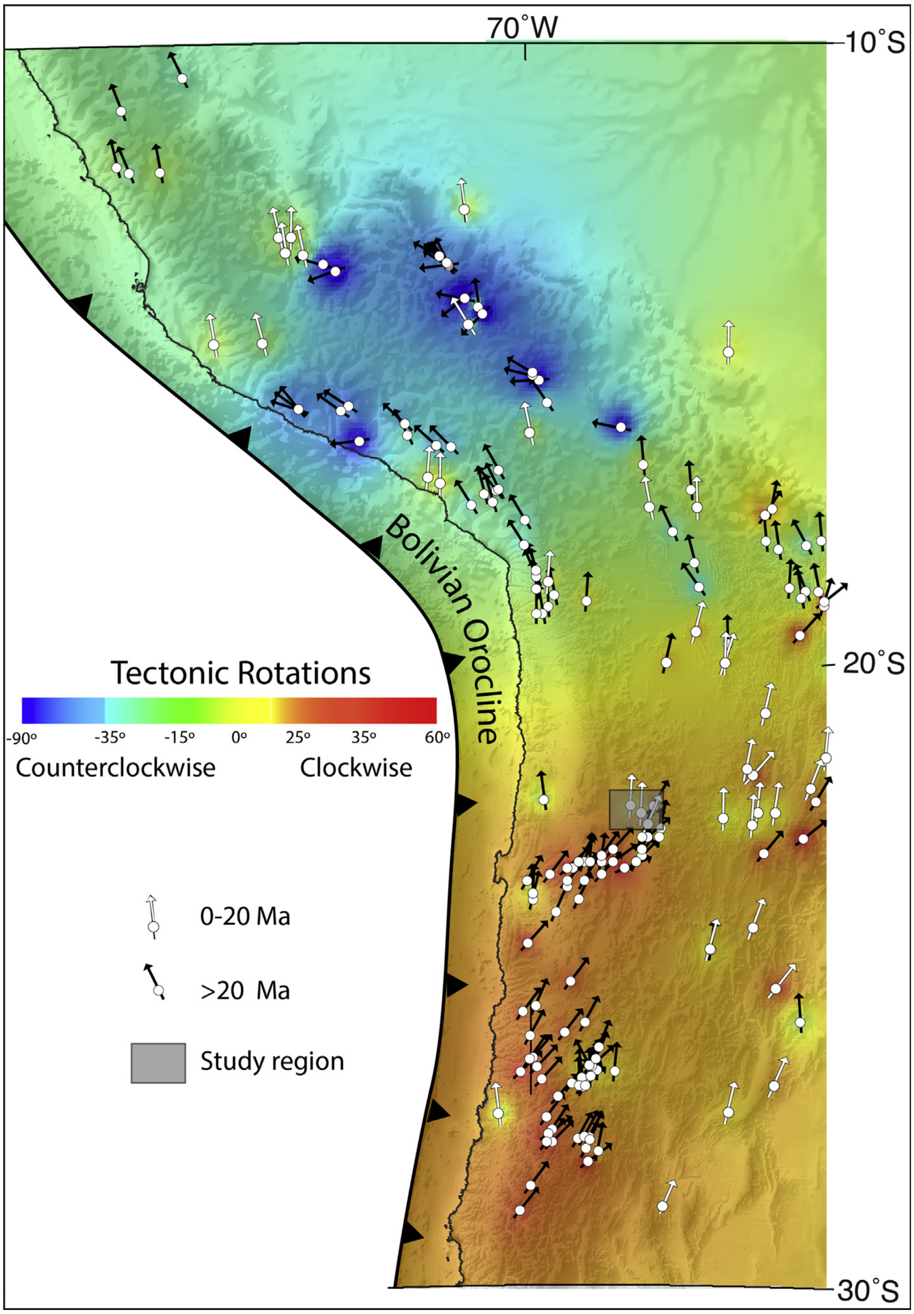

Fig. 1. Tectonic rotations in the central Andes. A raster surface based on the magnitude of rotations has been created by using the inverse distance weighting interpolation method. Paleomagnetically determined block rotations about vertical axes are shown as white arrows for rocks younger than 20 Ma and black arrows for rocks older than 20 Ma. Clockwise (counterclockwise) rotations are shown in warm colors (cool colors). The paleomagnetic database of the central Andes was obtained from Roperch et al. (2006) (see auxiliary material, available at ftp://ftp.agu.org/apend/tc/2005tc001882) and the database of the southern central Andes from Arriagada et al. (2006) (see auxiliary material, available at ftp://ftp.agu.org/apend/tc/2005tc001923).

Purilactis and Barros Arana Formations) lie on top of the former, in slight angular unconformity. A proximal, alluvial sedimentary environment is registered from the Late Oligocene onwards (Tambores Formation), which was deposited in angular unconformity over the Cretaceous and Paleogene units. The paleomagnetic sampling made for this study was performed on two first order morphostructural units: the Cordillera de Domeyko (Fig. 2), in the Cerros de Tuina Area, and the Barros Arana Syncline (Fig. 2), at the western border of the Salar de Atacama Basin.

The Cordillera de Domeyko of northern Chile, is a narrow, N–S oriented mountain chain situated in the Andean forearc. It is located between the Preandean Depression, which borders the Salar de Atacama to the east and the Central Depression to the west (Fig. 2). It has an average height of 3.000 m above sea level, and comprises successions of Paleozoic to Triassic volcano-sedimentary rocks, intruded by Carboniferous to Permian granitoids (Ramírez and Gardeweg, 1982). The volcano-sedimentary units found, whose bases are not exposed, are the Tuina Formation (Late Permian-Middle Triassic) (Raczynnski, 1963; Marinovic and Lahsen, 1984; Mundaca, 2002), the El Bordo Beds (Permian–Triassic) (Ramírez and Gardeweg, 1982), the Peine Group (Bahlburg and Breitkreuz, 1991), and the Cas Formation and its equivalents

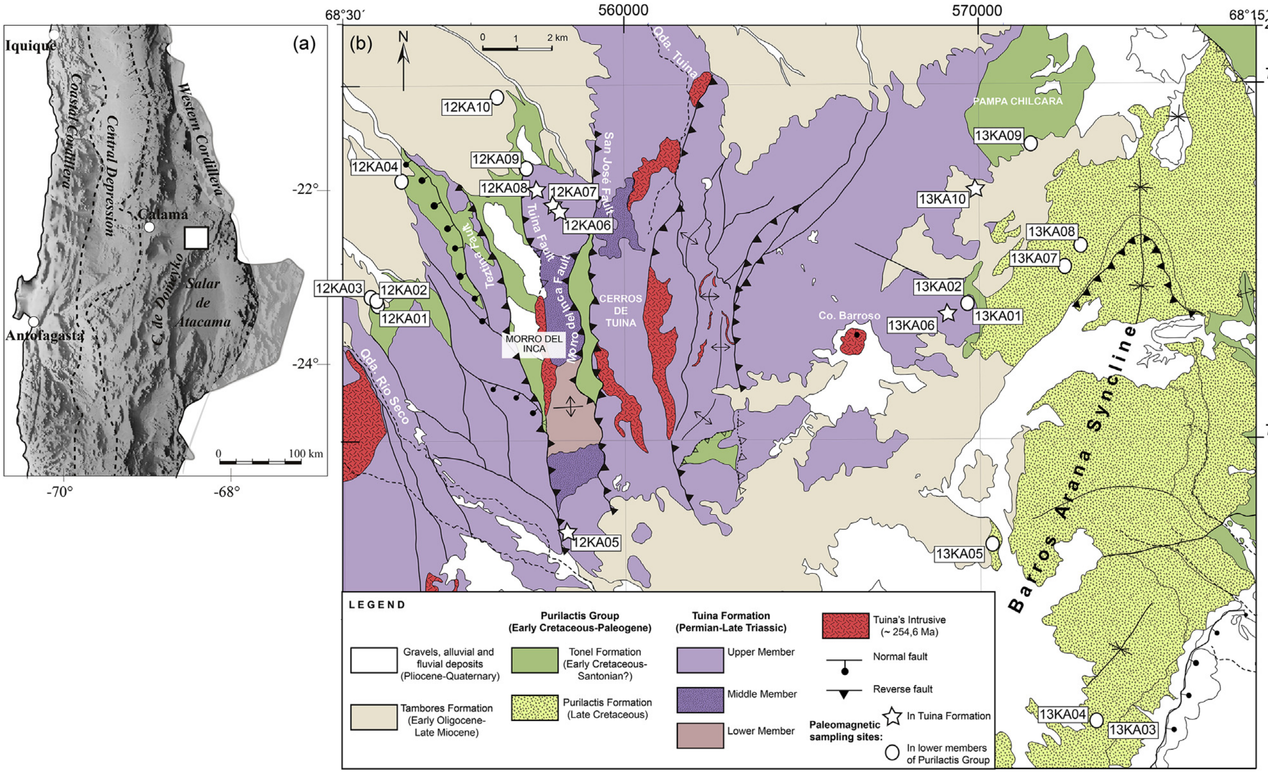

Fig. 2. (a) Location of study region (inside the white quadrate) within a schematic morphostructural map of northern Chile. (b) Simplified geologic map of the study region, showing the location of the paleomagnetic sites.

(Ramírez and Gardeweg, 1982). These last units are related to the Permian–Triassic rifting episode found along Chile and part of Argentina, which was characterized by the development of extended depocenters (Charrier et al., 2007). The Upper Paleozoic to Triassic volcano–plutonic complexes constitute the main pre-Jurassic outcrops found in northern Chile (Breitkreuz and Zeil, 1994).

Between the Late Cretaceous and the Early Oligocene, the Cordillera de Domeyko was the center of subduction-related magmatism, thus representing the magmatic arc at that time

Table 1
Location of the paleomagnetic sampling and magnetic properties.

Sites	Lithology	Latitude	Longitude	NRM (A m^{-1})	K (SI)	Strike	Dip
Barros Arana Syncline: basal sedimentary units of the Purilactis Group (Late Cretaceous)							
Vizcachita member							
13KA03	Sandstone red-brown	22°40.555′	68°17.314′	0.0087	0.00115	199.72	29.18
13KA04	Sandstone red-brown	22°40.534′	68°17.366′	0.0082	0.00230	199.72	29.18
Licán member							
13KA05	Red sandstone	22°37.881′	68°19.152′	0.0043	0.000264	45.6	36
13KA07	Red sandstone	22°33.674′	68°17.840′	0.0079	0.000147	36.4	21.8
13KA08	Red sandstone	22°33.354′	68°17.596′	0.0104	0.000193	47.1	29
Tonel formation							
12KA01	Red sandstone	22°34.225′	68°29.124′	0.0133	0.000160	240	57
12KA02	Red sandstone	22°34.239′	68°29.154′	0.0227	0.000233	248.7	58
12KA03	Sandstone red-brown	22°34.173′	68°29.192′	0.0345	0.000171	246.7	51.6
12KA04	Sandstone red-brown	22°32.407′	68°28.667′	0.0717	0.000282	330	15
12KA09	Red Sandstone	22°32.177′	68°26.663′	0.0235	0.000277	294.5	46.6
12KA10	Orange Sandstone	22°31.094′	68°27.124′	0.0142	0.000115	317.4	21.6
13KA01	Red sandstone	22°34.231′	68°19.450′	0.0172	0.000180	32.31	39.54
13KA02	Red sandstone	22°34.231′	68°19.450′	0.0371	0.000107	32.31	39.54
13KA09	Red sandstone	22°31.801′	68°18.433′	0.0191	0.000181	21.2	47.6
Cordillera de Domeyko: volcanic and sediments units of Tuina Formation							
(Permian–Middle Triassic)							
12KA05	Red sandstone	22°37.695′	68°25.996′	0.0171	0.000242	85.2	26.7
12KA06	Gray Ignimbrite	22°32.827′	68°26.145′	0.0990	0.00105	275.3	45.4
12KA07	Gray ignimbrite	22°32.746′	68°26.220′	0.423	0.000021	280.6	47.3
12KA08	Dacitic Lava	22°32.533′	68°26.465′	0.274	0.000262	287.1	39.2
13KA06	Gray ignimbrite	22°34.381′	68°19.785′	0.0199	0.000179	35.5	25.9
13KA10	Ignimbrite	22°32.502′	68°19.319′	0.0414	0.000140	22.75	25.625

NRM is geometric mean intensity of magnetization in Am^{-1}; K is geometric mean susceptibility (SI), strike and dip are bedding corrections.

(Mpodozis and Ramos, 1990; Scheuber and Reutter, 1992; Reutter et al., 1996). Around the same time, the volcanoclastic, clastic and evaporitic successions of the Purilactis Group (Charrier and Reutter, 1990, 1994; Hartley et al., 1992b) were being deposited east of the magmatic arc, in a foreland basin setting (Mpodozis et al., 2005; Arriagada et al., 2006b; Bascuñán et al., 2015). A first important episode of compressive deformation known as the Peruvian Orogenic Phase (Steinmann, 1929) occured during the Late Cretaceous along the Cordillera de Domeyko (Mpodozis et al., 2005; Arriagada et al., 2006b; Bascuñán et al., 2015). Another deformation episode occurred around the Cretaceous-Cenozoic boundary (K-T event; Cornejo et al., 2003; Somoza et al., 2012). Through the Middle Eocene, the Incaic Orogenic Phase, affected northern Chile especially along the Cordillera de Domeyko and the western border of the Salar de Atacama Basin (Mpodozis et al., 1993; Reutter et al., 1996; Tomlinson and Blanco, 1997; Maksaev and Zentilli, 1999; Mpodozis et al., 2005; Arriagada et al., 2006b). During the Oligocene, the western border of the Salar de Atacama Basin would have been affected by extension, as shown by the accumulation of the continental San Pedro and Tambores Formations (Jordan et al., 2007). The volcanic arc, which was more or less around the same position, shifts to the east in the Miocene (Charrier et al., 2009). The compressive deformation from the Miocene onwards is mainly focused at the borders of the Salar de Atacama Basin and in its central area, along the Cordillera de la Sal (Ramírez and Gardeweg, 1982; Marinovic and Lahsen, 1984). This deformation could be affecting the Pleistocene volcanic units (González et al., 2009). The eastern border of the Cordillera de Domeyko is a 900 m high scarp (the El Bordo Scarp, found south of the study area), which runs for over 120 km along the western margin of the Salar de Atacama Basin. Along this scarp, the Paleozoic basement (the Tuina Formation and the El Bordo Beds in the northern and central segment, respectively) is either detached or overlain by approximately 6.000 m of fine sandstone and conglomerate successions accumulated during the Late Cretaceous (Purilactis Group, Charrier and Reutter, 1994; Arriagada et al., 2000, 2006b; Mpodozis et al., 2005). These successions are part of the lower sedimentary infill of the Salar de Atacama Basin (Macellari et al., 1991; Muñoz et al., 1997).

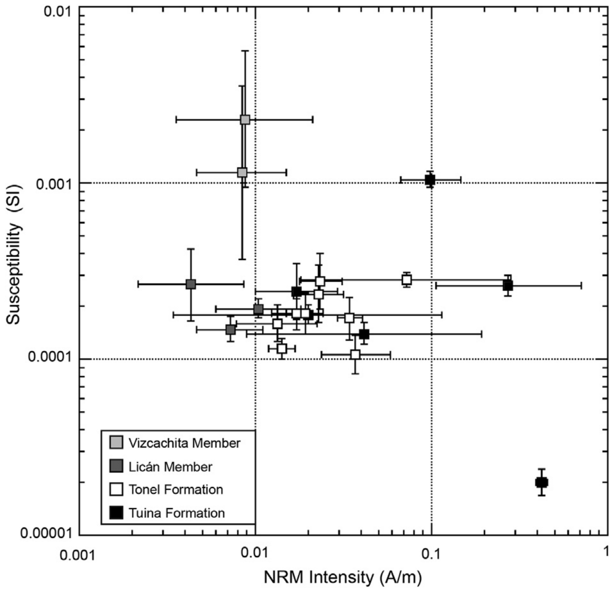

Fig. 3. Geometric site-mean intensity of Natural Remanent Magnetization (A/m) versus magnetic susceptibility (SI). The NRM intensity is usually <0.43 A/m.

3. Paleomagnetic sampling

A total of 181 paleomagnetic samples were drilled at 20 sites in the volcano-sedimentary Tuina Formation and the sedimentary units belonging to the lower members of the Purilactis Group (Table 1, Fig. 2). Unfortunately, only 16 sites gave good results.

Six sites were drilled in the Tuina Formation, four of which were performed in the Cerros de Tuina area. Three of these (12KA06, 12KA07 and 12KA08) are volcanic rocks found NW of Quebrada Tuina and north of Morro del Inca, and belong to outcrops of the Upper Member of the Tuina Formation. The only site with sedimentary rocks (12KA05) of this formation is located immediately east of Quebrada Río Seco. The last two sites (13KA06 and 13KA10) were drilled in the volcanic outcrops east of Cerros de Tuina and

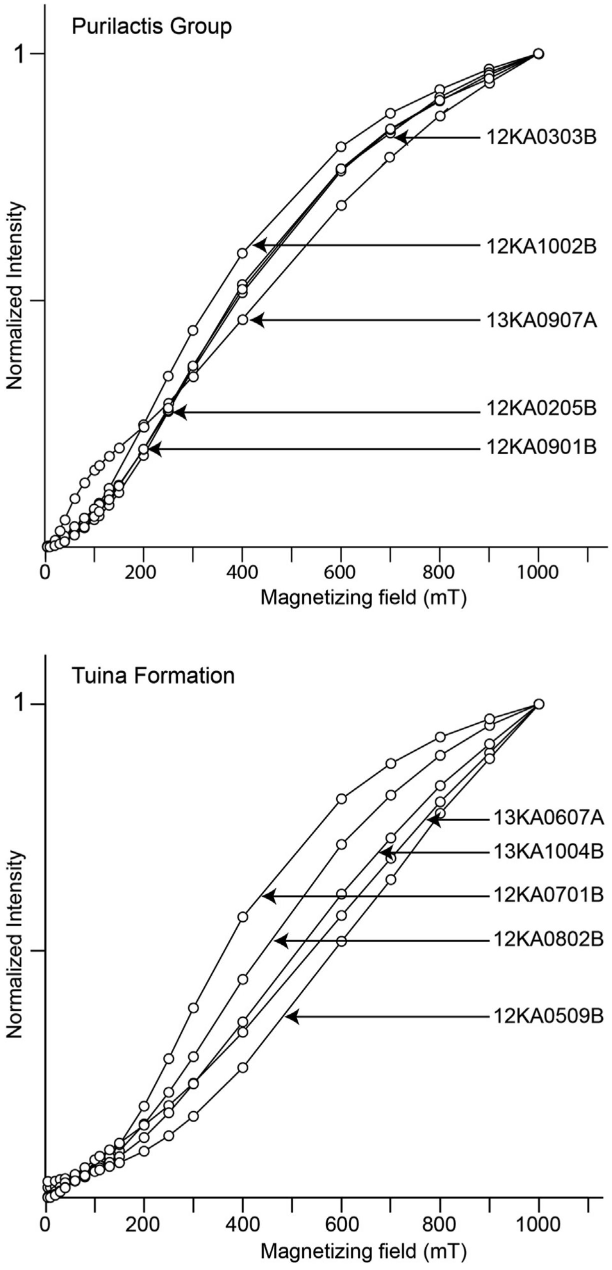

Fig. 4. Isothermal remanent magnetization (IRM) acquisition in five different samples of both the Tuina Formation and the basal members of the Purilactis Group. This analyses show the presence of hematite and scarce magnetite for all samples.

south of Pampa Chilcara, near the western limb of the Barros Arana Syncline (Fig. 2). The remaining 14 sites were obtained in the sedimentary successions of the Tonel and Purilactis Formations. Sites labeled 12KA were drilled in creeks found at the westernmost part of the Cerros de Tuina area, in successions lying directly on top of the Tuina Formation. Sites labeled 13KA were obtained in different points of the western limb of the Barros Arana Syncline. It is important to mention that sites 13KA03 and 13KA04 were the only ones drilled in the eastern limb of the aforementioned syncline (Fig. 2).

Sites in volcanic rocks include only samples from a single flow. Secular variation was thus not averaged at these single bed sites. In contrast, in sedimentary rocks, sampling included different beds along several meters of stratigraphic section. In such cases, mean-site paleomagnetic results should average the secular variation and provide a good estimate of tectonic rotations at the site. Bedding corrections were applied to all sedimentary and volcanic sites (Table 1).

4. Paleomagnetic techniques and magnetic properties

Remanent magnetism was measured with Molspin or Agico JR5A spinner magnetometers at the Universidad de Chile. Magnetic Susceptibility was measured with a Bartington susceptibilimeter. Magnetic susceptibility was also measured after each thermal demagnetization step in order to check magnetic mineralogical changes upon heating. To better constrain the magnetic mineralogy, isothermal remanent magnetism (IRM) acquisition and variation of the susceptibility during heating (K-T) was performed for 10 samples. IRM were obtained with a pulse electro-magnet and

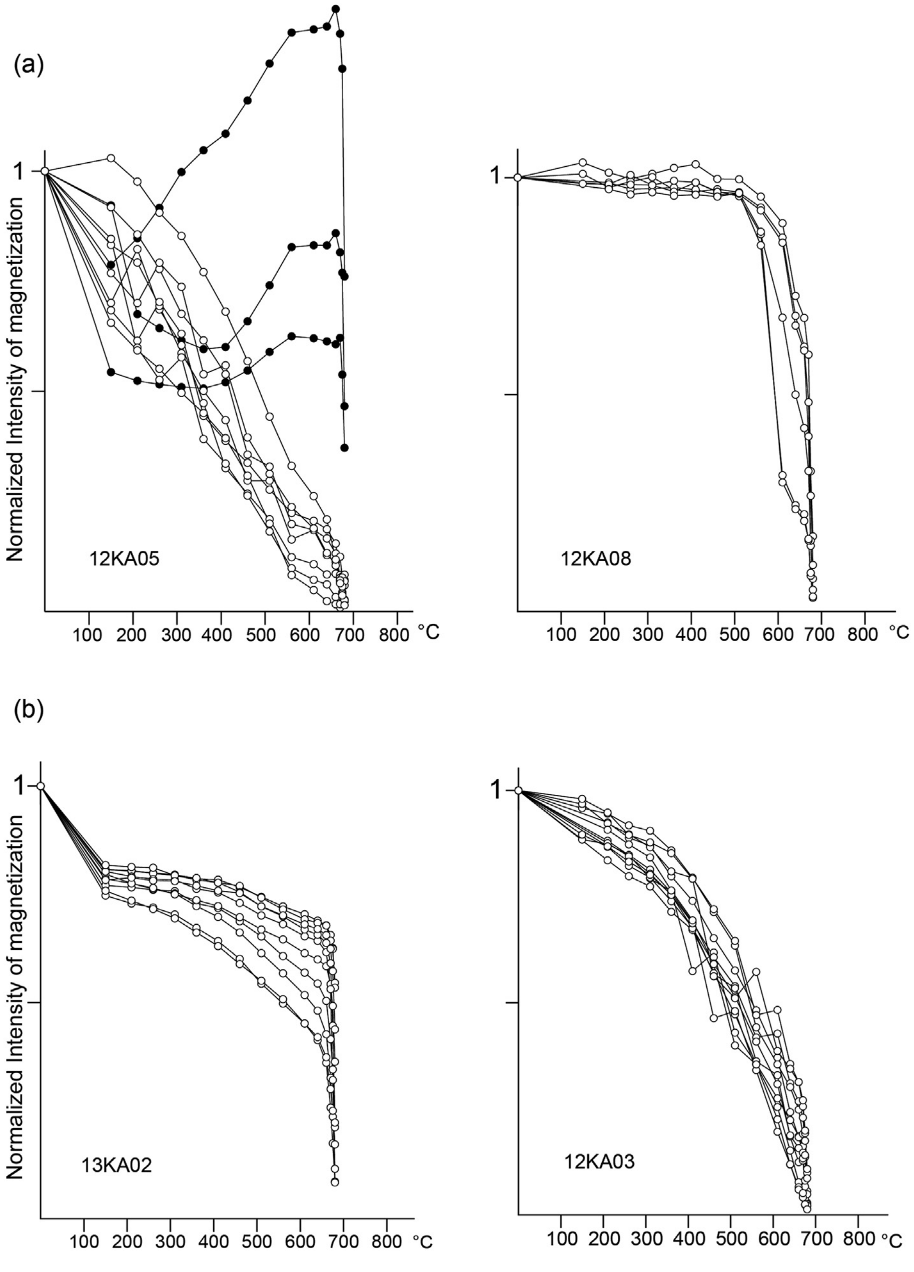

Fig. 5. Variation in the intensity of the remanent magnetization during thermal demagnetization. The demagnetization had to be done at high temperatures, near the Curie temperature for hematite (670–680 °C). (a) Samples from the Tuina Formation. Black circles correspond to three samples with reversed polarity. (b) Samples from the Purilactis Group.

K-T experiments were done with the AGICO KLY3-CS3 instrument.

For all samples, one specimen per mini core was subjected to stepwise thermal demagnetization (12–15 steps) in an ASC Scientific, TD-48 model oven.

A total of 34 samples were subjected to Alternating-Field demagnetization (12–15 steps), but it was not enough to unravel the whole magnetic record (the direction of the characteristic remanent magnetism did not reach the origin).

Demagnetization data were plotted on orthogonal diagrams (Zijderveld, 1967) (Figs. 6 and 7). Principal component analysis (Kirschvink, 1980) was applied to determine sample characteristic remanent magnetism (ChRM) directions. Evidence of secondary overprint was found at a few sites. In these cases, the site-mean characteristic direction including planes and lines was calculated using the procedure described by McFadden and McElhinny (1988). The expected direction and tectonic rotations at a paleomagnetic sites were calculated using the appropriate age reference paleomagnetic pole for South America. We use the Besse and Courtillot (2002) APWP for the Mesozoic units and the reference pole at 250Ma provided by Torsvik et al. (2012) for the Amazonia block (Table 2).

The average magnetic susceptibility and remanent natural magnetization intensity values obtained in the different sites show some variation according to the sampled lithology (Table 1, Fig. 3). The highest NRM values obtained in volcanic rocks was found in site 12KA07, which is also the site with the lowest magnetic susceptibility (Tuina Formation). The highest magnetic susceptibilities obtained in sedimentary rocks were found in the Vizcachita Member samples, belonging to the Purilactis Formation (sites 13KA03 and 13KA04). The sedimentary rock samples of the Tonel Formation (12KA10 and 13KA02) show the lowest magnetic susceptibility. The variation of the magnetic susceptibilities seen in the samples of the Licán and Vizcachita Members may suggest that both units had different sedimentary sources. Overall, the IRM analyses show hematite as the main magnetic carrier (Butler, 1992) with scarce magnetite for all the studied samples (Fig. 4). Consistently, the demagnetization had to be done at high temperatures, near the Curie temperature for hematite (670–680 °C) (Figs. 5–7).

5. Characteristic directions

The analysis of the characteristic directions was straightforward, given the presence of stable magnetizations that point towards the origin (sites 13KA01, 13KA02 and all sites labeled 12KA except 12KA05 and 12KA10). However, some sites also showed unstable magnetizations (sites 13KA08 and 13KA09). In these cases, the method developed by McFadden and McElhinny (1988) was used to find the characteristic directions. In general, the characteristic directions of the Tuina Formation are obtained at 410–680 °C (Figs. 5 and 6). For the Purilactis Formation samples, the characteristic directions are obtained at 560–680 °C (primary directions) and at 345–660 °C (secondary directions) (Figs. 5 and 7).

Site 12KA05 represents a particular case, due to the fact that three of its samples have a magnetization of reversed polarity at high temperature while the other samples present a normal polarity magnetization (Fig. 6). As such, two characteristic directions were calculated using the aforementioned methods (McFadden and McElhinny, 1988; Kirschvink, 1980) (Table 2).

6. Paleomagnetic results

In general, the scatter between sites diminishes after applying tilt correction to the samples (Fig. 8, TC stereonet), either for the Tuina Formation or the Purilactis Group. Normal and reversed polarities directions are obtained for the Tuina Formation. Site 12KA05, drilled in sedimentary rocks, shows both polarities. The

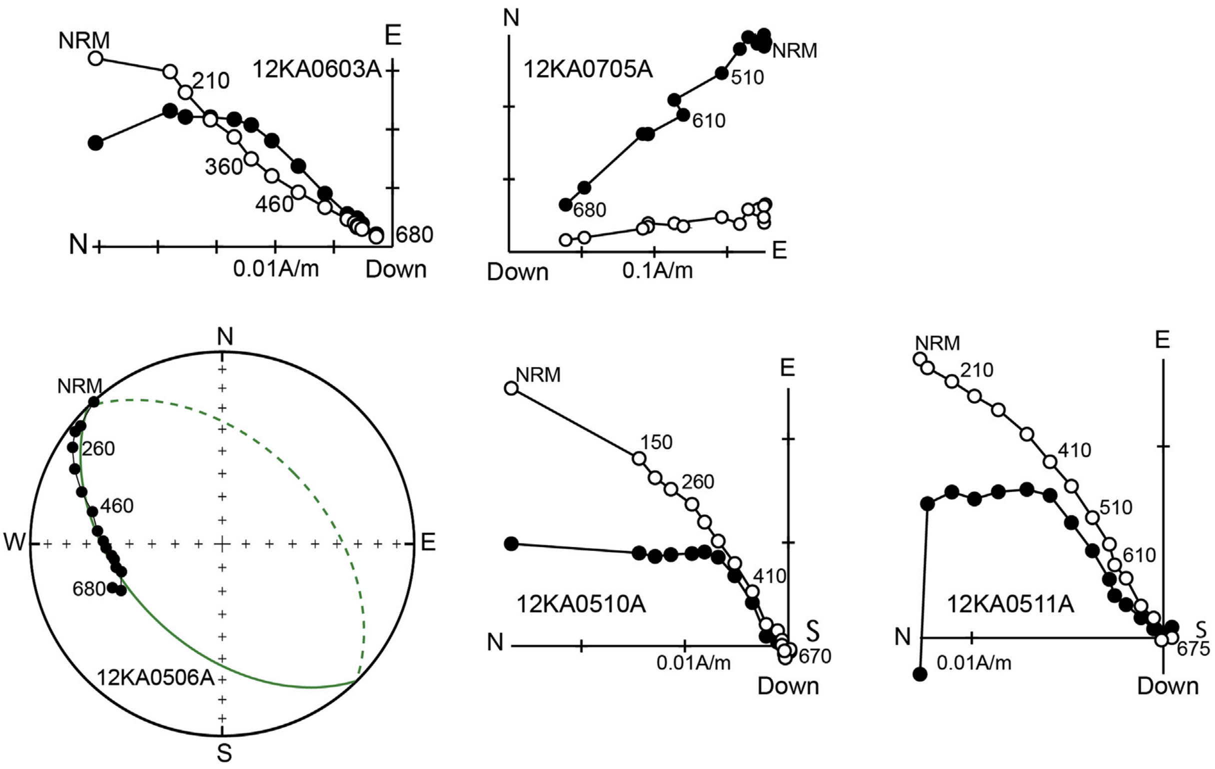

Fig. 6. Selected orthogonal stepwise demagnetization diagrams for sedimentary (sample 12KA05) and volcanic samples belonging to the Tuina Formation (in in situ coordinates). Open circles are projection in the vertical plane, while black circles correspond to the horizontal plane. Numbers indicate temperature steps in °C.

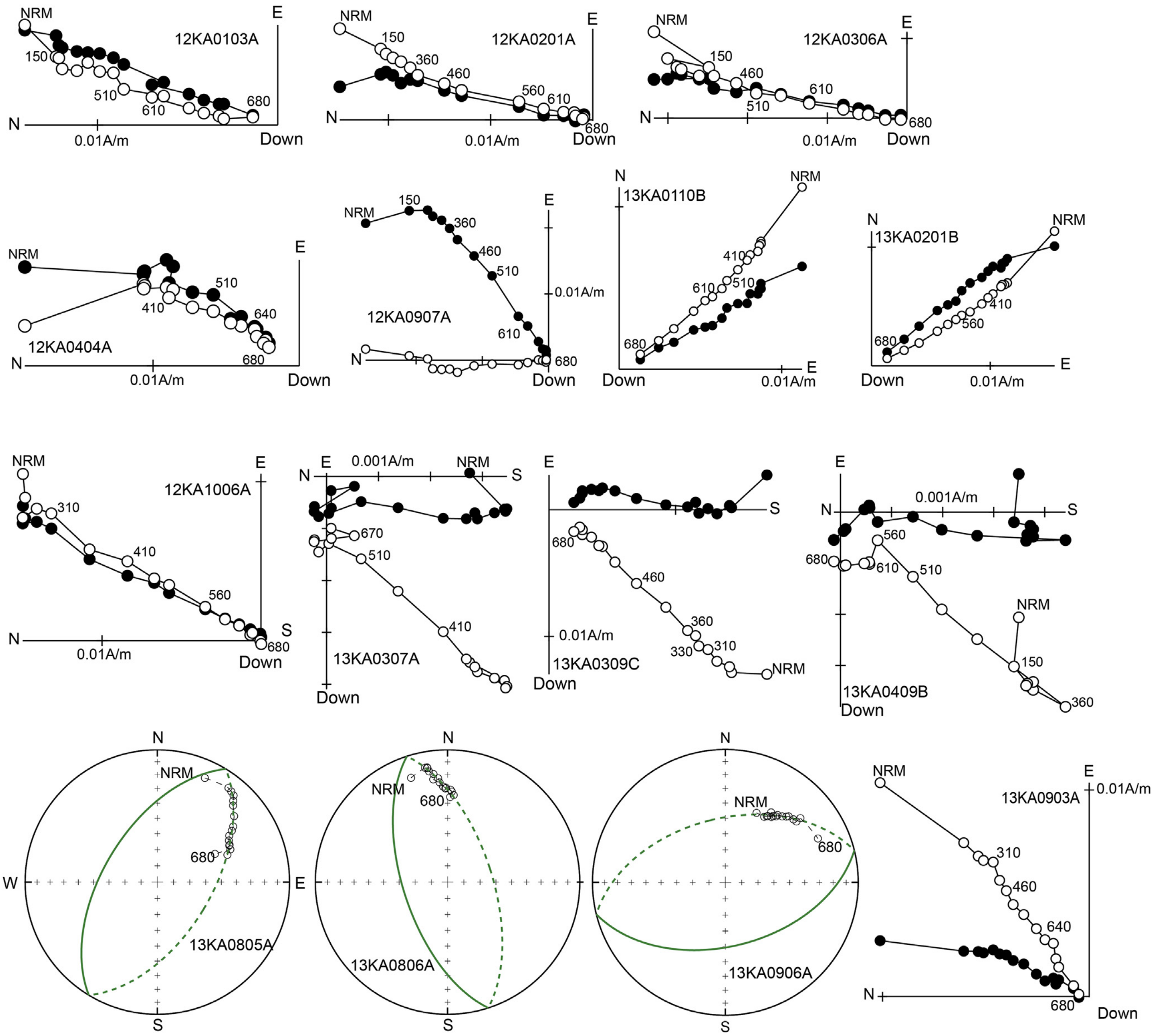

Fig. 7. Selected orthogonal stepwise demagnetization diagrams for sedimentary samples belonging to the basal members of the Purilactis Group (in in situ coordinates). In some cases a soft viscous overprint is removed during the first step of thermal demagnetization.

reversed polarity direction is antipodal, or about 180° away from normal polarity directions. The decrease in scatter, together with the antipodal character of the directions, indicates that the magnetization obtained in the Tuina Formation sites is primary and acquired previous to tilting. The low magnetic susceptibility as well as the highly stable and relatively strong remanent magnetization recorded at site 12KA07 are magnetic characteristics often observed in recent ignimbrites (Paquereau-Lebti et al., 2008), thus supporting the interpretation of a primary magnetization in the Tuina volcanics.

A similar pattern as that described previously by Hartley et al. (1992a), Arriagada et al. (2000) and Somoza and Tomlinson (2002) has been identified for the Purilactis Group (Table 2, Fig. 10). The magnetic inclination after tilt correction shows a better grouping both in the Tuina Formation and in the Purilactis Group. However, the declinations present some scatter. This suggests that, though clockwise rotation is evident, the magnitude of it might be variable and controlled partially by local deformation.

Table 2 shows the calculated tectonic rotation per site, and the inclination difference (flattening) from the expected inclination. The Tuina Formation sites yield fairly high rotation magnitudes between 38 and 79° clockwise (Fig. 9). The Purilactis Group sites shows rotations between 7 and 64° clockwise (Fig. 9). Sites 13KA05, 13KA06, 13KA07 and 13KA10 could not be included in the final results due to the complex and erratic magnetic behavior shown by the samples during demagnetization process. In in situ coordinates, the mean characteristic direction obtained in site 13KA09 is comparable to the mean characteristic direction observed in the other sites belonging to the Tonel Formation after tilt correction suggesting a post-folding magnetization (Table 2).

7. Discussion

7.1. Age of magnetization

Four of the sites obtained in the Tuina Formation show stable

Table 2
Paleomagnetic results.

Site	l	p	t	In situ				Tilt corrected		VGP			Rotation	Inclination	Age
				D (°)	I(°)	α_{95}	k	D(°)	I(°)	Lat(°)	Long(°)	P95	(°)	Error (°)	(Ma)
Barros Arana Syncline: basal sedimentary units of the Purilactis Group (Late Cretaceous)															
Vizcachita member															
13KA03	9	0	9	193.2	40.7	8.3	39.9	216.4	35.4	82.3	228.4	6.9	43.7 ± 10.0	0.8 ± 10.7	80
13KA04	10	0	10	190.3	43.5	6.2	62.4	216.4	39	82.3	228.4	6.9	43.7 ± 8.7	4.4 ± 9.7	80
Licán member															
13KA08	3	6	9	32.6	−45	14.4	15	9.6	−34.2	82.3	228.4	6.9	16.9 ± 15.2	0.3 ± 14.2	80
Tonel formation															
12KA01	5	0	5	14.4	−9.3	10.6	53.5	39.2	−39.1	87.8	29.2	11.5	36.8 ± 14.8	−1 ± 15.2	100
12KA02	5	0	5	13.7	−11.3	5.1	222.2	43.6	−48.1	87.8	29.2	11.5	41.2 ± 11.7	8 ± 13.3	100
12KA03	11	0	11	10.6	−9.4	4.9	88.7	32.3	−45	87.8	29.2	11.5	29.9 ± 11.4	4.9 ± 13.3	100
12KA04	4	1	5	40.2	−37.5	9.4	77.2	35.8	−51.9	87.8	29.2	11.5	33.4 ± 15.8	11.8 ± 14.7	100
12KA09	9	0	9	56	−0.5	4.1	157.1	67	−36.4	87.8	29.2	11.5	64.6 ± 10.8	−3.7 ± 13.1	100
12KA10	10	0	10	22.4	−25.1	4.9	99.5	16.4	−45	87.8	29.2	11.5	14 ± 11.4	5 ± 13.3	100
13KA01	9	0	9	47	−28.8	7.9	43.5	21.9	−33.9	87.8	29.2	11.5	19.5 ± 12.6	−6.2 ± 14.2	100
13KA02	10	0	10	55.5	−29.2	5.0	93.3	27.9	−39.6	87.8	29.2	11.5	25.5 ± 11.3	−0.5 ± 13.3	100
13KA09	10	0	10	20.4	−46.5	2.9	271	340.0	−31.7						
Cordillera de Domeyko: volcanic and sediments of Tuina Formation (Permian-Late Triassic)															
12KA05	1	2	3	231.1	48	9.4	473.1	213.1	31.1	74.1	160.2	3.6	47.1 ± 9.4	−20.8 ± 8.1	250
12KA05	8	0	8	46.9	−44.1	4.7	142.3	32.3	−26.3	74.1	160.2	3.6	46.4 ± 5.4	−25.6 ± 4.9	250
12KA06	4	0	4	43.4	−23.1	3.8	574.4	73.3	−49.1	74.1	160.2	3.6	87.4 ± 5.8	−2.7 ± 4.3	250
12KA07	6	0	6	49.4	−6	3.2	427.6	64.9	−36.9	74.1	160.2	3.6	79 ± 4.7	−14.9 ± 4.0	250
12KA08	6	0	6	44.3	0.4	1.0	4450.7	50.9	−32.1	74.1	160.2	3.6	65 ± 3.5	−19.7 ± 3.2	250

The l and p are numbers of lines and planes used to calculate the mean ChRM direction. $t = l + p$; D. I. α_{95}. and k. the declination. inclination. angle of confidence at 95% and Fisher parameter k. respectively; Latitude and Longitude are the virtual geomagnetic pole (VGP). P95 is the angle of confidence at 95% for the VGP. Age. estimated age of the magnetization and of the reference pole after Besse and Courtillot (2002) for the Mesozoic units and Torsvik et al. (2012) for the Tuina Formation used to calculate the rotation.

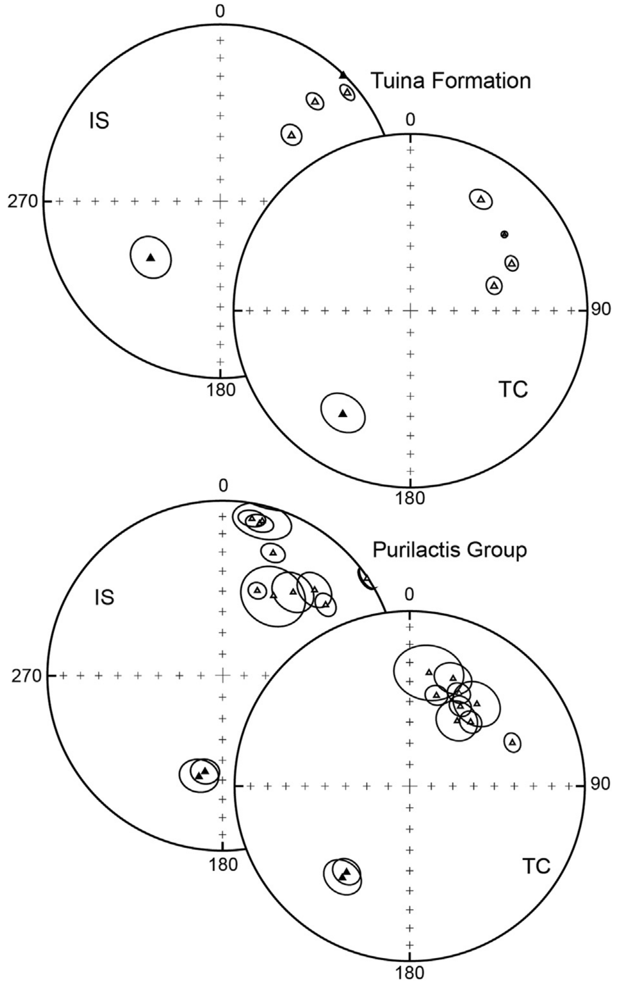

Fig. 8. Simplified geological map showing variation in the magnitude of tectonic rotations. The largest rotations observed are in an area bounded by two reverse faults of opposite vergence (Tuina and Morro del Inca faults).

magnetization. Marinovic and Lahsen (1984) assigned a Permian age to this unit. Recent studies (Henríquez et al., 2014), based on five new U–Pb zircon ages obtained from samples belonging to the Middle and Upper Members of the formation, allow to place it in the Late Permian (Lopingian)-Middle Triassic age. These analyses, together with the primary magnetization data acquired, suggest that the age of magnetization of the four sites would be close to 236–253 Ma.

Regarding the units overlying the Tuina Formation, Bascuñán et al. (2015) estimate that the Tonel Formation would have been deposited between the Albian-Santonian (113–84 Ma), while the Purilactis Formation would have been deposited between the Campanian-Danian (84–61 Ma). These ages are consistent with other paleomagnetic studies that place the Tonel Formation and the basal units of the Purilactis Formation in the “middle” Cretaceous normal polarity superchron (119-84 Ma; Arriagada el al., 2000). The characteristic directions of the primary magnetizations obtained in this study for the Tonel Formation and the basal units of the Purilactis Formation show, preponderantly, normal polarity.

Based on these results, it is possible to conclude that the age of magnetization of the sites belonging to the Tonel and Purilactis Formations range between 110 and 80 Ma.

7.2. Origin of the rotations

The data obtained in the study area show that the Permian–Triassic (Middle Member of the Tuina Formation) and Cretaceous (Purilactis Group) units possess the same rotation pattern (30–40° clockwise), which matches the pattern yielded previously in earlier work (Hartley et al., 1992a; Arriagada et al., 2000; Somoza and Tomlinson, 2002) (Figs. 8–10). This suggests that its origin could be closely associated with the Incaic Orogenic Phase and the building of the Bolivian Orocline (Isacks, 1988; Roperch and Carlier, 1992; McFadden et al., 1995).

Additional tectonic rotations of 57–79,4° clockwise were obtained in the Upper Member of the Tuina Formation (sites 12KA06, 12KA07 and 12KA08) and in a site belonging to the Tonel Formation (12KA09). All these sites overlie the ones belonging to the Tuina

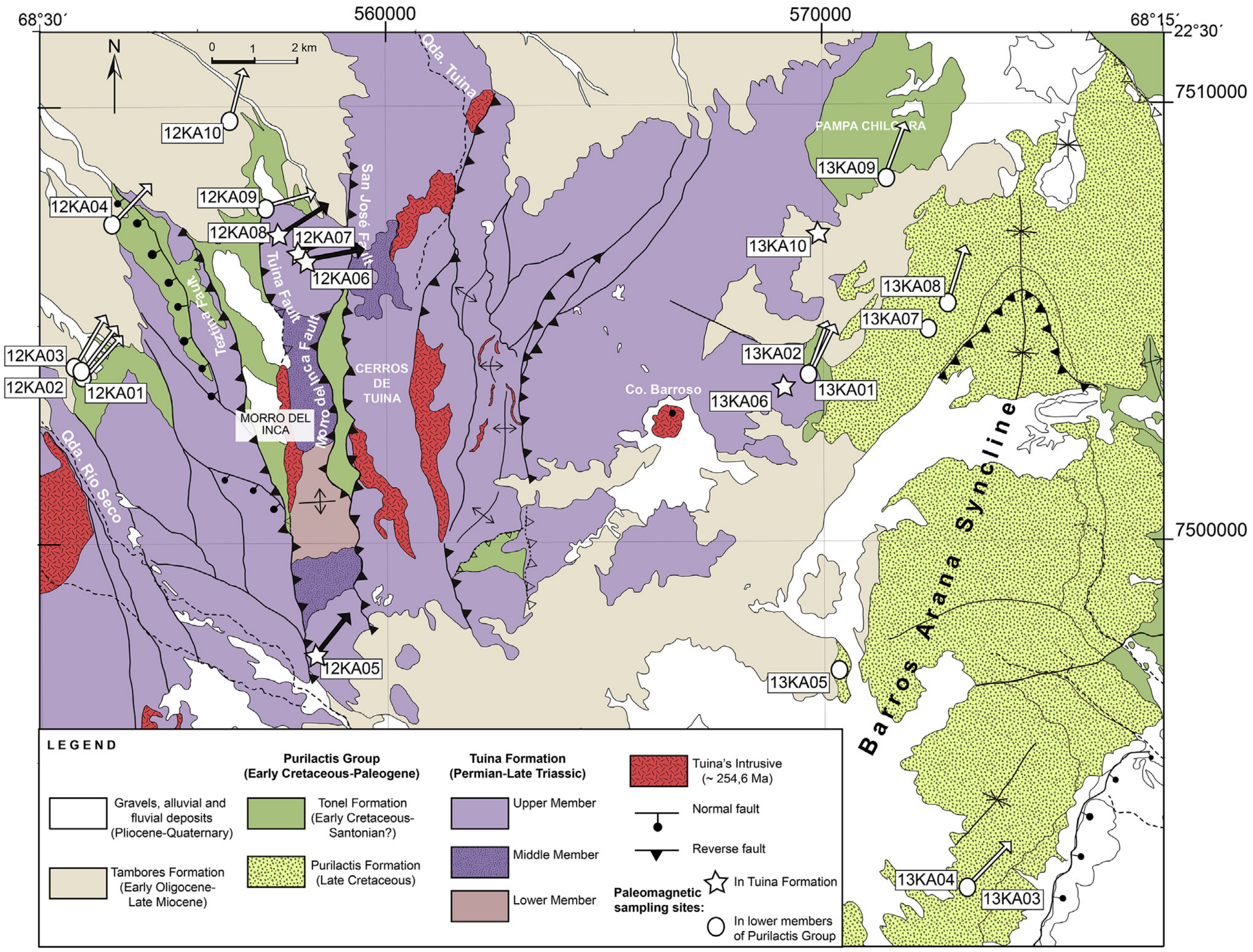

Fig. 9. Equal-area plot of the characteristic directions of the Tuina Formation and the Purilactis Group. IS, in situ. TC, tilt corrected. Upon tilt corrected, there is a significant decrease in the dispersion of the directions.

Formation. The complex structural pattern of this zone may suggest a domain with a higher degree of rotation. The "excess" clockwise rotation could be explained, given the fault geometry (Figs. 8–10), by local, dextral transpressive tectonics. This dextral shear would affect a block bounded by the Tuina, Morro del Inca and San José blocks, effectively increasing the average clockwise rotation locally.

Randall et al. (2001) and Astudillo et al. (2008), who studied structural subdomains of the Domeyko Fault System north and south of the study area, document the presence of anomalous rotations, attributed to the complex kinematic history of the fault system. The magnitude and, at times, sense variation cannot be explained merely by a first order rotation process, as would be expected of an oroclinal bending (Randall et al., 2001).

8. Conclusions

In regard to the magnetic properties, it is possible to conclude that:

- Considering the high temperatures reached during demagnetization (670–680 °C) and the IRM results, it is safe to conclude that the mineral carrying the magnetization is mainly hematite, with a small presence of magnetite in some cases. The magnetic directions observed in the Zijderveld diagrams correspond to univectorial magnetizations pointing towards the origin. We interpret the magnetic vectors as primary magnetizations acquired during the emplacement and the cooling of the volcanic rocks belonging to the Tuina Formation. In the case of the Purilactis Group and site 12KA05 of the Tuina Formation, the magnetization could be associated with either diagenesis, due to the presence of hematite cement, and/or detrital magnetization during sedimentation of these successions.
- The presence of primary magnetizations showing normal and reversed polarities within the Tuina Formation allows discarding a middle Permian age (Kiaman Reversed Polarity Chron) for the studied samples of the Middle and Upper Members. These paleomagnetic results are consistent with a U–Pb age of 236,3 ± 2,5 Ma (Late Triassic) obtained in tuffs belonging to the Upper Member of this formation.
- The Purilactis Group shows normal polarity magnetizations, except for sites 13KA03 and 13KA04, which belong to the Vizcachita Member and show reversed polarities.

It has been possible, for the first time in this area, to obtain favorable measurements in the units belonging to the basement of the Cordillera de Domeyko (Tuina Formation). It is possible to recognize, both in samples belonging to the Tuina Formation as well as the Purilactis Group, the clockwise rotation pattern described previously in this area (Hartley et al., 1992a; Arriagada et al., 2000; Somoza and Tomlinson, 2002). The results obtained point to the existence of 30–40° clockwise tectonic rotations. Some

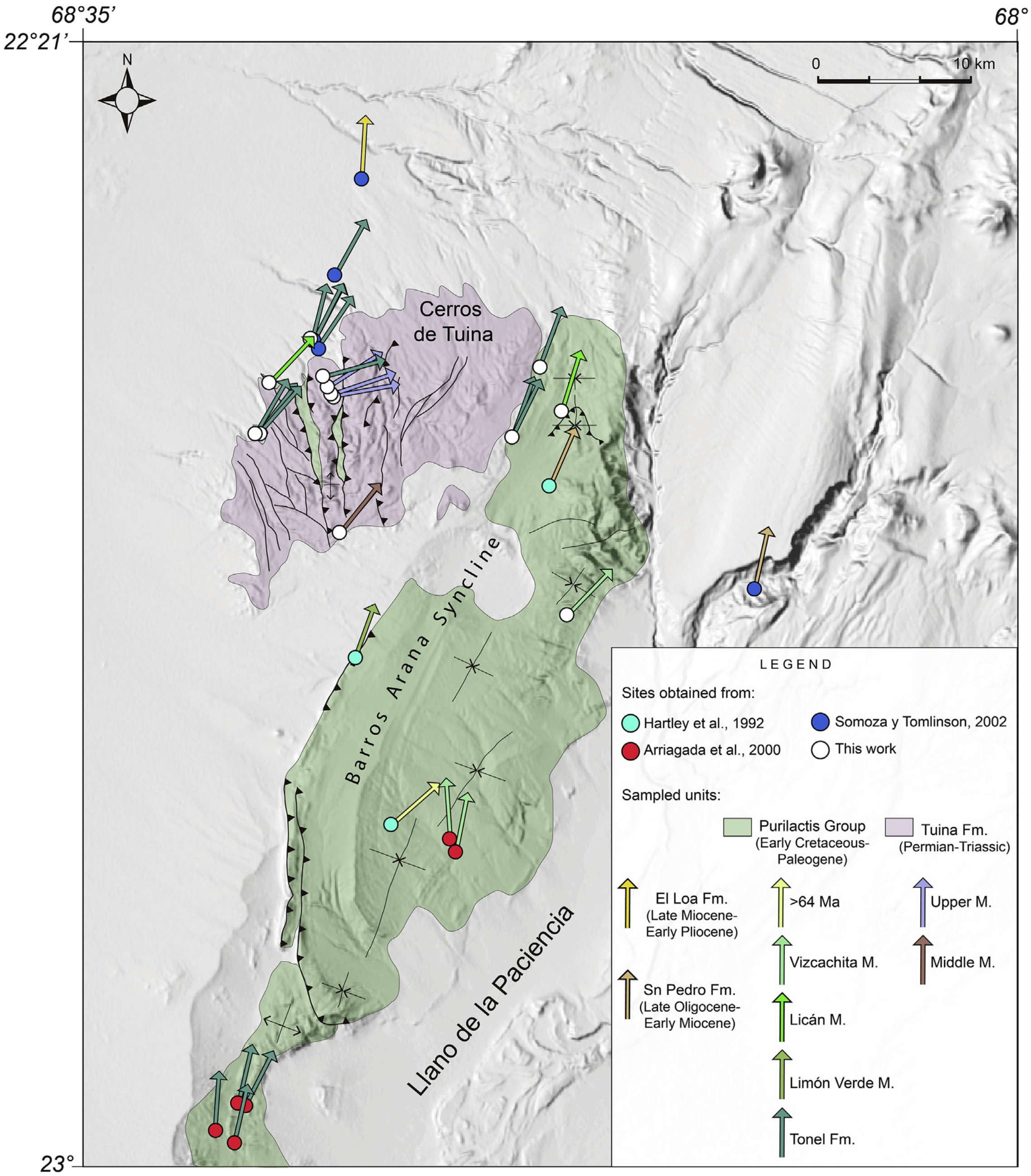

Fig. 10. Compilation of tectonic rotations in the northern part of the Atacama basin. It is possible to recognize, both in samples belonging to the Tuina Formation as well as the Purilactis Group, the clockwise rotation pattern described previously in this area.

sites record even larger clockwise rotations but they are limited to a structural domain bounded by reverse faults of opposite vergence. This domain is probably controlled by a local, dextral transpressive tectonic regime, highlighting the complex kinematic history of this region. Additionally, we conclude that there is not enough evidence of significant rotations in this area, neither in the Permo-Triassic unit (Tuina Formation), nor in the lower members of the Purilactis Group, previous to the rotations which formed the Bolivian Orocline. It is possible to assert that the Peruvian and K-T tectonic phases did not generate significant tectonics rotations in the area.

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