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Paleomagnetic evidence of earliest Paleocene deformation in Calama (∼22°S), northern Chile: Andean-type or ridge-collision tectonics?

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ABSTRACT

A paleomagnetic study from the earliest Paleocene Cerros de Montecristo Quartz Monzonite and its Jurassic to uppermost Cretaceous host rock (northern Chile, ∼22°S) provided high-temperature, high-coercivity magnetizations of dominantly reversed polarity. The remanences of the tilted host rock gave a negative fold-test and are indistinguishable from the remanences found in the pluton, indicating that the uppermost Cretaceous rocks underwent deformation before intrusion of the earliest Paleocene pluton, thus documenting a K–T deformation at the locality. Although this deformation may be another product of typical subduction-related noncollisional tectonics in the Central Andes, an alternative hypothesis, permitted by plate reconstructions, is that the event was associated with collision of an oceanic plate boundary. This latter hypothesis may also provide a context for several other tectonic events from northern Chile to the Patagonian Andes, wherein deformation would the consequence of a southward migrating triple junction between the latest Maastrichtian and Early Eocene.

1. Introduction

The Andean orogen has been growing since the Late Cretaceous, when westward motion of South America accelerated in response to a major plate reorganization (Somoza and Zaffarana, 2008) leading to an inversion of the Jurassic–Early Cretaceous extensional basins along the western continental margin (Mégard, 1989; Mpodozis and Ramos, 1990; Sempere et al., 1990; Ramos and Aleman, 2000). This Late Cretaceous to Recent orogenic stage of the Andean Cycle is characterized by a several contractional events separated by periods of relative quiescence or modest extension, and is frequently cited as the type example of a noncollisional orogen generated by ocean–continent plate convergence. The contractional events include the three classical, regional shortening phases: Peruvian (early Late Cretaceous), Incaic (Eocene) and Quechua (Late Cenozoic), but the full deformational history is unknown and its relation with plate kinematics uncertain. Deciphering the pre-Eocene deformational history has been difficult because of the widespread superposition of the Incaic and Quechua tectonic events over earlier events. One exception is the recognition of an Early Paleocene deformational event recorded and identified in several localities of northern Chile (Cornejo et al., 1997, 2003).

In this paper we present evidence for earliest Paleocene deformation in the Precordillera of northern Chile, west of Calama, by reporting new, well age-constrained, paleomagnetic data from the Cerros Montecristo Quartz Monzonite and its host rocks. Although in principle this event could be another product of simple Andean-type noncollisional deformation, plate reconstructions indicate that an origin related to ridge–trench collision, a common process at convergent margins, must also be considered.

2. The Cerros de Montecristo Quartz Monzonite and its host rocks

The Cerros de Montecristo Quartz Monzonite (Fig. 1) is an Early Paleocene, medium to fine-grained pluton with quartz, plagioclase, orthoclase, amphibole, pyroxene and biotite as its main primary minerals. Fibrous, greenish to colorless amphibole (actinolite–tremolite), chlorite and titanite occur as secondary minerals of likely deuteric origin. The quartz-monzonite unit is accompanied by a suite of apparently cogenetic gabbroic and dioritic rocks. The pluton intrudes variably tilted mudstones, siltstones and fine-grained quartzose sandstones of the Upper Jurassic – Lower Cretaceous San Salvador Formation and volcaniclastic conglomerates

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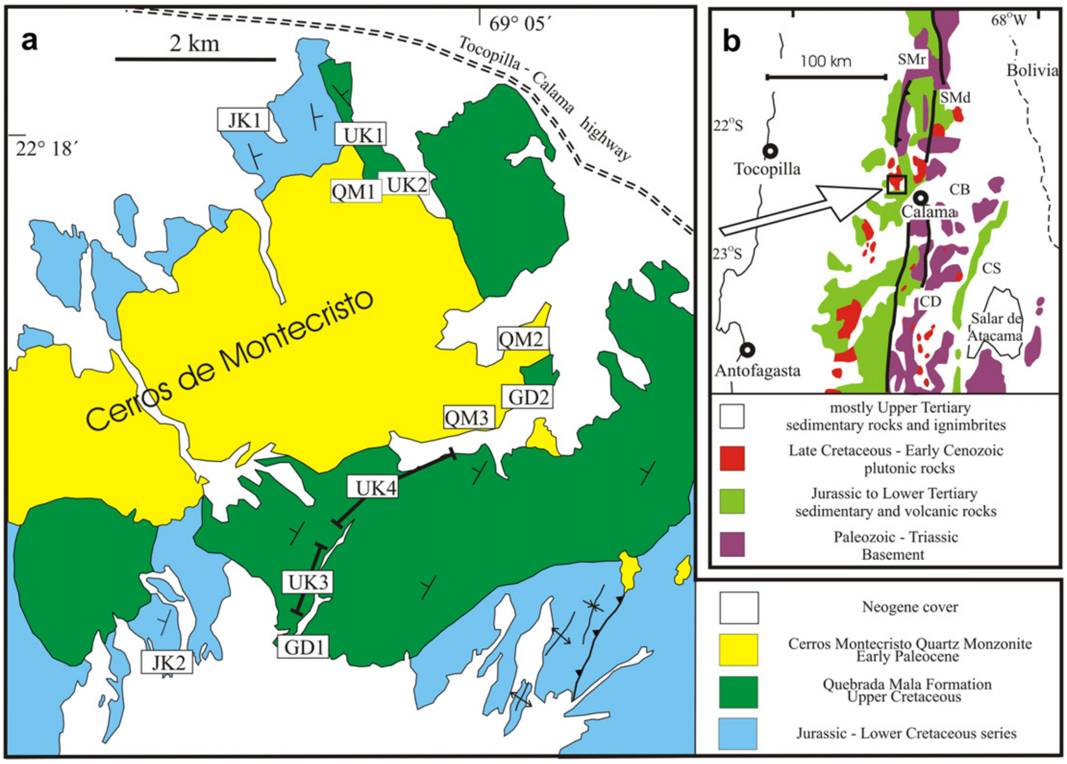

Fig. 1. a) Simplified geologic map with location of sampled sites. Bars in UK3 and UK4 indicate samples widely distributed along 100's of meters thick stratigraphic sections. b) location of the study area within a regional map of northern Chile. Codes are showing the location of the Sierra (range) de Moreno (SrM), the Sierra del Medio (Smd), the Calama Basin (CB), the Cordillera de la Sal (CS), and the Cordillera de Domeyko (CD).

and sandstones, andesitic lavas and silicic ignimbrites of the Upper Cretaceous Quebrada Mala Formation (Tomlinson et al., 2001).

Pervasive alteration is recorded in the Quebrada Mala Formation volcanic host rocks, whereas the pluton, intrusive mafic rocks and sedimentary rocks of the San Salvador Formation remain relatively unaltered. Upper Cretaceous andesitic lavas and immature volcaniclastic rocks show propylitic assemblages, represented by albite–epidote–sericite after plagioclase, and chlorite–epidote–magnetite pseudomorphically replacing mafic minerals (principally hornblende and pyroxene). Chlorite and carbonates are widespread and disseminated pyrite is locally observed. A higher temperature alteration assemblage is recorded adjacent to the pluton, where Upper Cretaceous lavas show actinolitic amphibole replacing magmatic clinopyroxene and hornblende, chloritization of olivine, and groundmass replacement by actinolite–opaques–titanite ± chlorite.

Overall, the observed mineral assemblages suggest an extensive hydrothermal system affecting the host Quebrada Mala Formation, with a gradient of increasing temperature toward the Cerros de Montecristo pluton. Alteration apparently was not related to fluids liberated from the quartz-monzonite and associated mafic intrusions, because their magmatic mineralogy is, at best, only weakly modified. Instead we infer that the pluton acted primarily as a heat engine for a circulation system that involved external fluids, such as formation waters or groundwater; in a manner similar to the mode of formation of propylitic alteration zones observed around shallow porphyry intrusive systems (Seedorff et al., 2005). The paucity of alteration in the underlying San Salvador Formation is likely due to the nonreactive quartzose composition of its constituent lithologies.

The Upper Cretaceous Quebrada Mala Formation overlies with angular unconformity folded strata of the Upper Jurassic–Lower Cretaceous San Salvador Formation and, east of the sampling area, it overlies unconformably mid-Cretaceous volcanic rocks of the Cuesta de Montecristo sequence (Tomlinson et al., 2001), documenting thus the presence of the early Late Cretaceous Peruvian contractional deformation phase. The Quebrada Mala Formation is in turn deformed into open, map-scale folds. Westward tilted Quebrada Mala Formation strata and lavas can be traced, with little change in orientation, for tens of kilometers from the east, beyond the study area, up to the Cerros de Montecristo Quartz Monzonite contact (Fig. 1), suggesting that any superposition of an intrusive-related deformation in the contact zone is minor. Upper Miocene gravels regionally dip very gently toward the west (~2° in the northern part of the pluton), defining the western monoclinal slope of the Late Cenozoic Central Andean plateau (Isacks, 1988; Jordan et al., 2010).

3. Paleomagnetic sampling and results: evidence of earliest Paleocene deformation near Calama

We drilled three sites in the quartz-monzonite (sites QM1–3, Fig. 1), and two sites from small outcrops of gabbro-diorite facies south and east of the main pluton (sites GD1–2, Fig. 1). In the host rock we took 19 samples in two sites from mudstones and siltstones of the Upper Jurassic–Lower Cretaceous San Salvador Formation (sites JK1–2 in Fig. 1). Sampling in the Quebrada Mala Formation comprises two sites from conglomerates in the northern sector (sites UK1–2, Fig. 1) and two sites from volcaniclastic sandstones, ignimbrites and lavas in the southern sector (sites UK3–4, Fig. 1).

Alternating field and thermal demagnetization allowed the isolation of a high coercivity, high unblocking temperature remanence of dominant reversed polarity and magnetite as the main carrier (Fig. 2). Site mean directions are well grouped in

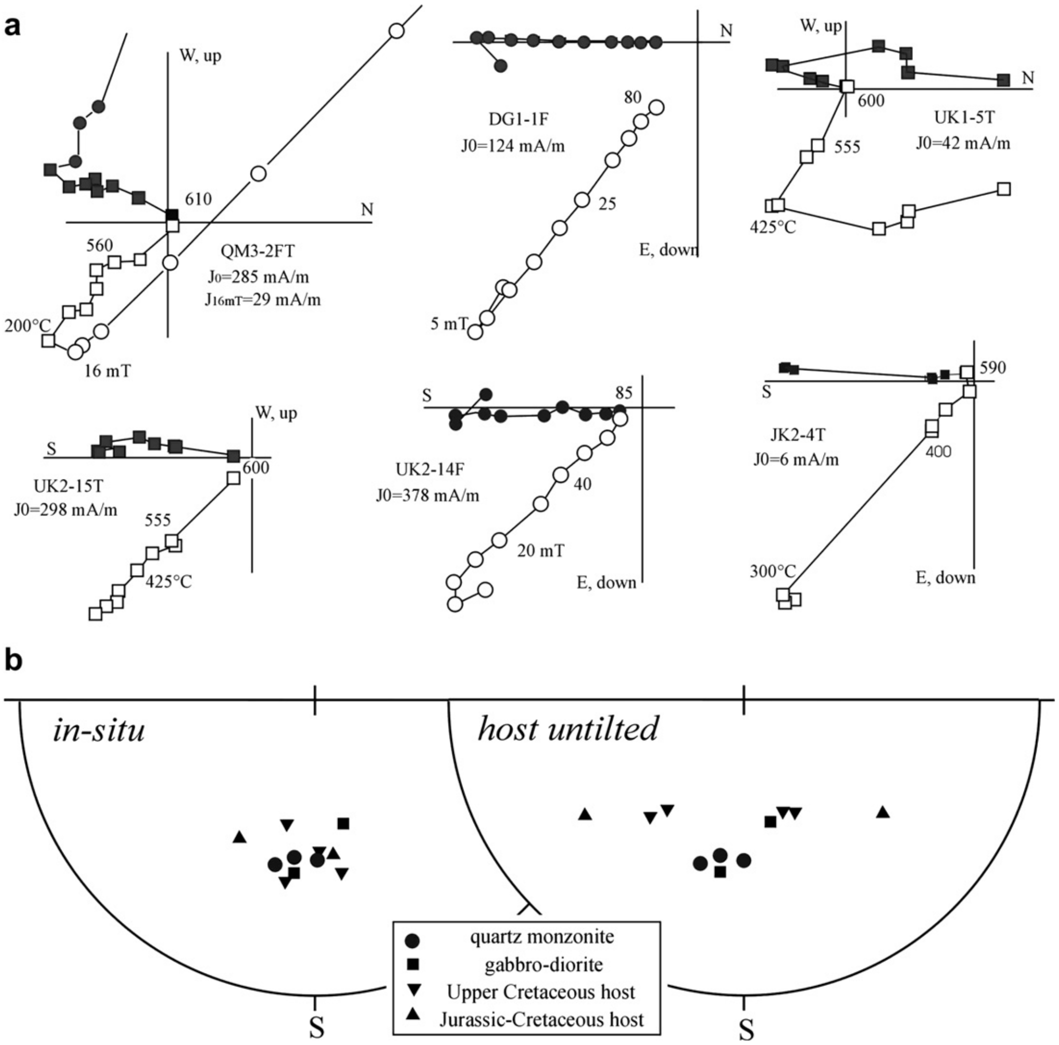

Fig. 2. a) Orthogonal diagrams illustrating examples of typical paleomagnetic behaviors. The first part of the sample name indicates the corresponding site (as shown in Fig. 1). b) stereonets showing the site-mean directions *in-situ* (left) and after restoring stratification to paleohorizontal for the host rock sites (right). The paleomagnetic database from stable South America (Somoza, 2007; Somoza and Zaffarana, 2008) indicates that the expected Late Cretaceous and Eocene paleomagnetic directions for the studied locality are Decl. 171°E, Incl. 45°; $\alpha_{95} = 4.2^\circ$ and Decl. 173°E, Incl. 47°; $\alpha_{95} = 5.5^\circ$, respectively. Comparison of the in-situ mean direction from all sites with the expected paleomagnetic directions indicates that the sampling locality underwent ~13° clockwise rotation after the intrusive event, possibly during the Eocene Incaic deformation phase as proposed by Arriagada et al. (2003) for tectonic rotations detected in other localities of the region.

geographical coordinates and scattered when the appropriate rotation to untilt the host rock is applied (Fig 2), indicating that the Jurassic to Upper Cretaceous rocks around the pluton were remagnetized after tilting. The dominant presence of reversed polarities in both pluton and host rock strongly suggest that the remagnetization of the latter is coeval with cooling of the pluton. Two samples from the UK4 section have a similar remanence direction as the rest, but with normal polarity (Table 1). One possible interpretation is that the site is only partially remagnetized and the normal polarities represent a primary remanence. However the mean direction is coherent with the in-situ mean directions for the rest of the sites, and thus also permits the inference that they too may represent a pluton-related remagnetization, though during emplacement of an intrusive pulse that is not represented by the group of intrusive sites sampled here. Because of uncertainty in its origin, the normal polarity result is omitted from the tectonic analysis.

The secondary mineral zonation around the pluton points to intrusive heating as the main factor contributing to both remagnetization and alteration in the host rock. Then, the grouping of site-mean directions in the remagnetized host rock indicates that observed deformation in the Upper Cretaceous rocks was complete before blocking of the remanences in the quartz-monzonite intrusion (Fig. 3). Deformation of the Upper Cretaceous rocks is thus bracketed between the youngest age obtained from the Quebrada Mala Formation (65.6 ± 0.4 Ma, U–Pb on zircon by conventional isotope dilution TIMS, Tomlinson et al., 2001) and the U–Pb zircon age of the Cerros de Montecristo pluton (63.2 ± 1.0 Ma, by LA-ICP-MS, Ballard et al., 2002; Campbell et al., 2006). Our tightly age-constrained paleomagnetic results thus document an earliest Paleocene deformation event in the area west of Calama (Fig. 1b), where most post Late Cretaceous deformation has been previously ascribed to the Eocene Incaic phase (Reutter et al., 1991; Günther et al., 1997; Günther, 2001).

4. Discussion: did latest Maastrichtian–Paleogene oceanic-ridge collision occur in the Chilean Andes?

Besides the deformation described in this contribution, Paleocene deformation in northern Chile has also been reported in the

Table 1
Paleomagnetic results.

Site	Lat. South	Long. West	n/N	Dec. geo.	Incl. geo.	α_{95}	k	Bedding	Dec. str.	Incl str.
QM1	22° 18.1′	69° 06.0′	6/6	188.0	45.8	7.9	50	–	188.0	45.8
QM2	22° 19.3′	69° 04.7′	5/6	194.2	42.1	10.6	35	–	194.2	42.1
QM3	22° 19.9′	69° 04.8′	5/5	179.6	45.1	9.3	45	–	179.6	45.1
GD1	22° 21.3′	69° 06.3′	8/8	167.8	55.2	3.4	868	–	167.8	55.2
GD2	22° 19.6′	69° 04.5′	5/5	187.5	40.8	2.1	1380	–	187.5	40.8
UK1	22° 18.0′	69° 05.8′	8/10	193.3	54.4	6.5	73	349/22	160.2	57.5
UK2	22° 18.1′	69° 05.8′	8/8	179.2	47.6	4.6	148	325/20	155.5	55.4
UK3	22° 21.0′	69° 06.3′	4/5	189.7	38.0	9.6	39	222/31	218.2	48.1
UK4	22° 21.1′	69° 06.3′	9/9	171.7	40.5	7.0	54	210/39	214.1	53.2
UK4[a]	22° 19.9′	69° 05.0′	2/2	352.8	−48.5	–	–	210/39	46.9	−56.6
JK1	22° 17.7′	69° 06.3′	12/12	173.7	46.7	3.0	175	340/45	129.0	39.0
JK2	22° 21.6′	69° 07.2′	6/8	209.4	46.0	9.5	66	200/30	233.7	34.5
In-situ			11	185.1	46.0	5.6	67			
Host unfolded			11			12.8	14		185.7	50.7

Lat. and Long. denote site location; n/N denotes number of samples used in statistics/number of samples collected; Dec. geo., Incl. geo. are declination and inclination of paleomagnetic vector in geographical coordinates; α_{95} is cone of 95% confidence level around mean direction; k is the *fisherian* precision parameter; bedding indicates strike and dip of bedding plane, with strike in degrees to the East and dip measured 90° clockwise from strike; Dec. str., Incl. str. are declination and inclination referred to paleohorizontal after applying bedding values observed in the host rocks.

[a] Not used in the tectonic analysis.

Salar de Atacama basin (23°S), El Salvador area (26°S) and Copiapo area (27°30′S). In the Salar de Atacama, Mpodozis et al. (2005) described a prominent angular unconformity between ~65 Ma volcanic rocks of the Totola Formation and the ~58 Ma Orange Formation, attesting to a Paleocene deformation which is clearly older than the ca 43 Ma beginning of the widespread Incaic deformation that affected the Salar de Atacama area. Farther south, in the El Salvador area, where the Early Paleocene deformation event was first recognized, a short (65–62 Ma) but significant episode of compressional deformation tightly folded volcanic and sedimentary rocks of the Upper Cretaceous–lowermost Paleocene Llanta Formation (80–65 Ma), which are unconformably overlain by 62–54 Ma Paleocene–Early Eocene volcanic sequences (Cornejo et al., 1997, 2003, 2009; Cornejo and Matthews, 2001; Matthews et al., 2006). Regional mapping indicates this deformation can be traced through much of the Central Depression from south of El Salvador (27°) to nearly the latitude of Antofagasta (24°) (Cornejo et al., 2003; Espinoza et al., 2009). Still farther south, near Copiapo (27°30′S), Taylor et al. (2007) found that uppermost Cretaceous to lowermost Paleocene rocks of the Hornitos Formation, with U–Pb zircon ages between 66.9 Ma and 65.2 Ma (Arévalo, 2005a, b; Maksaev et al., 2009), were deformed before the intrusion of Early Paleocene plutons with 64–59 Ma ^{40}Ar/^{39}Ar and K–Ar ages (Arévalo, 2005a, b; Taylor et al., 2007).

Given the intensity and short duration of the deformation event, Cornejo et al. (2003) proposed it may be related either to a plate motion readjustment or subduction of an aseismic ridge. Cornejo and Matthews (2001) noted that post-deformation volcanism has a transitional, calc-alkaline to intraplate geochemical signature, as might be expected if the supraslab mantle wedge where to be contaminated by sub-slab mantle rising through a slab window of a subducted spreading ridge (e.g. Gorring and Kay, 2001).

Mid-ocean ridge subduction is a consequence of the closure phase of the Wilson cycle and accordingly is an inevitable event in plate boundaries involving subduction of oceanic lithosphere; it is currently occurring at seven different points around the Pacific (Sisson et al., 2003). All of the paleogeographic reconstructions in the southeast Pacific show that the Phoenix–Farallon constructive plate boundary must have subducted somewhere along the Andean margin during the Late Cretaceous and Early Cenozoic, although the precise location of this oceanic ridge through time is uncertain. Cande and Leslie (1986) envisage an Early Cenozoic, southward

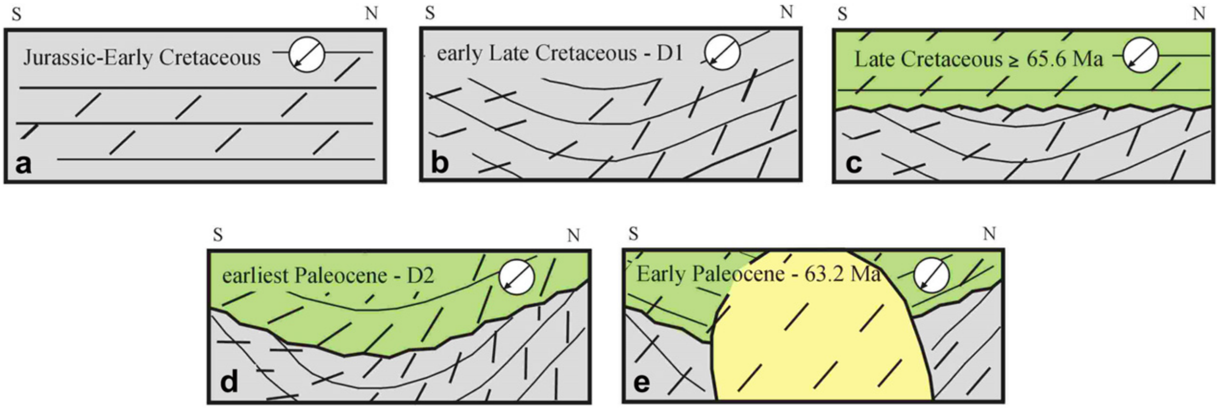

Fig. 3. Sketch schematically illustrating the inferred deformational and magnetization history for study area. Figures represent vertical planes containing the ambient paleomagnetic field (small circle in the right corner) for each time. a) deposition (bedding S0-1) and primary magnetization (paleomagnetic lineation PL-1) of the Jurassic-Lower Cretaceous San Salvador Formation as seen in cross section, b) folding of S0-1 and PL-1 during the early Late Cretaceous Peruvian contractional deformation phase (D1), c) deposition (S0-2) and primary magnetization (PL-2) of the Upper Cretaceous Quebrada Mala Formation, d) folding of S0-1, S0-2, PL-1 and PL-2 during earliest Paleocene deformation phase (D2), e) emplacement of Early Paleocene Cerros de Montecristo Quartz Monzonite resets the older, rotated paleomagnetic lineations into a new direction parallel to the ambient geomagnetic field at the time of the intrusion (PL-3), such that the older units carry the same paleomagnetic lineation as that of the intrusion.

migrating, ridge–trench collision history for southern South America. These authors suggested that the intraoceanic plate boundary (Phoenix–Farallon) may have been oriented at rather low angle with respect to the trench, implying the possibility of early Paleogene ridge–trench collision in northern Chile. Somoza and Ghidella (2005) confirmed this observation by using updated reconstructions (see also Somoza, 2005; Somoza and Ghidella, 2012). The reconstructions suggest simultaneous subduction of the Farallon plate, north of the trench–ridge–trench to trench–fault–trench triple junction, and the Phoenix plate south of the triple junction, lasting from Maastrichtian to Early Eocene times, with the triple junction migrating south along the Chilean margin during this time span (Fig. 4).

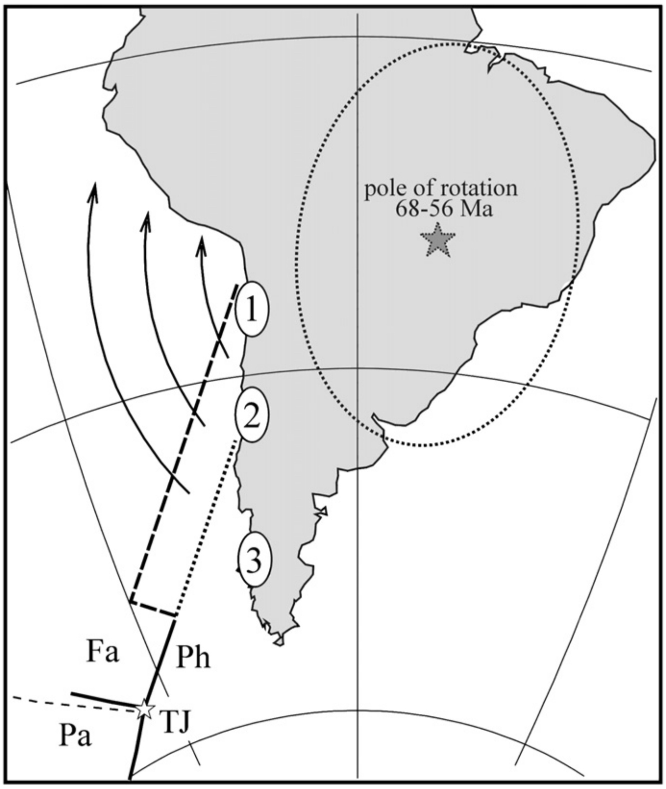

Fig. 4. Pole of rotation, and its corresponding confidence interval, describing the average motion of the Farallon plate toward South America for the latest Cretaceous to Paleocene time span (Somoza and Ghidella, 2012). The nominal position of the pole does not predict convergence of Farallon along most of the Chilean margin (curved lines with arrows illustrating Farallon to South America trajectories). On statistical grounds, the confidence interval allows central and southern Chile to lie in the domain of Phoenix plate subduction, as discussed by Somoza and Ghidella (2012). TJ is the reconstructed position of the Pacific (Pa)–Farallon (Fa)–Phoenix (Ph) triple junction at ~68 Ma, with the thin dashed line representing the trace of the triple junction. Two possible configurations are shown for the Farallon–Phoenix plate boundary, one of them involving a single ridge (thick dotted line) intercepting central Chile at 68 Ma, and another one with a transform (thick dashed line) that leads the plate boundary to intercept the trench in northern Chile. (1) denotes the Early Paleocene events in northern Chile discussed in the text; (2) indicates a zone with an apparent gap of arc-magmatic activity during the Paleocene (e.g. Gana and Wall, 1997); (3) Early Eocene deformation and large outpourings of slab window related magmas (Basalto Posadas). Note that the plate configuration involving a southern interception of the Farallon–Phoenix plate boundary with the trench (Fig. 4) would be incompatible with the hypothesis of the K–T event in northern Chile as related to an oceanic plate–boundary collision, prevailing thus the alternative of Andean-type noncollisional deformation in northern Chile, as discussed in the Introduction of the paper. Nevertheless, it is worth noting that the case of a southern interception of the oceanic ridge with the trench would allow the possibility of analyzing the origin of all the Late Cretaceous to Eocene plateau basalts in Patagonia (Ramos and Kay, 1992; Zaffarana et al., 2012) in terms of upward flow of sub-slab asthenosphere.

Recognizing ridge–trench collision events based on their structural, magmatic, metamorphic and sedimentary effects on margins has proven difficult such that they are likely under represented in tectonic models of orogens (Sisson et al., 2003). However, where ridge–trench triple junctions migrate along margins, the time-transgressive effects are a hallmark signature of the ridge–trench collision process. Soler et al. (1989) called attention to overthrusting faults involving crystalline basement, syntectonic filling of foreland basins and a gap in magmatic activity in southernmost Peru (ca 17°S) during the latest Cretaceous, attributing these events to the collision of an aseismic ridge. Likewise, Early Eocene deformation and slab window like magmatism in the Patagonian Andes has been ascribed to ridge–trench collision processes there (Ramos and Kay, 1992; Ramos, 2005). Taken in concert with the Early Paleocene deformation in northern Chile, the time-transgressive history is consistent with the plate reconstructions and supports the inference of a southward migrating collision between the Phoenix–Farallon plate boundary and the Chile trench from Late Cretaceous to Early Eocene (Fig. 4).

5. Summary

New paleomagnetic data indicates the occurrence of earliest Paleocene deformation in the region of Calama, northern Chile. Although this deformation may be another product of noncollisional, subduction-related tectonics in the Central Andes, plate reconstructions allow the alternative hypothesis that the event was associated with collision of an oceanic plate boundary. Furthermore, the time-transgressive nature of deformation along the margin, and slab window-like magmatic signature of post-deformation volcanism in some locations supports a ridge–trench collision model wherein a southward migrating ridge–trench triple junction affected northern Chile (southern Peru?) to the Patagonian Andes between the earliest Paleocene (latest Maastrichtian?) and Early Eocene.

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