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New kinematic constraints on the Cantabrian orocline: A paleomagnetic study from the Peñalba and Truchas synclines, NW Spain

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ABSTRACT

The Cantabrian orocline is a large structure that bends the Variscan orogen of Western Europe in NW Iberia. The extensively studied kinematics of its core, the foreland of the orogen, indicates that the structure is secondary, i.e. acquired after the formation of the orogenic edifice. However, the extent of the Cantabrian orocline away from its core is under debate. In this paper we study the kinematics of the Cantabrian orocline beyond the foreland. We collected and analyzed samples from the northern and central parts of the Truchas syncline, which provides new data within the hinterland of the orogen in NW Iberia. The analysis of 320 samples shows a late Carboniferous remagnetization with an E to NE declination and shallow downward inclinations. These results suggest a counter-clockwise rotation of ~60° and peri-equatorial but still southern hemisphere latitude for Iberia during the uppermost Carboniferous–Early Permian. This rotation fits with the expected kinematic evolution of the Truchas syncline if it indeed was part of the Cantabrian orocline.

1. Introduction

Oroclines are a rather common feature of orogenic belts on Earth, and involve crustal-scale or whole scale lithosphere deformation (e.g. Johnston et al., 2013). These curved features represent one of the most striking structures on Earth and have important implications on the configuration of mountain belts (Li and Rosenbaum, 2014). Oroclines can be classified according to the kinematics of their curvature into (Weil and Sussman, 2004): (i) inherited from preexistent geometries, also referred to as primary arcs (Hindle et al., 2000); (ii) coeval with the main orogenic deformation (progressive oroclines) (Meijers et al., 2016); or (iii) resulting from a subsequent rotation of an originally linear range (oroclines *sensu stricto*, or secondary) (Van der Voo, 2004; Musgrave, 2015).

The Western Variscan belt shows an impressive bend of ca. 180° running from Brittany to Central Iberia known as the Ibero–Armorican Arc (Argand, 1924; Bard et al., 1968; Carey, 1955; Arthaud and Matte, 1977). The core of this orogenic bend represents one of the best studied examples of a curved mountain belt on Earth: the Cantabrian orocline (e.g. Julivert et al., 1972; Matte and Ribeiro, 1975; Ries et al., 1980; Bonhommet et al., 1981; Perroud, 1986, Perroud et al., 1991; Julivert and Arboleya, 1984, 1986; Pérez-Estaún et al., 1988; Weil and Van der Voo, 2002; Shaw et al., 2012; Pereira et al., 2015). The Cantabrian orocline is located in NW Iberia in the non-metamorphic foreland of the Variscan orogen. It has been kinematically constrained according to paleomagnetic (e.g. Hirt et al., 1992; Weil et al., 2010; Weil et al., 2013a; Pastor-Galán et al., 2015a), structural (e.g. Kollmeier et al., 2000; Pastor-Galan et al., 2011; Shaw et al., 2015) and geochronologic studies (Gutiérrez-Alonso et al., 2015), as a secondary orocline that buckled around a vertical axis during late Moscovian to Asselian times (ca. 310–297 Ma.).

Most of the kinematic evidence used to unravel the kinematic evolution of the Ibero Armorican Arc comes from its core, the Cantabrian orocline. None of those studies resolve whether the kinematics observed in the Cantabrian orocline is relevant to understand the full extent of the Ibero Armorican Arc (Brun and Burg, 1982; Ribeiro et al., 1995; Gutiérrez-Alonso et al., 2004; Murphy et al., in this volume) or even beyond (Gutiérrez-Alonso et al., 2008; Pastor-Galan et al., 2015b). Among the many different interpretations on the origin of the Ibero Armorican Arc the most popular are: (i) a long lived evolution (from ca. 500 to ca. 385 Ma) involving an indenter and strike–slip crustal-scale faults (e.g. Quesada, 1991; Dias and Ribeiro, 1995; Ribeiro et al., 2007; Şengör, 2013; Simancas et al., 2013). This interpretation is supported on strain analysis and geometry and timing of several shear zones. (ii) Large-scale strike–slip shear zones formed during

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lateral extrusion of a continental wedge. This process would have been related to the dextral Mega-Shear zone developed in the central part of Pangea (e.g. Martínez-Catalán, 2011; Martínez-García, 2013). (iii) The Cantabrian Orocline and the Ibero Armorican Arc are the same structure, in which part of the Variscan orogen buckled around a vertical axis (e.g. Weil et al., 2001, 2010, 2013b; Gutiérrez-Alonso et al., 2008; Pastor-Galan et al., 2011, Pastor-Galán et al., 2015a; Shaw et al., 2015). In this volume, Murphy and co-authors present a model reviewing former studies and conciliating the indenter and orocline hypotheses.

Lack of kinematic data in the hinterland of the orogen, i.e. away from the Cantabrian orocline is a consequence of the inherent difficulties in discerning and interpreting structural and paleomagnetic data in hinterland areas. Available works found criteria supporting both the indenter (Quesada, 1991; Ribeiro et al., 2007; Braid et al., 2010) and orocline hypotheses (Perroud, 1986; Parés et al., 1994; Gutiérrez-Alonso et al., 2015; Pastor-Galán et al., 2015a). Some of them found the possible existence of a coupled orocline to the south of the Cantabrian Zone (Aerden, 2004; Pastor-Galan et al., 2011; Shaw et al., 2012, 2014).

In this study, we provide new paleomagnetic data from the Upper Ordovician limestones in the Peñalba syncline and Middle Ordovician volcanic rocks from the Truchas syncline, located in the hinterland of the orogen, away from the core of the Ibero Armorican Arc.

2. Geologic setting

The Variscan belt is the result of the collision between Gondwana, Laurussia and an unconstrained number of microplates resulting in the supercontinent Pangea during the Devonian and Carboniferous (Nance et al., 2010; Domeier and Torsvik, 2014). The earliest Variscan deformation in Iberia is interpreted to have occurred prior to c. 400 Ma (Dallmeyer and Gil-Ibarguchi, 1990; Quesada, 1991; Mendía-Aranguren, 2000; Fernández-Suárez et al., 2007; Gómez-Barreiro et al., 2007; Martínez-Catalán et al., 2009). Continental collision started at ca. 365–370 Ma (Dallmeyer et al., 1997; Rodríguez et al., 2003; López-Carmona et al., 2014) with the underplating of the Gondwanan margin below Laurussia, giving rise to an eastward (in present day coordinates) migration of deformation and related syn-orogenic sedimentation (Dallmeyer et al., 1997).

The Paleozoic outcrops of Iberia show differences in stratigraphy, structural style, metamorphism and magmatic activity that broadly reflect their relative position with respect to the Gondwanan margin. These differences were the foundation of the subdivision of the orogen

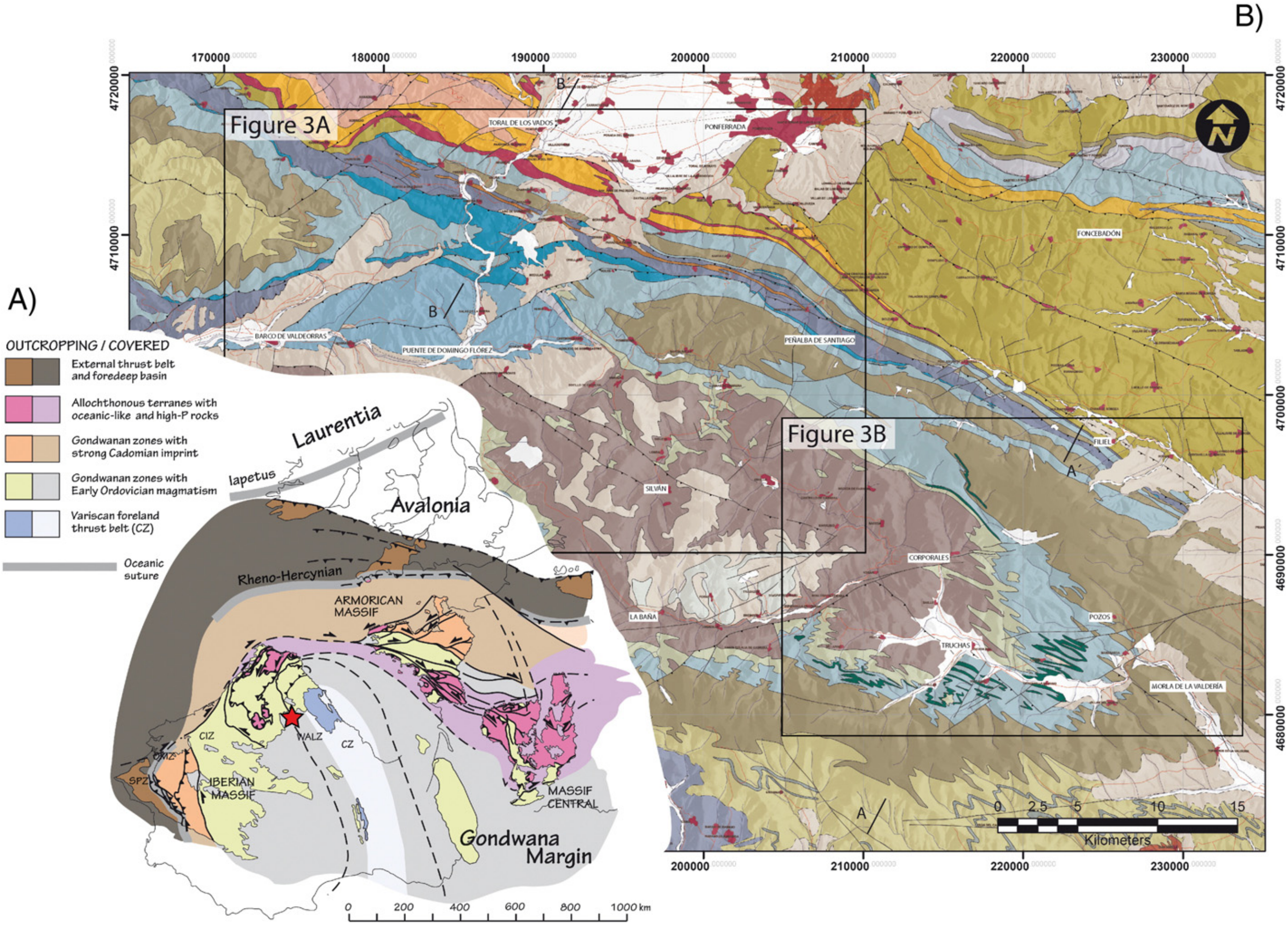

Fig. 1. A) Permian reconstruction and restoration of the Cantabrian orocline. Post-Permian clockwise rotation upon 25° has been restored in the eastern sector of the WALZ and CZ (Iberian Ranges) according to paleomagnetic data by Calvín et al. (2014). The Pyrenean Axial Zone has been transposed into its putative position in Permian times — i.e. ~100–150 km of calculated North–South (in present day coordinates) shortening during the Alpine, according to Roure et al. (1989); Muñoz (1992); Tugend et al. (2015). Red star indicates the location of the study area. CZ is the Cantabrian Zone; WALZ represents the West Asturian–Leonese Zone; CIZ is the Central Iberian Zone; OMZ stands for Ossa Morena Zone; and the SPZ represents the South Portuguese Zone. B) Geologic map of the Truchas syncline and surrounding areas based on Heredia-Carballo et al. (2002). Legend as in Fig. 2. Insets represent the studied areas shown in Fig. 3.

into different tectonostratigraphic zones (Lotze, 1945; Julivert et al., 1972; Farias et al., 1987; Murphy et al., 2008, Fig. 1). Of these zones, the Cantabrian Zone; the West-Asturian–Leonese Zone (hereafter WALZ); and the Central Iberian Zone are relevant to this study.

The Cantabrian Zone is the Gondwanan foreland fold–thrust belt of the Western European Variscan Belt. It consists of more than 7000 m of Neoproterozoic arc-related and lower Paleozoic platform sedimentary rocks that thin toward the east and are covered by a Carboniferous syn-orogenic sequence (Marcos and Pulgar, 1982). Deformation is characterized by a thin-skinned fold and thrust belt that verges toward the core of the Cantabrian orocline (Pérez-Estaún et al., 1988). This zone is further characterised by the absence of metamorphism (Gutiérrez-Alonso and Nieto, 1996; García-López et al., 2007; Pastor-Galán et al., 2013) and by low finite strain values (Gutiérrez-Alonso, 1996; Pastor-Galán et al., 2009). This Zone represents the majority of the Cantabrian orocline and provides the bulk of the kinematic data supporting a secondary origin for the larger scale Ibero Armorican Arc (e.g. Pastor-Galán et al., 2012a, 2012b; Weil et al., 2013a; Shaw et al., 2015).

The WALZ is located immediately to the west and south of the Cantabrian Zone and separated from it by large Variscan reverse ductile shear zones within the Narcea Antiform (Gutiérrez-Alonso, 1996). It consists of more than 7000 m of Cambro–Ordovician sediments, being the rest of the Paleozoic sequence absent except for minor Silurian outcrops. It forms part of the hinterland, features barrovian metamorphism – greenschists to amphibolite facies – and records a complex tectonic history (Martínez-Catalán, 1985; Martínez and Rolet, 1988). A first deformation phase produced east verging axial plane folds (D1). Subsequent thrusting happened during a second orogenic phase (D2). Finally, a late Variscan folding event (D3) gave rise to large wavelength upright folds, which folded previous structures (Marcos, 1973; Martínez-Catalán, 1985; Aller and Bastida, 1993).

The Central Iberian Zone consists of two domains: the "Schist-Greywacke" domain and the "Ollo de Sapo" domain, the latter being relevant to this work. This domain contains a 2000 to 4000 m succession of Cambrian to Ordovician rocks with minor occurrences of Siluro–Devonian rocks. It is characterised by the occurrence of a widespread volcanic and volcaniclastic formation called "Ollo de Sapo" (e.g. Díez-Montes et al., 2010). The domain consists of low to high grade metamorphic rocks with recumbent folds verging E–NE that underwent a tectonic evolution similar to the WALZ (Pérez-Estaún et al., 1990; Martínez-Catalán et al., 1997; Gutiérrez-Marco et al., 1999; Aramburu, 2002; Robardet, 2002, 2003; Robardet and Gutiérrez-Marco, 2004).

2.1. Local geology

We collected samples in the adjacent Truchas and Peñalba synclines (Figs. 2 and 3), which represent a diffuse boundary between the low- and high-grade metamorphic rocks of the WALZ and Central Iberian Zone, respectively (e.g. Valverde-Vaquero and Dunning, 2000; Díez-Montes et al., 2010; Fernández-Lozano, 2012; Talavera et al., 2013). The limit between both domains is probably represented by the tectonic inversion of a crustal-scale extensional detachment (Martínez-Catalán et al., 1992; Fernández et al., 2007) that controlled

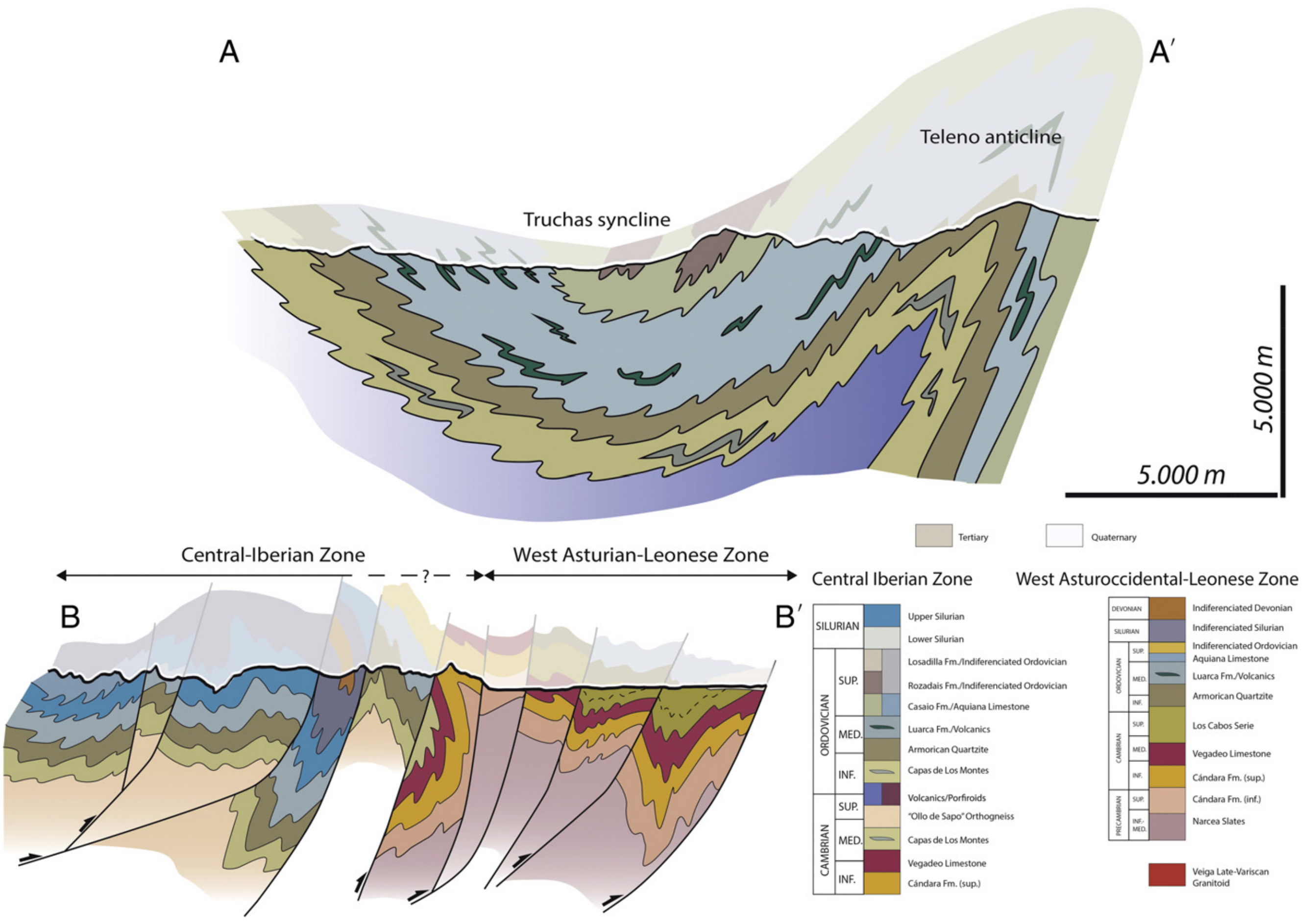

Fig. 2. Geological cross-sections shown in Fig. 1 along A–A′ and B–B′ profiles illustrating general structure of the Truchas syncline and the observed lithology variations related to normal fault activity subsequently inverted during the Variscan orogenic episode, along the northern limb of the fold.

the Ordovician–Silurian sedimentation (Fig.2B, profile B-B´) (Marcos, 1973; Pérez-Estaún, 1978; Pérez-Estaún et al., 1992; Marcos et al., 2004; Pérez-Estaún and Bea, 2004; Rodríguez-Fernández et al., 2015). We collected samples from volcanic and volcaniclastic members of the Luarca Fm. and limestones from the Aquiana Fm. (Fig. 3A and B).

2.2. Volcanic rocks (Luarca Fm.)

The Luarca Fm. (150–100 m) is a monotonous sequence of black and grey slates with interbedded layers of silicic to intermediate composition volcanic and volcaniclastic rocks (Pérez-Estaún, 1978; Villa et al., 2004). The fossil content (trilobites, brachiopods, conodonts and graptolites) constrain its age to Middle Ordovician (Gutiérrez-Marco et al., 1999; Gutiérrez-Marco et al., 2002). The volcaniclastic rocks are composed of weathered volcanic mafic fragments, dispersed chert and chlorite, volcanic quartz, white mica, plagioclase and K-feldspar. The intense alteration of volcanic fragments has led to the formation of an immature sandy texture characterised by an iron-oxide clay matrix. The matrix appears often replaced by chlorite minerals or iron oxides, whereas the vesicles in pumice fragments are commonly filled with silica and/or carbonates. According to the mineralogy and the internal structure observed, these rocks are deformed altered ignimbrites and tuffs that were reworked in a subaqueous to subaerial environment. These rocks were deformed, showing S–C planes, pressure shadows and mica-fish arranged between shear bands, which are marked by iron oxide seams (Fig.4).

2.3. Aquiana limestone (Aquiana Fm.)

The Aquiana limestone represents a massive light-colored recrystallized carbonate interval with varying thickness between 0 and 300 m. In some areas of the syncline, the limestone appears unconformably lying above late Cambrian to Middle Ordovician formations (Martínez-Catalán et al., 1992). The age of the Aquiana formation has been established as Late Ordovician, constrained by regional biostratigraphic observations (Sarmiento et al., 1999; Pérez-Estaún et al., 1980; Pérez-Estaún and Marcos, 1981; Martínez-Catalán et al., 1992). In the study area, the limestone banks show important thickness variations along the northern limb of the Peñalba syncline, increasing gradually towards the West, which is considered the result of a combined effect of erosion and tectonic activity (Martínez-Catalán et al., 1992; Sarmiento et al., 1999).

3. Paleomagnetism

We drilled a total of 320 cores with a petrol engine drill in five different localities (TRC1, TRC2, TRV1, TRV2, TRV3) consisting of several sites (Figs. 2 and 3; Table 1; see the Supplementary data for exact locations). 187 cores were drilled in volcanic and volcaniclastic rocks of the Luarca Fm. (coded TRV) and 133 in the Aquiana limestone Fm. (coded TRC).

Magnetic remanence of samples was studied through thermal and alternating field (AF) demagnetization. Stepwise thermal demagnetization was carried through 20–50 °C increments up to complete

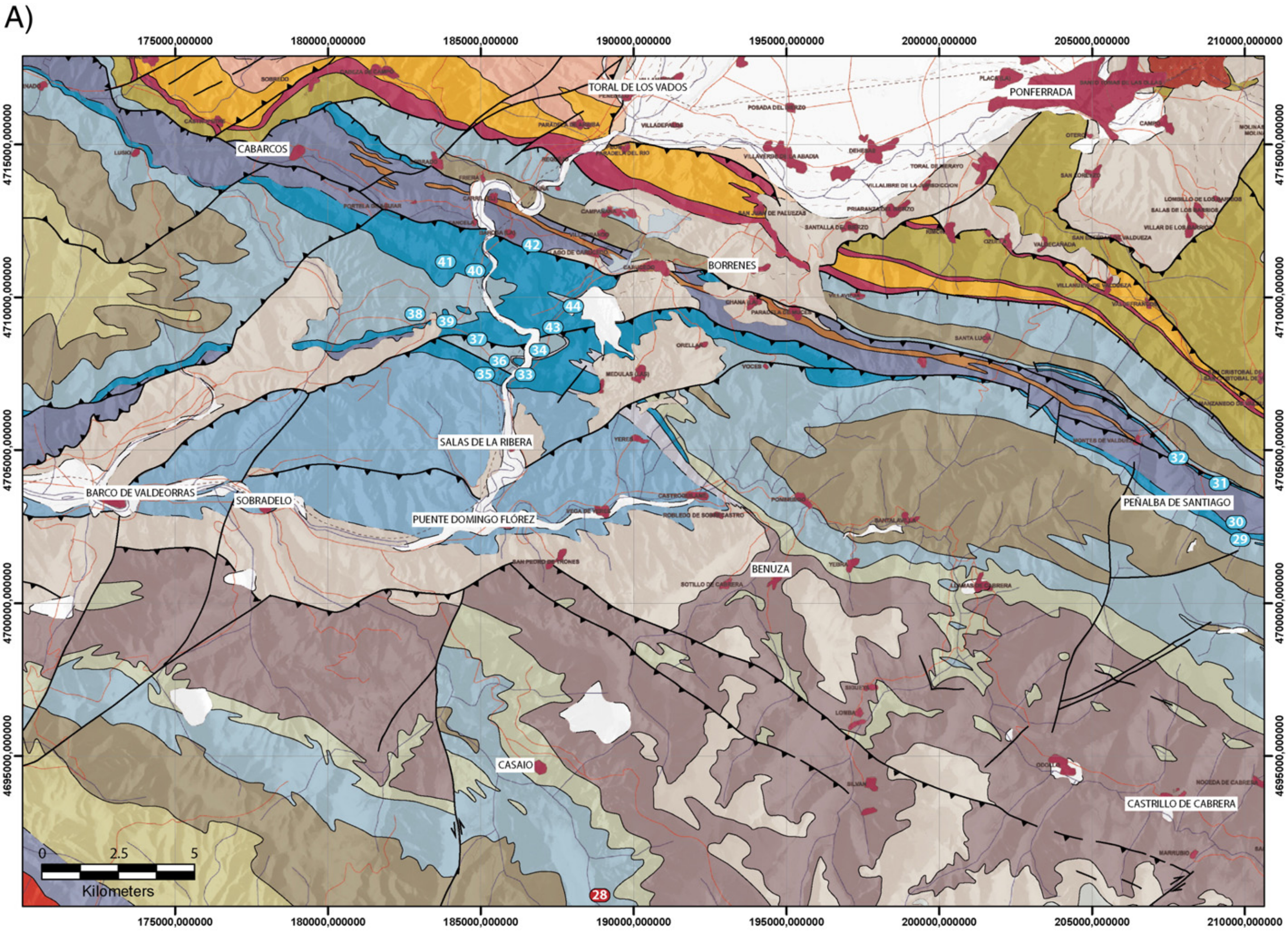

Fig. 3. A) Geologic map of the northern limb of the Peñalba syncline and Aquiana limestone sample location (TRC) (modified after Heredia-Carballo et al., 2002). B) Geologic map of the periclinal closure of the Truchas syncline and location of the volcanic rocks sample sites (TRV) (after Heredia-Carballo et al., 2002).

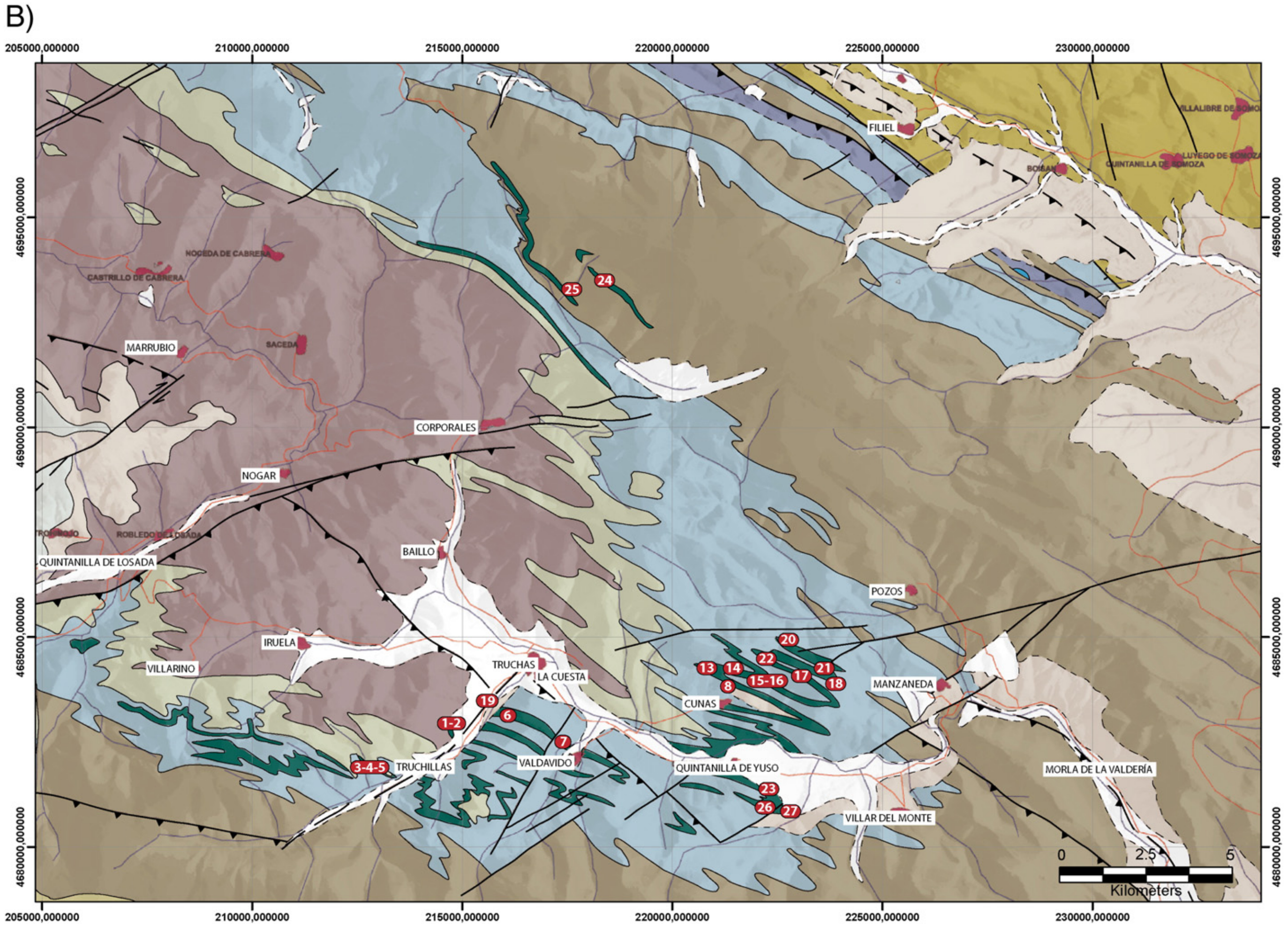

Fig. 3 (*continued*).

demagnetization. AF demagnetization was carried through variable field increments (4–10 mT) up to 100 mT. In those samples where high-coercitivity, low-blocking temperature minerals (e.g. goethite, maghemite) were expected, a pre-heating to 150 °C was coupled with AF demagnetization (Van Velzen and Zijderveld, 1995). Principal component analysis (Kirschvink, 1980) was used to calculate magnetic component directions from “Zijderveld” vector end-point demagnetization diagrams (Zijderveld, 1967). Representative Zijderveld diagrams are shown in Fig. 5. In a few cases, a second component could not be entirely removed during demagnetization; from such samples we determined remagnetization great circles. We used the approach of McFadden and McElhinny (1988), Fig. 6) in combining great circles and linear best fits (setpoints).

Mean directions (Table 1) were evaluated using Fisher statistics of virtual geomagnetic poles (VGPs), corresponding to the isolated directions (ChRM). Here, the N-dependent A95 envelope of Deenen et al. (2011) was applied to assess the quality and reliability of the ChRM distributions. We applied a fixed 45° cut-off to the distribution of each locality VGP's. Table 1 summarizes the paleomagnetic results obtained both from limestones and volcanic rocks. We have performed the interpretation and statistics of paleomagnetic data with the open-source and freely available software Paleomagnetism.org (Koymans et al., in press).

4. Results

Paleomagnetic results show polarity distribution of declinations ranging from 57° in the volcanic rocks of the Luarca Fm. to 122° in the Aquiana Fm., and inclinations from 9° to 32°, respectively. The Aquiana Fm. shows a good degree of success (Table 1), and a reasonable clustering on VGP ($K = 18$). Locality TRC2 site shows A95min < A95 < A95max, which following Deenen et al. (2011) means a correct averaging of paleomagnetic direction scattering (including paleosecular variation and minor errors in measurements or structural complications); whereas locality TRC1 shows an elongated VGP in which A95 is > A95max.

Contrarily, the volcanic rocks from Luarca Fm. (Table 1) show low success rate. Only 58% of the samples yielded interpretable values (103/187). From these 103 samples only 61 (56%) pass the 45° cut-off; (Fig. 6). In total, only 33% of the collected samples were considered. However, even after cut-off, K values on VGPs remained too small or even unacceptable (<8 see Table 1).

We have performed 2 fold-tests following the Tauxe-Watson method (Tauxe and Watson, 1994; Fig. 6), yielding non-conclusive results. However, locality distributions cluster better before any tectonic correction (Fig. 7), suggesting that remagnetization occurred after the main Variscan deformation events in the region.

5. Discussion

Our paleomagnetic data from the Truchas syncline show consistent reverse polarity and absence of reversals, post-folding character and shallow inclinations, which constrains their magnetization to the reverse polarity Kiaman superchron (late Carboniferous to middle Permian, Langereis et al., 2010). Shallow downward inclinations indicate that Iberia was situated at equatorial latitudes, but still in the southern Hemisphere, and therefore the secondary magnetization was acquired

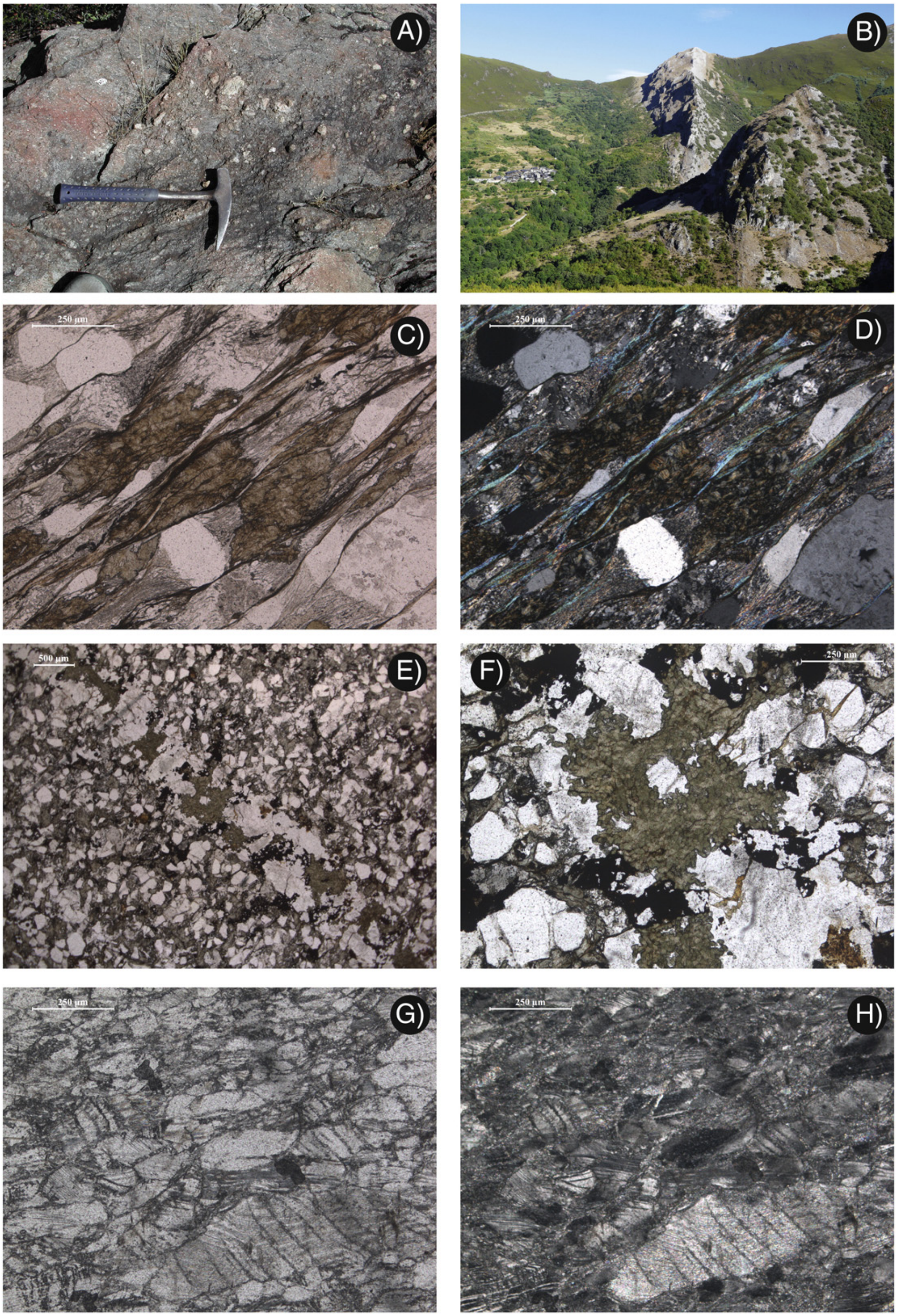

Fig. 4. Field examples of the volcanic rock textures included in the Luarca Fm. (A); and Aquiana massive limestone outcrop (B). Thin sections illustrating volcanic textures and shear deformation (C and D). Chlorite transformation as a result of secondary alteration of the volcanic matrix (E and F). Example of strongly recrystallized fossiliferous Aquiana limestone (G and H).

prior to Iberia crossing the equator during the early Permian (Weil et al., 2010). Comparison of two studied localities (TRC1 and TRC2) with Permian pole reported by Weil et al. (2010), suggests that counter-clockwise rotation occurred before Early Permian.

TRC1's VGP is very elongated and shows consistent inclinations and dispersion of ~60° in declination (Fig. 5). Such elongation can only be explained in terms of vertical axis rotations (Deenen et al., 2011). The locality shows no changes in strike of the major structures and therefore

Table 1
Statistical analysis and correction parameters from paleomagnetic samples.

Localities	N45	N	Geographic		R	k	α95	K	A95	A95min	A95max	ΔDx	ΔIx	λ	Tilt corrected	
			mDec	mInc											mDec	mInc
TRC1	42	45	116.9	9.8	38.9	13.4	6.3	18.7	5.2	2.7	7.8	5.3	10.2	5	126.9	1.2
TRC2	47	50	122.8	14.2	41.4	8.3	7.7	18.4	5	2.6	7.3	5	9.5	7.2	133.6	-3.1
TRV1	27	44	66.5	20.3	23.4	7.3	11.1	12.9	8	3.2	10.3	8.2	14.6	10.5	70.2	18.2
TRV2	20	43	57.9	19.9	16.9	6.1	14.4	7.4	12.9	3.6	12.4	13.1	23.6	10.2	136.4	12.5
TRV3	14	21	57.1	31.7	12	6.5	16.9	7.4	15.7	4.2	15.6	16.4	24.8	17.2	123.9	48.6

no major local differential rotations within site are possible. We interpret that rocks at locality TRC1 were remagnetized during the counter-clockwise (CCW) rotation of the southern limb of the Cantabrian orocline. The same process has also been described by Pastor-Galán et al. (2015a), for other sectors of the CIZ. Locality TRC2 shows the same degree of rotation but, in contrast, VGP distribution is circular, suggesting a more punctual magnetization during the formation of the Cantabrian orocline. Overall, the obtained results show a pervasive remagnetization that occurred immediately before and coevally with vertical axis rotations as observed in other studied regions of Iberia (Weil et al., 2013a, 2013b; Pastor-Galán et al., 2015a). We interpret these remagnetizations as related to the post-folding magmatic event in NW Iberia (Gutiérrez-Alonso et al., 2004, Gutiérrez-Alonso et al., 2011).

The paleomagnetic data from Truchas volcaniclastic rocks may suggest larger CCW rotations than those obtained from the limestones. These additional ~25° of rotation (Fig. 7) could indicate some local increase in the magnitude of the vertical axis rotations or an earlier magnetization acquisition episode recording some other previous rotation event. However, due to the poor quality of data at TRV localities, caution is required in any interpretation.

Following the timing of magnetization of TRC and TRV localities (post-main Variscan deformation) and the consistence with the results in the Cantabrian zone, we interpret the observed rotation as, at least, partially being caused by the secondary Cantabrian orocline (e.g. Weil et al., 2013a,b). Our data is not compatible with a progressive origin of the curvature due to indentation (Dias and Ribeiro, 1995). We suggest, therefore that the Cantabrian orocline and the Ibero Armorican arc are the same structure that acquired its curved shape during a process of orocline buckling as first suggested by Gutiérrez-Alonso et al. (2004). Our data is indeed compatible with the model proposed by Murphy et al. (2016). They suggest the existence of a Gondwanan indenter that would keep the tectono-stratigraphic zones approximately linear. In this manner, the deformation associated with initial collision was accommodated by sinistral (SW Iberia) and dextral (Armorican Massif) motion along shear zones on either side of the promontory, but the curved shape was acquired later on due to oroclinal buckling.

Regional strike variations of paleomagnetic, structural and stratigraphic data along the Cantabrian Zone have been interpreted as the result of N-S shortening during the Cantabrian orocline development (Gutiérrez-Alonso et al., 2004; Pastor-Galan et al., 2011; Johnston et al., 2013; Weil et al., 2013a,b; Shaw et al., 2015). However, recent findings on vertical axis rotations during the Carboniferous in rocks from southern Ireland and the Iberian CIZ suggest that the kinematics of the Cantabrian orocline should be considered in the light of more global process (Pastor-Galán et al., 2015a; Pastor-Galan et al., 2015b) (Fig.8).

In order to produce such a plate-scale orocline scenario, a ~90° change in the maximum shortening direction must be assumed to have occurred during the Moscovian. Such hypothetical scenario is not yet fully understood and has yet to be considered in late Paleozoic reconstructions of Pangea (e.g., Stampfli et al., 2013; Domeier and Torsvik, 2014). Different interpretations have been recently proposed to investigate the possible causes that led to the observed change in shortening directions as a result of large-scale processes that resulted in the amalgamation of Pangea (e.g. Weil et al., 2001; Quesada, 2006; Gutiérrez-Alonso et al., 2008; Braid et al., 2011; Martínez-Catalán, 2011; Martínez-García, 2013; Şengör, 2013; Simancas et al., 2013; Pereira et al., 2014; Pastor-Galán et al., 2015a). However, none of them have been able yet to fully explain and document all the geologic processes that would have been involved in the development of such a large-scale structure.

6. Conclusions

Our paleomagnetic analysis of Middle–Upper Ordovician limestones and volcaniclastics rocks outcropping in the Peñalba and Truchas synclines, reveals the presence of a pervasive remagnetization, characterized by shallow inclinations of paleomagnetic poles, indicating a NE–SE trending direction. These directions of magnetization are consistent with other counter-clockwise rotations previously observed in the southern limb of the Cantabrian orocline.

The overall present-day structural trend of the Peñalba and Truchas synclines can be correlated with the evolution of the Cantabrian orocline, as evidenced by these new paleomagnetic data and the axial traces of major (D3) folds trending NW–SE, which run parallel to the strike of the southern orocline limb. The final configuration of these synclines was finally achieved during the Late Carboniferous to Early Permian (310–297 Ma.), coevally with the rotation (~60°) of the surrounding areas as a result of the Cantabrian ocrocline formation.

Acknowledgments

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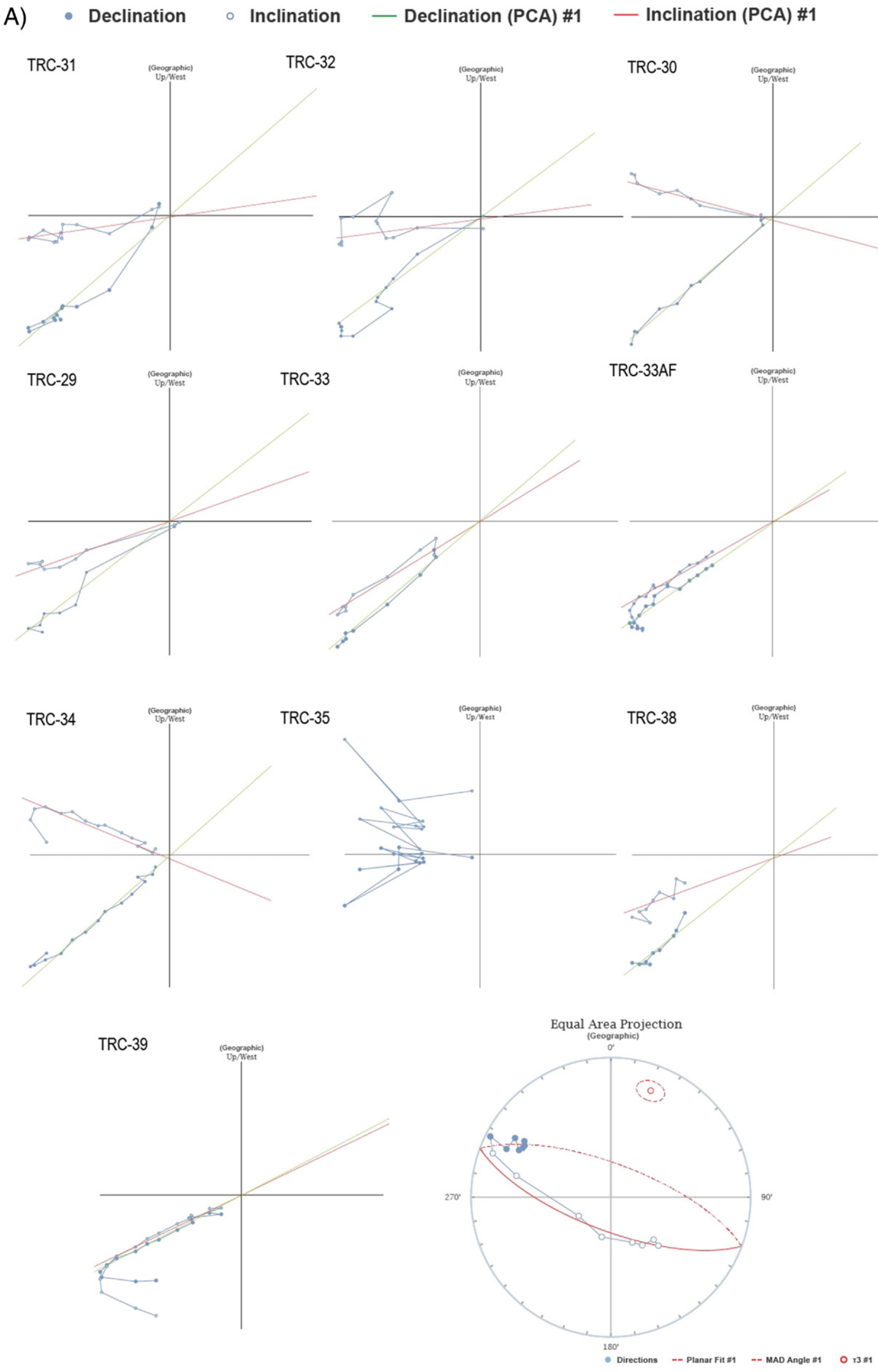
Appendix A. Supplementary data

Supplementary data asssociated with this article can be found in the online version, at doi: 10.1016/j.tecto.2016.02.019.These data include the Google maps of the most important areas described in this article.


A)
● Declination
○ Inclination
Declination (PCA) #1
Inclination (PCA) #1
TRC-31
TRC-32
TRC-30
TRC-29
TRC-33
TRC-33AF
TRC-34
TRC-35
TRC-38
TRC-39
(Geographic)
Up/West
Equal Area Projection
(Geographic)
0°
90°
180°
270°
Directions
Planar Fit #1
MAD Angle #1
τ3 #1

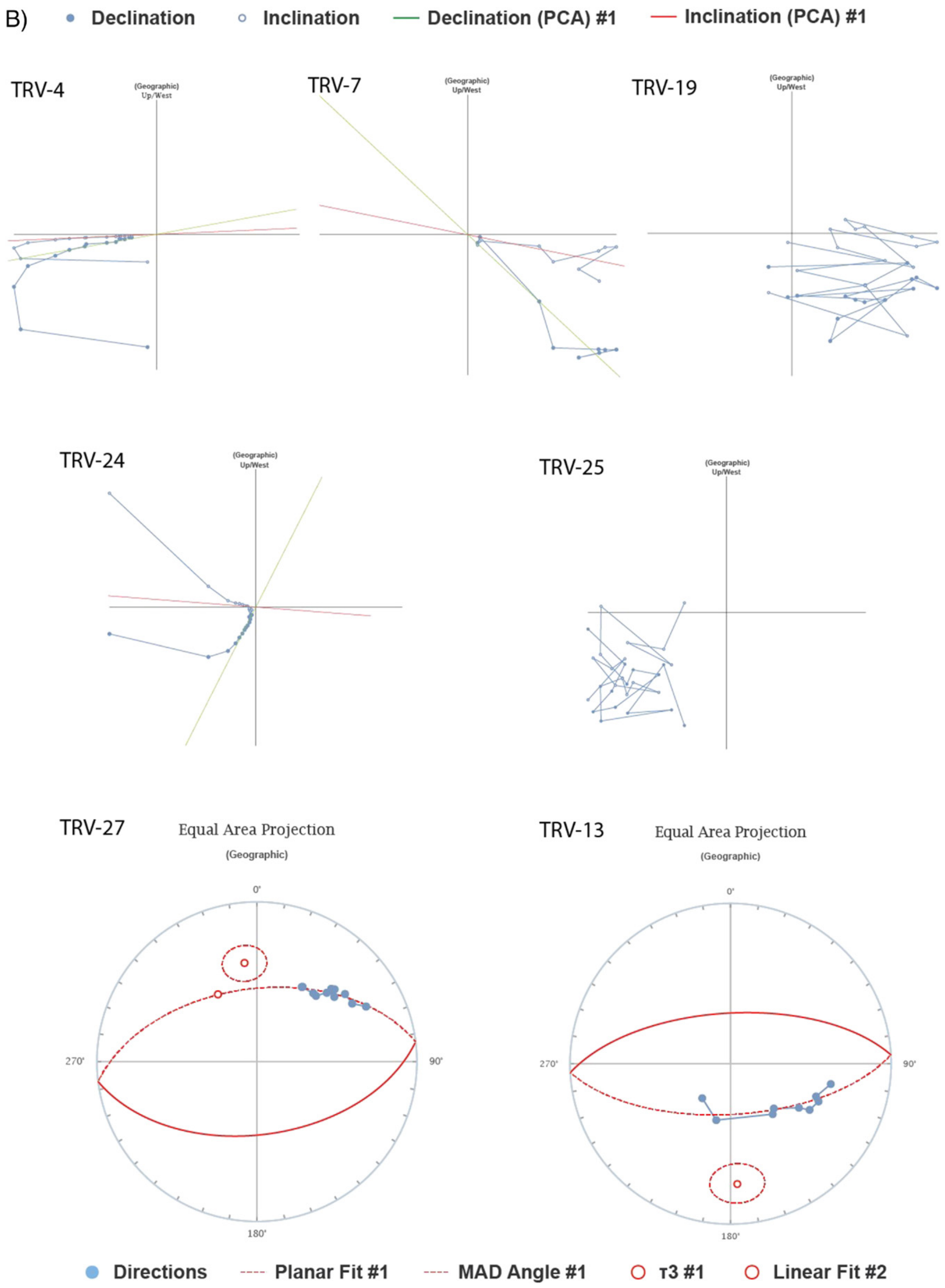


Fig. 5. Zijderveld diagrams illustrating progressive thermal and alternating field demagnetization behavior of limestone (A) and volcanic samples (B) from the study area (Zijderveld, 1967).

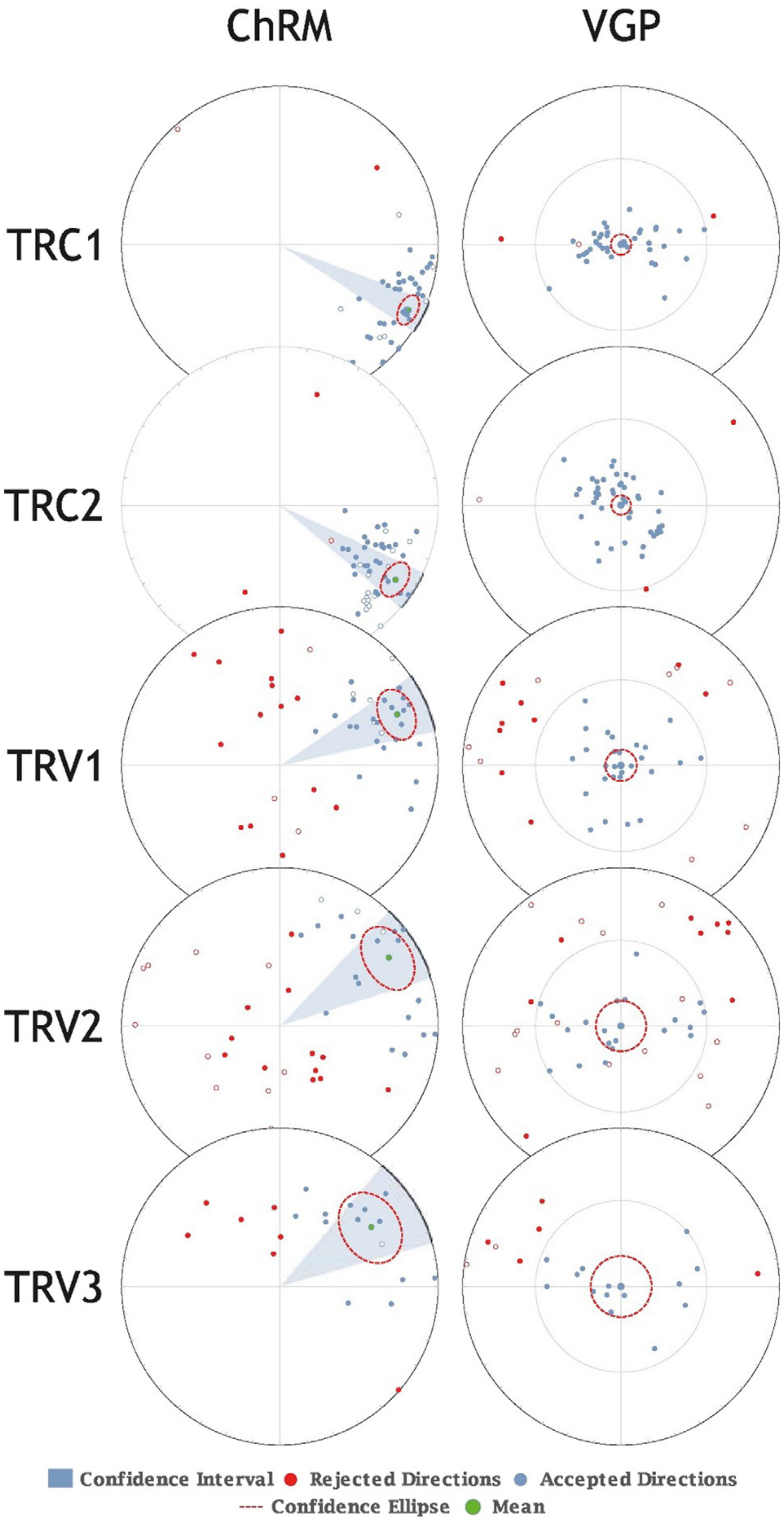


Fig. 6. Equal area projections for characteristic remagnetization (ChRM) and virtual geomagnetic pole reconstruction (VGP) for the Aquiana Limestone and volcanic samples.

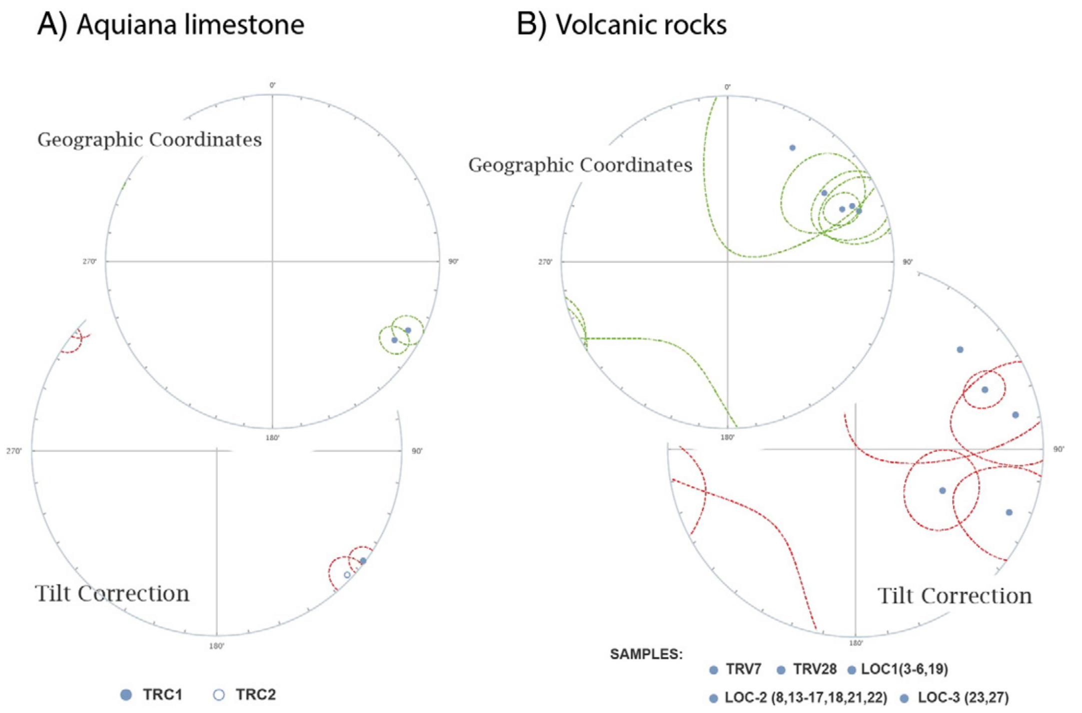


Fig. 7. Equal area projection showing the obtained results in geographic coordinates and the tilt correction performed for Aquiana Limestone (A) and the volcanic samples (B), respectively.

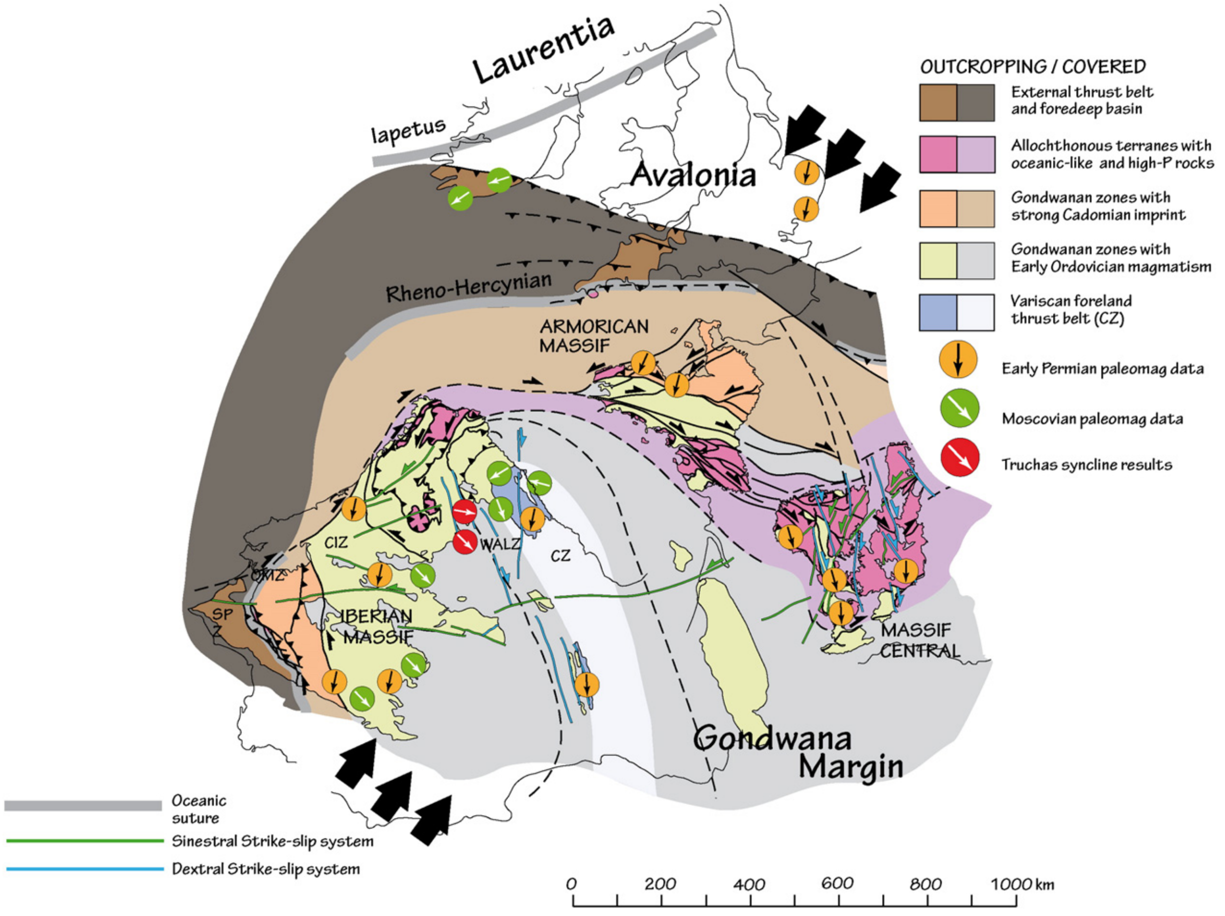


Fig. 8. Permian reconstruction and restoration of the Cantabrian orocline (see Fig. 1). Paleomag vectors showing the geometry of the Cantabrian orocline are indicated by Carboniferous (Moscovian) arrows (blue), while Early Permian vectors (green) fossilises the arc structure. Paleomag data from Spain, France and eastern Great Britain and Ireland was compiled from Van der Voo (1967,1969); Hernando et al. (1980); Turner et al. (1989); Osete et al. (1997); Gomes et al. (2004); Liss et al. (2004); Chen et al. (2006); Weil et al. (2010); Weil et al. (2013a); Pastor-Galán et al. (2015a); Pastor-Galan et al., (2015b).

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