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The evolution of the paleomagnetic fold test as applied to complex geologic situations, illustrated by a case study from northern Spain

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Abstract

Paleomagnetic results are most useful if the age of the magnetization can be established with respect to the rock age or the age of specific structural or alteration events. The fold test is a particularly powerful tool; not only can it be used to determine whether magnetizations are pre-, syn- or post-folding, but it can also reassure us that structural corrections need (or need not) be applied to a given magnetization. This study traces the evolution of various fold and tilt tests developed in the 50-some years since the classical test of Graham was published. Syn-deformational magnetizations are a very special case, usually characterized as such by an incremental tilt test. In regions where rotations about (near-) vertical axes are to be expected, a strike test is the best tool for determining them. A case study of syn-deformational magnetizations in the Cantabria-Asturias Arc (CAA) of northern Spain is presented, which illustrates the application of the various tilt and strike tests. One ancient post-deformational and two syn-deformational magnetizations have been recorded in CAA Devonian carbonates, each characterized by different optimal (peak) percentages of unfolding in incremental fold tests. The structural corrections required to bring the individual site-mean magnetization directions into alignment can be used to restore the beds to their attitudes at the times when the magnetizations were acquired. Furthermore, these structural corrections provide robust constraints on the kinematics of the deformation phase that is being removed. In the CAA, removal of late-stage folding about steeply inclined fold axes, due to Permian oroclinal bending, restores the belt to its first folding and thrusting configuration, and produces north–south trending cylindrical folds that formed during the Late Carboniferous. The separate deformations, consisting of earlier folding and thrusting and later oroclinal bending, have implications for the final collisional movements between Gondwana and Laurussia during the end of the Variscan Orogeny. This case history of the use of multiple fold, tilt, and strike tests confirms their value, especially when combined with an understanding of the folding and faulting style in a region.

Keywords: Fold test; Paleomagnetism; Statistical methods; Syn-folding; Cantabria-Asturias Arc; Remagnetizations

1. Introduction

1.1. The fold test: 1949–1985

Variations on Graham's (1949) fold test constitute the most widely used of all paleomagnetic field tests for constraining the age of magnetization acquisition. Graham's elegantly simple test relied on rotation of measured magnetic vectors about local strike; the test was deemed positive, implying a pre-folding remanence acquisition, if the directions were dispersed in situ and clustered upon untilting. The two reasons that this worked so well for the classical site of Graham's fold test in Maryland, were (1) that the magnetization was essentially univectorial, so that the lack of demagnetization was not influential, and (2) that the tilts were large, scattering the directions to such an extent that statistical significance did not need to be quantified (French and Van der Voo, 1979). The lack of statistical criteria for judging a result's significance was addressed when McElhinny (1964) used Fisher's (1953) k parameter (an estimate of the degree of clustering of directional data on a sphere) to determine the statistical significance of both pre- and post-folding distributions.

McElhinny's (1964) fold test was, and still is, widely used by paleomagnetists; nevertheless, McFadden and

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Jones (1981) have argued that using Fisher statistics for paleomagnetic datasets in their 'incorrect attitude' (e.g. in a sample set's in situ attitude when the magnetization was acquired pre-tilting) is inappropriate and mathematically invalid because then the overall population should not be Fisher distributed. This led McFadden and Jones (1981) to devise a new test that rephrased the question to be asked to this: "Assuming a Fisher distribution at the time of magnetization acquisition, is the structure of the magnetic observations consistent with the magnetization having been acquired with the beds in some particular orientation?" As such, the new test requires strata with little or no internal distortion in order to give a statistically significant result. The McFadden and Jones (1981) fold test relies on a comparison of two groups of Fisher distributed site groupings from opposing fold limbs in their in situ and tilt-corrected positions. This technique demands some evidence of the underlying distribution of magnetic vectors at the time of magnetization acquisition. Although requiring more intensive sampling, the McFadden and Jones (1981) test provides statistical significance under far less stringent conditions.

With the advent of more sensitive cryogenic magnetometers in the 1970's, paleomagnetists began investigating weakly magnetized sedimentary rocks, especially carbonates. In less than a decade it became apparent from these studies, particularly those from the Appalachian margin of North America, that shallow-water and platform carbonates often carry only secondary magnetizations that were acquired *during* orogenic events (McCabe et al., 1983; Bachtadse et al., 1987; Jackson, 1990; Suk et al., 1990). The use of either the McElhinny (1964) or McFadden and Jones (1981) test to determine the statistical significance of pre- and post-tilting magnetizations proved to have little value in assessing magnetizations that were acquired during folding. This led Scotese and Van der Voo (1983), who had been studying the directions of remagnetized Appalachian carbonates acquired during Alleghenian folding, to use an incremental fold test. Calculation of the statistical significance of variously clustered distributions at incremental unfolding steps allowed for the introduction of a third fold test result, the so-called syn-folding magnetization. This type of magnetization acquisition, inferred from incremental fold tests, became evident in many complex structural regions all over the world.

1.2. The fold test: the early 1980's–2001

Recently, McFadden (1990) devised a new fold test to alleviate the McFadden and Jones (1981) test's lack of flexibility and its logistically impractical sampling demands. The McFadden (1990) test is based on correlation between distributions of magnetic directions and tectonic information, but the test still requires site-mean clustering and strategic site sampling. However, by relaxing the sampling demands the statistical significance of the test becomes relatively weak. Bazhenov and Shipunov (1991) proposed a similar test that places no restriction on the attitudes of beds sampled and allows for division of bedding pole distributions into smaller groups, making sampling requirements even easier. Like the McFadden (1990) test, the Bazhenov and Shipunov (1991) test becomes a weak test, because sampling requirements are relaxed. Neither the Bazhenov and Shipunov (1991) nor McFadden (1990) tests have been fully incorporated in standard paleomagnetic practice.

As an alternative to the statistical significance tests described above, several researchers have proposed treating the fold test as a parameter estimation problem. By doing this, a simple bootstrap or Monte Carlo approach can be used to create large pseudo-samples to determine the confidence limits and significance of the maximum clustered distribution of paleomagnetic fold test data (Fisher and Hall, 1990; Tauxe et al., 1991; Watson and Enkin, 1993; Tauxe and Watson, 1994). Watson and Enkin (1993) proposed a Monte Carlo technique to estimate the total amount of tectonic tilting, including its 95% confidence limit, at the time of magnetization acquisition. However, their test relies on Fisher distributions, which, as argued by Tauxe et al. (1991), are rarely achieved with fold test data. Tauxe and Watson (1994) proposed an alternative test that does not rely on a pre-requisite Fisher distribution. Their test involves eigen analysis of a given paleomagnetic data set to estimate the degree to which the directions are parallel. Confidence limits for this technique are derived using bootstrap and parametric bootstrap techniques, depending on the size of the data set and whether or not the data set has a Fisher distribution. McFadden (1998) argues against using parameter estimation techniques because of its flawed assumption that the magnetizations are most tightly clustered with the beds in their correct orientation. Although possibly true for the underlying distribution, maximizing the magnetization's clustering may very well not hold true for finite samples. This assumption can lead to an inherent bias for producing syn-folding magnetization results, because the maximum clustering in a particular configuration may be deceptive if factors other than structural tilts (e.g., plunging folds, unrecognized minor overprints, etc.) played a role in producing actual distributions of directions.

The statistical and parameter estimation techniques illustrate the application of the paleomagnetic fold test to anticlines and synclines with a simple cylindrical geometry and horizontal fold axes. However, in many orogenic settings fold axes plunge; moreover, multiphase deformation may have occurred that resulted in folds with curved fold axes on the local scale. In addition, many mountain belts have curved structural trends on the regional scale, which may have been produced by oroclinal bending. This led to the realization that the "fold test" should really be called a tilt test, and to supplement the standard fold tests mentioned above, the inclination-only tilt test was created (McFadden and Reid, 1982). The inclination-only tilt test is designed to determine the relationship between magnetization acquisition and deformation in sinuous folds and other areas where rotations about vertical axes may have occurred. This test ignores declination scatter and tracks the statistical significance of inclination clustering during incremental unfolding of a structure, independent of relative rotations. To make a formal distinction between fold test and tilt test, we propose that the term 'fold test' should be used when the fold axis is known or inferred, whereas the tilt test would not need to have well-defined fold axes in regions with variable bedding dips.

On the regional scale, Schwartz and Van der Voo (1983) devised a linear regression test for determining the relationship of rotations with magnetization acquisition in mountain belts with curved structural trends. This "strike test" is a new variant of the fold test, and presumes, of course, that the folding is about a vertical axis. The strike test determines the correlation between variations in paleomagnetic declinations with change in regional structural trend (Eldredge et al., 1985). If the correlation is one-to-one then true oroclinal bending has occurred, implying that the belt was originally straight. If there is no declination variation, then the belt retained its originally arcuate shape or alternatively, the magnetization was acquired after rotation.

Even though the methods of determining uncertainty in tilt tests, and the types of tilt test to be used, are continuously debated amongst paleomagnetists, the test is still an important, if not the most important test of stability used in paleomagnetic analysis. With more and more paleomagnetic investigations being undertaken in structurally complex terranes the tilt test has become an integral part of data analysis and interpretation, and appropriate sampling strategies must be planned accordingly.

At this point, it is of interest to note that paleomagnetic–tectonic studies, especially those in orogenic belts, can be designed with one of two goals in mind. The first goal could be to contribute to an apparent polar wander path (APWP), which mandates that one obtains accurate and well-dated directional information about the earth's magnetic field for a given location at a given time. In complex folded and faulted regions this becomes increasingly challenging, because of the difficulties in determining the necessary structural corrections. Penetrative strain within strata can compound this uncertainty by actively rotating the rock's natural remanent magnetization.

The second type of goal for paleomagnetic–tectonic studies in orogenic belts is more readily accomplished and is the inverse of the first goal. If a well determined APWP is already available, its reference paleopoles can be used for predicting paleomagnetic directions for a given age at a given site. Comparing observations with these predictions will then allow (with a limited degree of freedom) the determination of the necessary structural corrections to bring the two into agreement. When magnetizations are pre-folding (as determined from inclination-only tilt tests), and given that it is usually not difficult to determine the bedding dip, the most significant potential outcome from such a comparison is a quantification of real or apparent tectonic rotations, caused by folding about inclined or vertical axes (e.g., MacDonald, 1980; Chan, 1988; Stewart, 1995). The net result of successive rotations about differently inclined axes equals the effect of a single net rotation about an inclined axis, and it is usually impossible to determine the individual deformation phases separately. Moreover, cumulative rotations are not commutative and must always be restored in the reverse order, a procedure that is often very difficult to determine correctly. However, when multiple magnetizations are superposed in a sample collection, and if some of these are acquired early and others are late syn-deformational, then it may be possible to develop an evolutionary scenario of the deformation. The case history described later in this study illustrates such a scenario.

Chan (1988) constructed declination anomaly charts in an attempt to provide paleomagnetists with a technique to test whether an appropriate axis was used for paleomagnetic restoration. Stewart (1995) attempted a similar approach that tries to quantify the errors that are imparted on paleomagnetic data if the wrong rotation- or fold axis is used for restoration. In both cases the authors emphasize the need to fully understand the local and regional geology before undeforming complex structures. Stewart (1995) recognized that this is particularly true in areas where complex folds are produced due to underlying structural or stratigraphic features (e.g. ramp surfaces, basement topography, sedimentary pinch-outs etc.).

Strain is another important potential source of error in paleomagnetic directional analysis involving the fold test. A high degree of internal strain has been shown to cause rotation of magnetization vectors, and can result in the perception of a syn-folding outcome for a component that is actually pre-folding (van der Pluijm, 1987; Kodama, 1988; Stamatakos and Kodama, 1991; Borradaile, 1997). This is particularly important in areas where flexural slip folding dominates (Facer, 1983). In this case, simple shear strain during folding can cause heterogeneous strain that results in partial (but unrecognized) rotation of pre-existing magnetization remanence (Kodama, 1988). Therefore, the assumption in all fold tests is that fold restoration involves rigid-body rotation with no appreciable accumulation of

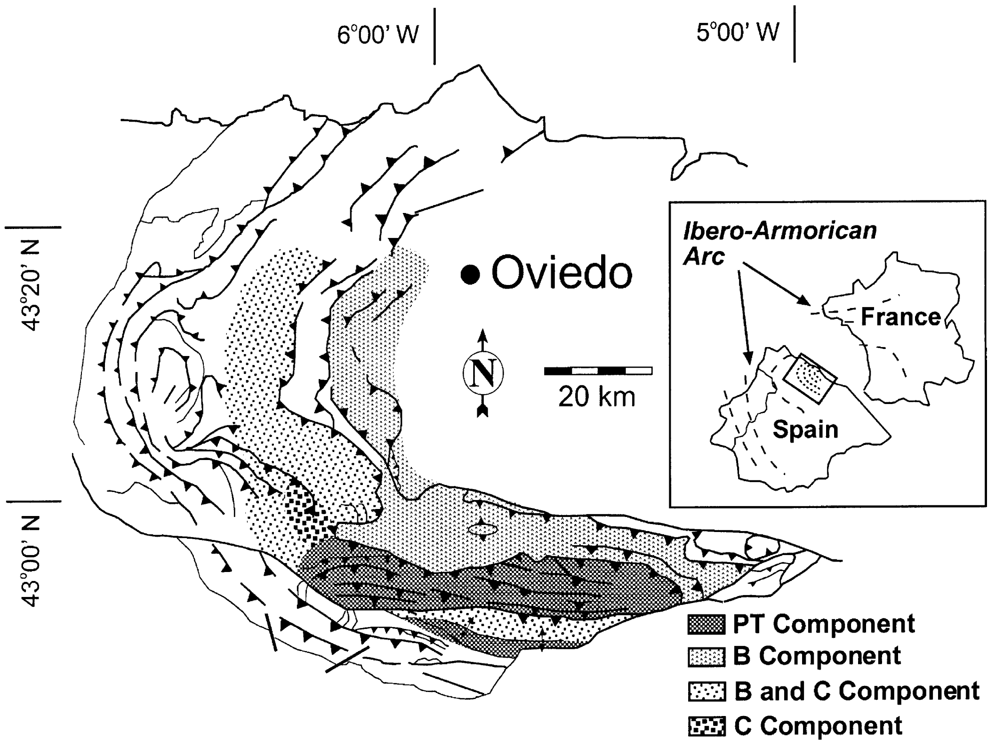

Fig. 1. Schematic geologic map of the CAA highlighting the distribution of the three ancient remagnetizations (PT, B and C) carried by the Devonian Santa Lucia and Portilla formations. Inset shows the CAA's location (small box) with respect to the larger Ibero-Armorica Arc. Spain is rotated 35° to its position prior to the opening of the Bay of Biscay.

heterogeneous strain (Borradaile, 1997). Consequently, strain-induced rotations during folding will result in an erroneous fold test unless more complex structural corrections are applied. Although structural geologists routinely measure, determine, and restore strain in rocks (Ramsay and Huber, 1983), only rarely have paleomagnetists (e.g., Stamatakos and Kodama, 1991; Cogné and Perroud, 1985; Kligfield et al., 1983) combined such methods with paleomagnetic directional analysis, not in the least because of a lack of consensus about the effect of strain on paleomagnetic remanence.

The fold or tilt test has contributed greatly to our understanding of orogeny (Van der Voo and Channell, 1980) and should in the future continue to be extremely useful in structurally complex regions. A case study is presented below from the Cantabria-Asturias Arc (CAA) of northern Spain (Fig. 1), which elucidates the usefulness of paleomagnetism and the various fold test types in areas of multiphase deformation. The data used for this study are taken from Weil et al. (2000, 2001).

2. Cantabria-Asturias Arc

The CAA is a thin-skinned fold-thrust belt and a classic example of a mountain belt formed by multiphase deformation (Julivert, 1971; Weil et al., 2001). CAA deformation occurred during the Variscan orogeny and is tectonically related to the convergence between Gondwana and Laurussia in the Late Paleozoic. The CAA is an unusual orogenic belt in that its main structural geometry is concave toward the foreland, with fold-thrust vergence directed toward the core of the arc (Fig. 1). Because of its large degree of curvature, thought to be in part or wholly secondary, it provides an ideal setting for using paleomagnetism to document syn-orogenic rotations.

Carey's (1955) classic paper on curved mountain belts proposed that the CAA formed by secondary bending of an originally linear belt. Since then, many models have been proposed for the formation of the CAA including: indentation (Matte and Ribeiro, 1975; Matte, 1986), promontory-salient collision (Lorenz, 1976), progressive rotational thrust emplacement (Pérez-Estaún et al., 1988), crustal wrenching (Brun and Burg, 1982), oroclinal bending of an originally east–west trending belt (Ries et al., 1980; Ries and Shackleton, 1976), and oroclinal bending of an originally north–south trending belt (Weil et al., 2001).

The CAA's deformation history consists of two main generations of Variscan deformation (Julivert, 1971). The early generation resulted in major thrust initiation and formation of folds that today parallel the trend of the arc. The folds are related to thin-skinned thrust emplacement and are generally thought to have been characterized by initially horizontal fold axes and steep axial planes. The second generation is characterized by a 'radial' fold set dominated by steep fold axes (Julivert, 1971; Julivert and Marcos, 1973; Weil et al., 2000). Our most recent tectonic model (Weil et al., 2001) suggests that the two major generations of deformation found in the CAA result from a change in the regional stress field from east–west in the Late Carboniferous to north–south in the Permian. We inferred that this change was the result of changing plate interactions during the final collisional adjustments within Pangea.

2.1. Paleomagnetism

Weil and Van der Voo (2002) show that the Devonian carbonates in the CAA carry secondary chemical remanent magnetizations acquired during Variscan deformation in the Late Paleozoic. A total of four magnetic components are isolated by detailed thermal demagnetization (Fig. 2) in the CAA: a viscous present-day field (A) component, a Permo–Triassic (PT) component that postdates all CAA deformation, an Early Permian (B) component (Van der Voo et al., 1997) that is largely post-tilting yet pre-rotation, and a Late Carboniferous (C) component (Van der Voo et al., 1997) that is syn-tilting. The PT, B and C components are thus distinguished by their behavior in incremental fold tests (Fig. 3), as well as in their whole-rock magnetic properties (Weil and Van der Voo, 2002). Fig. 1 shows the distribution of the three ancient magnetization components within the structural domains of the CAA studied by us. The three magnetizations have yielded mean inclination values, upon appropriate structural correction as described below, and these are plotted together with reference inclination values (from Stable Europe, the Iberian Meseta and the Pyrenees) versus age in Fig. 4. This plot suggests ages of latest Permian–Triassic, Early Permian and Late Carboniferous for the PT, B and C components, respectively.

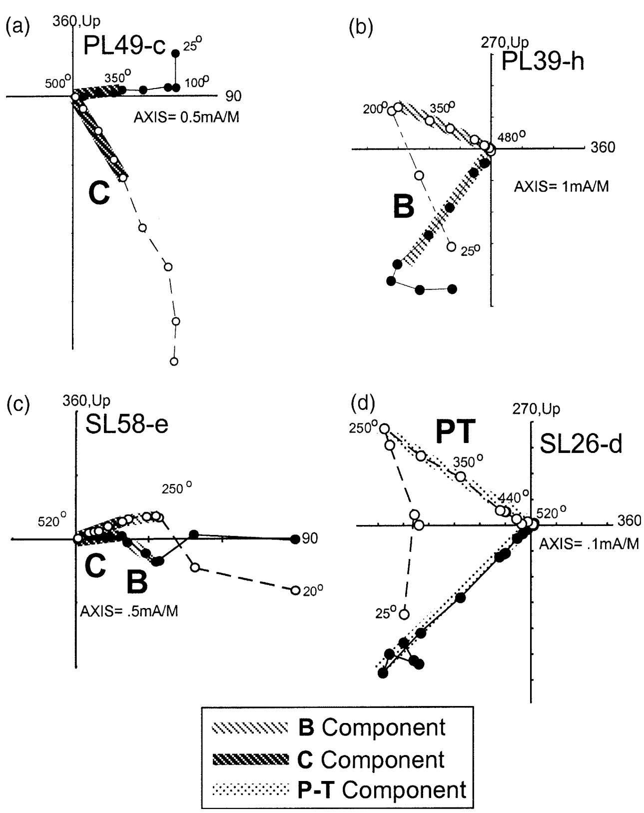

Fig. 2. Typical examples of orthogonal projection plots in in situ coordinates showing the ancient remagnetization components held by CAA carbonates: (a) C component, (b) B component, (c) B and C component, and (d) PT component. Open circles represent projections onto the vertical plane; closed circles represent projections onto the horizontal plane. Thermal demagnetization temperatures are given in degrees Celsius (Figure modified from Weil and Van der Voo, 2002).

The CAA's unique multicomponent magnetization history facilitates the investigation of the arc's incremental structural evolution, which otherwise would be extremely difficult to determine. Integral to the understanding and interpretation of these remagnetizations is the ability of fold and tilt tests to constrain the relative age of magnetization acquisition, which ultimately allows for age determination and structural characterization of different deformation events (Weil et al., 2000).

2.1.1. PT component

The PT component is restricted to a limited area in the southern limb of the arc. Two fold tests are shown in Fig. 5 that document the typical behavior of the PT component. Fig. 5c is a regional test that combines several complex fold structures, which trend from ENE to WSW and from ESE to WNW (Fig. 5a). The in situ directions for all 10 sites are to the southeast and moderately up. Upon incremental structural correction the directions scatter increasingly (Fig. 5c) indicating a post-deformational magnetization acquisition. The second test is of five sites at the eastern terminus of a large east–west trending syncline (Fig. 5b). Upon untilting the directions scatter to both the upper and lower hemisphere (Fig. 5d) confirming a post-deformational magnetization. Both tests are from within the fault-bounded Pedrosa Synclinorium, which has similar magnetization behavior throughout.

The distinction of the PT component as post-folding and post-rotation can be confirmed by comparing the in situ paleopole position calculated from 30 paleomagnetic sites located in the southern zone of the CAA (Weil et al., 2001) with stable Iberia's Late Paleozoic and Mesozoic APWP (Parés et al., 1996). This comparison yields a latest Permian–Early Triassic age. Sites from elsewhere in the east–west trending southern limb of the CAA show easterly to northeasterly in situ declinations, suggesting a high degree of counterclockwise rotation subsequent to magnetization acquisition. Therefore, the PT component, interpreted as being acquired after

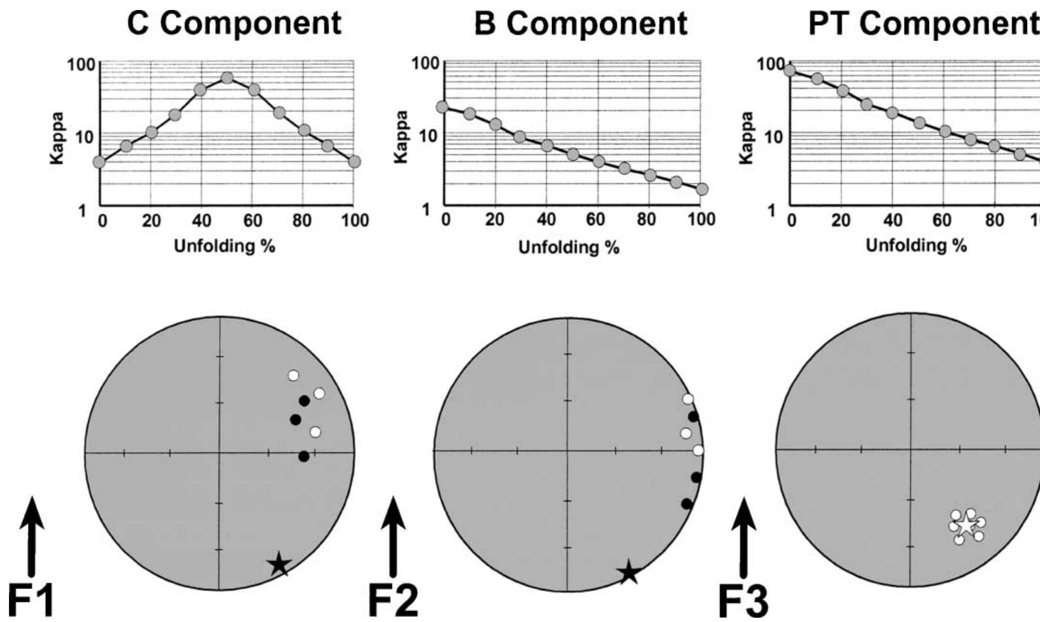

Fig. 3. Schematic representation of the CAA's three ancient remagnetizations as distinguished by incremental fold tests and in situ site-mean behavior. Incremental and inclination-only fold tests plot kappa versus percent unfolding. Accompanying stereonets display both upper hemisphere (open symbols) and lower hemisphere (closed symbols) projections. Circles represent idealized examples of in situ site means from the three respective components (C, B, and PT). Stars represent mean directions of the three ancient remagnetizations (Van der Voo et al., 1997; Weil et al., 2000; Weil et al., 2001). The relative age of the three Variscan folding events with respect to magnetization acquisition are distinguished by black arrows.

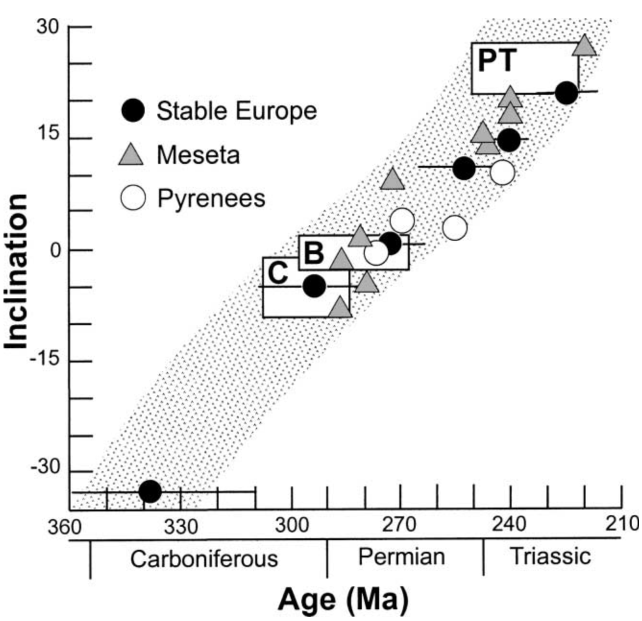

Fig. 4. Plot of inclination versus time for Iberia. Stippled swath represents Iberia's northward movement in the Late Paleozoic. Inclinations and ages are constrained by available paleomagnetic data from Stable Europe, the Iberian Meseta and the Pyrenees. White boxes represent the inclinations, with their respective errors, of the three (C, B and PT) ancient CAA remagnetizations discussed in the text.

Variscan deformation had ceased, allowed Weil et al. (2001) to put an upper boundary on the timing of final deformation in the CAA.

2.1.2. B component

The B component is found throughout the hinge and southern zones of the arc (Fig. 1). With the exception of the Proza Anticline and the northern part of the southern limb (Figs. 1 and 6a), the B component was found in conjunction with the C component. Three tests from the Proza Anticline are shown in Fig. 6 that document the typical behavior of the B component. Fig. 6b is a local fold test of a meter-scale fold (sites SL41e and SL41w). The in situ directions are to the southeast and shallow down. Upon unfolding the directions scatter indicating a post-folding magnetization acquisition. However, as can be seen in Fig. 6a, the in situ declinations from throughout the Proza structure show a strong correlation with changes in local structural trend, suggesting that they were acquired prior to the late orogenic rotations. The magnetization, therefore, is consistent with a B component magnetization. The second test is an inclination-only tilt test between six sites at the northern terminus of the Proza Anticline (Fig. 6c). Upon untilting the directions scatter confirming a post-tilting magnetization.

To further test whether the magnetization was acquired prior to the rotations, one must examine the declination patterns, and ideally a "declination-only test" should be devised to determine rotations about (near-)vertical axes. However, such a test hinges critically on the proper choice of corrections for declination variations, which is not a simple exercise, given that

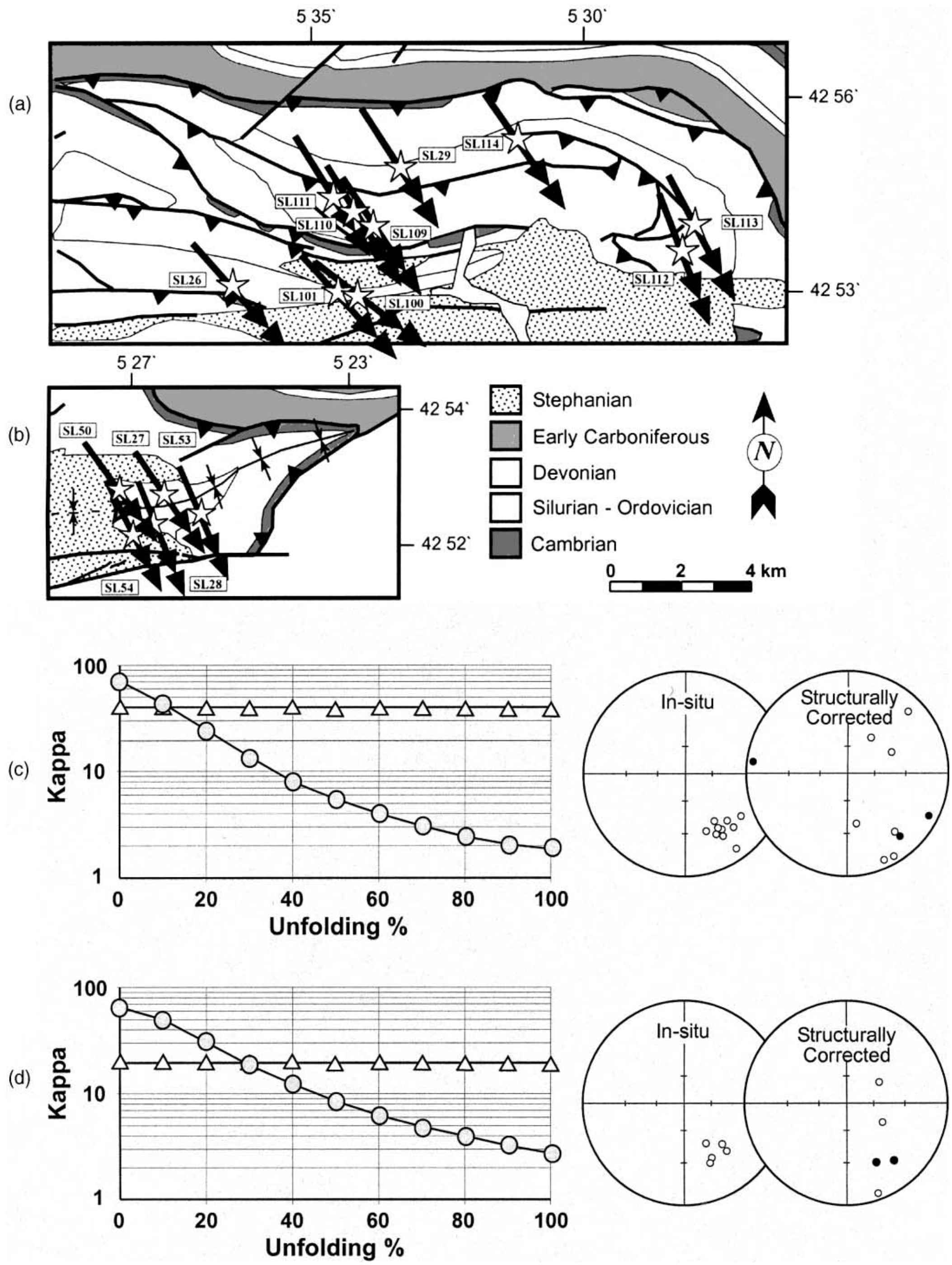

Fig. 5. Schematic geologic maps and local incremental fold tests for the Pedrosa unit. Open stars represent site locations and black arrows represent mean in situ paleomagnetic declinations. Local incremental fold tests plot kappa (circles) and CR (triangles) versus percent unfolding. CR represents the critical ratio above which the kappa values become significant at the 95% confidence level. (a) Geologic map of the central Pedrosa unit. (b) Geologic map of the terminal syncline at the eastern end of the Pedrosa unit. (c) Local incremental fold test for the 10 sites from (a) showing a post-folding and post-rotation PT magnetization. Accompanying stereonets show the in situ and structurally corrected site means for the 10 sites in (a). Open symbols represent upper hemisphere projections; closed symbols represent lower hemisphere projections. (d) Local incremental fold test for the five sites from (b) showing a post-folding and post-rotation PT magnetization. Accompanying stereonets show the in situ and structurally corrected site means for the five sites in (b).

measured bedding strikes do not necessarily reflect rotations in accurate fashion. This is probably why such a declination-only test has not yet been proposed. Instead, a strike test (Schwartz and Van der Voo, 1983), using generalized structural trends, was performed on five sites from the southwestern limb of the Proza Anticline.

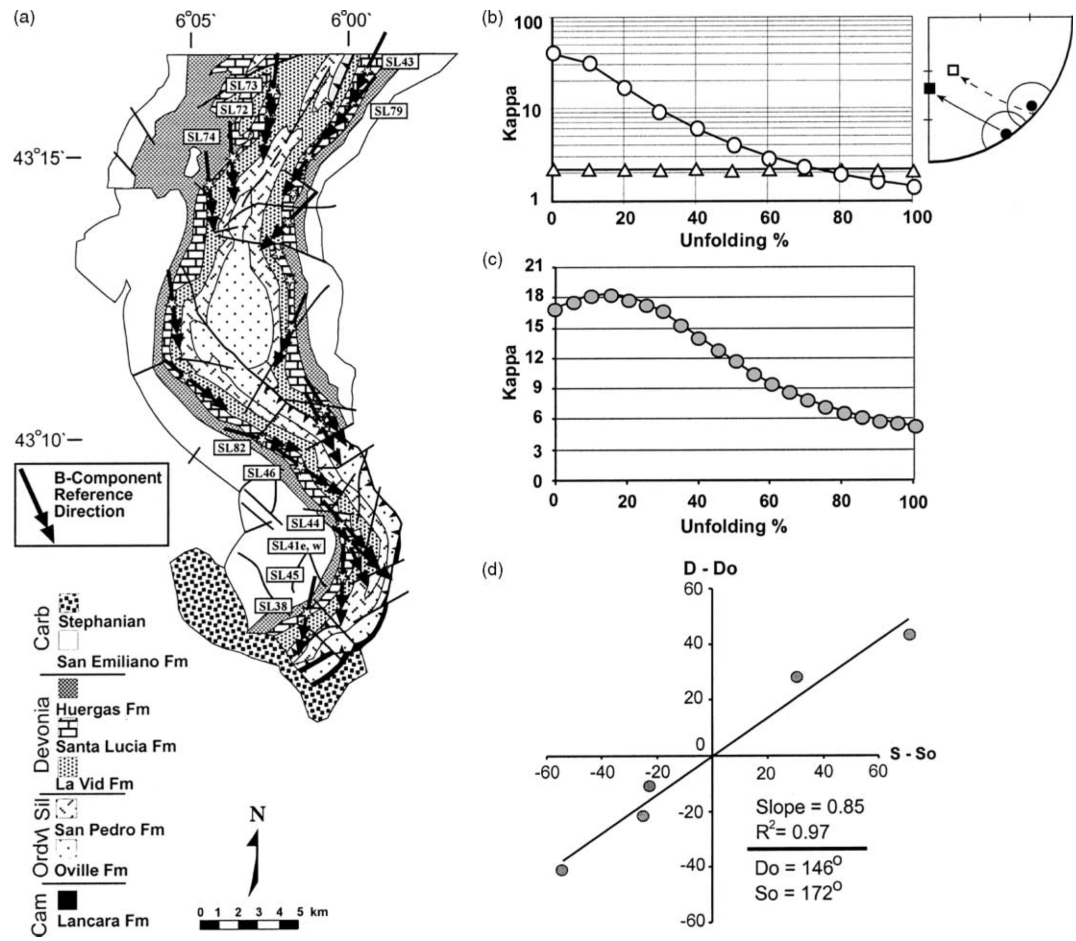

Fig. 6. (a) Schematic geologic map of the Proza Anticline. Open stars represent site locations and filled arrows represent mean in situ paleomagnetic declinations. (b) A local incremental fold test of sites SL41e and SL41w plotting kappa (circles) and CR (triangles) versus percent unfolding. CR represents the critical ratio above which the kappa values become significant at the 95% confidence level. The maximum kappa at 0% unfolding indicates a post-tilting B component. Accompanying stereonet show the in situ (circles) and structurally corrected (squares) site means for sites SL41e and SL41w. Open (closed) symbols represent upper (lower) hemisphere projections. (c) Local inclination-only fold test plotting kappa versus percent unfolding for the six northern sites from (a). The maximum kappa at 15–20% unfolding indicates a post-tilting B component. (d) Strike-test for the five southern sites plotting deviations in local structural trend versus deviations in declination. The 0.85 slope of the linear regression line indicates that the magnetizations are pre-rotation. The ordinate–axis term $[D - D_0]$ represents the declination from each site minus the average declination of all sites. The abscissa–axis $[S - S_0]$ term represents the regional structural strike at each site minus the average strike of all sites. The choice of D_0 and S_0 are chosen so that the regression line passes through the origin of the plot, and the strike for a given site is chosen as the tangent to the regional trend of major structures.

These five sites (SL38, SL44, SL45, SL46, SL82) are located along an amphitheater-like structure (Fig. 6a) that resulted from secondary folding of an originally linear feature about a steeply plunging axis. Thus, if the magnetization was acquired prior to rotation, albeit subsequent to original folding of the anticline, the correlation between deviation in structural trend and deviation in declination should be one-to-one. Fig. 6d shows that the strike test yields a slope of 0.85, which indeed indicates a pre-rotation acquisition for the magnetization.

When found in conjunction with the C component, the B component is distinguished by the outcome of local and regional tilt tests. The Vega de los Viejos Syncline is an example of a structural domain that carries both the B and C components (Fig. 7a). In all cases throughout the arc it was established that when the B and C components were found together the higher temperature component constituted the C magnetization, whereas the low temperature component represented the B magnetization. Fig. 7b shows a tilt test for the low temperature components from sites SL64 and SL69 located on opposite limbs in the northern part of the structure. The test reveals a post-tilting magnetization, consistent with a B component magnetization. In summary, the B component was acquired in the Early Permian, after the initial phase of deformation (thin-skinned folding and thrusting), but prior to the final phase of near-vertical-axis rotations due to oroclinal bending.

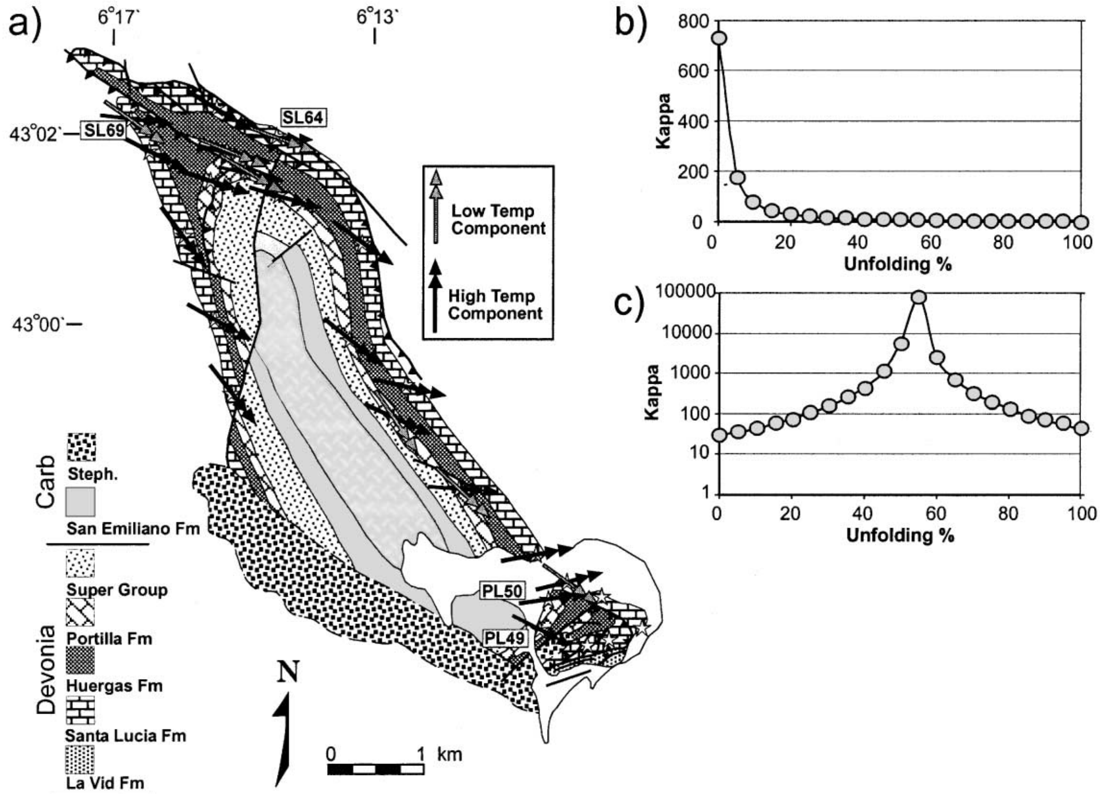

Fig. 7. Schematic geologic map and local incremental inclination-only fold tests for the Vega de los Viejos Syncline. Open stars represent site locations and arrows represent mean in situ paleomagnetic declinations. Incremental inclination-only fold tests plot kappa versus percent unfolding. (a) Geologic map of the Vega de los Viejos Syncline. (b) Inclination-only fold test for the low temperature components from sites SL64 and SL69 showing a post-tilting B magnetization. (c) Inclination-only fold test for the high temperature components from sites PL49 and PL50 showing a syn-tilting C magnetization.

2.1.3. C component

The C component is also found throughout the hinge and southern zones of the arc (Fig. 1), but was found without the B component in only one structural domain, the La Queta Syncline (Fig. 8a). Everywhere else the C component was found in conjunction with the B component overprint. In a generalized way (Fig. 3), the C component directions need a rotation- and a partial-tilt correction, given that both the declinations and the inclinations are typically scattered. The degree to which tilt corrections must be applied is determined from the incremental inclination-only tilt tests, whereas the rotations are deduced from the declination deviations of the tilt-corrected directions of C as well as the in situ site-mean B components (Weil et al., 2000).

Fig. 7c shows an inclination-only tilt test between the high temperature component from sites PL49 and PL50, located on opposite limbs in the southern part of the Vega de los Viejos Syncline (Fig. 7a), which formed as part of the Late Carboniferous thin-skinned fold-thrust deformation. The test reveals a syn-folding magnetization, indicating acquisition of the C magnetization during initial CAA folding.

Three inclination-only tilt tests from the La Queta Syncline are shown in Fig. 8, also documenting the typical behavior of the C component. All three tests indicate a C magnetization acquisition during initial folding of the main axial La Queta syncline.

Both B and C components, the latter interpreted as being acquired during the initial generation of deformation in the Late Carboniferous, can thus be used to constrain the timing and geometry of Late Carboniferous phases of folding during the CAA's initial compressional event (Weil et al., 2000) and both pre-date the Permian phase of oroclinal bending.

2.2. Orocline test

When the 115 paleomagnetic sites that carry the B and/or the C magnetization component sampled by Parés et al. (1994), Van der Voo et al. (1997) and Weil et al. (2000, 2001) are combined in a regional strike test (Fig. 9), it becomes clear that the CAA represents an ideal example of oroclinal bending (Carey, 1955). Schwartz and Van der Voo's (1983) linear regression analysis of the 115 sites shows a near one-to-one correlation

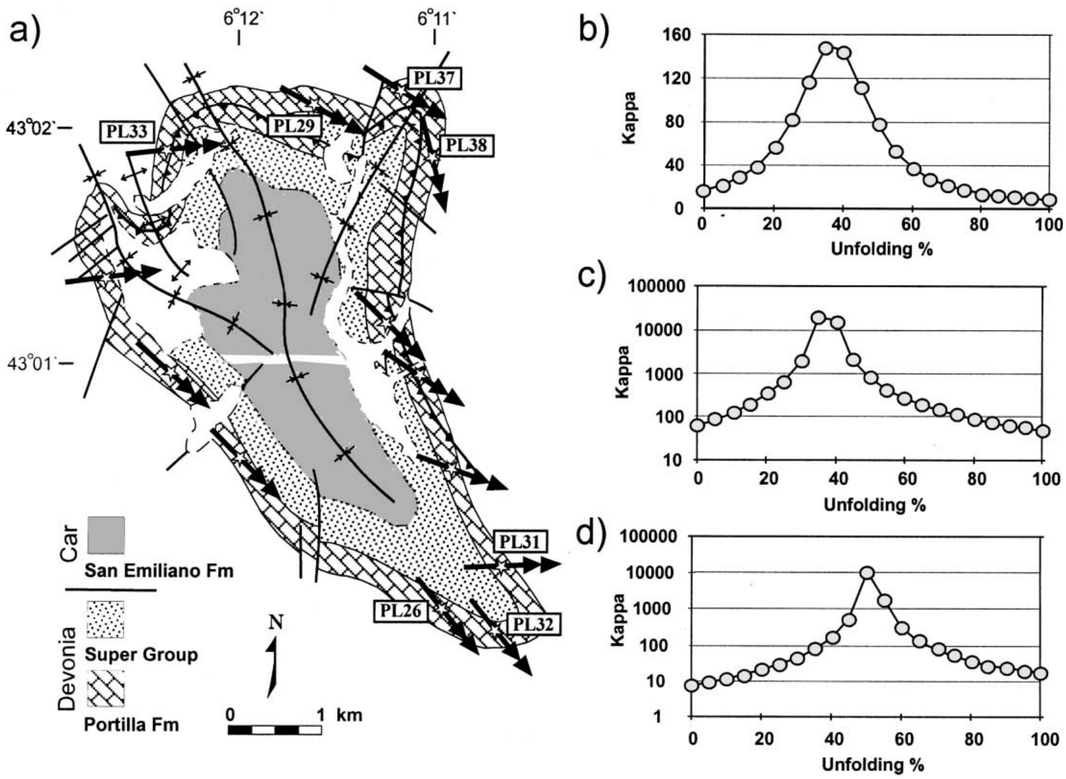

Fig. 8. Schematic geologic map and local incremental inclination-only fold tests for the La Queta Syncline. Open stars represent site locations and black arrows represent mean in situ paleomagnetic declinations. Incremental inclination-only fold tests plot kappa versus percent unfolding. (a) Geologic map of the La Queta Syncline. (b) A local fold test of sites PL26, PL31, and PL32 showing a syn-tilting C component. (c) A local fold test of sites PL29 and PL33 showing a syn-tilting C component. (d) A local fold test of sites PL37 and PL38 showing a syn-tilting C component.

between deviations in declination from a given reference direction (rotation) and deviations in strike from an average structural trend (curvature). The linear dependence of these two variables indicates that oroclinal bending has occurred and that today's nearly 180° of CAA curvature is the result of deformation of an originally linear belt. For readers interested in how declinations are obtained and used in steeply plunging fold settings, such as associated with the F3 deformation phase of Fig. 3, we refer to Weil et al. (2000).

A model of nearly 100% oroclinal bending determined from both regional and local paleomagnetic strike tests explains many of the previously unanswered complexities associated with today's CAA geometry. This unique geometry led previous researchers to call upon different models for CAA formation (Pérez-Estaún et al., 1988; Lorenz, 1976; Matte, 1986; Nijman and Savage, 1989; Dias and Ribeiro, 1995; Brun and Burg, 1982), which now seem unlikely, not in the least because Permian oroclinal bending clearly occurred later than, and separately from, the Late Carboniferous folding and thrusting.

The results also indicate that previous paleomagnetic studies of the region routinely underestimated the total amount of rotation as recorded in ancient magnetizations. This was due in large part to incorrect interpretations of incomplete (non-incremental) fold and tilt tests as indicating primary magnetizations, but over-simplification of structural style also played a role. Sparse paleomagnetic sampling in previous studies of the southern limb did not facilitate the recognition of the separate PT, B and C components, and inclusion of erroneously tilt-corrected PT directions in strike tests increased the scatter and decreased the slope of the regression lines. Consequently, the total rotation recorded by paleomagnetic components was underestimated by ~50% (Perroud, 1983; Hirt et al., 1992; Parés et al., 1994). Weil et al. (2001) demonstrated that when the post-rotation PT data are removed from analysis, the arc shows ~80° counterclockwise rotation of the southern limb and ~90° clockwise rotation of the northern limb with respect to an average (southern hinge zone) strike of 151° (Fig. 9).

3. Conclusions

Our study shows that complex structural deformation can be unraveled under the right circumstances by restoration of characteristic remanent magnetizations to a reference direction. This type of investigation has been a growing area of study over the past few decades and has

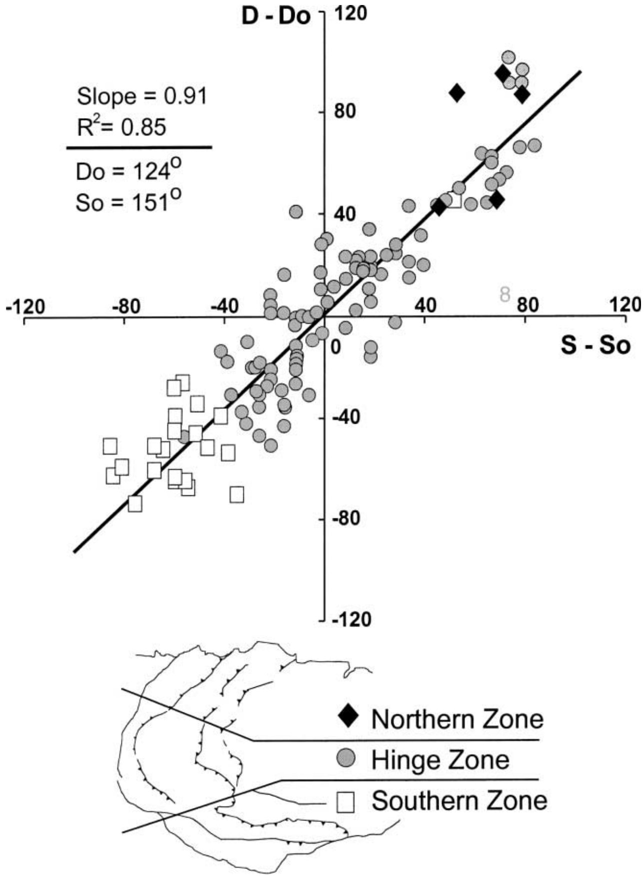

Fig. 9. Declination deviations from mean reference direction ($D_0 = 124°$) of site means plotted against strike deviations from reference strike ($S_0 = 151°$) (after Schwartz and Van der Voo, 1983). Data compiled from Parés et al. (1994), Van der Voo et al. (1997) and Weil et al. (2000, 2001). Also shown is linear regression line through data with accompanying slope and correlation coefficient R. The ordinate–axis term $[D - D_0]$ represents the declination from each site minus the average declination of all sites. The abscissa–axis $[S - S_0]$ term represents the regional structural strike at each site minus the average strike of all sites. The choice of D_0 and S_0 are chosen so that the regression line passes through the origin of the plot, and the strike for a given site is chosen as the tangent to the regional trend of major structures.

led to many new insights into orogenic processes. From Graham's (1949) original untilting method, to the more complex parameter estimation techniques, and then to the incremental inclination-only tilt test and the strike test—which is basically a test of folding about vertical axes—the fold test has been at the foundation of paleomagnetic investigations in regions of past tectonic activity. With the application of paleomagnetism to increasingly complex structural environments, more functional and increasingly more elaborate paleomagnetic fold tests have been needed to decipher the relationship between deformation and magnetization acquisition. Thus, the importance of the test, when used properly, is undeniable. Not only can the fold test help determine a magnetization's stability and the relative timing of acquisition, but when multiple magnetizations are present, scenarios can be constructed for the structural evolution of a region and the relative age of folding events.

Our detailed structural and paleomagnetic study carried out in the CAA further confirms the strength of the fold test when combined with an understanding of the folding and faulting style in a region. This is especially true when multiple secondary syn-folding magnetizations are present. The simple untilting of rock strata to their horizontal position as described by Graham (1949) rarely takes into account the total accumulation of rotation that a rock has undergone subsequent to magnetization acquisition.

Our paleomagnetic investigation of the CAA is a good example of the power and applicability of paleomagnetism and its tests to regions that have undergone complex multiphase deformation. Detailed sampling of individual structures and application of multiple incremental and inclination-only tilt tests allowed for the discrimination between three ancient remagnetizations, which otherwise would have been impossible to distinguish. The many tilt tests performed throughout the arc established the need, where necessary, for structural corrections for a given magnetization component, and provided temporal constraints on the age of discrete folding events associated with the Late Paleozoic Variscan orogeny.

Application of an orogen-scale strike test (Schwartz and Van der Voo, 1983) to the available paleomagnetic data from throughout the arc provides a robust model for the formation of arcuate curvature in the CAA (Fig. 9). The slope of nearly one for the strike-declination correlation shows that today's 180° of arc curvature is the result of deformation of an originally linear belt, thus representing a true (100%) orocline as first described by Carey (1955). Because the oroclinal bending is demonstrably younger than the Late Carboniferous folding and thrusting, the arc evolved in two stages (Weil et al., 2001). The two-stage model replaces previously proposed models for arc formation.

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