Oroclinal bending and evidence against the Pangea megashear: The Cantabria-Asturias arc (northern Spain)

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ABSTRACT

The Cantabria-Asturias arc of southwestern Europe is a highly curved Variscan belt that formed along the ancient plate boundary between Gondwana and Laurussia during the assembly of Pangea. New paleomagnetic data from 59 sites in the southern limb of the arc were combined with previously published data from 109 sites to determine the evolution of the arc. A previously unrecognized postrotation magnetization is found in the southern limb, refuting earlier models of arc formation that concluded secondary rotation of only 50% of present-day arc curvature. The new data show that the arc underwent true (100%) oroclinal bending of an originally linear belt in a two-stage tectonic history. This history represents two regional compression phases: (1) east-west in the late Carboniferous (Pennsylvanian) and (2) north-south in the Permian (both in present-day coordinates). The north-south compression phase coincides with the northward movement of Gondwana and its final collision with Laurussia. This tectonic scenario argues against an indentor scenario, and does not support a 3500 km dextral megashear proposed in earlier reconstructions.

Keywords: orocline, fold-and-thrust belts, paleomagnetism, Cantabria-Asturias arc, Variscan orogeny, Pangea.

INTRODUCTION

From the continuous magnetic reversal record of the modern oceanic seafloor, geologists have long argued that Pangea was in an A-type configuration prior to its breakup in the Jurassic (Pitman and Talwani, 1972). Paleomagnetic data from Pangea's major blocks confirm this configuration back to the Late Triassic. However, paleomagnetic results from Permian through Early Triassic time are incompatible with a Pangea A-type fit (Fig. 1A). For these times the paleopoles from the southern continent of Gondwana mandate a more northerly paleolatitude than allowed by the position of the northern Laurussia continent in a Pangea A fit. To avoid an impossible overlap, a Pangea B reconstruction for times prior to the Late Triassic has been proposed (Fig. 1B). However, the more easterly position of Gondwana in Pangea B requires a 3500 km megashear to accommodate the dextral translation needed to arrive at a Pangea A-type fit that would have taken place in the Permian (Muttoni et al., 1996), possibly extending into the Triassic (Irving, 1977).

Whereas the Pangea B hypothesis solves the overlap in paleolatitude for Gondwana and Laurussia, new problems are created by the required megashear. Foremost is the lack of geologic evidence for a continuous 3500 km dextral fault system along the ancient plate boundary (Hallam, 1983; Smith and Livermore, 1991). The enormous length and the irregular plate-boundary geometry mandated by a Pangea B fit (Fig. 1B) would result in a fault system with regions of transpression and transtension, similar to that observed along the San Andreas fault of western North America (Sibson, 1986). In particular, southwestern Europe would have undergone extensive transpression as a result of the westward translation of Gondwana.

One of the key areas near the proposed megashear is the Ibero-Armorica arc. In its core is the Cantabria-Asturias arc, which is the foreland fold-and-thrust belt of northern Iberia's Variscan orogen (Fig. 2). The arc's location between Laurussia and Gondwana makes the belt ideal for studying regional deformation associated with late Paleozoic collisional activity within Pangea.

The Cantabria-Asturias arc is an unusual belt that has 180° of curvature, with thrust vergence toward the center of the arc and away from the hinterland. It was first described by Suess (1885), and later classified by Carey (1955) as an orocline, defined as an originally linear belt that underwent secondary curvature (see review in Marshak, 1988). Since Carey's original hypothesis, a number of tectonic models have been proposed for the formation of the arc. These include cover deformation related to basement wrench faults (thick-skinned tectonics; Nijman and Savage, 1989), curvature due to microplate displacement (Matte and Ribeiro, 1975), counterclockwise rotation of an east-west belt (Ries et al., 1980), and progressive rotational thrust displacements due to protracted deformation (Pérez-Estaún et al., 1988).

Paleomagnetism has also been used to characterize the Cantabria-Asturias arc's deformation history, demonstrating that at least some of the arc's curvature is secondary (Perroud, 1986; Hirt et al., 1992; Parés et al., 1994; Stewart, 1995; Van der Voo et al., 1997). Weil et al. (2000) showed that the arc's curvature is accompanied by interference of original north-south–trending structures with superimposed variably plunging east-west structures in the hinge zone. Here we report new paleomagnetic results from the southern arm of the arc that have implications for the belt's oroclinal history as well as the controversial Pangea megashear.

STRUCTURAL SETTING

Two phases of Variscan deformation have been described in the Cantabria-Asturias arc. The early phase consisted of two east-west compression events (present-day coordinates) in Namurian through Stephanian time that resulted in arc-parallel folds and thrusts (F1 and F2). These early folds are characterized by horizontal fold axes and steep axial surfaces. The later phase (F3) began in the Sakmarian (Early Permian) and marks the final stage of Variscan deformation in northern Iberia. This phase is characterized by a radial fold set (Julivert, 1971) dominated by variably plunging fold axes that are within the limbs of early arc-parallel folds (Weil et al., 2000).

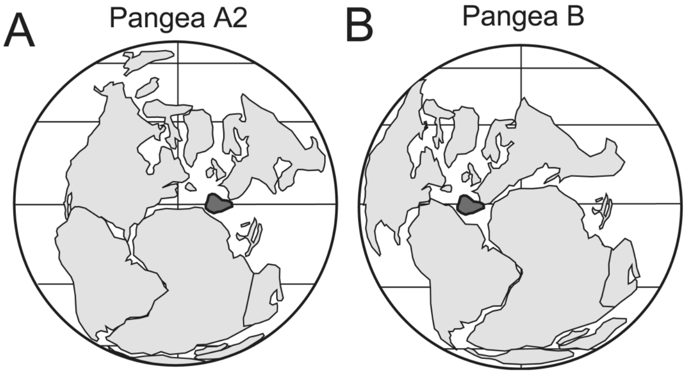

Figure 1. Pangea reconstructions highlighting latitudinal adjustment of Gondwana relative to Laurussia in Permian. A: Pangea A2 after Van der Voo and French (1974). B: Pangea B after Morel and Irving (1981).

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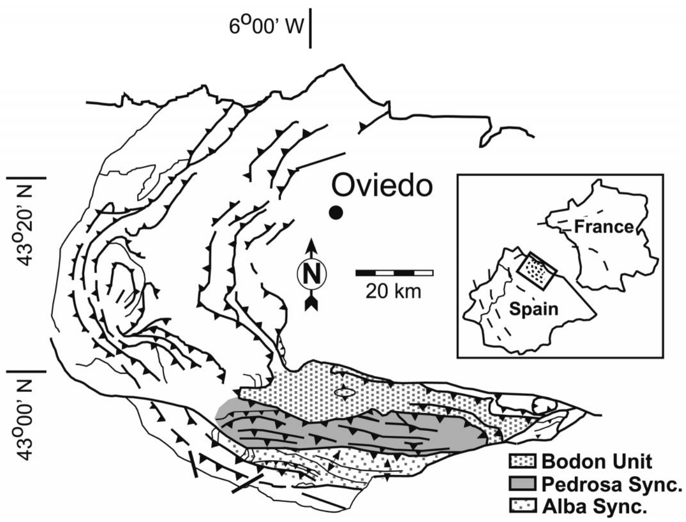

Figure 2. Generalized map of Cantabria-Asturias arc and its location in larger Ibero-Armorica arc. Three structural domains described in text are labeled.

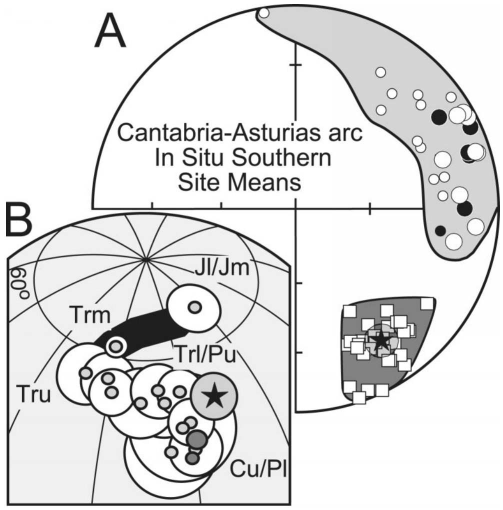

Figure 3. A: Stereonet projection of in situ paleomagnetic site-mean directions for southern arm of Cantabria-Asturias arc. Open symbols represent upper hemisphere projections, closed symbols represent lower hemisphere projections. Squares represent PT (Permian-Triassic) component, large circles represent B component, and small circles represent C component. Black star with accompanying α_{95} represents mean PT direction. B: Apparent polar wander path for Iberia after Parés et al. (1996). Black star represents PT paleopole, large dark gray circle represents B paleopole, and adjacent small dark gray circle represents C paleopole. Jl—lower Jurassic; Jm—middle Jurassic; Trl—lower Triassic; Trm—middle Triassic; Tru—upper Triassic; Pu—upper Permian; Pl—lower Permian; Cu—upper Carboniferous.

The east-west–trending southern arm of the Cantabria-Asturias arc can be divided into three structural domains; from north to south, these are the Bodon, Pedrosa, and Alba units (Fig. 2). The northernmost Bodon unit is characterized by large open folds. The central Pedrosa unit is characterized by multiple overthrust sheets that form an imbricated thrust system (Alvarez-Marrón, 1985). The southernmost Alba unit shows a large cumulative synformal structure and marks the southern extent of Paleozoic exposure in this region of the arc.

RESULTS

The paleomagnetic behavior of the samples analyzed is similar to that reported in studies of the Devonian Santa Lucia and Portilla Formations in the Cantabria-Asturias arc elsewhere. Sampling and experimental methods, site information, demagnetization results, and structurally corrected paleomagnetic data for the southern arc are presented in the GSA Data Repository[1]. In situ site means from all three domains in the southern zone are presented in Figure 3A.

Three magnetic components have been isolated (often superimposed in the same sample): a present-day field (A) component removed by 250 °C, an Early Permian (B) component with a mean inclination of $+1.5° \pm 3.1°$ and unblocking temperatures to 500 °C, and a Pennsylvanian (late Carboniferous, C) component with a mean inclination of $+5.0° \pm 6.6°$ and unblocking temperatures to 550 °C. This study identifies an additional and previously undocumented ancient component (PT) that is Permian-Triassic in age and postdates Variscan deformation in the arc. As discussed in the following, the PT, B, and C components are distinguished by their behavior in incremental fold tests. The PT component is dated by comparing the pole position of in situ sites from the Central Pedrosa synclinorium with stable Iberia's apparent polar wander path (Fig. 3B). The PT component has a mean inclination of $-24.0° \pm 3.8°$ and is restricted to the Pedrosa unit and the southern portion of the Alba unit.

BODON UNIT

We sampled 10 sites in the Bodon unit, all within the Devonian Santa Lucia Formation. A single, east-northeasterly and shallow negative magnetization was found in all but one site (SL121). Two fold tests provide the relative timing of magnetization acquisition with respect to deformation (Fig. 4). In three sites collected within a northeast-trending anticline (sites SL102–SL104) the in situ magnetic directions are uniformly east-northeast and shallow, and upon full-tilt correction become highly scattered. At 0% untilting, the inclinations cluster at $-2°$ with maximum kappa of 19 (Fig. 4). The second fold test includes all reliable sites collected from the Bodon unit. At 10% untilting, the

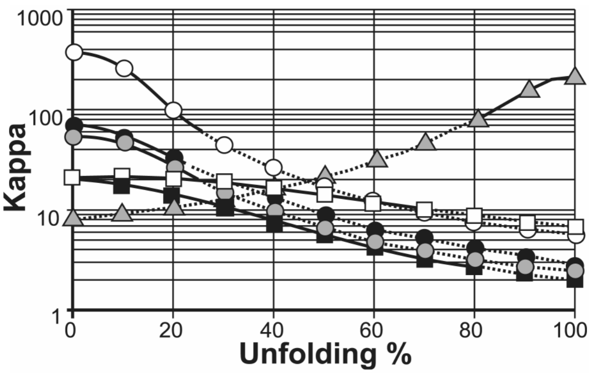

Figure 4. Incremental and inclination-only fold tests from southern arm of arc, plotting kappa vs. percent unfolding. Solid portions of lines represent unfolding percent above which kappa is statistically significant at 95% confidence level. Bodon unit is represented by squares (open squares are sites SL102–SL104; closed squares are entire Bodon unit); Pedrosa unit is represented by circles (closed circles are eastern terminus syncline; open circles are northwest-verging recumbent fold; gray circles are all Pedrosa sites); Alba unit inclination-only fold test is represented by gray triangles.

[1]GSA Data Repository item 2001112, Sampling and experimental methods and demagnetization data, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2001.htm.

inclinations cluster at +1° with maximum kappa of 19 (Fig. 4). Given the posttilting result of the two fold tests, the Bodon unit is interpreted as carrying the B magnetization component acquired between F2 and F3 deformation.

PEDROSA UNIT

We sampled 23 sites in the Pedrosa unit, one in the Devonian Portilla Formation and 22 in the Santa Lucia Formation. A highly clustered, southeasterly, and negative in situ magnetization was found in all sites. Three fold tests were completed (Fig. 4). In a syncline at the eastern terminus of the Pedrosa unit (sites SL27, SL28, SL50, SL53, and SL54) the in situ magnetic directions are uniformly southeast and upward, and upon full-tilt correction become highly scattered. At 0% unfolding, the inclinations cluster at −31° with maximum kappa of 63 (Fig. 4). A west-northwest–verging recumbent fold was sampled in the east-central portion of the Pedrosa unit (sites SL109–SL111). Given the general northwest-southeast trend of structures in this area, this test examines a possible sampling bias in the remaining Pedrosa sites that all have an east-west structural trend. The fold has a maximum kappa of 376 at 0% unfolding, with an inclination of −23°. For the entire Pedrosa unit, at 0% unfolding the inclinations cluster at −25° with maximum kappa of 69 (Fig. 4). On the basis of these fold tests, and because no rotation correction needs to be applied, the Pedrosa synclinorium is interpreted as carrying the magnetization component (PT) that was acquired after F3 folding.

ALBA UNIT

We sampled 26 sites in the Alba unit, 17 in the Portilla Formation, and 9 in the Santa Lucia Formation; 6 of the sites had unstable magnetizations. Of the 20 sites that carried stable remanence directions, 13 were collected from the northern limb of the main syncline, 6 of which carried two stable ancient components, and 7 from the southern limb, all of which carry a single ancient component. The northern limb sites all have easterly to northerly declinations, whereas the southern limb sites all have southeast declinations. Because no structural correction is able to bring these two groups of directions into coincidence, we conclude that the two populations are different magnetizations. The northern sites are interpreted as carrying an ancient pre-F3 component owing to their observed counterclockwise rotation, and the southern sites carry the post-F3 component (PT), given their directional similarity with in situ site means from the Pedrosa unit.

The Alba unit is dominated by southeast-striking bedding orientations in the west and northeast orientations in the east. Four sites were collected in a pair of tight folds in the central part of the Alba unit. High-temperature in situ declinations range from northerly to easterly, and inclinations range from shallow and up to intermediate and down. Because field observations suggest tilting as well as near vertical-axis rotations, an inclination-only fold test was applied (McFadden and Reid, 1982), and maximum kappa of 198 is achieved at 100% unfolding (Fig. 4). Given that the tilt test was performed on a subsidiary fold of an original F1 syncline limb, the pretilting result confirms that the high-temperature component is a pre-F2 magnetization. In the six sites that carry two ancient components, the high-temperature component is always more northerly than the low-temperature component, indicating a larger rotation of the former. Consequently, the northern Alba high-temperature magnetization is interpreted as the post-F1, C component, and the low-temperature magnetization is interpreted as the post-F2 (but pre-F3) B component, similar to observations in the hinge zone of the arc (Weil et al., 2000).

Each site that carried a pre-F3 magnetization (B and C) was evaluated to determine the best correction to undo postmagnetization rotations. Steeply dipping axes were determined by calculating the best-fit rotations to match in situ magnetic vectors with their respective reference directions. Applying the individual site rotation parameters, pre-F3 strikes calculated for the entire southern arm give a generally north-south–trending structure in present-day coordinates.

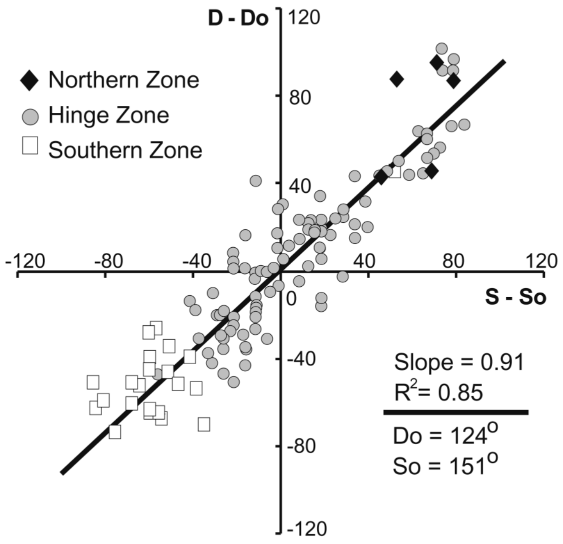

Figure 5. Declination deviations from mean reference direction (Do = 124°) of site means plotted against strike deviations from reference strike (So = 151°), including data from Weil et al. (2000), Van der Voo et al. (1997), and Parés et al. (1994). Choice of Do and So are so that regression line passes through origin of plot, and strike for given site is tangent to trend of major structures.

KINEMATIC IMPLICATIONS

The B and C components were acquired during and at the end of initial Carboniferous deformation (F1 and F2), and subsequent rotations are attributable to a Permian deformation (F3). If the arc is a true secondary orocline, deviations in declination from a given reference direction (i.e., rotation) should be consistent with deviations in strike from a reference structural trend (i.e., curvature). Figure 5 is a plot of all B and C magnetization components from this study plus data from Parés et al. (1994), Van der Voo et al. (1997), and Weil et al. (2000), using the method of Schwartz and Van der Voo (1983). Of the 168 total paleomagnetic sites, 115 carried stable B and/or C components. Linear regression of these 115 paleomagnetic sites results in a best-fit line with a slope of 0.91 (R^2 = 0.85). This correlation shows that today's 180° of arc curvature is a result of deformation of an originally nearly linear belt. F3 deformation resulted in refolding about steeply plunging axes of major, initially north-south–trending thrusts and folds in the hinge zone, and arc tightening due to counterclockwise rotation in the southern zone and clockwise rotations in the northern zone.

Previous kinematic models for Cantabria-Asturias arc formation based on paleomagnetic data underestimated the total amount of rotation recorded by ancient magnetizations due to oversimplification of structural style, incomplete paleomagnetic sampling, and failure to recognize a Permian-Triassic postrotation (PT) magnetization component in the southern zone (e.g., Hirt et al., 1992; Parés et al., 1994). However, as evidenced by the Alba and Bodon domains, where these postrotation directions are not observed, the arc's southern arm shows a nearly 90° counterclockwise rotation with respect to the hinge zone.

The analysis of rotations in the Cantabria-Asturias arc thus reveals a nearly linear north-south–trending fold-and-thrust belt that was established in the Carboniferous as a result of east-west compression (F1 + F2). This was followed by a change in regional stress field to north-south compression in the Permian (F3) (see also Kollmeier et al., 2000). True oroclinal bending explains many of the unanswered complexities associated with the arc's present-day geometry. Foremost is

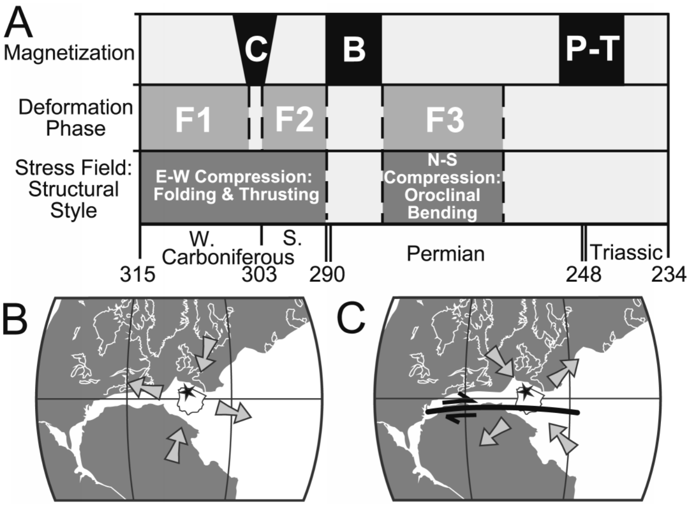

Figure 6. A: Time line of Variscan deformation of Cantabria-Asturias arc as represented by three recorded folding phases (F1, F2, and F3), their accompanying stress field, and structural style. Components are: PT—Permian-Triassic; C—late Carboniferous (Pennsylvanian); and B—Early Permian. B: Regional stress field for Early Permian in Iberia determined from our study. C: Regional stress field for Iberia inferred for Pangea B–Pangea A dextral megashear (heavy black line).

the long-standing question concerning the formation of a curved belt that is concave toward the foreland, rather than the hinterland, as in other curved mountain belts. This geometry led previous researchers to call upon synthrusting rotation and primary curvature models to explain the arc's formation (e.g., due to differential thrusting or an indentor). Moreover, scenarios that require counterclockwise rotation of the central and southern limbs of an originally linear east-west–trending belt (Ries et al., 1980; Brun and Burg, 1982; Martinez-Catalan, 1990) are also not supported by our reconstruction of the belt.

TECTONIC IMPLICATIONS

Our structural and paleomagnetic observations from the Cantabria-Asturias arc show that arc formation resulted from two main tectonic phases: (1) east-west compression forming the Cantabria-Asturias fold-and-thrust belt in Pennsylvanian time (F1 + F2), followed by (2) north-south compression from Gondwana's northward migration toward Variscan Europe and Laurentia in Permian time (F3). The timing and kinematics of these deformation events are punctuated by the successive C, B, and PT remagnetizations in the Cantabria-Asturias arc (Fig. 6A). In this tectonic model, final Variscan deformation (F3) has a north-south paleostress field in present-day coordinates, or north-northeast–south-southwest in paleogeographic coordinates (Fig. 6B).

In a Pangea B configuration, the Permian is thought to mark the beginning of westward translation of Gondwana relative to Laurussia along a 3500 km dextral megashear. This megashear would require a northwest-southeast remote compressive paleostress in paleogeographic coordinates for Iberia (Fig. 6C). Given the disagreement between the observed paleostress field for the Cantabria-Asturias arc and the predicted paleostress field for a dextral megashear, the Pangea B to A transformation is not supported for Early Permian time by our analysis. Moreover, younger translation would require fast geologic slip rates of ~7 cm/yr to accommodate the 3500 km of dextral motion. Combined with the lack of geologic evidence for Triassic strike-slip deformation along this boundary, the existence of a Pangea B to A megashear is unlikely.

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