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Conical folding in the core of an orocline. A geometric analysis from the Cantabrian Arc (Variscan Belt of NW Iberia)

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A R T I C L E I N F O

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A B S T R A C T

The Cantabrian Arc of the Variscan Belt has been recently defined as a true orocline, constraining kinematics and deformation timing. This curved sector of the orogenic belt is characterized by two different fold sets: (1) one runs parallel to the outcrops of the main thrusts and describes a horseshoe shape concave towards the east, and (2) another is radial to the arc. A detailed geometric study of the fold interference patterns in the Cantabrian Arc revealed the conical nature of the folds belonging to the radial set. These conical folds developed with different geometrical characteristics (semi-apical angles and axis attitudes) depending on the initial orientation and geometry of the folded surfaces. They are interpreted to result from a vertical axis rotation during oroclinal buckling of the Variscan Belt in NW Iberia. This study of conical folds in the Cantabrian Arc highlights that conical folds in curved orogenic arcs are a powerful tool for establishing the sequence of tectonic events because interference patterns due to vertical axis secondary differential rotations provide unique geometrical characteristics observed in the Cantabrian Arc that can be extrapolated to other oroclines.

1. Introduction

Conical folding is primarily a geometrical arrangement of deformed layers that can be readily recognised on stereographic plots by a distribution of poles to planes lying along a small circle. In space, a conical surface can be generated by rotating a line (the generator), oblique to a defined rotation axis. Initial interest in conical folding was spurred by the problem of reconstructing bedding-parallel sedimentary lineation orientations (Cummins, 1966; Wilson, 1967; Ramsay, 1967 p. 496–498) and, more recently, the problem of how to restore paleomagnetic data (Pueyo et al., 2003). Although Ramsay (1967 p. 349) indicated that these folds are rare in nature and Ramsay and Huber (1987, p. 311) suggested that the geometry of natural surfaces is probably more complex than a simple conical geometry, which is probably a more accurate assessment of the situation at most scales. Nevertheless, conical folding is often a valid approximation at suitably chosen scales.

Webb and Lawrence (1986) described the geometry of largely cylindrical folds whose terminations are demonstrably conical. The geometry is related to the development and growth of folds during which both, the interlimb tightening and the fold axial lengthening occur. More recently Keppie et al. (2002) described a conical fold termination with associated auriferous veins and presented geochronological data supporting the asynchronous development of folds by progressive lengthening in the axial direction. Additionally, Mandujano and Keppie (2006) studied cylindrical folds with conical terminations in the Gulf of Mexico and found that the junction between the cylindrical and conical parts of the folds are a favourable location for hydrocarbon reservoir rocks due to increased fracturing densities related to high curvatures at the cone apex. Moreover, conical folds can also form due to fold interference (Ramsay, 1962; Wilson, 1967), which is of particular relevance to the present study. Nicol (1993) demonstrated that surfaces formed by fold interference can be analysed as composite surfaces with of segments displaying conical geometries that may vary spatially. Furthermore, spatial variations in orientation data and fold geometry may be related to the characteristics of the interfering fold pattern (Mulchrone, 1991; Nicol, 1993). Groshong (2006) emphasized the importance of distinguishing between cylindrical and conical folds because conical folds terminate along their axial trend.

Curved orogens may be a likely location for conical folds when deformation is primarily due to differential rotation around a vertical axis affecting a population of geological surfaces with a variety of initial orientations. Curved orogens have been studied from the end of 19th century (Suess, 1885) and more intensively

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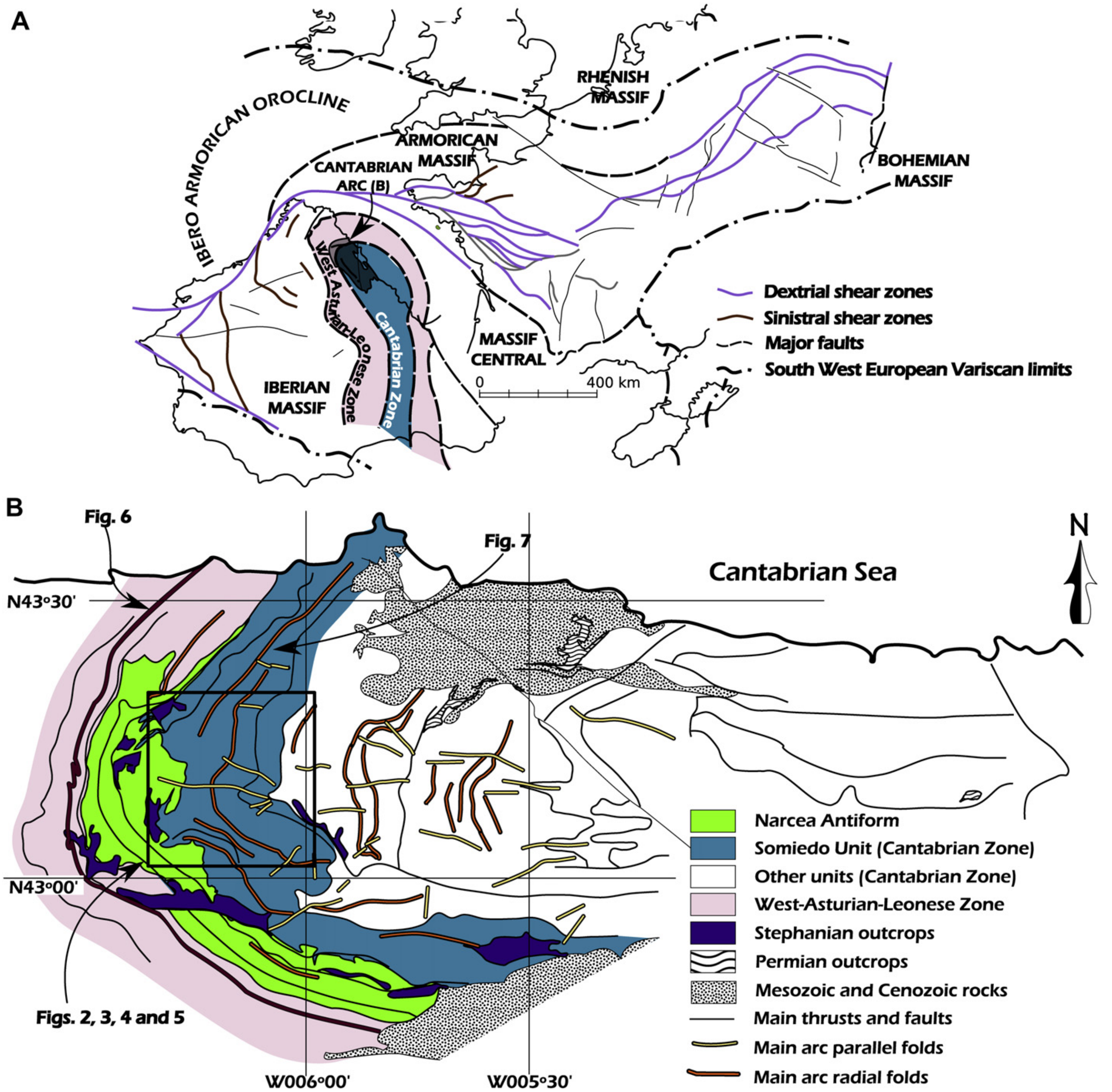


Fig. 1. A) Simplified map showing the location of the Ibero-Armorican Orocline in its original position prior to the opening of Biscay Bay, and the major structures including the Cantabrian Arc area, the Cantabrian Zone and the West Asturian-Leonese Zone. B) Location and main structures of the West Asturian-Leonese zone, the Narcea Antiform and the Somiedo unit from the Cantabrian Zone. Box shows study area.

during and after the development of the concept of plate tectonics (e.g. Carey, 1955; Irving and Opdyke, 1965; Molnar and Tapponnier, 1975; Engelder and Geiser, 1980; Schwartz and van der Voo, 1983; Johnston, 2001; Allmendinger et al., 2005). Curvature in plan view is recognized in a large number of ancient and modern orogens (e.g. Weil and Sussman, 2004; Marshak, 2004; van der Voo, 2004; Johnston and Gutiérrez-Alonso, 2010). Weil and Sussman (2004) proposed a kinematic classification for curved orogens: (1) when an orogen is initially curved and maintains that curvature without subsequent vertical-axis rotation it is known as a primary arc; (2) an orogenic belt that either acquires curvature during development or amplifies an initial curvature during formation, it is a progressive arc; and (3) when a bent orogenic belt is produced by buckling an originally more linear orogen it is an orocline or secondary arc. Recognizing the timing of the different deformation phases is necessary for classifying orogenic arcs as primary, progressive or secondary arcs. However, unravelling the kinematics and dynamics of a curved orogen is not a simple task. It requires a multidisciplinary effort combining different techniques such as structural geology, paleomagnetism, geochemistry, geochronology, etc. (e.g.

Weil and Sussman, 2004; Weil et al., 2001, 2010; Marshak, 2004; Gutiérrez-Alonso et al., 2004, 2011a, 2011b; Johnston and Mazzoli, 2009; Pastor-Galán et al., 2011).

A well known orocline or secondary arc is the Ibero-Armorican Arc (Weil et al., 2001; Gutiérrez-Alonso et al., 2004) which contains in its core the ca. 180° (isoclinally) buckled foreland fold-and-thrust belt of the Carboniferous Variscan orogenic belt, known as the Cantabrian Arc.

In this paper, we build on the structural analysis performed by previous workers (Julivert and Marcos, 1973; Bastida et al., 1984; Aller and Gallastegui, 1995) in the core of a curved orogenic belt, which was classified as a true orocline (Weil et al., 2001, 2010) with new data. We investigate conically folded surfaces resulting from the interference of sequential episodes of folding with horizontal and vertical rotation axis, respectively, in the uppermost crust of the West European Variscan Orogenic Belt. The conical folds are interpreted to support a secondary origin for the curvature of the Cantabrian Arc and exemplify orocline-related structures found in curved orogens of oroclinal buckling origin.

2. Geological setting

The Cantabrian Arc is located in the innermost central zone of the Ibero-Armorican Orocline (Fig. 1A), which is nestled within the Western European Variscan Belt (e.g. Martínez-Catalán et al., 2009 and references therein). This region was one of the first curved orogens described in the literature, and it was referred to as the "Asturian knee" (Suess, 1885). This orocline is recognized by the changes in structural trend of thrusts and fold axes that trace an isoclinal shape (Fig. 1B). During the last 50 years, the Cantabrian Arc has been studied intensively for the purpose of deciphering its kinematics, dynamics, mechanics and lithospheric implications (e.g. Julivert, 1971; Julivert and Marcos, 1973; Pérez-Estaún et al., 1988; Weil et al., 2000, 2001, 2010; Weil, 2006; Gutiérrez-Alonso et al., 2004; 2008, 2011a, 2011b; Pastor-Galán et al., 2011). Several hypotheses about the origin of the Cantabrian Arc curvature exist, including: (1) a primary arc inherited from an embayment (Lefort, 1979). (2) A progressive arc, either a resulting from the indentation of continental block (Brun and Burg, 1982; Ribeiro et al., 1995, 2007; Simancas et al., 2009), a non-cylindrical collision (Martínez-Catalán, 1990), or a thin-skinned origin with a progressive change in thrust transport direction (Pérez-Estaún et al., 1988); and (3) recently a secondary arc or orocline formed by the rotation around a vertical axis of an originally linear orogen (e.g., Weil et al., 2000, 2010; Martínez Catalán, 2011).

The orocline model for the Ibero-Armorican arc relies on a wealth of paleomagnetic (e.g. (Parés et al., 1994; Weil et al., 2000, 2001, 2010; Weil, 2006) and structural data (e.g. Julivert

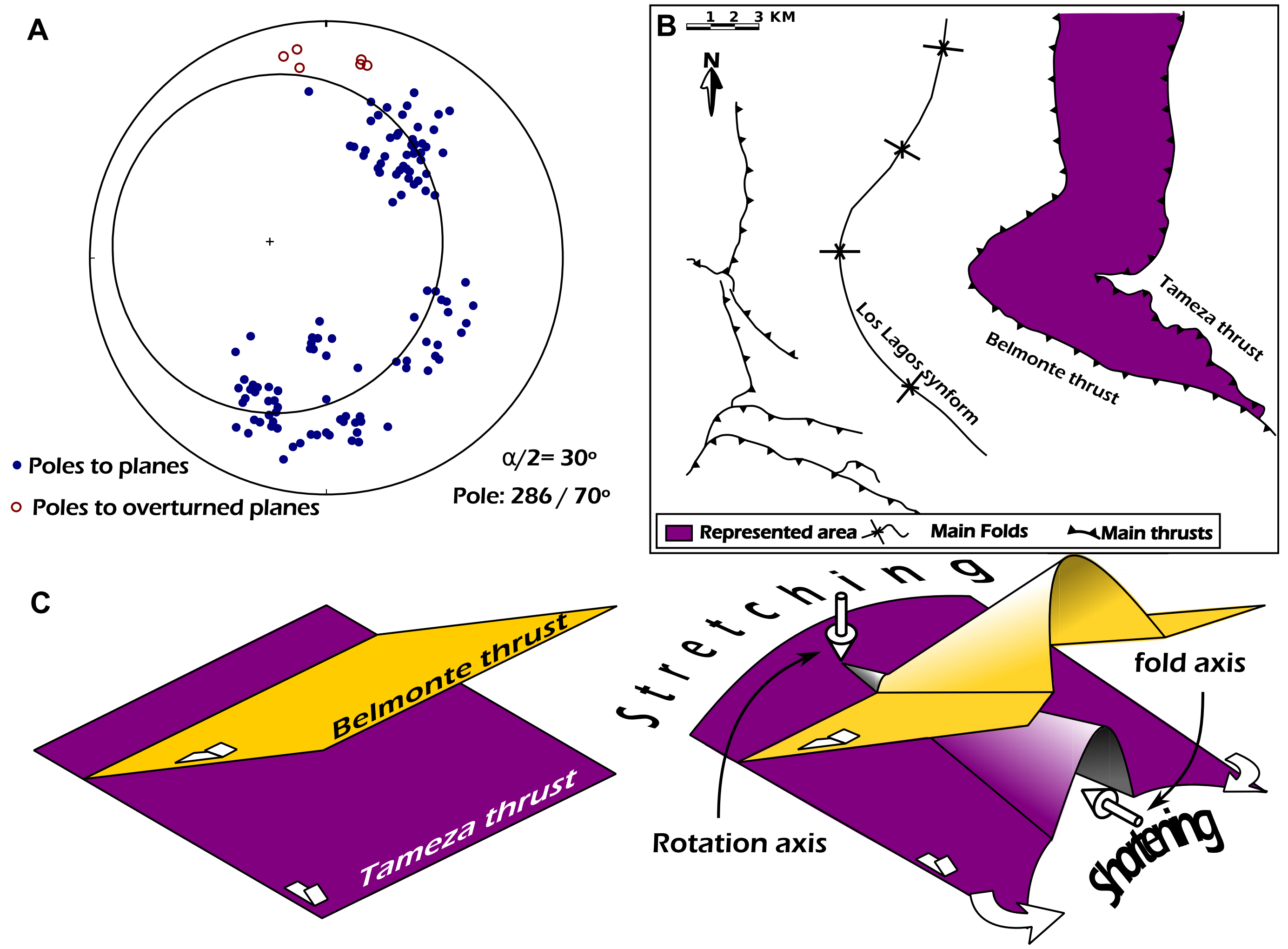


Fig. 2. A) Stereographic projection of the data from the Tameza thrust unit depicting a conical shape with a semi-apical angle of 30° and an axis trace orientation of 286/70. B) Location of Tameza Thrust unit in the Somiedo Unit. C) Interpretation of the formation of the two conically folded thrust surfaces in the Somiedo unit.

and Marcos, 1973; Aller and Gallastegui, 1995; Kollmeier et al., 2000; Pastor-Galán et al., 2011), and has early longitudinal thrust and folds generated due to an East-West compression (in present coordinates) subsequently folded by a North-South shortening (e.g. Julivert and Marcos, 1973; Álvarez-Marron and Pérez-Estaún, 1988) and probably slightly retightened during the Cenozoic N-S shortening that originated the Pyrenean-Cantabrian Mountain belt (Alonso et al., 1996; Pulgar et al., 1996). Based on geological (Merino-Tome et al., 2009; Pastor-Galán et al., 2011) and paleomagnetic constraints (Van der Voo et al., 1997; Weil et al., 2000, 2001; 2010; Weil, 2006), the N-S compression that buckled the Variscan chain into an orocline occurred during a period of ca. 10 Ma in the uppermost Carboniferous (from 310 to 300 Ma).

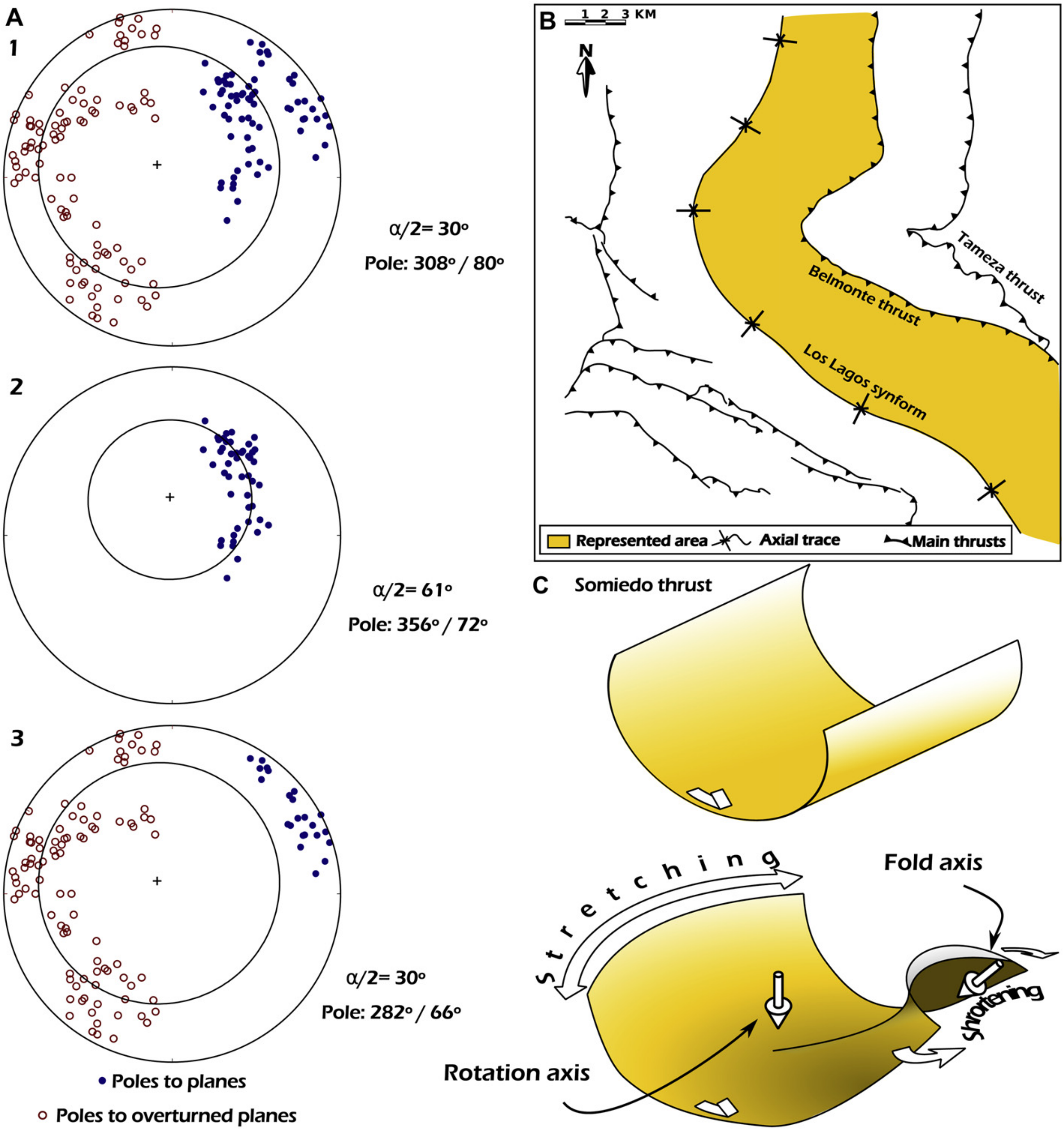


Fig. 3. A) Stereographic projection of the data from the eastern limb of the Los Lagos synform. 1) all data, with a semi-apical angle of 30° and an axis orientation of 308°/80° 2) Data from the limbs of the E-W-trending fold ($\alpha/2 = 61°$; axis = 356°/72°) and 3) data taken on the cone apex ($\alpha/2 = 30°$; axis = 282°/66°[a]). B) Location of the eastern limb of Los Lagos synform in the Somiedo unit, where the yellow area yielded the data in the stereographic projections. C) Interpretation of the formation of conical fold in a bedding surface already recording a cylindrical fold. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The Ibero-Armorican Arc was recently interpreted as a thick-skinned lithospheric-scale orocline that triggered lithospheric delamination and mantle replacement (Gutiérrez-Alonso et al., 2004, 2011a, 2011b; Ducea, 2011). Gutiérrez-Alonso et al. (2008) also proposed the self-subduction of the Pangaean global plate as mechanism possibly driving this oroclinal buckling. This interpretation is in contrast to that for other curved mountain belts that developed in foreland fold–thrust belt systems without a recognizable associated lithospheric response (Marshak, 2004). Recent studies (Aerden, 2004; Martínez-Catalán, 2011; Shaw et al., in press) in central and southern Iberia suggests that the Ibero-Armorican Orocline is one of a pair of oroclines, which define an “S” shape through Iberia continuing to the south into the Central Iberian Orocline.

The boundary between the hinterland and the foreland of the Western European Variscan belt in northern Iberia (Fig. 1A) is located at a curved outcrop, ca. 200 km long, of Neoproterozoic rocks known as the Narcea Antiform (NA), which is an asymmetric foreland-verging structure that contains major thrusts and associated km-scale shear zones (Gutiérrez-Alonso, 1996). This structure bounds the hinterland metamorphic realm known as the West Asturian Leonese Zone (WALZ) to the west, and the unmetamorphosed foreland of the Cantabrian Zone (CZ) to the east. Both zones are characterized by a Paleozoic sedimentary sequence interpreted as the northern Gondwana passive margin that unconformably overlies Ediacaran slates and greywackes with minor intrusive, volcanic and volcanoclastic intercalations from a past active margin (Fernández-Suárez et al., 1998).

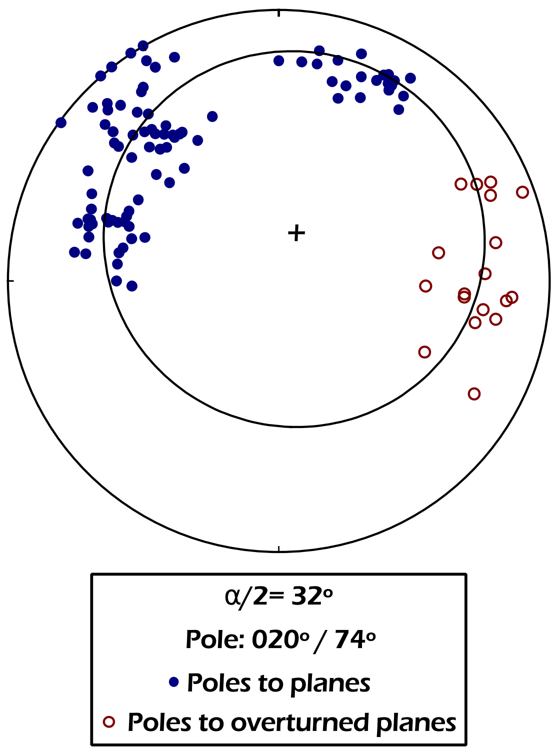
The WALZ is part of the hinterland of the orogen and has intermediate to intensely strained rocks and greenschist facies metamorphism (e.g. Martínez and Rolet, 1988). This zone consists of Cambro-Ordovician, mostly siliciclastic sediments, and scarce Silurian outcrops with the rest of the pre and syn-orogenic sequence is absent.

The CZ consists of a sedimentary sequence of pre-orogenic, lower Paleozoic platform sediments that thin towards the core of the arc. These pre-orogenic strata are covered by a Carboniferous syn-orogenic sequence and a post-orogenic (Stephanian) continental succession (Heward, 1978). Structurally, the CZ is characterized by thin-skinned tectonics with a transport direction towards the core of the arc (Pérez-Estaún et al., 1988). Alonso et al. (2009) divided the CZ into five units: the Somiedo Unit to the west and south of the CZ (Fig. 1B); the Bodón-Ponga Unit in the central and northeast; and the Esla, Valsurvio and Pisuerga-Carrión units in the southeast (Fig. 1B). The basal thrust for the whole imbricate system is imaged as a flat surface in a deep seismic survey parallel to the axial trace of the Cantabrian Arc (Pérez-Estún et al., 1994). Deformation in the CZ is characterized by small finite strain values (Gutiérrez-Alonso, 1996; Pastor-Galán et al., 2009) and the absence of metamorphism (García-López et al., 2007).

While the orocline is considered a major fold refold of both the WALZ and the CZ, two sets of smaller folds are distinguished within the CZ: (1) a longitudinal set parallel to the Variscan thrusts trend; and (2) and a set perpendicular to the thrust traces with a radial pattern in the Somiedo Unit (Fig. 1B), which is the focus of our analysis.

3. Treatment and description of conical fold data

Geometrically, a conical fold is characterized by the trend and plunge of its axis and by the angle between the generatrix of the conical surface and the fold axis, also known as semi-apical angle ($\alpha/2$) (Wilson, 1967; Pueyo et al., 2003). Perfect cylindrical folds, which are considered as a special case of a conical fold; have $\alpha/2$ equals 0°. Identification and analysis of conical folds in nature are conducted using stereographic projection of geologic surfaces, typically bedding (π-diagrams) which, when truly representative of a conical surface, scatter along a small circle on the stereonet. Given



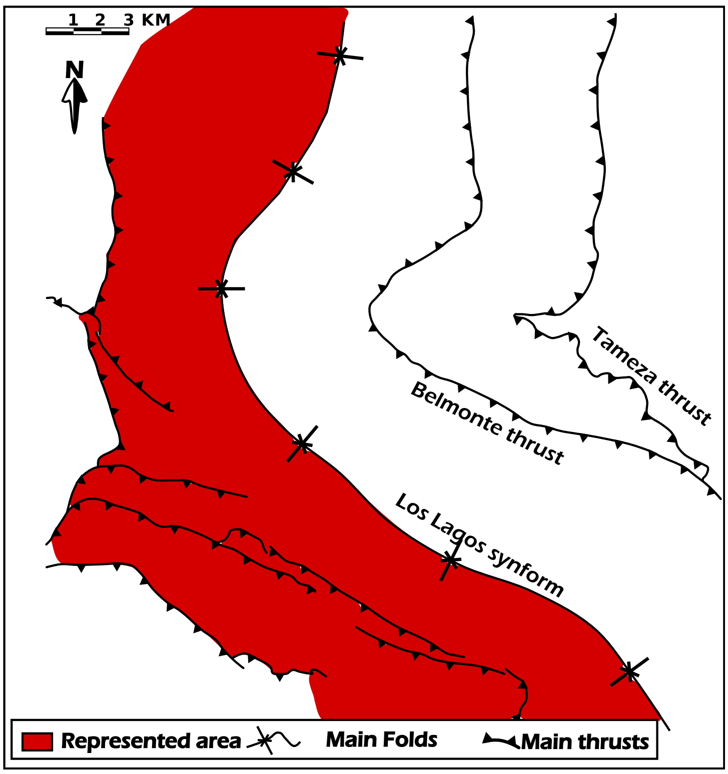


Fig. 4. Stereographic projection of the data from western limb of the Los Lagos synform and location of this limb in the Somiedo unit showing an $\alpha/2 = 32°$ and axis orientation of 020°/74°).

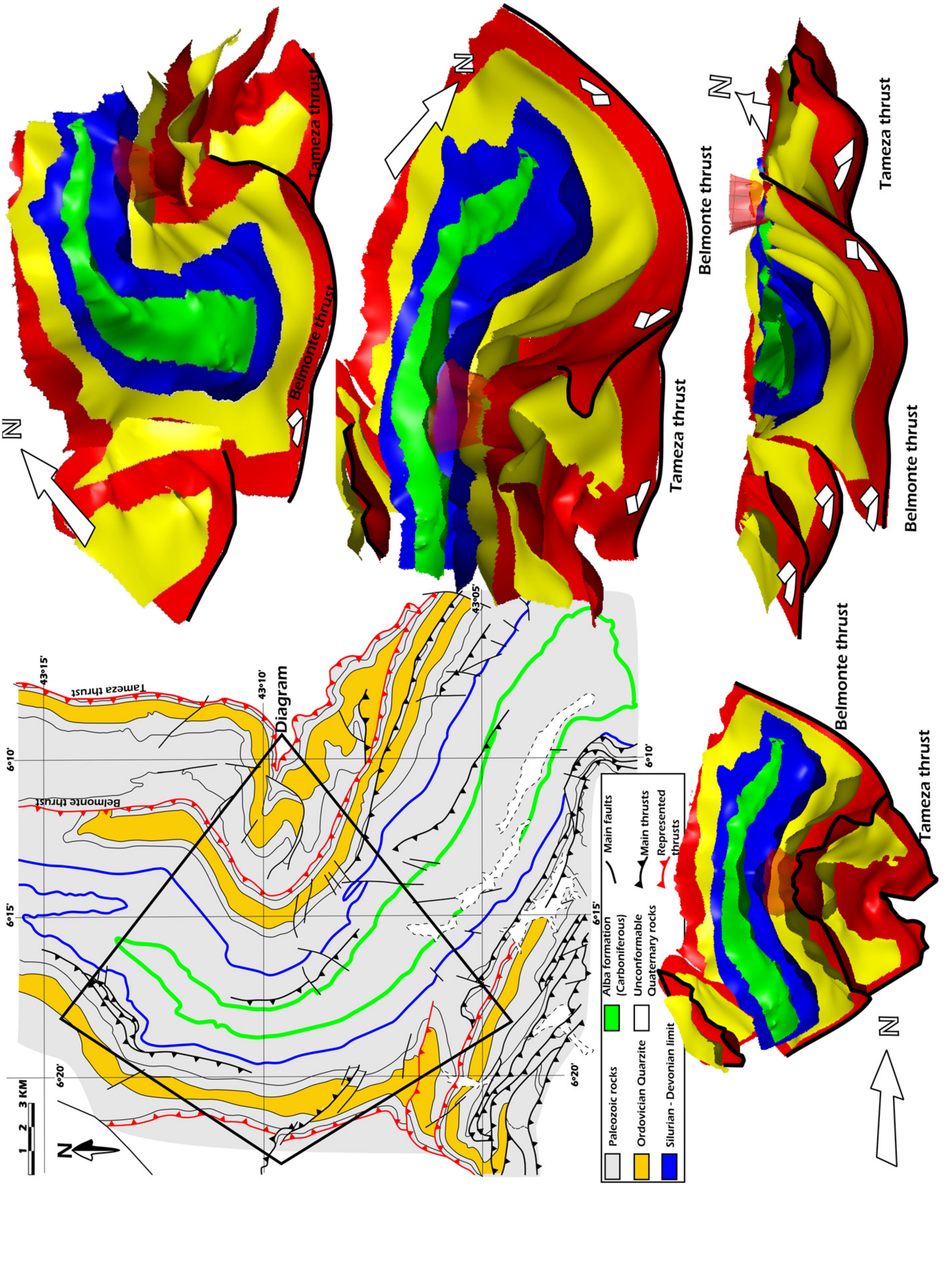


Fig. 5. Diagrams illustrating conical fold geometry for four different views with map showing position of the diagram. North area in diagrams and map for relative reference between them. For an interactive 3D view of the diagram see the data repository.

the nature of geologic orientation data, mathematical methods have been developed to fit measurements to a small circle and to quantify the suitability of the calculated fit (e.g. Ramsay, 1967; Fisher et al., 1987).

Approaches to fitting planar data to a cone typically involve least-squares minimisation of a function involving the direction cosines of poles to planes (Ramsay, 1967; Venkitasubramanyan, 1971; Cruden and Charlesworth, 1972) and provide estimates for the orientation of the cone axis and the semi-apical angle. Problems associated with these initial methods were resolved by minimising the squares of the actual angular deviations (Kelker and Langenberg, 1982; Fisher et al., 1987) making the minimisation problem non-linear and requiring iterative techniques to determine a solution. The problem may also be solved using the least eigenvector of the orientation matrix (Nidd and Ambrose 1971; Fisher et al., 1987, p. 33) though this approach only works for symmetrical data sets with a semi-apical angle less than 45°. Bingham's distribution on a sphere can be used to find the best-fit great circle to fold data forming a pair of, which is often the case for geological data (Kelker and Langenberg, 1976). Subsequently, using a transformation to spherical coordinates (Stockmal and Spang, 1982), a least-squares best fit was identified for the simulated data of Cruden and Charlesworth (1972). Methods able to cope with elliptical conical folds and statistical tests for distinguishing between circular and elliptical data have also been developed (Kelker and Langenberg, 1987, 1988). Mainstream statisticians have also shown an interest in this problem (Mardia and Gadsden, 1977; Rivest, 1999). Data presented in this paper have been fit using an implementation of the iterative algorithm presented by Fisher et al. (1987) p. 140–143 which is based on the method of Mardia and Gadsden (1977) and the improved least-squares algorithm of Gray et al. (1980). This method is robust to non-symmetrical data

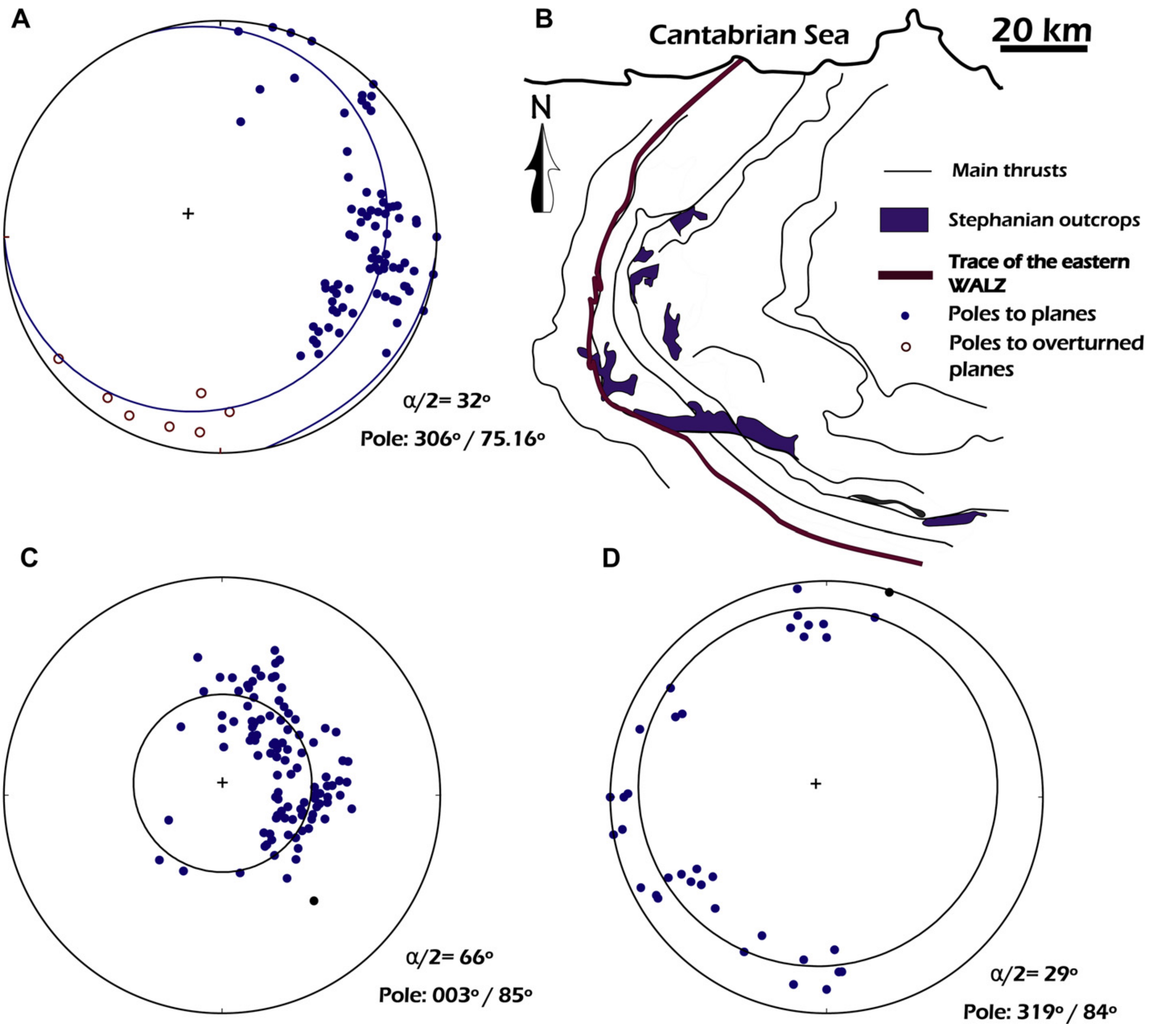


Fig. 6. A) Stereographic projection of data from the eastern West Asturian Leonese Zone showing a semi-apical angle of 32° and an axis orientation of 306°/75°. B) Location of the trace of the eastern WALZ and the Stephanian outcrops. C) Steregraphic projection of the less steep limb of the Stephanian synclines showing a conical morphology with a sub-vertical plunging axis and a larger semi-apical angle (66°). D) Stereographic projection of the steeper flank of the Stephanian synclines depicting a smaller semi-apical (29°) angle and a sub-vertical axis.

and has been proven to provide accurate solutions to different cases of real and simulated conical folds.

Data consisting of 578 strike and dip measurements were collected from bedding surfaces of Cambrian Limestones and Ordovician quartzites in the CZ and the eastern limit of the WALZ for the geometric analysis of the map-scale folds because these units contain very few smaller folds that would yield data that could obscure large-scale geometries. To compare the data with folds generated in rocks that were not deformed prior to the orocline formation, data were collected in the post-orogenic Stephanian outcrops (Corrales, 1971; Colmenero et al., 2008) around the boundary between the WALZ and the CZ. To obtain the best conical fit folds that have overturned limbs were projected in the lower hemisphere together with the data from the normal limbs.

In the CZ, data were collected in the Somiedo Unit (Fig. 1B), comprising two main thrust units, the Tameza thrust unit to the east and the Belmonte thrust unit to the west (Fig. 2). Within the latter unit, the data were subdivided into three subsets from areas with different initial orientations of the reference surfaces (bedding and thrust surfaces) and thereby resulting in different interference responses. The three areas are the Tameza thrust unit (Fig. 2) and the eastern and western parts of the Belmonte unit (Figs. 3 and 4 respectively; Fig. 5). The other two datasets are located in the easternmost part of the WALZ (Fig. 6A and B) and the unconformable Stephanian outcrops (Fig. 6B and C).

3.1. Conical folds in the Somiedo unit

The Somiedo unit contains two sets of thrusts: the first generation with a detachment level in the Cambrian limestone, roots to the west into the Neoproterozoic rocks of the NA, and large displacements of tens of km; and the second generation, out-of-sequence thrusts with much smaller displacements (Bastida et al., 1986; Heredia, 1984; Bastida and Gutiérrez-Alonso, 1989) and formed during second-stage thrusting in the Cantabrian Zone (Pérez-Estaún et al., 1991) or orocline formation (Alonso et al., 2009). The Tameza and Belmonte thrust units (Fig. 2B and Fig. 3B) were passively folded into a large synform named the Los Lagos synform, during development of the antiformal stack to the west, in the NA.

Two different fold sets are recognized in the Somiedo unit (Julivert and Marcos, 1973). The thrust-parallel set, or longitudinal set, contains the classical thin-skinned foreland fold-and-thrust structures (e.g. Dahlstrom, 1969). These folds are cylindrical and have horizontal or sub-horizontal axes, for example, the Viyazón-Reigada syncline (Fig. 7). The second radial set deformed all the previous structures, strongly modifying the geometry of the Somiedo unit and, in general, the entire foreland fold-and-thrust belt, producing an asymmetric structural pattern in both flanks of the unit. Six major radial folds with different amount of shortening are recognized in the Somiedo unit (Fig. 8; Julivert and Marcos, 1973; Weil et al., 2000). All these radial folds are localized in the eastern flank of the Somiedo unit, but only the two southern folds crosscut the axial trace of the longitudinal Los Lagos synform (Fig. 8). On the other hand, in the western flank of the Somiedo Unit, in the western limb of the Los Lagos synform, while the rocks are refolded by the host fold to the six radial folds, they do not deform the limb. (Figs. 4–6, Fig. 8).

The E-W-trending fold produces a sharper bend in the cartographic trace of the thrust surfaces even though the folds does not crosscut the axial plane of the Los Lagos synform (Figs. 2,3 and 8). In the Tameza thrust unit, the radial fold produces a conical shape with a semi-apical angle of 30° and axis plunging 70° towards the west (Fig. 2A). In the eastern flank of the Los Lagos synform, which base is the Belmonte thrust, is also conical (Fig. 3A-1) with a similar 30° semi-apical angle, but with an axis plunging 80° towards a more northwest direction (308°). In the latter case, the cone shape is more complex and the fit, is better understood when the data are divided into data collected far from the cone apex (Fig. 3A-2) and data collected near the cone apex (Fig. 3A-3). Data near the cone apex exhibits a slightly shallower plunging cone axis, 66° towards the west with a semi-apical angle of 30° (Fig. 3A-3), as compared to data measured away from the cone apex (Fig. 3A-2) with a cone axis plunging 71° towards the north and a very different semi-apical angle of 61°.

The presence of lateral ramps, for example the termination of the Tameza sheet under the Somiedo sheet (Fig. 8), complicates the ideal cylindrical geometry (Gutiérrez-Alonso, 1992), some of the conical folds have complex forms, including slightly overturned or sub-vertical flanks where shortening is large, due to fold amplification. Equivalent examples of amplified folds coincident with lateral ramps have been described immediately north of the studied region (Bastida and Castro, 1988) and also to the east in the Ponga region (Alvarez Marrón and Pérez Estaún, 1988; Weil, 2006).

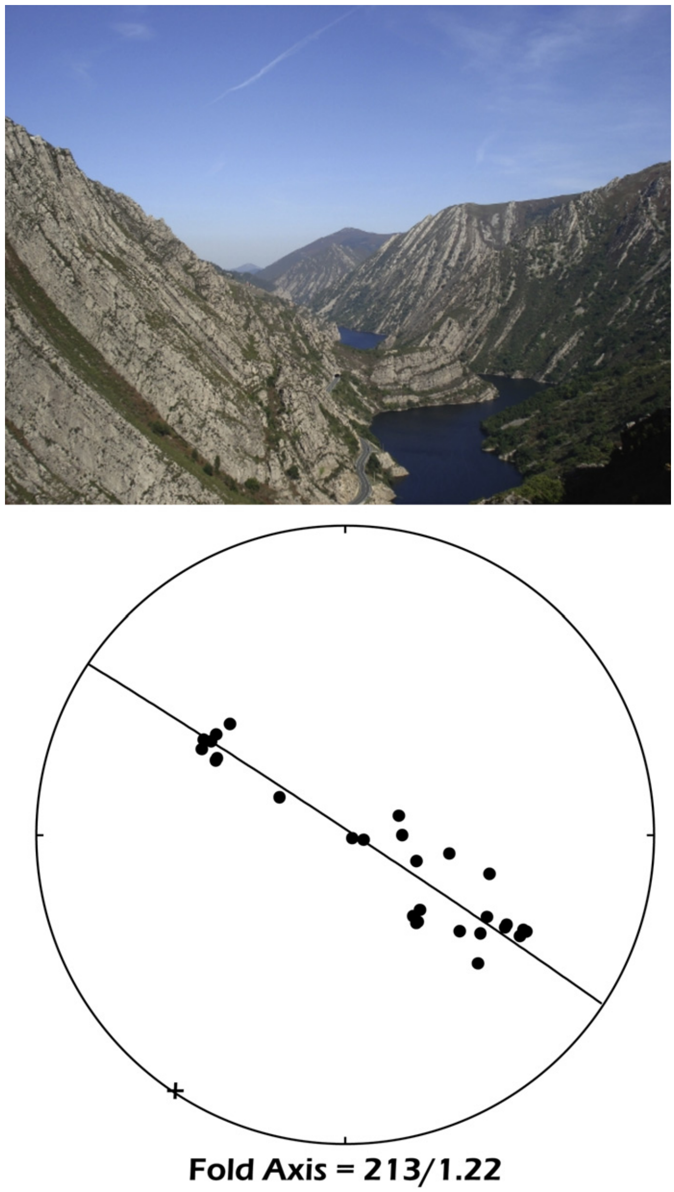


Fig. 7. Photograph of the Viyazón-Reigada synclyne, one of the longitudinal folds and the stereographic projection showing its cylindrical shape and sub-horizontal axis.

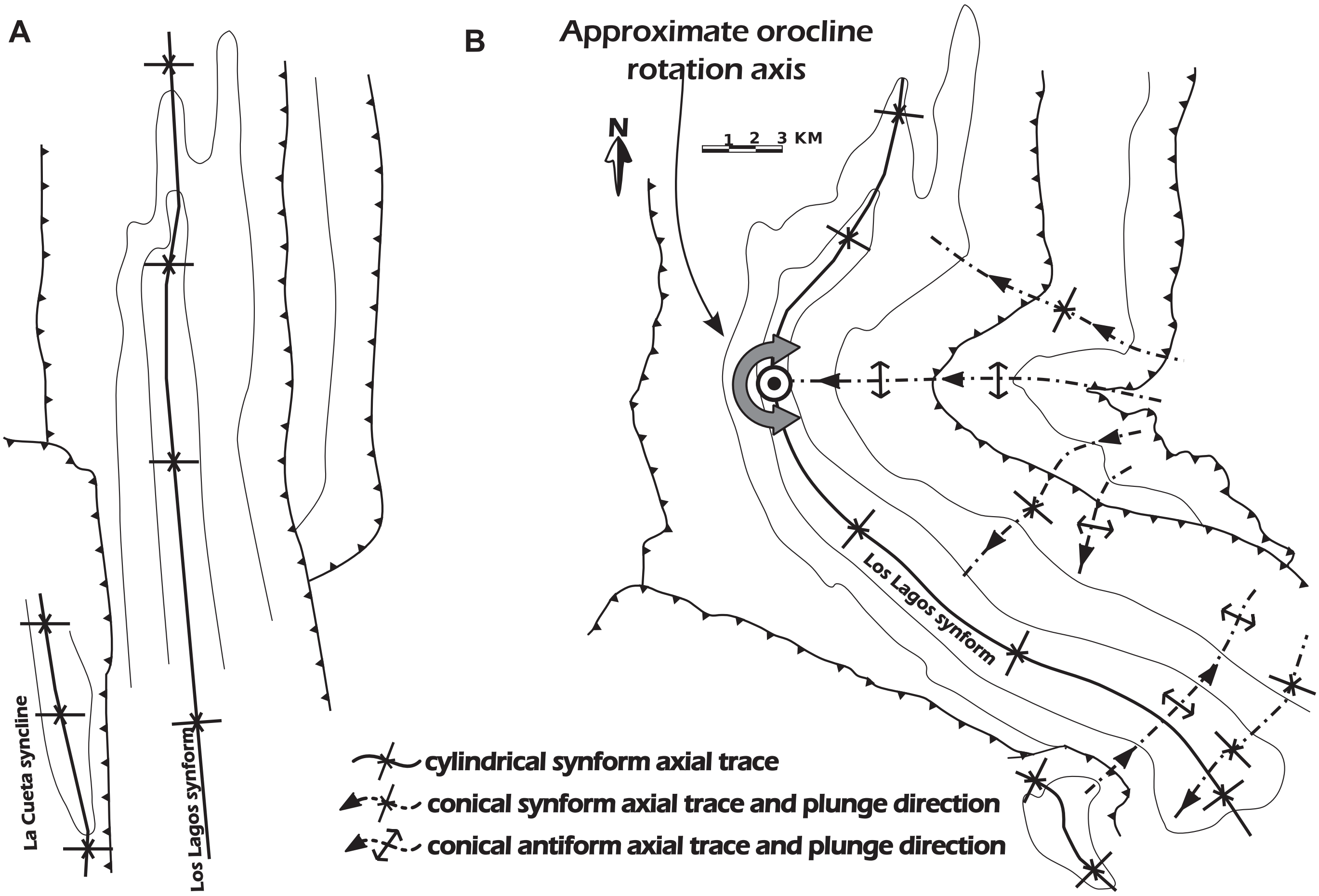


Fig. 8. A) Schematic map of the Somiedo unit structure prior to the orocline buckling. B) Schematic map of the present-day Somiedo unit showing the axial traces of the longitudinal and radial folds. Folds with an E-W axial trace have the greatest shortening, where most of the differential rotation took place within the studied thrust units. More open folds are present where much less differential rotation is in evidence.

In the western flank of the Somiedo Unit, which corresponds with the western limb of the Los Lagos synform, the radial fold set is represented by a single fold that has much a larger wavelength and can be traced through the whole Cantabrian Arc close to its axial trace. The shape of this fold is also conical with a semi-apical angle close to the values obtained in the eastern flank (31°) and similar axial plunge (75°) but in this case, towards the northeast (Fig. 4). We interpret that this difference is principally due to the position of this flank in the outer zone with respect to the rotation axis of the Cantabrian Arc (Fig. 3C and Fig. 4) and also to an initially different bedding attitude, dipping towards the east.

The interference between the longitudinal and radial folds in the Somiedo unit define a type 2 interference pattern of Ramsay (1967), or the third and fourth mode according to Ghosh et al. (1992, 1993; Simón, 2004). Given that the axes of the radial set are sub-vertical, the interference patterns draw "worms" instead of "mushrooms" (Julivert and Marcos, 1973).

The overall refold geometry of the Somiedo unit is shown in Fig. 5 and the 3D interactive model PDF file in the data repository. This diagram was constructed from serial crossed sections based on the data collected in this study and previous work (Bastida et al, 1984; Bastida and Gutiérrez-Alonso, 1989; Gutiérrez-Alonso, 1992) using the PETREL software.

We interpret these folds to be the result of a vertical axis rotation during the orocline buckling process that formed the Cantabrian Arc. Hence, the sub-horizontal non-outcropping basal detachment of the Somiedo Thrust and all the west-dipping-related imbricated thrust sheets folded conically with different axes and semi-apical angles (Fig. 2C and Fig. 3C).

3.2. Geometry of eastern WALZ

West of the NA, in the WALZ, the lower Paleozoic sedimentary rocks can be traced almost continuously depicting the curvature of the Cantabrian Arc for more than 200 km (Fig. 6B). We have analysed the bedding attitude around the bend and the results show great similarity with those obtained for the western flank of the Somiedo unit. As can be observed in the stereonet of Fig. 6A, the data fit a conical geometry with a semi-apical angle of 32° and an axis plunging 75° towards the northwest due to its initial orientation. We interpret that the origin of this conical fold is identical to that of the western flank of the Somiedo unit except that its oppositely dipping initial orientation resulted in the different plunge for the conical fold axis.

3.3. Geometry of the Stephanian basins

To compare the fold geometry in the pre-orocline rocks to the fold geometry to rocks deposited during oriclinal formation, the Stephanian continental deposits were also investigated. The synforms have eastern-shallow-dipping limbs towards the core of the arc, and a western, steep to overturned, limbs away from the core.

Both flanks of the Stephanian outcrops where plotted separately and describe two different conical folds with sub-vertical

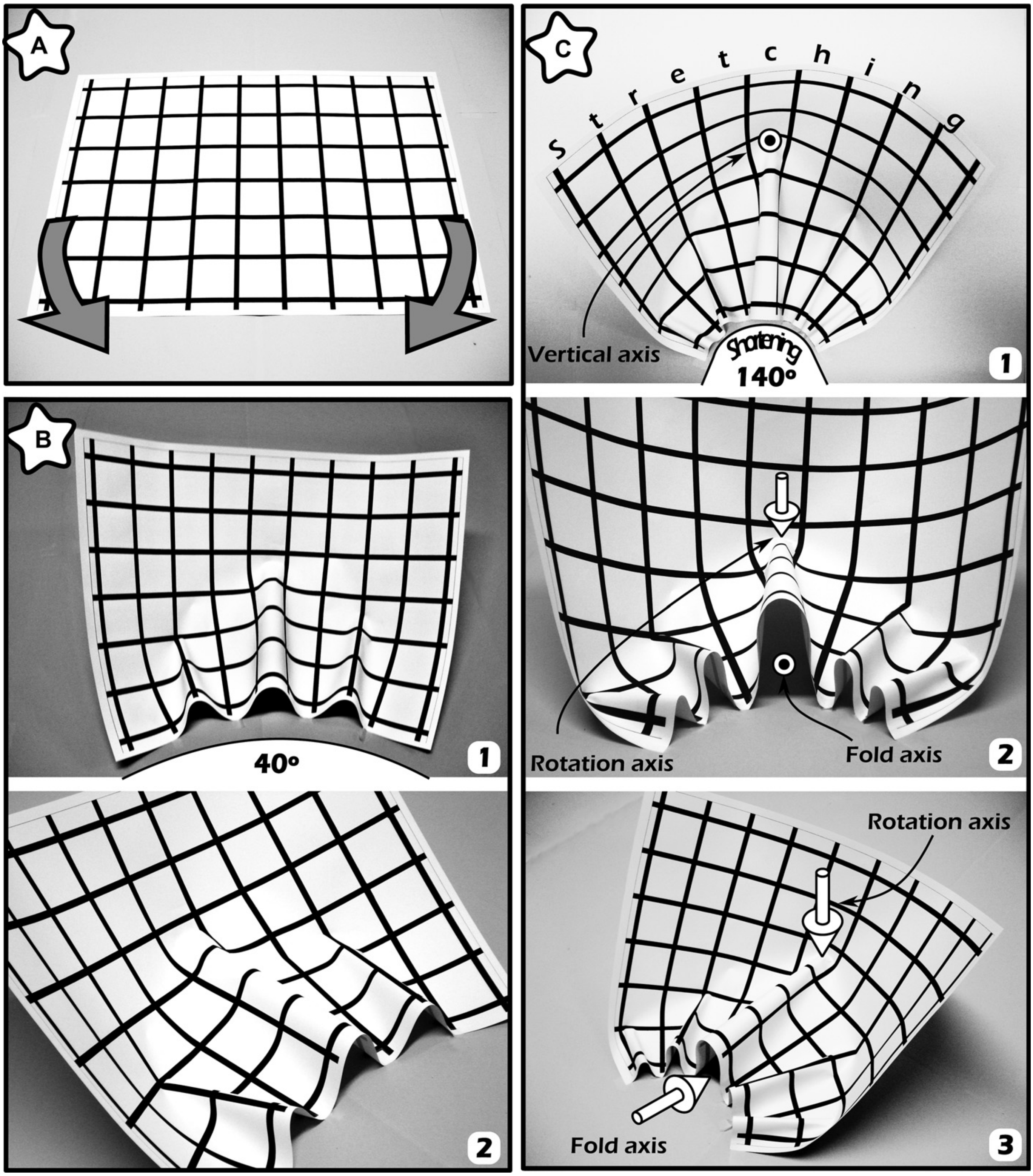


Fig. 9. Cartoon showing deformed a paper depicting the formation of conical folds when a horizontal surface is folded with a vertical axis. A) Original shape. B) Shape when the fold interlimb angle is about 40°, creating three horizontal conical folds in the shortened region whereas the stretching zone is uplifted due to the rheological characteristics of the paper. C) Shape of the paper when the angle is about 140°, producing five conical folds in the shortened region. The stretching region has greater uplift.

axes, ca. 85° (Fig. 6C). The eastern flank describes a large semi-apical angle (66°) (Fig. 6C-1), whereas the western flank shows a cone (Fig. 6C-2) with an apical angle very similar to the outer section of the Somiedo unit (i.e. 30°, Fig. 4) and the eastern WALZ (Alonso, 1989).

4. Discussion and interpretation

The fold interference patterns of the Cantabrian Arc help to understand the mechanisms of folding in the uppermost crust during an orocline buckling process. Conical folds deform rocks

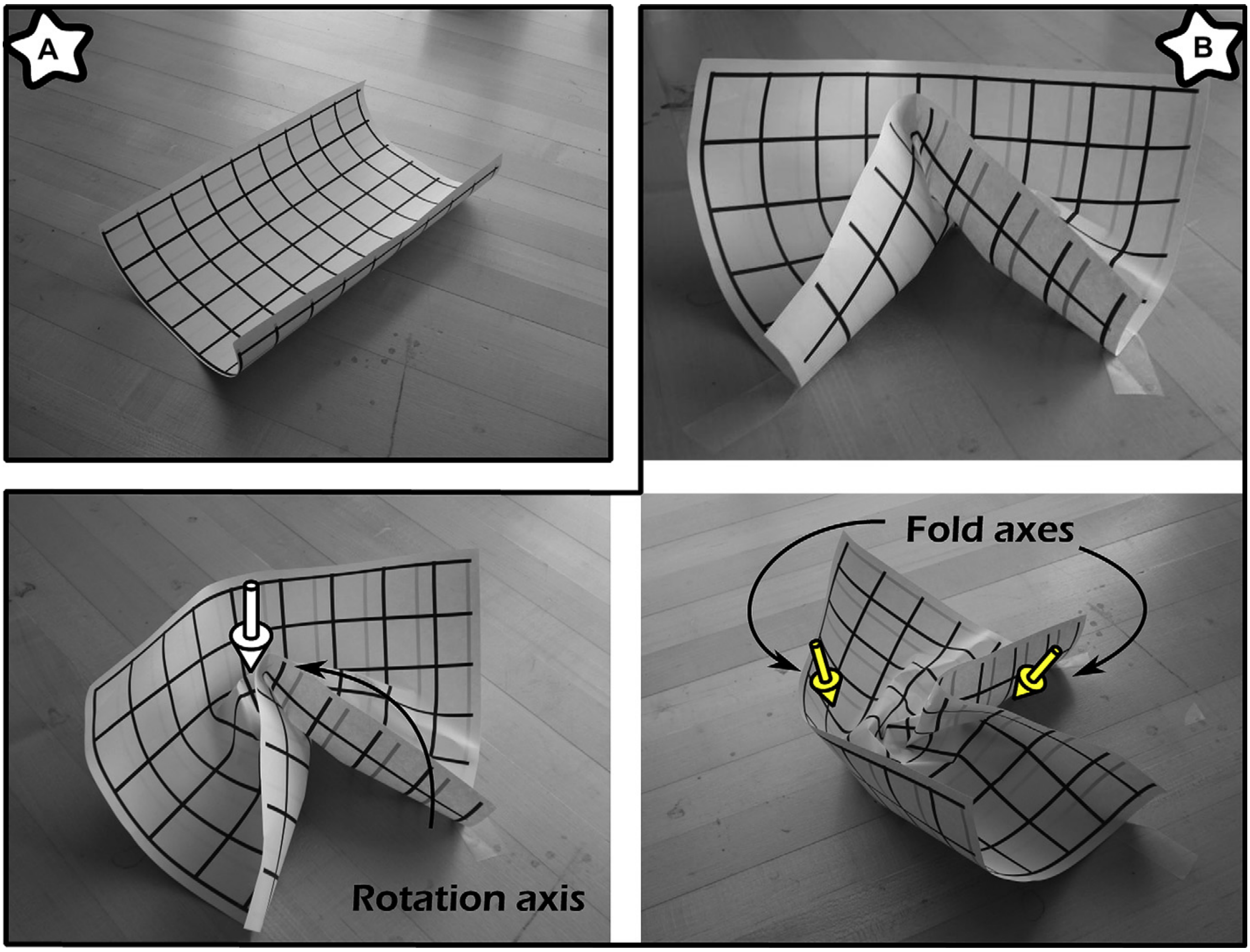


Fig. 10. Cartoon made with a cylindrically pre-folded piece of paper showing conical folds developed when the older structure is folded with a vertical axis. A) Inner arc original syncline shape. B) Final shape showing the formation of a complicated multi-axes conical fold in the shortened region and a large wavelength conical fold in the stretching region.

such that lines initially parallel to the future cone axis, will no longer be parallel to the cone axis as the fold develops. Consider a situation where a layer is deforming under the action of a rotation about some axis, then a conical fold develops when the rotation axis is not parallel to the layer. The semi-apical angle for the fold increases as the angle between rotation axis and the pole to the layer decreases and reaching a maximum value when the rotation axis and pole are parallel (Figs. 9 and 10). On the other hand, if the rotation axis is normal to the pole to the layer, then a cylindrical fold develops.

When a horizontal or sub-horizontal layer is folded by a rotation axis at low angles to its pole together with tangential longitudinal strain mechanism (Ries and Shackleton, 1976), two different structural regimes appear. Those portions of the reference surface located in the inner arc of the fold become shortened and develop radial conical folds with sub-horizontal axes plunging towards the rotation axis. In contrast, the portions of the reference surface in the outer arc undergo stretching, which when an initial slope is present yields a large wavelength fold with a conical geometry (Ramsay, 1967 pp. 490–517). The difference in behaviour of the outer arc as a function of the absence or presence of a dipping surface is illustrated by comparing Fig. 9 without the dip and Fig. 10 with the dip and the large wavelength fold.

In the Cantabrian Arc, the initial geometry is complicated by the existing Variscan fold and thrust belts that created a variety of surface geometries for inclusion in the subsequent conical folding. In the eastern portion of the Somiedo Unit, located in the inner arc, conical folds developed with axes plunging towards the rotation axis. In contrast, the western portion developed a large wavelength, vertical-axis cone (Figs. 5,8,10 and 11). Some conical folds may have nucleated at previous thrust-related lateral ramps (Bastida and Castro, 1988; Gutiérrez-Alonso, 1992), which provided a favourable location for the radial-fold development as is interpreted for easternmost thrust units within the Cantabrian Zone (Álvarez-Marrón and Pérez-Estaún, 1998; Weil, 2006).

The Cantabrian Arc is interpreted to have been produced by a vertical or near vertical-axis rotation of the Western Europe Variscan belt (Weil et al., 2000, 2001; 2010) and longitudinal tangential strain has been proposed as the main mechanism of deformation (Gutiérrez-Alonso et al., 2004, 2008; Pastor-Galán et al., in press), implying that every geologic surface with the exception of the initially vertical surfaces would be conically folded in both inner arc and outer arc.

Fig. 11 and video 1 depict a simplified reconstruction of the geometry of the Cantabrian Arc in the Somiedo Unit. Fig. 11A shows the geometry of the basal thrust of the Somiedo Unit in the

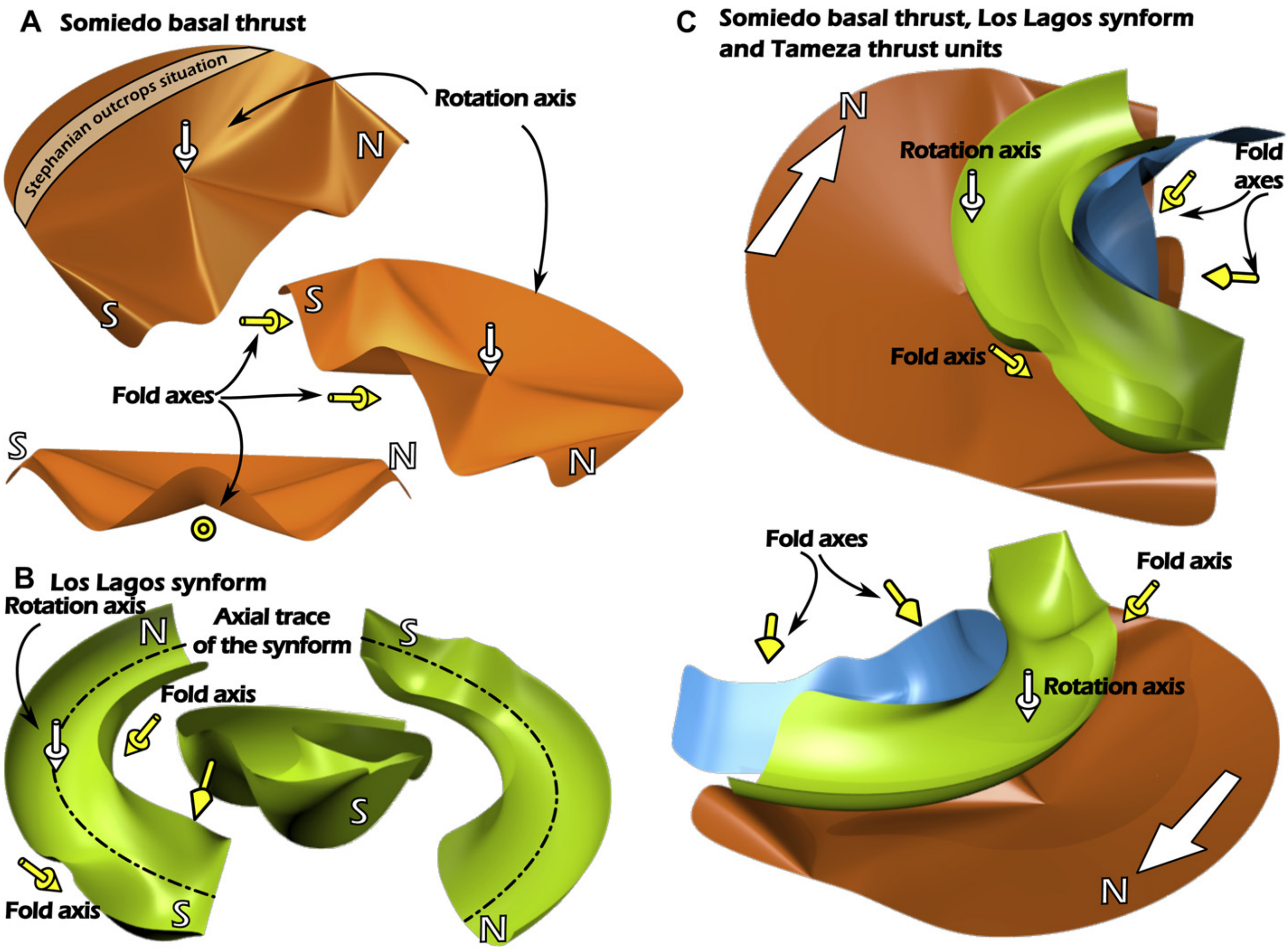


Fig. 11. Simplified reconstruction of the geometry of the Somiedo Unit. A) Idealized shape of the Somiedo basal thrust with the hypothetical situation for the Stephanian outcrops. B) Three different perspectives of an idealized and simplified shape of the Los Lagos synform unit displaying the different conical folds formed and the position of the rotation axis. C) Schematic and simplified diagram of the Somiedo unit showing the basal thrust, the Los Lagos synform, and the Tameza thrust units displaying several cone axes and the interpreted rotation axis.

Cantabrian zone, which can be compared with any other surface that was approximately horizontal prior to the orocline development, such as the Stephanian outcrops. The geometry is similar to that obtained folding a horizontal surface around a vertical rotation axis (Fig. 9). Fig. 11B shows the morphology of Los Lagos Synform including the southernmost section reinterpreted from Julivert and Marcos (1973), which is similar to folding a cylindrical fold about a vertical rotation axis (Fig. 10). Fig. 11C shows the overall structure including the easternmost Tameza thrust.

Supplementary video related to this article can be found at doi:10.1016/j.jsg.2012.02.010.

The distribution of radial conical folds, which only occur to the east of the Los Lagos syncline axial trace, as compared to the unique large-wavelength change in bedding strike west of this axial trace (Figs. 2 and 8) indicate that the local rotation axis for the Cantabrian Arc is likely located near the Los Lagos axial trace as in the paper models of Figs. 9 and 10. The axial trace of Los Lagos syncline acted as the local finite neutral line (Frehner, 2011) in the study area and localizes the change from, outer-arc extension to inner-arc shortening, observed in both limbs of the primary syncline. The deformation distribution is in agreement with a tangential longitudinal strain mechanisms for the development of the studied sector of the Cantabrian Arc (Gutiérrez-Alonso et al., 2004). In addition, the radial fold set becomes less evident towards the flanks of the Cantabrian Arc, which are only well preserved at is hinge. Nevertheless, in the hinge to the east of the studied region, the orocline related folds exhibit a less conical geometry (Julivert and Marcos, 1973; Aller and Gallastegui, 1995) and display a constant E-W trend instead of a radial divergent disposition due to the larger shortening in the inner arc of the Cantabrian Arc. These data also support the idea of a local upper-crust orocline axis situated in the neighbourhood of the Los Lagos axial plane (Fig. 8).

5. Conclusions

The detailed study of conical folds in curved mountain belts resulting from the interference of superposed orthogonal shortening events is a powerful tool for establishing the sequence of tectonic events that give rise to oroclines. Conical folds develop with different semi-apical angles and axis attitudes depending on the initial orientations of the geological surfaces and their position with respect to the vertical rotation axis responsible for the orocline formation.

Considering the Cantabrian Arc, the geometry of the conical folds in the Somiedo unit and the innermost section of the WALZ indicate that the local vertical rotation axis should be placed somewhere near the axial trace of the syncline described by the Belmonte thrust (Los Lagos synform). All the rocks within the Somiedo unit located to the east of this axial trace are situated in the shortening domain of the orocline, which is a wide strip tracing the arc. The axial trace of this syncline acted as the neutral line, where rocks are neither shortened nor stretched. Finally, all rocks to the west of this neutral fibre are located in the stretching zone. The conical folds studied in the Cantabrian Arc indicate the general usefulness of conical folds in recognising and interpreting orocline development in other curved mountain belts.

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Appendix. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jsg.2012.02.010.

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