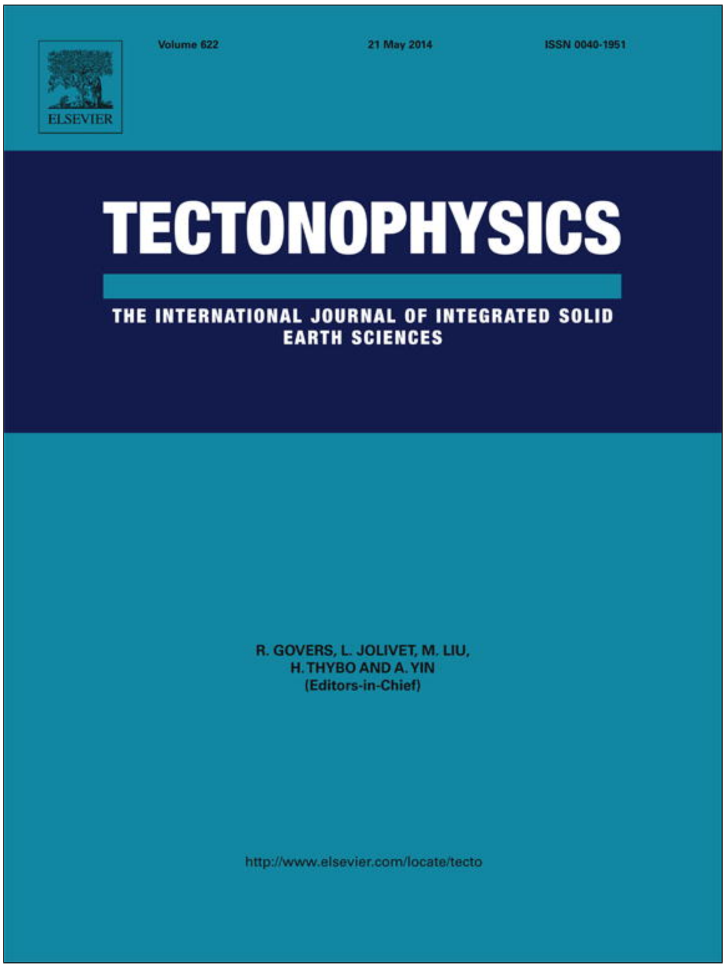
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Timing and structural evolution in the limb of an orocline: The Pisuerga–Carrión Unit (southern limb of the Cantabrian Orocline, NW Spain)

Daniel Pastor-Galán [a,b,*], Germán Martín-Merino [b], Diego Corrochano [b]

[a] *Department of Earth Sciences, Paleomagnetic Laboratory "Fort Hoofddijk", Utrecht University, Budapestlaan 17, 3584 CD Utrecht, The Netherlands*
[b] *Department of Geology, University of Salamanca, Pza. De los Caídos s/n, 37008 Salamanca, Spain*

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ABSTRACT

Oroclines are the largest scale folds on Earth, and the process of oroclinal formation is a key topic in tectonics. However, most studies of oroclines have focused on the hinge areas, where the changes in strike, and therefore the orocline shape, are most obvious. In this paper, we investigate the deformation mechanisms, the timing, and the structural and tectonic evolution of the Pisuerga–Carrión Unit, situated on the southern limb of the Cantabrian orocline at the NW of the Iberian Peninsula. The Cantabrian Orocline located in the Variscan Belt of Western Europe has been recently defined as a secondary orocline, constraining kinematics and deformation timing. Our study in the Pisuerga–Carrión Unit reveals that an out-of-sequence thrust system developed and reactivated existing structures by a flexural-slip mechanism that was diachronous with respect to oroclinal formation. Joint analysis of unconformity-bounded rock sequences provide a late Moscovian age for oroclinal initiation (ca. 308 Ma), at least locally. Additionally, comparing those joint sets found in different series we quantify a minimum of 40° counterclockwise vertical axis rotation for the Pisuerga–Carrión Unit during the Late Pennsylvanian.

1. Introduction

Oroclines are the largest scale folds on Earth, as they represent buckling or bending at the lithospheric scale (Johnston et al., 2013). Whereas some orogens are roughly linear in map view, others have up to 180° of curvature in a simple orocline or a complex system of oroclines. Examples of single oroclines are the Calabrian Arc (e.g. Maffione et al., 2013) or the Kazakhstan Orocline (e.g. Abrajevitch et al., 2008; van der Voo, 2004). The architecture of other mountain belts shows two oroclines in a "Z" or "S" shape as the Alaskan oroclines (e.g. Johnston, 2001), the Carpathian–Balkan bends (e.g. Dupont-Nivet et al., 2005; Shaw and Johnston, 2012) or the Bolivian–Peruvian oroclines (e.g. Johnston et al., 2013; Maffione et al., 2009). Some orogens show several linked oroclines, for instance the New England orogen of eastern Australia has four linked tight bends (e.g. Cawood et al., 2011; Li et al., 2012; Rosenbaum et al., 2012).

Most studies of oroclines focus on the kinematics of formation to determine if the curvature was acquired before, during or after the development of the orogen, paying particular attention to their hinges, where the changes in strike are most evident (e.g. Cifelli et al., 2008; Marshak, 1988, 2004; Weil and Sussman, 2004; Yonkee and Weil, 2010). Quantifying the kinematics of oroclinal formation helps us to understand the mechanical processes that drive orogeny and ultimately the crustal growth. Kinematically, oroclines can be subdivided into three categories with two end members (Weil and Sussman, 2004): (1) primary oroclines, those whose curvature was inherited from previous orographic features (e.g. the Jura Mountains, Hindle et al., 2000) and (2) secondary or "true" oroclines, which were quasi-linear orogens that were subsequently bent (e.g. the Bolivian Orocline, Allmendinger et al., 2005). A third category, progressive oroclines have aspects of both end members and are curved orogens that acquired their curvature during the orogenesis (e.g. the Sevier thrust-belt, Yonkee and Weil, 2010).

Few studies have aimed at understanding deformation in the limbs of secondary oroclines (e.g. Weil et al., 2013a). In this paper, we examine the kinematics and development of uppercrust syn-oroclinal structures in the limbs of a secondary orocline. For this purpose, we studied the Pisuerga–Carrión Unit in the southern limb of Cantabrian Orocline, one of the best constrained secondary oroclines (e.g. Kollmeier et al., 2000; Weil et al., 2001: Pastor-Galán et al., 2011, 2012a; Weil et al., 2013b), situated in the NW Iberian peninsula (Fig. 1).

Paleomagnetism is a commonly used tool to quantify vertical axis rotations (e.g. Van der Voo and Channel, 1980; Schwartz and Van der Voo, 1984; Weil and Sussman, 2004). However, this technique depends on the existence of suitable rocks to perform the paleomagnetic analyses. The presence of widespread small igneous bodies and regional alteration (Fig. 5B) related to the Late Carboniferous lithospheric foundering process (Gasparrini et al., 2006; Gutiérrez-Alonso et al., 2004, 2011a, 2011b; Pastor-Galán et al., 2012b, 2012c) and the lack of in situ rocks due to gravitational collapse and synsedimentary soft deformation (slumping and olistolithic movements), make the Pisuerga–Carrión Unit not appropriate for paleomagnetic analysis (Arlo Weil,

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[*] Corresponding author at: Department of Earth Sciences, Paleomagnetic Laboratory "Fort Hoofddijk", Utrecht University, Budapestlaan 17, 3584 CD Utrecht, The Netherlands.

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personal communication). Among the structures developed under low-grade metamorphic conditions and low strain regimes in the upper crust, joint sets provide a sensitive record of the syn-kinematic stress field at the time of deformation (Whitaker and Engelder, 2005). This is especially true when the studied region has angular unconformities that constrain the age of different tectonic pulses (Pastor-Galán et al., 2011). For this reason, systematic joint sets are useful for studying the kinematics and structural evolution of curved orogens, as used, for example, in the Ouachita salient (Whitaker and Engelder, 2005), the Appalachian plateau (Engelder and Geiser, 1980), or the Idaho–Wyoming (Yonkee and Weil, 2010). When multiple joint sets are present, caution is needed in using the spatial pattern of joints across a region to interpret tectonic history (e.g. Engelder and Geiser, 1980). In this paper we study the structure and kinematics of the Pisuerga–Carrión Unit, catalog systematic joint sets, characterize the tectonic history, determine the mechanisms of deformation, and constrain the degree of vertical axis rotation of the area.

2. Geological background

2.1. Regional geology

The Variscan belt resulted from the collision among Gondwana, Laurussia and several microplates during the Devonian–Carboniferous closure of the Rheic Ocean (e.g. Martínez-Catalán et al., 1997; Matte, 2001; Von Raumer et al., 2009). Continental collision in Iberia began at ca. 365 Ma (e.g. Dallmeyer et al., 1997) with the eventual extensional collapse of the thickened hinterland between 340 and 320 Ma (Arenas and Catalan, 2003; Martínez-Catalán et al., 2009; Pereira et al., 2012). The latter event was coeval with the development of the non-metamorphic foreland fold-thrust belt of Gondwana (e.g. Pérez-Estaún et al., 1994), which is only preserved today in the Cantabrian Zone of NW Iberia. The remnants of this mountain belt are today found in southern and central Europe, tracing out a sinuous "S" shape through Iberia (Fig. 1A; Aerden, 2004; Martínez-Catalán, 2011, 2012; Shaw et al., 2012). Traditionally the main arcuate

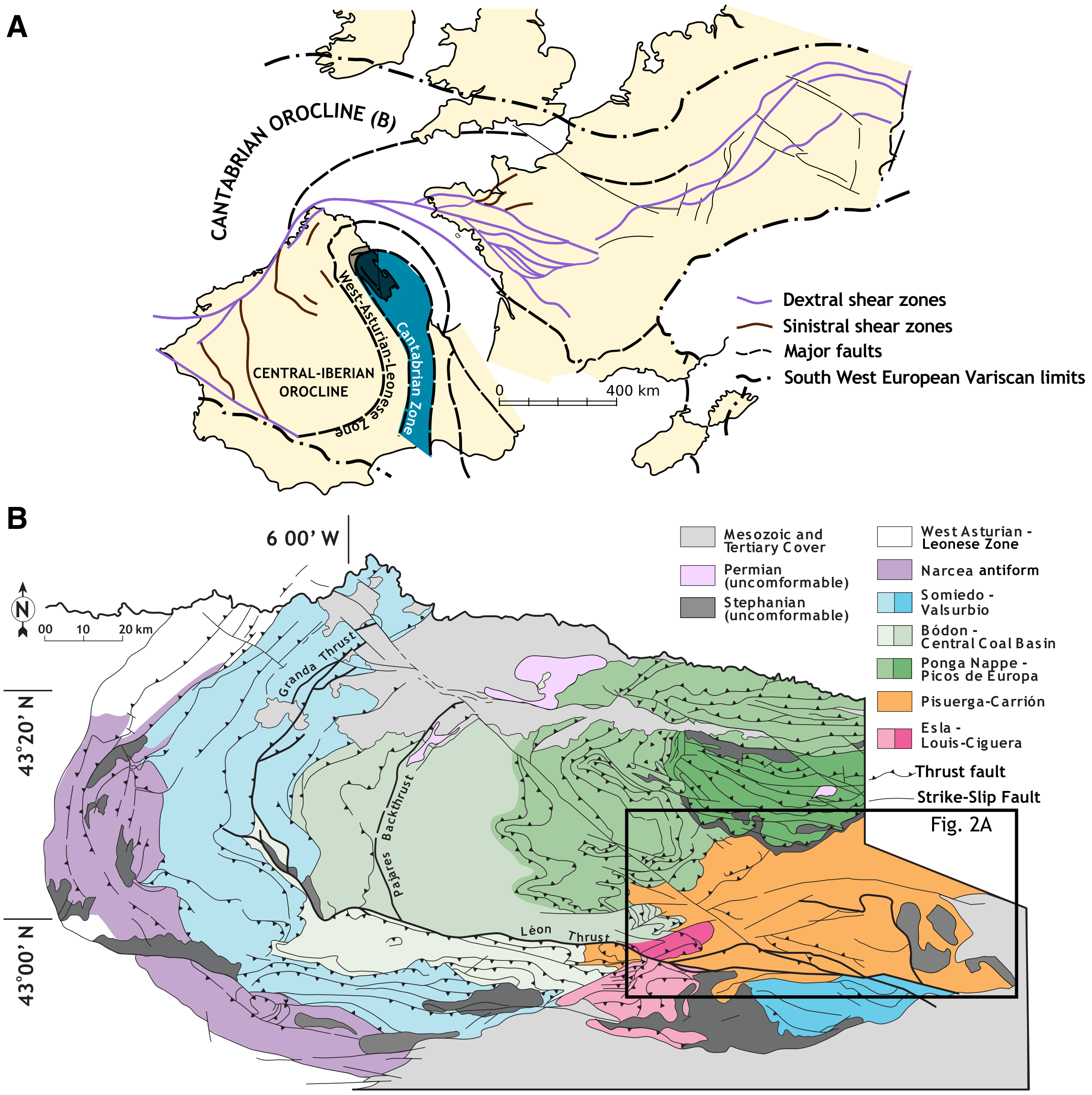

Fig. 1. A) Situation of the Cantabrian Orocline into the Variscan Belt of Western Europe. Note that the Iberian Peninsula is rotated to fit to a pre-opening of Biscay Bay situation; The Cantabrian Zone is marked in blue. B) Map of the Cantabrian Zone after Alonso et al. (2009) showing the different units and sub-units and the studied area.

structure is referred to as the Ibero–Armorican Arc (e.g. Bard et al., 1968), which more recently has been subdivided into the Cantabrian Orocline in the north and the Central Iberian Orocline in the South (Fig. 1A; e.g. Weil et al., 2013b).

Many authors have studied the Cantabrian Orocline over the past few decades, resulting in a variety of hypotheses for the orocline origin (see detailed review by Weil et al., 2013b). Some of the most important are: (1) a primary arc inherited from some physiographic feature (Lefort, 1979); (2) a progressive orocline, resulting from the indentation of a continental block (Brun and Burg, 1982; Ribeiro et al., 1995, 2007 and Simancas et al., 2009, 2013) or from non-cylindrical collisions (Martínez-Catalán, 1990; Pérez-Estaún et al., 1988); and (3) a secondary orocline formed by the rotation around a vertical axis of an originally quasi-linear orogen (e.g., Gutiérrez-Alonso et al., 2012; Martínez-Catalán, 2011; Weil et al., 2000; Weil et al., 2010; Weil et al., 2013b).

The secondary origin for the Cantabrian Orocline relies on a wealth of paleomagnetic (e.g. Pares et al., 1994; Weil, 2006; and Weil et al., 2000, 2001, 2010) and structural data (e.g. Julivert and Marcos, 1973; Aller and Gallastegui, 1995; Kollmeier et al., 2000 and Pastor-Galán et al., 2011, 2012a). These studies document two different phases of

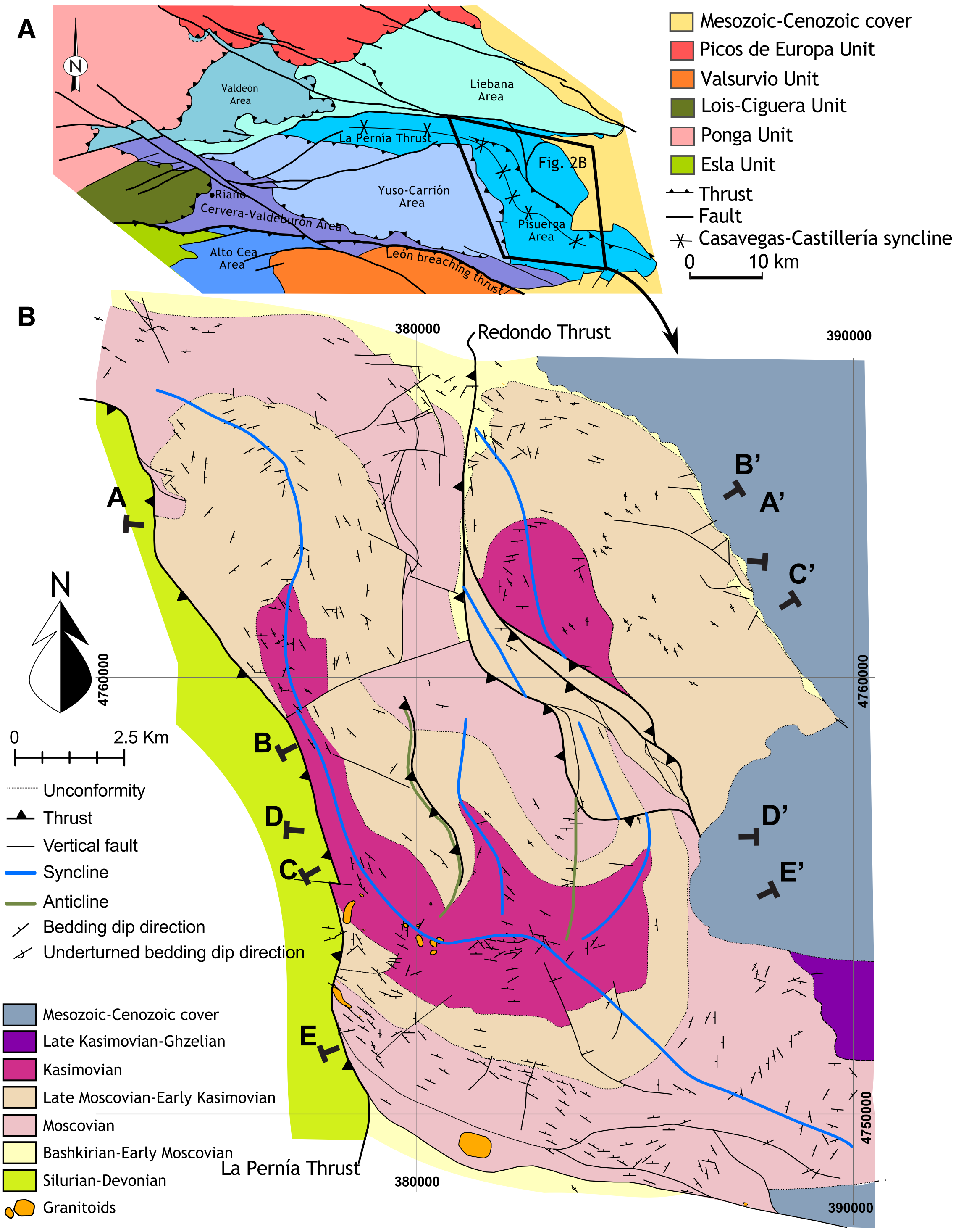

Fig. 2. A) Map of the Pisuerga–Carrión Unit. Pisuerga Area is situated at the east of the map. B) Detail map of the Pisuerga Area with locations of the cross-sections.

deformation for the Cantabrian Orocline: (1) an E–W shortening in present-day coordinates (e.g. Gutiérrez-Alonso, 1996; Julivert and Marcos, 1973) that formed the Variscan Orogen; (2) and a subsequent N–S shortening (in present-days coordinates) that produced the Cantabrian Orocline (e.g. Julivert and Marcos, 1973; Alonso, 1989, 2009; Merino-Tome et al., 2009; Pastor-Galán et al., 2012a). The orocline shape was likely tightened during Cenozoic N–S shortening during the formation of the Pyrenean–Cantabrian Mountain belt (Alonso et al., 1996 and Pulgar et al., 1996). Based on geological (Merino-Tome et al., 2009; Pastor-Galán et al., 2011; Shaw et al., 2012; Weil et al., 2013b) and paleomagnetic constraints (Van der Voo et al., 1997; Weil, 2006; Weil et al., 2000, 2001, 2010), the N–S shortening event that buckled the Variscan chain into an orocline occurred during a period of ca. 10 to 15 Ma in the uppermost Carboniferous and Early Permian (from ca. 310 to 295 Ma).

The Cantabrian Orocline has been also interpreted as a thick-skinned lithospheric-scale orocline whose formation and development triggered lithospheric delamination and mantle replacement (Gutiérrez-Alonso et al., 2004, 2011a, 2011b). The mechanisms of formation that could produce such thick lithospheric scale deformation are under debate (Gutiérrez-Alonso et al., 2008; Martínez-Catalán, 2011; Weil et al., 2013b; Pereira et al., 2014). 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 (e.g. Marshak, 2004; Weil and Yonkee, 2009; Johnston et al., 2013). In contrast, the Central Iberian Orocline is still kinematically unresolved so its relationship with the tectonic mechanisms that produced the Cantabrian Orocline (e.g. Martínez-Catalán, 2011; Pastor-Galán, 2013; Weil et al., 2013b) is still speculative.

2.2. Local geology

2.2.1. The Cantabrian Zone

The Cantabrian Zone is located in the core of the Cantabrian Orocline (e.g. Weil, 2006; Gutiérrez-Alonso et al., 2008; Pastor-Galán et al., 2012a; Fig. 1A and B) and represents a major division of the Iberian Massif interpreted to be the thin-skinned Gondwana foreland fold-and-thrust belt of the Variscan Orogen (e.g. Pérez-Estaún et al., 1988). Structurally, the foreland fold-and-thrust belt is characterized by tectonic transport towards the core of the orocline (Pérez-Estaún et al., 1988), low finite strain values (Gutiérrez-Alonso, 1996; Pastor-Galán et al., 2009), and locally developed cleavage. Illite crystallinity and conodont color alteration indexes are consistent with diagenetic conditions to very low-grade metamorphism (e.g. Bastida et al., 2004; Brime et al., 2001; Colmenero et al., 2008; García-López et al., 2007, 2013; Gutiérrez-Alonso and Nieto, 1996).

Deformation in the Cantabrian Zone began in the Late Mississippian (Serpukhovian; Dallmeyer et al., 1997) and resulted in the development of several clastic wedges related to different thrust units that progressively narrowed the foreland basin to the east. The latest stages of E–W shortening (in present-day coordinates) occurred during the Middle Pennsylvanian (Moscovian) with the emplacement of the Ponga nappes (Alvarez-Marron and Perez-Estaun, 1988; Weil, 2006). On the basis of tectonic and stratigraphic features, the Cantabrian Zone has been subdivided into several units, one of them, the Pisuerga–Carrión Unit, which is located at the southeast Cantabrian Zone, is the focus of this study (Fig. 1B).

2.2.2. The Pisuerga–Carrión Unit

The Pisuerga–Carrión Unit is limited to the north by the southward-verging frontal thrust of the Picos de Europa Unit, to the west by the frontal thrust of the Esla–Lois–Ciguera and Ponga Nappe Units (eastward verging), and to the south by the León Thrust (Fig. 2A). Recent studies suggest that the Picos de Europa Unit and León Thrust developed in response to the N–S shortening coevally with the development of the Cantabrian Orocline (Alonso et al., 2009; Keller et al., 2007; Merino-Tome et al., 2009). Alonso et al. (2009) interpreted the León Thrust as a large out-of-sequence north-verging thrust. Keller et al. (2007) suggested that the León out-of-sequence thrust is rooted into a lower crust detachment. García-López et al. (2013) argued that the thrust facilitated emplacement of Early Permian igneous rocks and the circulation of associate hot fluids.

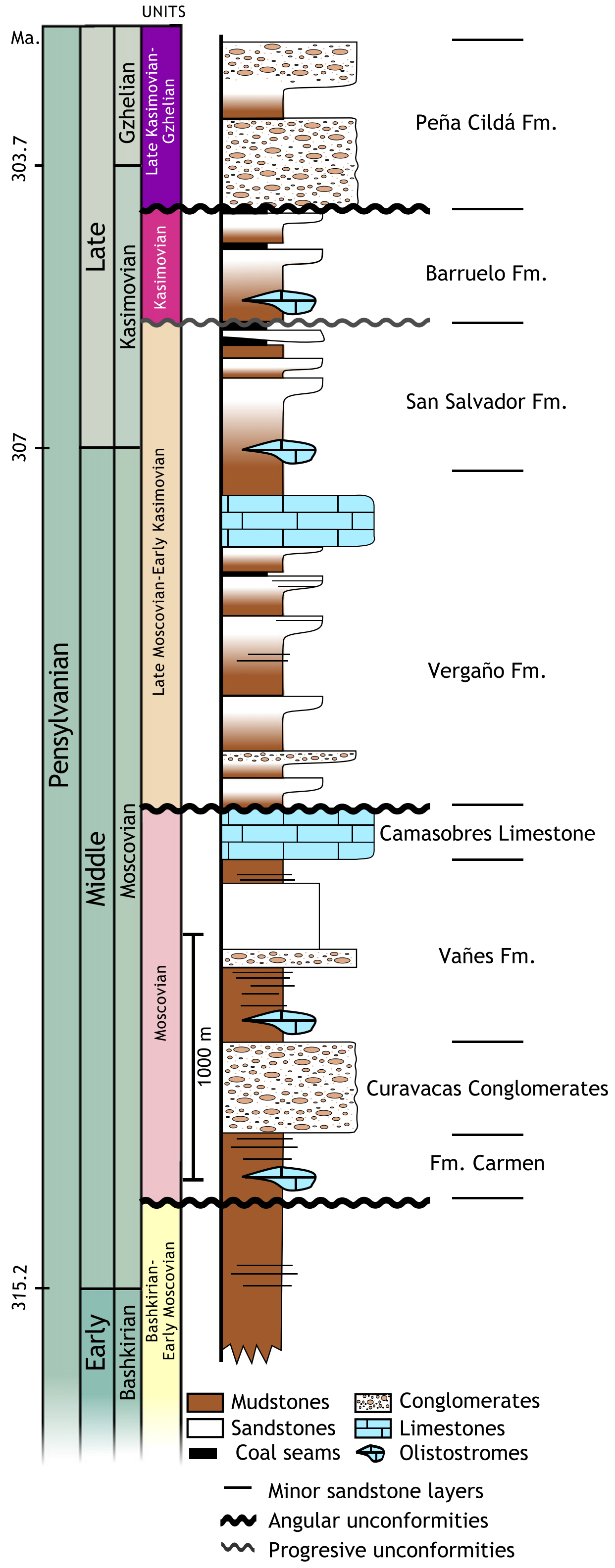

Fig. 3. Synthetic stratigraphical column of the Pisuerga Area showing the major unconformities.
Modified from Martín-Merino et al. (in press).

The Pisuerga–Carrión Unit is dominated by a ca. 5000 m thick Pennsylvanian sedimentary succession characterized by deep water and submarine slope deposits (i.e. olistostromes, breccias, turbidites, etc.) with lateral changes in facies and thickness. Three regional angular unconformities and one progressive unconformity are preserved in the Pisuerga–Carrión Unit. Previously, authors have used the unconformities for regional correlation and for subdividing the Pisuerga–Carrión Unit into several informal units. However, unit names are controversial and involve a complex nomenclature (for a review see Colmenero et al., 2002). In this paper we use the timing of the unconformities for identification, avoiding local nomenclature. The main unconformities are: (1) early Moscovian, (2) late Moscovian, (3) early Kasimovian; and (4) late Kasimovian.

The Pisuerga–Carrión Unit recorded four tectonic events: (1) early Moscovian emplacement of thrusts showing a present-day emplacement direction of N30°E and development of folds (Rodríguez-Fernández, 1994); (2) subsequent development of out-of-sequence-thrusts and secondary modification of previously formed folds (Alonso et al., 2009; Rodríguez-Fernández, 1994); and (3) late formation of strike-slip faults that cut the out-of-sequence thrusts; (4) intrusion of Permian igneous bodies in the surroundings of the out-of-sequence thrusts (Alonso, 1987; Rodríguez-Fernández and Heredia, 1987; Rodríguez-Fernández and Heredia, 1990). During the early Permian, several igneous bodies were intruded near the post-Variscan thrusts and strike-slip faults of the Pisuerga–Carrión Unit (Gallastegui et al., 1990; Gutiérrez-Alonso et al., 2011b; Valverde-Vaquero, 1992). Finally, the Pisuerga–Carrión Unit underwent minor shortening during the Alpine orogeny (Marín et al., 1995).

Several authors have described the pre-Carboniferous rocks in the Yuso–Carrión Area (Fig. 2A and B) as an allochthonous unit. These strata are part of the metamorphic West Asturian–Leonese Zone to the south (now cover by Cenozoic strata), and were likely emplaced gravitationally (i.e. as a kilometer scale olistostrome) in the latest stages of E–W shortening, but prior to N–S shortening (Frankenfeld, 1983; Marquínez and Marcos, 1984; Rodríguez-Fernández, 1994; Rodríguez-Fernández and Heredia, 1990).

2.2.3. The Pisuerga Area

This study focuses in the Pisuerga Area located in the southeastern part of the Pisuerga–Carrión Unit (Fig. 2A), which is one of the less studied areas in the Cantabrian Zone (Wagner, 1971; Van de Graaff, 1971; Bahamonde and Nuño, 1991; Martín-Merino et al., in press). The Pisuerga Area preserves a more than 5000-m-thick Moscovian, Kasimovian and Ghzelian succession composed of olistostromes, turbidites, shallow delta-fed siliciclastic deposits and shallow-water marine carbonates that are capped by late Kasimovian–Gzhelian continental strata (Fig. 3). The sedimentary depocentres are preserved in two N–S to NW–SE-trending synclinoriums: Casavegas–Castillería (W) and Redondo (E) (Figs. 2B and 4).

We have subdivided the Pennsylvanian succession outcropping in the Pisuerga Area into five, unconformably bound, mappable units (Fig. 2B). Each unit is named on the basis of its chronostratigraphic range (Bashkirian–early Moscovian, Moscovian, late Moscovian–early Kasimovian, Kasimovian, late Kasimovian–Gzhelian). Kasimovian–Gzhelian strata only outcrop unconformably in a few exposures at the eastern edge of the Pisuerga Area (Fig. 2B). The relative ages of the

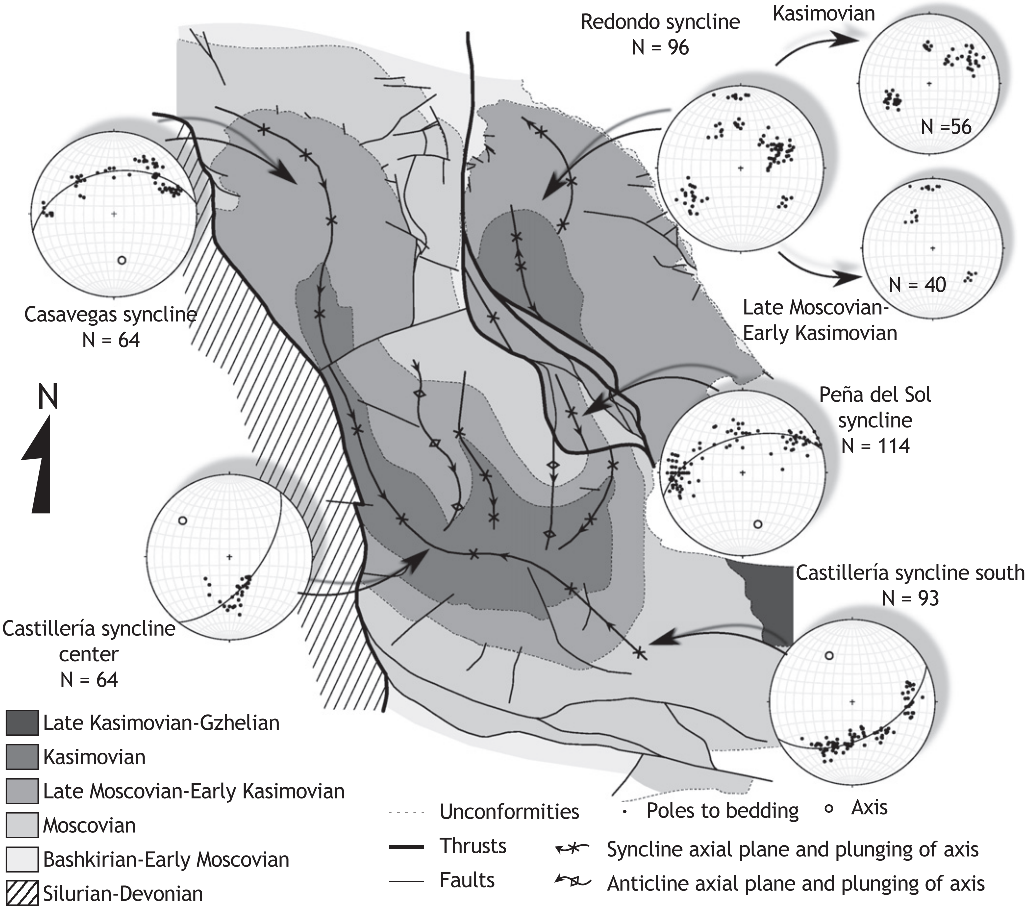

Fig. 4. Structural analysis of folds in the Pisuerga Area. Note the varying trend and plunge of fold axes, and the aberrant axis of Redondo syncline.

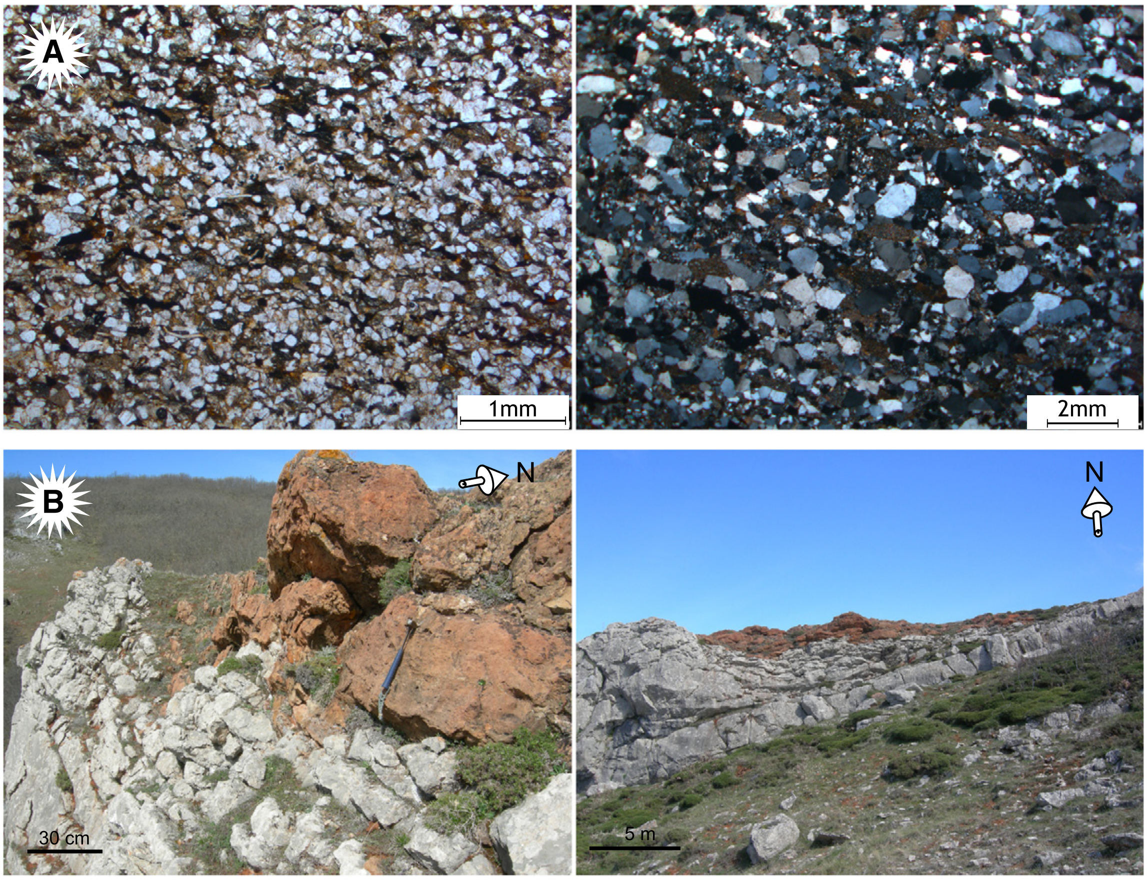

Fig. 5. A) Thin sections of two different sandstones (Early and Late Moscovian in age from left to right) showing no evidences of internal deformation. B) Examples of dolomitizations in the area.

different strata used are based on the biostratigraphy of fusulinids and plant remains (Ginkel, 1965; Instituto Geológico y Minero de España, 1987, 1988a, 1988b; Martín-Merino et al., in press).

3. Structure of the Pisuerga Area

In this study we mapped the Pisuerga Area at a scale of 1:10,000 and collected ca. 800 bedding measurements (Fig. 2B) and fold and fault data when possible (Figs. 4 and 5). We also did an analysis of systematic joints, described in Section 4. Half of our measurements were concentrated at 38 stations (about 10 measurements per station, see location in Supplementary Files 1 and 2) in order to obtain a statistically significant number of measurements for structural analysis (Engelder and Geiser, 1980; Fig. 4). Five cross-sections (Fig. 6) were constructed following the methodology of Dahlstrom (1969) and Mount et al. (1990). To plot field data, we used the software Stereonet (Allmendinger et al., 2012; Cardozo and Allmendinger, 2013), which uses the approach of Mulchrone et al. (2013). Several thin sections of sandstones were examined to document internal strain that could not be observed in the field. Thin sections show no metamorphic minerals, internal strain nor development of structural fabrics (Fig. 5A).

The Pisuerga Area (Fig. 2A) consists of two large thrust-bounded synclinoria, the Casavegas–Castillería and Redondo synclines (Fig. 2B and 4). The Casavegas–Castillería syncline is a non-cylindrical and non-planar fold that has a sinuous axial trace and a variably plunging fold axis (Fig. 4). It is cut by a NE–SW trending vertical fault with few meters of displacement (Figs. 2B and 4). The syncline has been subdivided into four sections: (1) the northernmost section with an E–W axial trace and subhorizontal axis (Fig. 2A, locally called the Cucayo syncline, Rodríguez-Fernández, 1994); (2) A ca. N–S trending axial trace (Casavegas syncline) with an axis plunging 40° to the SE (Fig. 4); (3) a ca. E–W trending section that we refer to as the Castillería syncline with an axis plunging 25° NW; and (4) a NW–SE trending section at the southernmost part of the Pisuerga Area, where the axis plunges ca. 30° to the NW. In the area of the Casavegas–Castillería syncline, the early Moscovian unconformity is particularly evident, with a difference of several degrees in strike and about 60° in dip between the underlying and overlying units (Fig. 2B; Martín-Merino et al., in press). The late Moscovian unconformity in this syncline is a disconformity with the strata below and above the unconformity surface being approximately concordant (Fig. 6). The early-Kasimovian progressive unconformity is especially evident in the eastern limb of the sinclyne (Fig. 6).

The eastern flank of the Casavegas–Castillería syncline has two minor anticlines and synclines (Figs. 4 and 6D). The anticlines developed over minor thrusts as fault-propagation folds (Fig. 6). Both anticlines and synclines have a sinuous N–S trend, and a south plunging axis (Fig. 2B). Peña del Sol is the only fold that outcrops well enough to do a proper structural analysis (Figs. 2B, 4 and 6).

The Redondo syncline is a complex structure. The Bashkirian–early Moscovian unit in this structure is absent (Fig. 2B; Martín-Merino et al., in press), and therefore the late Moscovian–early Kasimovian unit lie directly on top of Bashkirian–early Moscovian unit. In addition, the structural effect of the Kasimovian progressive unconformity is remarkable: whereas along the western flank the late Moscovian–early Kasimovian and Kasimovian units run sub-parallel, along the eastern flank is observed a significant angular difference that reaches 70° (Fig. 6, sections A–A′ and B–B′). Consequently, the Kasimovian unit depicts a close upright syncline (Figs. 2B and 6), whereas the late Moscovian–early Kasimovian show a recumbent fold along its eastern flank (Figs. 2B and 6). In addition, a thrust cuts the fold obliquely, including the axial trace, which produced minor drag-anticlines close

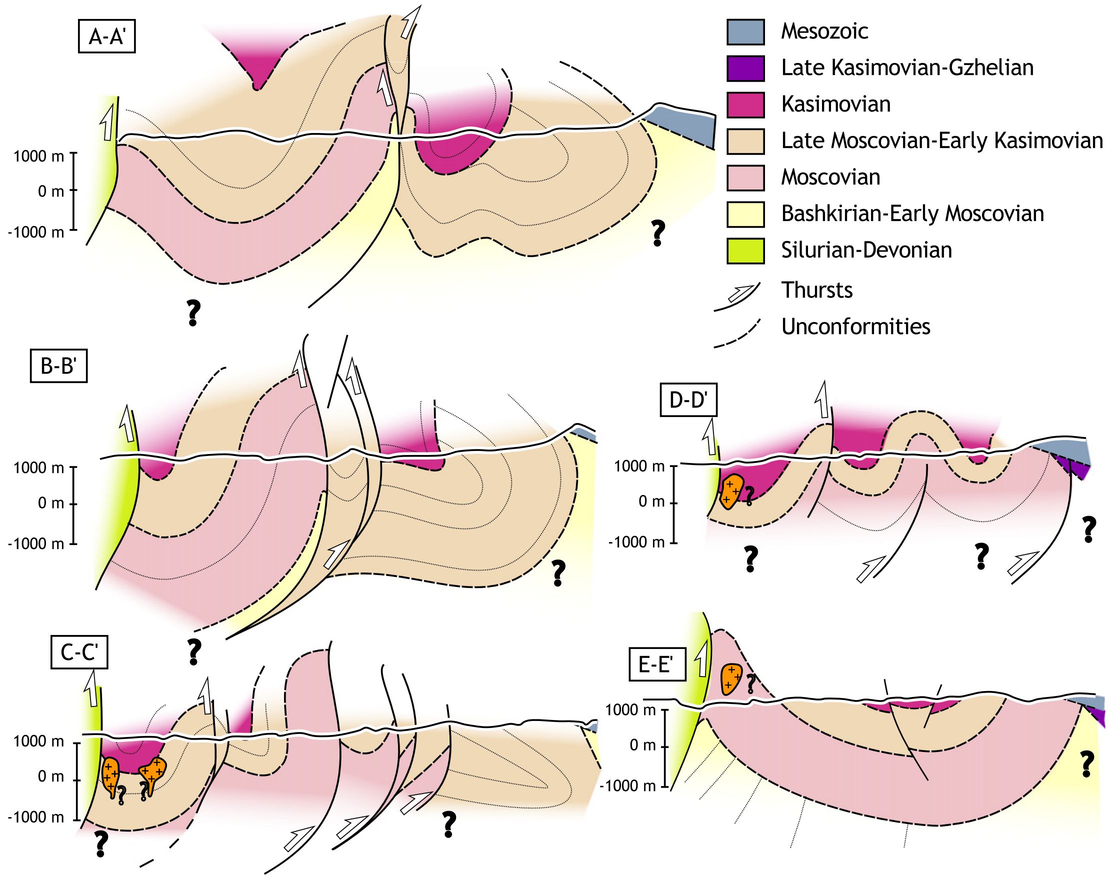

Fig. 6. Cross-sections showing the style of deformation of the Pisuerga Area. Minor faults have not been represented. See text for further information.

to the thrust (Figs. 2B and 6) and a steepening of the fold axis. Bedding data from this fold (Fig. 4) reveal a small-circle-like pattern, which we interpret to reflect a synopsis of the bedding attitudes due to the progressive unconformity (Figs. 2B and 6), giving this non-cylindrical shape. We have analyzed the different units of the fold separately to resolve the geometry of the over- and under-unconformity folds. Π-diagrams show that both members are non-cylindrical folds (Fig. 4). The progressive unconformity, which caused large variations in stratigraphic thickness in the area (Fig. 6; Martín-Merino et al., in press), and the effect of local thrusting produced the locally complex geometry and the difficulty to integrate it in the regional analysis.

In the Pisuerga Area two main thrusts and several minor ones have been identified (Fig. 2B): (1) the Pernía thrust, which bounds the synclines in the west; and (2) the Redondo thrust, which separates the Casavegas–Castillería syncline from the Redondo syncline. Both thrusts are presently vertical or even overturned in many localities along the southern limb of the orocline. Unfortunately, the thrusts do not provide kinematic markers. Therefore, we inferred the transport directions, perpendicular to the thrusts, and the kinematics (discussed in section 5) from the geometry of the structures and the temporal bracket provided by the unconformities.

4. Joint analysis

Angular unconformities can help to constrain the timing of joint set formation into pre- and post-unconformity sets when abutting relationships are not clear. From this point of view, if a joint set is only developed in an older rock, and is not present in rocks that overly an unconformity, it is assumed that the joint set developed prior to deposition of the post-unconformity rocks. If subsequent tectonic events affect the entire rock sequence, new joint sets can be superposed onto the lower and upper rock sequences that allow constraints to be placed on the relative timing of joint formation.

We analyzed the spatial and temporal distribution of systematic tensile joints from 22 stations to constrain any possible vertical-axis rotation. At least 30 joints per station were measured following the methodology described by Engelder and Geiser (1980) for a total of greater than 800 measurements (see Supplementary File 2). Joints in the Pisuerga Area preserve the characteristic plumose decoration of the joint planes when developed in fine grained clastic rocks, with no apparent record of shear. Lack of slip indicators suggests that the observed joints originated as Mode I (tensile) fractures that were not re-activated. We documented abutting relationships to establish the relative timing of the different joint sets; however, it was difficult to recognize enough relationships to establish a temporal sequence for joint development. The most useful temporal criteria available to constrain the age of joint sets were provided by the unconformities. Since the total time span of the stratigraphic column represents ca. 15 million years and none of the unconformities represent a long gap in the sedimentological record (Martín-Merino et al., in press; Fig. 3), we compared only the pre-folding joint sets in each unit bracketed by unconformities in order to obtain constraints on the timing of formation of each set. All joint sets were back-tilted. The advantage of the back-tilting method is that it concentrates pre-folding and syn-folding joint sets while it scatters the post-folding joint sets.

After back-tilting we did not further consider joint set orientations that represent less than 4% of the total measured population, discarding in this manner the post-folding and post-Carboniferous joint sets or local joint sets developed in response to near-field stress. Unfortunately, due to the poor structural control in the Bashkirian–early Moscovian strata and in the Redondo Syncline (Fig. 4) it was impossible to back-tilt these data accurately and therefore measurements taken in this area were not used in further analysis.

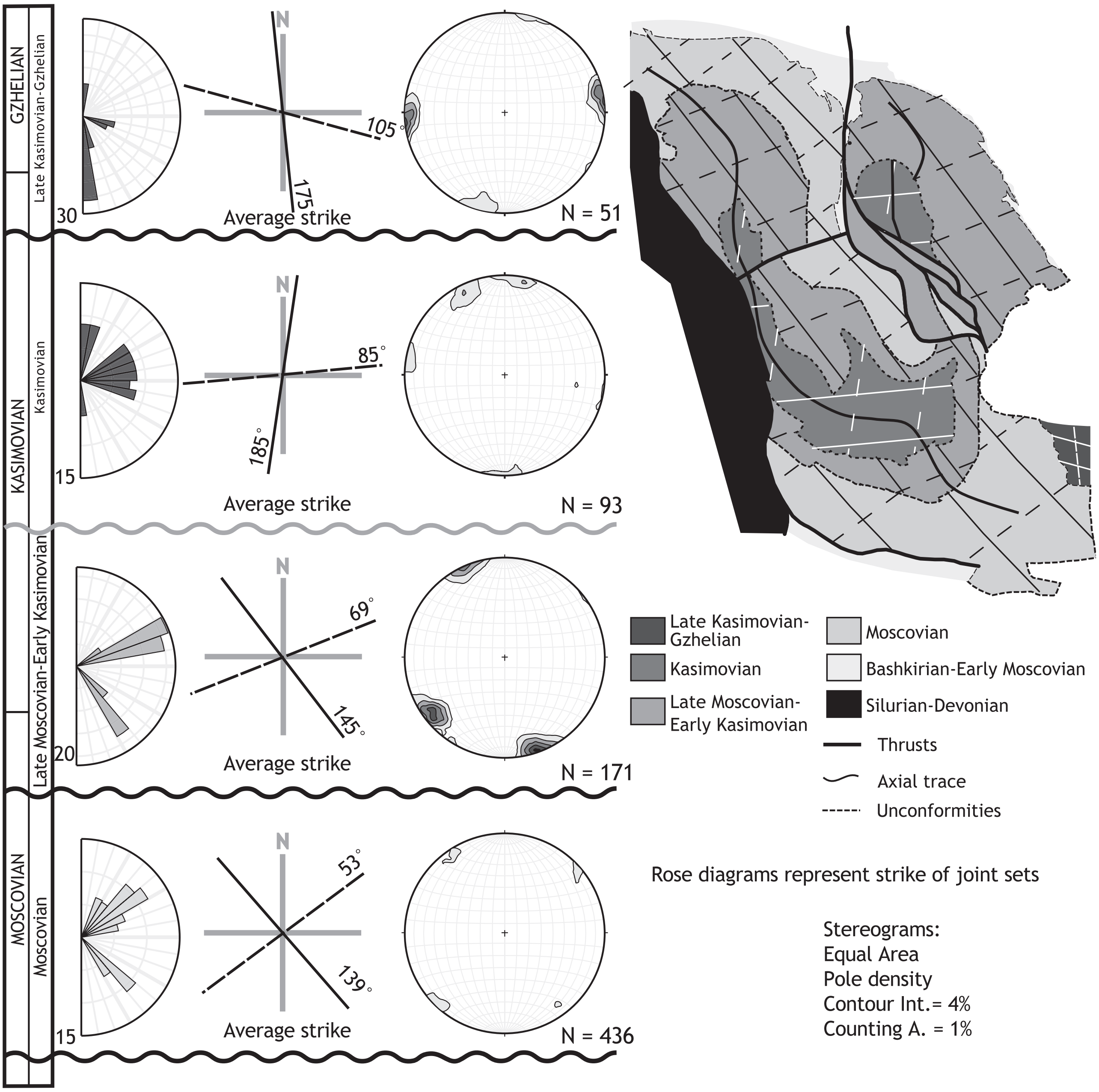

Fig. 7. Joint sets found in the different unconformity-bounded sequences after backtilting. The image displays both rose diagrams of the strike of joints and density of poles the orientation of these joint sets. A rotation of 40° of the joint sets can be observed when comparing the average strike diagrams.

Joint sets were categorized according to orientation criteria. Two perpendicular or sub-perpendicular joint sets are found in the different described units (Fig. 7). Those joint sets do not correspond with the common strike-parallel and strike-perpendicular usually developed in fold-and-thrust regions (e.g. Hancock, 1985). Both joint sets cross-cut the axial trace of the folds with different angles (Fig. 7). The orientation of joint sets is different for each unconformity-bounded unit (Fig. 7). The average strikes of the joint sets in the different intervals are: (1) Moscovian, 53° and 139°; (2) late Moscovian–early Kasimovian, 69° and 145°; (3) Kasimovian, 85° and 185°; and (4) late Kasimovian–Gzhelian, 105° and 175°. In general, individual joint-strikes are well concentrated around the average strike of the set, however there is a noticeable dispersion, especially evident in the Kasimovian joint sets (Fig. 7). We attribute this dispersal to the fact that Kasimovian outcrops are limited to the Redondo Syncline – where the structural control is poor (see description in Section 3) – and the core of the Casavegas–Castillería syncline where the only outcrops were sub-horizontal, which increases measurement and back-tilting error.

5. Fitting the Pisuerga Area into the big picture

5.1. Local evolution

The regional trend of the Pisuerga Area differs from the consistent N30° strike of the Pisuerga–Carrión region and the southern limb of the Cantabrian Orocline (Figs. 1B and 2A), especially in the case of the La Pernía Thrust. This thrust system transects previous Variscan thrusts (Rodríguez-Fernández, 1994; Rodríguez-Fernández and Heredia, 1987) and affects rocks as young as Kasimovian (Fig. 2B). Additionally, the rocks deposited over the early Moscovian unconformity in the Pisuerga–Carrión Unit were not deformed by the Variscan E–W shortening event (Rodríguez-Fernández, 1994). Taking these arguments into account we argue that La Pernía, Redondo and other minor thrusts in the Pisuerga Area are part of a Kasimovian out-of-sequence thrust system whose main fault is the León thrust formed during the N–S shortening event (Alonso et al., 2009; Pastor-Galán et al., 2011). Following this reasoning, the N–S trending sections of the thrusts in the Pisuerga Area are explained as lateral ramps that accommodated the observed small displacements whereas the ca. E–W sections correspond with main ramps.

Joint sets in the Pisuerga Area are not geometrically linked with folds. They are neither parallel nor perpendicular to the fold axes, indicating that folding in the Pisuerga Area responded to the near-stress field since joints-sets are filtered to be representative of the far-field stress (see section 4). We interpret the rocks in the Pisuerga Area to have been passively folded by means of bending. The deformation happened during the emplacement of the out-of-sequence thrusts due to its movement and the flexural slip reactivation of previous structures in a similar way as Alonso (1989) described for late Kasimovian–Gzhelian rocks in the Esla Unit (Fig. 1B: Fig. 8).

Joint analysis revealed that joint sets change in orientation between the oldest (Moscovian) and the youngest (late Kasimovian–Ghzelian) rocks by ca. 40° (Fig. 7). None of the joint sets are coincident with post-Permian sets described in Pastor-Galán et al. (2011) nor were they

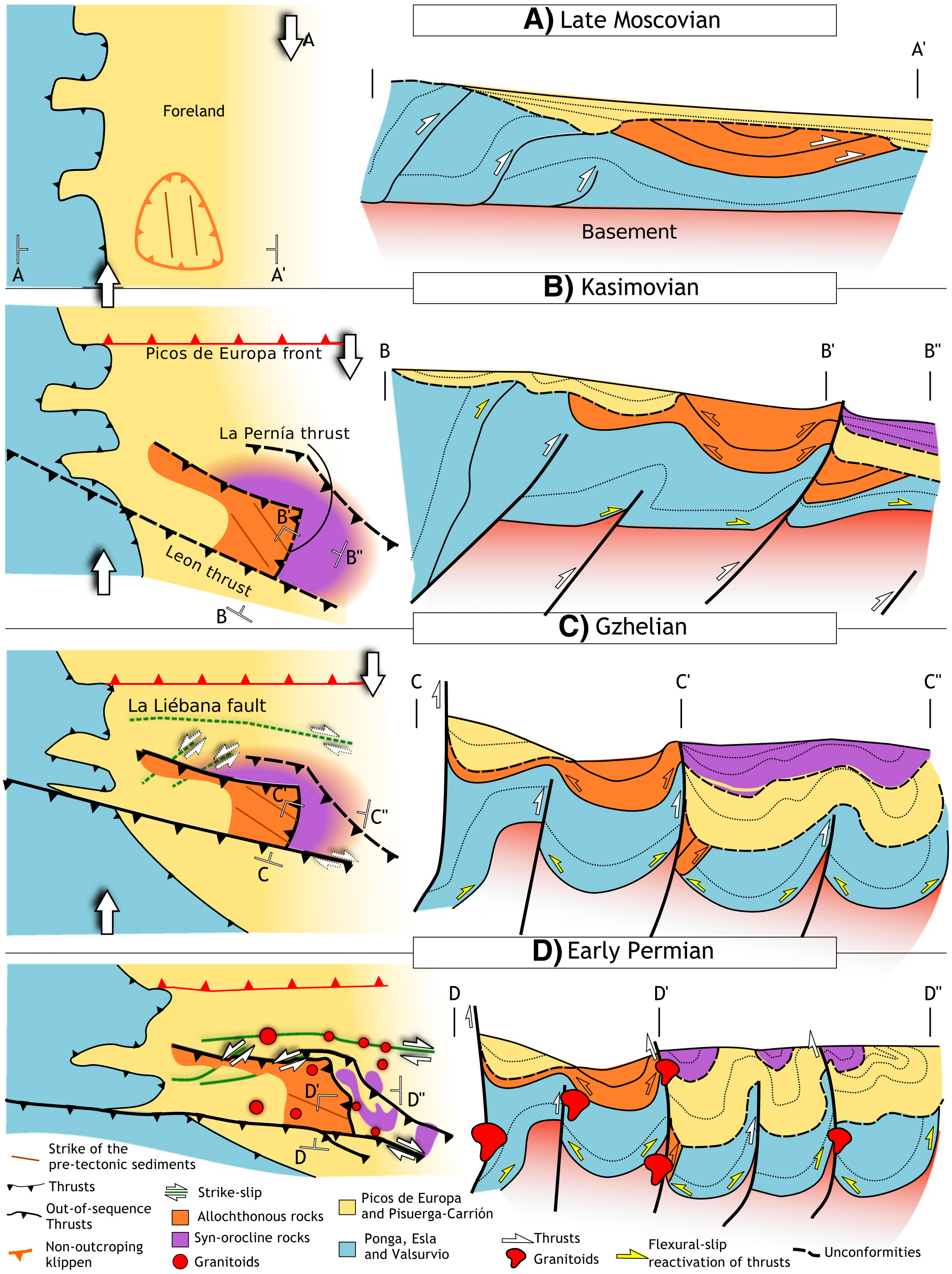

Fig. 8. Synthesis of the tectonic evolution of the Pisuerga–Carrión Unit from early Moscovian to Early Permian based on the data presented in this paper and a review of the literature (e.g. Wagner, 1971; Heward and Reading, 2009; Marcos and Pulgar, 1982; Alonso, 1987, 1989; Nijman and Savage, 1989; Heredia, 1992; Rodríguez-Fernández, 1994; Alonso et al., 2009; Weil et al., 2013a). See text for details. Map and cross sections are sketches, not to scale.

developed during the main phase of E–W shortening during Variscan orogeny since the early Moscovian unconformity marks the end of the Variscan orogeny in this region (Rodríguez-Fernández, 1994). We interpret that the all joint sets were developed under the same stress field that produced the N–S (present day coordinates) shortening event responsible for the formation of the Cantabrian Orocline. The difference in orientation between the Moskovian and late Kasimovian–Gzhelian units is then attributed to rotation of orogen, where the oldest joint sets are the most rotated relative to the stress field, whereas the youngest joints are the least. We also interpret that this change in orientation of joint sets is the total amount of block rotation for the Pisuerga Area, about 40° counterclockwise rotation. Additionally to a degree of rotation, joint sets provide a time constraint for the onset of orocline buckling. The low amount of rotation between the Moscovian joint sets and the late Moscovian–early Kasimovian sets indicate that the late Moscovian unconformity marks the beginning of oroclinal formation, at least locally.

5.2. Regional evolution

During the latest pulses of the Variscan Orogeny, the Valsurvio, Esla and Ponga Units were emplaced while the Bashkirian–Moscovian syn-orogenic rocks were deposited and slightly folded and thrusted on top of the clastic wedge in the Pisuerga–Carrión Unit (Rodríguez-Fernández, 1994). The emplacement of the Palentian Nappes (orange body in Fig. 8) occurred diachronously during these latest movements (e.g. Marcos and Pulgar, 1982; Rodríguez-Fernández, 1994). During this time span a molasse was deposited over the Pisuerga–Carrión Unit (Fig. 8A). Several authors argue that the vertical axis rotation registered in the Cantabrian Orocline is due to a N–S shortening (in present day coordinates) that produced the buckling of the Variscan Orogen (e.g. Gutiérrez-Alonso et al., 2012) and that might be also related with the formation of the Central Iberian Orocline (e.g. Shaw et al., 2012). This N–S shortening has also been related to the emplacement of the Picos de Europa Unit (Merino-Tome et al., 2009); the development of a crustal-scale out-of-sequence thrust system (Alonso et al., 2009; Keller et al., 2007) and flexural slip deformation in the upper-crust that made use of existing thrusts (Alonso, 1987; Fig. 8A and B). The emplacement of the out-of-sequence thrust system gave rise to new clastic wedges, progressive unconformities and angular unconformities as described in previous Sections (Fig. 8B and C; for further information, see Martín-Merino et al., in press). The progressive emplacement of the out-of-sequence thrusts and the flexural slip reactivation of previous structures produced fault-propagation folds and fault-bend folds in these new clastic-wedges (Figs. 6 and 8).

However, the 40° of counterclockwise rotation recorded in the Pisuerga Area is less than expected if we follow the average strike of the Pisuerga–Carrión Unit (N30°E; Rodríguez Fernández, 1994; Fig. 8). If the Variscan Orogen was a N–S quasi-linear orogen (in present day coordinates, e.g. Weil et al., 2013a), it would mean that the Pisuerga–Carrión Unit, which currently strikes N30°E, is rotated about 60° counterclockwise. We interpret that these 20° differences between the Pisuerga–Carrión Unit and the Pisuerga Area were accommodated by dextral strike-slip movements that happened after emplacement of the out-of-sequence thrusts, but before Early Permian intrusion of igneous rocks (e.g. Alonso, 1987). There is no evidence of reactivation of joints as strike-slip faults in the Pisuerga Area, although the out-of-sequence thrusts may accommodate partially this latter movement as the Leon thrust did (Alonso, 1987). We interpret that this late strike-slip movement affected the basement and reactivated some former structures as strike-slip faults while Moscovian–Gzhelian rocks in the Pisuerga Area accommodated the deformation by means of transcurrency instead of rotating around the vertical axis (Fig. 8C). The presence of Early Permian igneous rocks emplaced in the surroundings of out-of-sequence-thrusts and strike-slip faults (Fig. 8D) has been taken as evidence for a lithospheric scale orocline (Gutiérrez-Alonso et al., 2004), as igneous rocks are not a common occurrence in foreland basins under thin-skinned deformation conditions.

The generation of such a large structure in extent and depth after the Variscan orogenesis, and therefore, after the amalgamation of Pangea, is likely related with processes of global importance. During the Late Carboniferous and Permian a large amount of plate configurations and/or modifications of plate motions have been suggested that could be responsible of the formation of the Cantabrian Orocline. Several authors have supported the hypothesis of a Pangea scale shear zone that could have changed the configuration of the supercontinent during the Late Carboniferous and Permian (e.g. Muttoni et al., 2003) and produced the Cantabrian Orocline (Martínez-Catalán, 2011). Gutiérrez-Alonso et al. (2008) proposed that the self-subduction of Pangea was responsible for a global change in the stress field in the late Paleozoic, producing among other features the separation of Cimmeria ribbon-continent and the Iberian oroclines. Yet another hypothesis was proposed by Pereira et al. (2014), in which the onset of the subduction of the Paleo-Tethys ocean would be responsible of orocline formation and magmatism in Iberia.

6. Conclusions

The structural analysis of the Pisuerga Area reveals that during the initial stages of oroclinal formation in the Cantabrian Orocline, a crustal-scale imbricate system of out-of-sequence thrusts developed while pre-existing structures reactivated by a mechanism of flexural slip. This mechanism produced bending of syn-oroclinal strata by means of fault-propagation folds and fold-bend folds and development of several unconformities. In the latest stages of oroclinal formation the deformation was accommodated by strike-slip faults including the reactivation of out-of-sequence thrusts. Our analysis sheds light on the mechanisms of deformation that can affect upper-crust rocks situated in the limbs of oroclines during the formation processes.

The study of systematic joint sets in rock sequences bounded by unconformities provides geometric constraints on rotation around a vertical axis. Such constraints can help unravel the kinematics of regions where other structural or geophysical criteria are unavailable. The systematic analysis of joint sets in the Pisuerga–Carrión Unit supports the secondary origin of the Cantabrian Orocline and gives 40° of vertical axis counterclockwise rotation for the region. Finally, these data are consistent with a late Moscovian age for the initiation of oroclinal formation, at least locally.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.tecto.2014.03.004. These data include Google map of the most important areas described in this article.

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