Tectonophysics 622 (2014) 110–121

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

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

ARTICLE INFO

Article history:
Received 10 October 2013
Received in revised form 6 February 2014
Accepted 3 March 2014
Available online 11 March 2014

Keywords:
Orocline
Out-of-sequence thrusting
Vertical axis rotation
Structural analysis
Joint analysis
Variscan orogeny

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,

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

http://dx.doi.org/10.1016/j.tecto.2014.03.004
0040-1951/

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

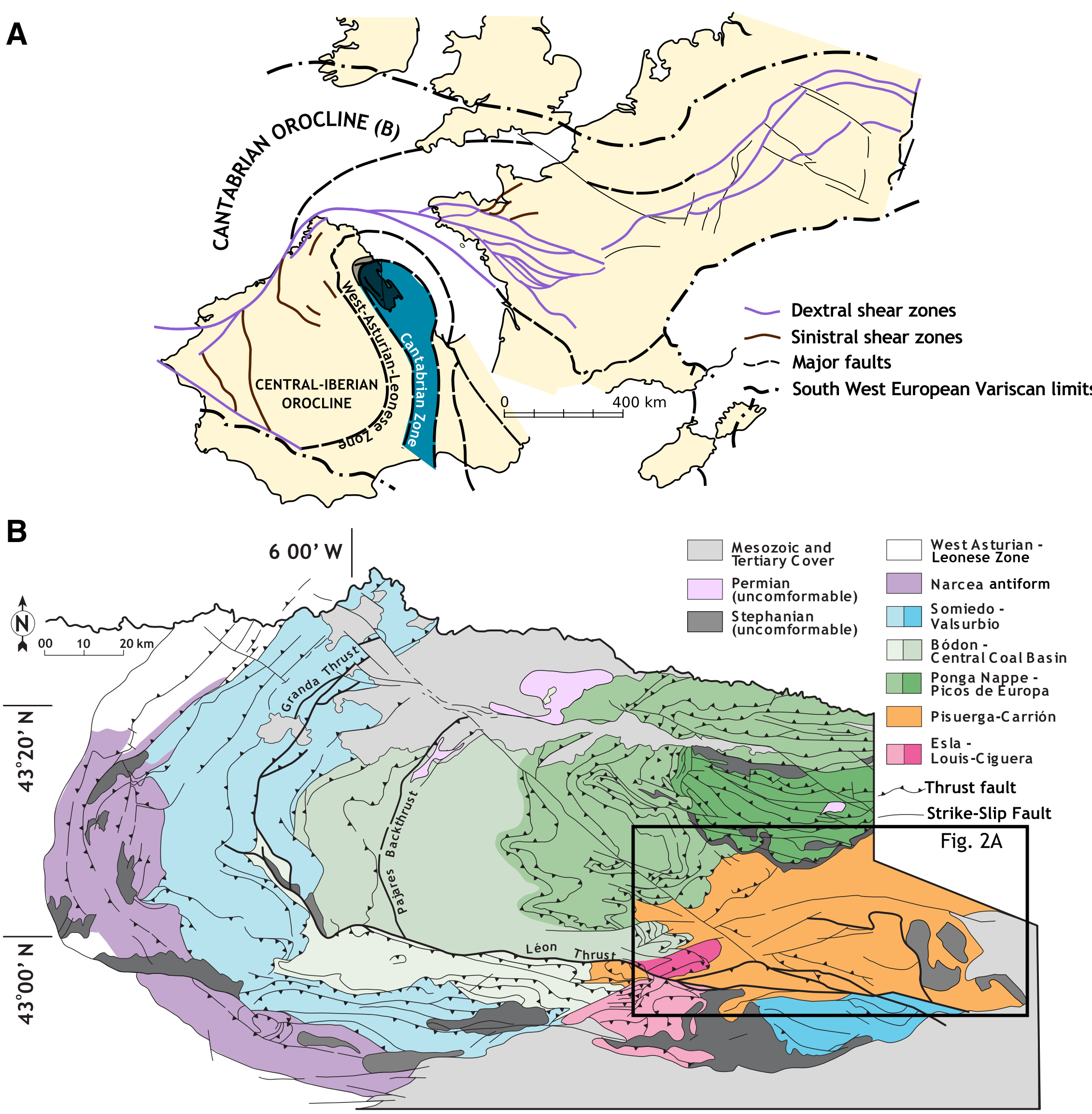

Fig. 1. A) Situation of the Cantabrian Orocline into the Variscan Belt of Western Europe. Note that the Iberian Peninsula is rotated to fit to a pre-opening of Biscay Bay situation; The Cantabrian Zone is marked in blue. B) Map of the Cantabrian Zone after Alonso et al. (2009) showing the different units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