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Saw-tooth structures and curved veins related to folds in the south-central Pyrenees (Spain)

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ABSTRACT

Two generation of folds (F_1 and F_2) and associated structures, developed in the Eocene turbidites of the south-central Pyrenees, are analyzed in this paper. F_1 folds are close, have sub-horizontal axes and southwards vergence. They have an associated cleavage S_1. Competent layers were folded by layer-parallel shortening, tangential longitudinal strain, some possible flexural flow and an obliquely superimposed homogeneous strain due mainly to simple shear. Flexural slip is also an important mechanism in the whole multilayer. F_2 folds are gentle and scarce; they fold the S_1 cleavage.

Among the structures associated with F_1 folds, there are sets of veins with curved form in the competent layers. The displacement of each vein gave rise usually to a step in the layer boundary, so that a set of veins produces a structure that is named "saw-tooth structure". The veins initiated as small faults that made flexural slip difficult and gave rise to a concentration of stress on the steps, leading to an opening of the fractures and a propagation of them along a curved path, as suggested by a simple mechanical model. This propagation agrees with finite element models developed by other authors.

1. Introduction

In the Eocene turbidites (Hecho Group) of the south-central Pyrenees, abundant metric folds developed during the Alpine deformation. It is observed in some areas that on their limbs, the competent layers contain a notable variety of veins with curious geometry. In many cases the veins have a curved wedge shape opening towards a bed boundary and involve a displacement that gives rise to the development of steps on this boundary, which is usually the stratigraphical base of the bed. As a consequence, an exotic structure not previously described in the geological literature often appears, which is named in this paper 'saw-tooth structure'.

The aim of this paper is to make an analysis of these folds and veins and to construct a mechanical model to explain their development. In the first part of the paper, the folds are described and the kinematical mechanisms involved in their evolution are analyzed. In order to accomplish that, in addition to observations and field data, computer simulations of folds have been used. This first part of the paper is necessary to explain the context and development of veins and saw-tooth structures, which are analyzed in the second part of the paper. In the latter, a mesoscopic and microscopic description of these structures is made and a model for their development is presented.

2. Geological setting

The Pyrenees is an Alpine belt that includes the boundary between the Iberian Peninsula and the rest of the European continent, following an E–W direction (Fig. 1). It can be divided into three parts: a central part (Axial Zone), with outcrops of a Paleozoic basement involved in the structure, and two thrust systems, a northern system with vergence to the north (North Pyrenean Zone) and a southern system with vergence to the south (South Pyrenean Zone). Despite this arrangement, the belt is asymmetrical, since the South Pyrenean Zone is wider than the North Pyrenean Zone, and overall a southerly vergence dominates. Alpine deformation took place between the Late Cretaceous and the Early Miocene. In the western and central parts of the South Pyrenean Zone (Jaca-Pamplona sector), a major foredeep basin developed, where syntectonic turbiditic sediments belonging to the Hecho Group were deposited during the Early-Middle Eocene. The studied structures developed in rocks of this group, and they have been analyzed along the N–S valleys that cross these western and central parts (Fig. 1).

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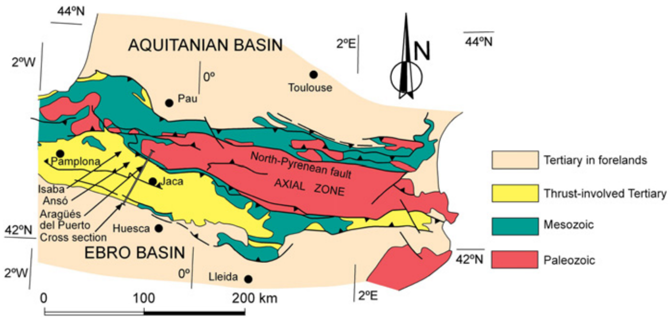

Fig. 1. Geological map of the Pyrenees with the location of the cross-section shown in Fig. 2 (after Mansurbeg et al., 2009). Isaba, Ansó, Aragüés del Puerto and Jaca are localities in the N–S valleys where the study folds are located.

The Hecho Group (Mutti et al., 1972) consists of a succession of arenites (hybrid arenites – sensu (Zuffa, 1980), calclithites – sensu Pettijohn et al., 1972, and siliciclastic sandstones) and shales in turbidite facies that reaches a maximum thickness of about 4500 m (Mansurbeg et al., 2009; Caja et al., 2010). The siliciclastic sandstones and the hybrid arenites contain calcite and/or dolomite cement that occludes the primary porosity.

The structure of the Jaca-Pamplona sector consists of several minor thrust systems with a basal décollement located within Triassic rocks (Gavarnie-Guarga thrust system) and a broad syncline with the trough zone in the southern part of the sector (Fig. 2). Teixell and García-Sansegundo (1995) and Teixell (1996) distinguished two generations of structures in this sector. The first consists of gently dipping thrusts with scarce associated folds and the second consists of an imbricate thrust system with numerous associated folds at mesoscopic to macroscopic scales. These folds are very common in the turbidites of the Hecho Group and have an associated cleavage in the incompetent layers. These folds and their associated veins are the main structures considered in this paper.

3. Analysis of folding

Observations of folds in the field permit two folding phases (F_1 and F_2) to be distinguished. F_1 folds are the most frequent and correspond to the second generation of regional structures; they are close folds with vergence to the southwest and an associated cleavage, S_1 (Fig. 3). F_2 folds are scarce; they are gentle folds upright or weakly vergent towards the NNE, and they fold the S_1 cleavage (Fig. 4). The main features of F_1 folds are described below.

F_1 folds have axes sub-horizontal or gently plunging towards the southeast or the northwest (Fig. 5a). Their axial surfaces are steeply or moderately dipping towards the NNE (Fig. 5b). Most of them are close folds (Fig. 5c). In most cases the aspect ratio (height/width ratio of the fold limb between the hinge and inflection points taking the tangent to the hinge point as horizontal) is lower than 3 and the folds mainly range in shape from chevron to parabolic (Fig. 6a), though fractures and the disorganised character of the beds prevent classification in some cases. Hence, the chevron shape is more frequent in the outcrops than it is reflected in Fig. 6a. The geometry of the competent folded beds is shown by the s_1–s_2 diagram of Bastida et al. (2005) of Fig. 6b; there is a great dispersion of points, although class 1C folds are dominant.

An S_1 cleavage, associated with F_1 folds, is well developed in the incompetent layers, mainly when the incompetent/competent thickness ratio is high. In most cases the cleavage shows divergent fanning, mainly in the hinge area (Fig. 7); nevertheless, in cases in which the incompetent beds are dominant, the cleavage tends to be parallel to the axial plane. In the competent layers, the cleavage is not developed or appears as a widely spaced convergent cleavage (Fig. 7), in which many cleavage surfaces have the appearance of fractures.

Folds approximating to chevron style have typical accommodation structures described by Ramsay (1974), such as bulbous hinges (Fig. 8a) and reverse limb faults, both associated with anomalously thick competent layers, and dilation spaces in the hinge zones with hinge collapse (Fig. 8) or flow of incompetent material towards them. Some remarkable structures have been observed on some limbs of F_1 folds. These are mainly curved wedge-shaped carbonate veins in competent folded beds; they are described below.

Structures associated with folding by tangential longitudinal strain are frequent, such as wedge-shaped extension fractures opening towards the outer arc in the hinge zone of competent beds (Fig. 9). These fractures are usually filled with carbonate minerals and represent a brittle expression of the tangential longitudinal strain with area change (PTLS of Bobillo-Ares et al., 2006). Exceptionally, concentric extension veins can be observed close to the inner arc of the hinge zone of the competent folded layers, also indicating tangential longitudinal strain (Fig. 7b).

Syntectonic carbonate fibres along S_0 can be observed in many cases in the competent–incompetent interface or inside the incompetent material. They have been found preferentially on the reverse limbs and their direction always makes an angle greater than 75° with the axial direction (Fig. 10). When fibre steps can be seen, they indicate a slip sense in agreement with the flexural slip folding mechanism, which can be associated with the tangential longitudinal strain of the competent layers.

The folds of the competent layers have a slight layer thickening in the hinge zone. Ramsay's classification of a fold in the Roncal valley made by Gil et al. (2006) suggests a flattening value ($\sqrt{\lambda_2/\lambda_1}$) between 0.7 and 0.85. However, the asymmetry between the two limbs requires an obliquity of the axes of the superimposed strain ellipse with respect to the axial plane and some heterogeneity in the flattening. This heterogeneity is also suggested by the dispersion of points in the s_1–s_2 diagram (Fig. 6b).

A folded competent layer with an axial plane dipping 57° southwards and located in the same train of folds as the fold analyzed by Gil et al. (2006) has been fitted by Aller et al. (2010) by a fold simulated by computer using the program 'Fold Modeler' (Bobillo-Ares et al., 2004) (Fig. 11). A good fit of this fold is obtained with a first folding step of isochoric layer-parallel shortening ($\sqrt{\lambda_2/\lambda_1} = 0.49$), a second step of tangential longitudinal strain without area change (ETLS of Bobillo-Ares et al., 2006) with an aspect ratio of 0.67, and a third step of flattening (pure shear with $\sqrt{\lambda_2/\lambda_1} = 0.71$) with a $\sqrt{\lambda_1}$ direction making an angle of 20° with the axial trace (angle measured clockwise facing west from the fold axial trace) (oblique flattening of Hudeleston, 1973). The considerable initial layer-parallel shortening agrees with the convergent arrangement of the cleavage present in the competent layers. The consistent direction of vergence of the folds towards the foreland and their association with thrusts with the same vergence, some of them forming duplexes at the outcrop scale near the analyzed folds (Gil et al., 2006), suggest that the folds of this area probably resulted within a rotational bulk deformation regime. Assuming a regime of simple shear strain, the strain ellipse axial ratio cited above would correspond to a foreland-directed simple shear with $\gamma = 0.35$ superimposed on a pre-existing fold and with a top-to-the-south shear sense and a direction plunging 17° north. Once the shear direction is obtained, and the γ value and the present dip of the fold axial plane are known (Aller et al., 2010), the dip of the axial plane prior to the superimposition of the simple shear can be determined; this dip was about 66° northwards and it could be