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Reliability of magnetic fabric of weakly deformed mudrocks as a palaeostress indicator in compressive settings

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ABSTRACT

In this work we compare the results of anisotropy of magnetic susceptibility (AMS) with palaeostress analysis at local scale. The AMS data refer to 14 sites from weakly deformed mudrocks (Lower and Middle Miocene lacustrine sediments) from two areas of the internal part of the Ebro foreland basin, the Bardenas Reales and Monegros areas. Nine sites display a magnetic fabric related to a subtle tectonic overprint showing a roughly E–W magnetic lineation, whereas the rest of sites (most of them located at the Monegros area) show a sedimentary fabric without a well-defined magnetic lineation. Palaeostress data result from fault populations and joint sets exposed in the limestone beds interbedded with the mudrocks at the nearest possible outcrop from the AMS site. The origin of the magnetic lineation is related to a N–S compression coeval with the earliest diagenesis of the studied sediments prior to consolidation. The comparison between magnetic fabric and palaeostress data demonstrates the coaxiality between the AMS and palaeostress ellipsoids both at local and regional scales, thereby validating the reliability of AMS as palaeostress indicator in compressive settings.

1. Introduction

The anisotropy of magnetic susceptibility (AMS) is a fast and non-destructive technique that has gained the acceptance of earth scientists because it allows characterizing even very subtle rock fabrics and provides valuable information on the origin and subsequent deformational history of rocks (e.g. Tarling and Hrouda, 1993; Borradaile and Henry, 1997). Of particular interest for structural geologists is the study of the AMS of weakly deformed mudrocks, since it records the initial stages of deformation both in compressive (Kissel et al., 1986; Mattei et al., 1997; Sagnotti et al., 1998, 1999; Parés et al., 1999; Larrasoaña et al., 2004; Cifelli et al., 2004a) and extensional settings (Mattei et al., 1997, 1999; Sagnotti et al., 1994; Cifelli et al., 2004a,b, 2005; Borradaile and Hamilton, 2004). We refer to weakly deformed mudrocks as these very fine-grained, clay-rich rocks (e.g. mudstones, claystones and siltstones) are either flat-lying or gently tilted or faulted and do not show any fabric apart from that related to deposition and compaction (see Parés, 2004). Following this definition, weakly deformed mudrocks include the so-called "undeformed" clays of Kissel et al. (1986) and Cifelli et al. (2004b, 2005). In the last years, the AMS of weakly deformed mudrocks has experienced a renewed interest since a growing body of evidence suggests that their magnetic fabric is locked-in during the earliest diagenesis, when the mudrocks are still unconsolidated, flat-lying, and the presence of water allows particulate flow by intergranular slip and kinking (Parés et al., 1999; Larrasoaña et al., 2004). During this incipient deformation, even in very low strain conditions, tectonic deformation is able to overcome the initial sedimentary fabric and to reorient phyllosilicate grains according to the prevailing stress field (Richter et al., 1993; Benn, 1994). Such reorientation results in development of a magnetic lineation which is perpendicular to the shortening direction in compressive settings (Kissel et al., 1986; Mattei et al., 1997; Sagnotti et al., 1998, 1999; Parés et al., 1999; Parés and van der Pluijm, 2002; Parés, 2004; Larrasoaña et al., 2004) and parallel to the stretching direction in extensional contexts (Mattei et al., 1997, 1999; Sagnotti et al., 1994; Cifelli et al., 2004a,b, 2005; Borradaile and Hamilton, 2004; Soto et al., 2007). Based on this, magnetic fabric has been considered as reliable indicators of palaeostress directions, which is important because mudrocks are ubiquitous in most tectonic settings, and the study of their magnetic fabric might provide new palaeostress results from structural units that very often lack strain markers and lithologies prone to be studied by

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standard palaeostress methods (e.g. fault and joint populations). Despite the potential of magnetic fabric as palaeostress indicators in weakly deformed mudrocks, there are few cases where the reliability of such magnetic fabric has been contrasted against palaeostress results (Kissel et al., 1986; Lee et al., 1990; Sagnotti et al., 1994, 1999; Mattei et al., 1997, 1999; Borradaile and Hamilton, 2004; Cifelli et al., 2004a, 2005; Soto et al., 2007).

In this paper, we present new AMS results from weakly deformed mudrocks that crop out in two sectors (Bardenas Reales and Monegros areas, Fig. 1) from the central part of the Ebro foreland basin (northern Spain). These results are combined with previously published (Arlegui and Simón, 1998, 2001; Simón et al., 1999), unpublished and new palaeostress data obtained from fault populations and joint sets developed on limestone beds interbedded with the mudrocks. Systematic comparison of AMS and palaeostress results, both at local and regional scales, provides a detailed evaluation of the origin and significance of the magnetic fabric in the studied mudrocks. The knowledge of the evolution of the Neogene stress field in the Ebro basin within the geodynamic scenario of the northeastern Iberian Peninsula (see Arlegui, 1996) makes the Ebro basin an ideal location to contrast the reliability of magnetic fabric as palaeostress indicator.

2. Geological setting

2.1. The Ebro foreland basin

The Ebro basin is a triangular-shaped basin that formed during the Tertiary at the foreland of the Pyrenees, the Iberian, and the Catalan Coastal ranges fold-and-thrust belts (Alonso-Zarza et al., 2002) (Fig. 1). Tectonic uplift occurred in the latest Eocene in the western Pyrenees and the Catalan Coastal Ranges cut the connection of the Ebro basin with the open ocean (Alonso-Zarza et al., 2002). The Ebro basin subsequently developed as an internally drained depression until the Late Miocene (Alonso-Zarza et al., 2002), when the Mediterranean drainage network captured the basin (García-Castellanos et al., 2003). The Ebro basin comprises a continuous sequence of latest Eocene, Oligocene and Miocene continental sediments (Alonso-Zarza et al., 2002). Thick conglomerate sequences deposited at the margins of the basin record the main tectonic events in the Pyrenees, the Iberian, and the Coastal Catalan ranges. Toward the central part of the basin, conglomerates grade to sandstones and mudstones of alluvial and fluvial origin. Such fluvial systems converged into the internal sector of the basin, where palustrine areas and extensive freshwater and saline lake systems developed depending on climate conditions. The stratigraphic sequence reaches more than 5500 and up to 3000 m in thickness in the Pyrenean (north) and Iberian (south) margins, respectively (Alonso-Zarza et al., 2002). Such difference between the northern and southern margins of the basin attests for the flexural subsidence of the foreland basin in response to tectonic loading by the Pyrenean allochtonous units (Muñoz, 1992).

2.2. Brittle mesostructures and palaeostresses in the Neogene Ebro basin

Continental sediments of the central part of the Ebro basin are affected by different fracture systems at the outcrop scale that include several joint sets as well as reverse, strike-slip and normal faults (Fig. 2) (Arlegui and Simón, 1998, 2001; Simón et al., 1999). These structures are especially well exposed in the lacustrine sediments that crop out at the Bardenas Reales and Monegros areas, where the presence of limestones favoured development of fractures, with preservation of kinematic indicators on their surface. The excellent exposure conditions allow determination of the geometry and timing relationships between different fracture systems, which developed according to the following general sequence: 1) E–W striking reverse faults; 2) NNW to NNE striking strike-slip faults; 3) N–S striking joints; 4) N to NE striking normal faults; and 5) E–W striking joints. E–W striking reverse and NNW to NNE striking

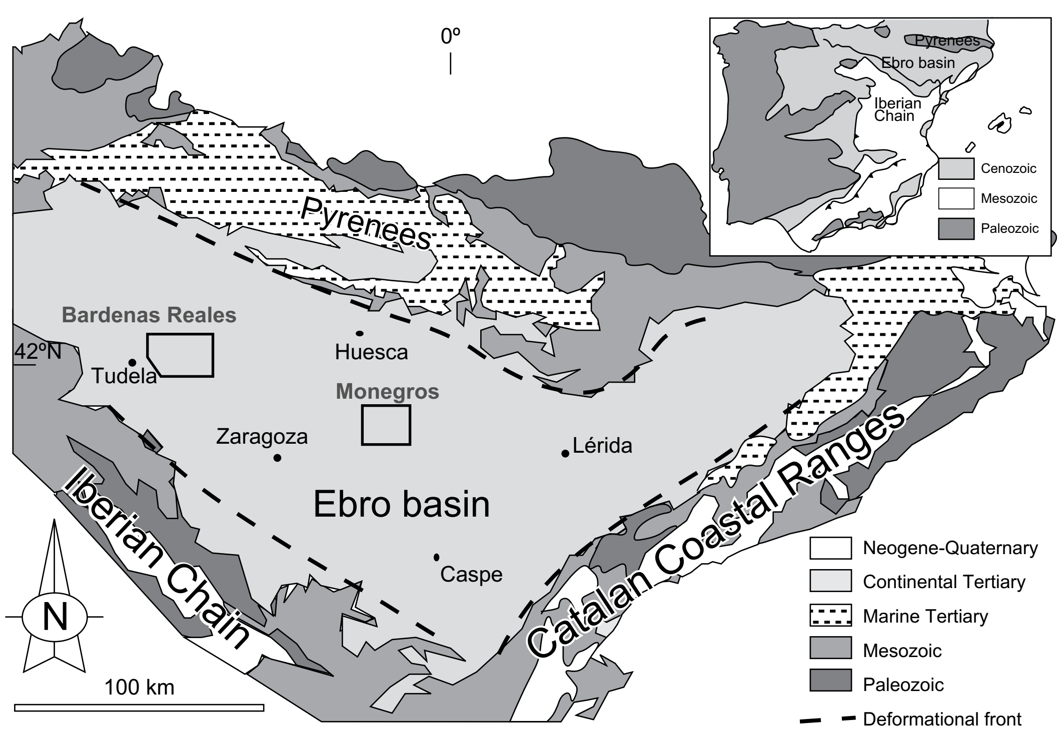

Fig. 1. Geological sketch map of the Ebro basin, with location of the Bardenas Reales and Monegros areas shown in Figs. 3 and 4.