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Paleomagnetic evidence for dextral strike-slip motion in the Pyrenees during alpine convergence (Mauléon basin, France)

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ABSTRACT

The paleomagnetic study of the Aptian–Albian black marls from the inverted Early Cretaceous Mauléon basin in the northern Pyrenees reveals two components of magnetization that both yield negative fold tests. The carriers of each component show different unblocking temperatures indicating that ferrimagnetic iron sulphides are the main carriers of the intermediate temperature component (ITC unblocks around 360–400 °C) and magnetite is the main carrier of the high temperature component (HTC unblocks around 460–500 °C). Both components show a clockwise deviation in declination with respect to the reference field directions (ITC: *D*&*I*: 274, −60, α_{95}: 10°, *k*: 17; and HTC: *D*&*I*: 059, 52, α_{95}: 28°, *k*: 4; both in *in situ* coordinates). The reference direction for stable Europe for the Cenozoic is: *D*&*I*: 001, 50, ΔD: 5, ΔI: 3. However, the reversal test for both of the magnetization components *in situ* is positive. The structural evolution of the basin involves transtensional deformation during the main stage of basin formation, and inversion during compression with migration of hydrocarbons and development of thrusts and folds with axial planar cleavage. Secondary magnetizations were acquired at the latest stages of the evolution of the inverted basin (post-folding) as the result of a chemical mechanism, and they were blocked during two different, and likely close-spaced in time, polarity chrons. The blocking of the two different magnetizations, with different carriers, implies chemical changes in the environment from anoxic, sulphate-reduction to oxic. Inferred clockwise rotation of the paleomagnetic vectors can be interpreted in terms of dextral shear across the North-Pyrenean Zone during the Tertiary (probably Eocene, according to the plate tectonic scenario). This distributed dextral shear was probably favored by discrete shear along cleavage planes, as shown by geologic markers of consistent dextral strike-slip motion in non-competent units with strong cleavage development. There is no evidence of such dextral movement in the South-Pyrenean Zone, thus indicating a strong partitioning of deformation during the Pyrenean orogeny.

1. Introduction

Paleomagnetic studies in deforming (shear) zones reveal different frames for the fault-bounded blocks to rotate, depending on the orientation of the faults respect to the shear zone (Lamb, 1987), which in turn depends on the heritage of the tectonic structures (orientation). Models for block rotations show that orientation of strike-slip faults/shear zones relative to the attending stress state, as well as the geometry of the rotating blocks, will have a major control on the sense and magnitude of rotation (Geissman, 2004). For example, Ron et al. (1984) suggest a mechanism that would result in anticlockwise rotations within the blocks of a sinistral shear zone, whereas Garfunkel (1989) finds clockwise rotations of the fault-bounded blocks that are associated with sinistral slip. McKenzie and Jackson (1983) discuss the possibility of finding blocks with clockwise rotations and also with anticlockwise rotations in a sinistral shear zone. However, when fault-bounded blocks are poorly defined if not completely undetermined in a shear zone, paleomagnetism can be the only technique that reveals the internal deformation within a shear zone with scarcity of strain markers (Burchfiel et al., 2007).

Some paleomagnetic studies in fold-and thrust belts reveal the presence of at least one secondary component of magnetization that provides information not only about the chemistry, temperature and development of the belt during the period of shortening (Jackson et al., 1988; McCabe and Elmore, 1989; Hirt et al., 1992; Hillegeist et al., 1992; Suk et al., 1993; Appel et al., 1995; Villalaín et al., 1994; Juárez et al., 1998; Stamatakos et al., 1996; Enkin et al., 2000; Dinarès-Turell and García-Senz, 2000; Elmore et al., 2001; Weil and Van der Voo, 2002; Larrasoaña et al., 2003; Otofuji et al., 2003; Aiello et al., 2004; Oliva-Urcia and Pueyo, 2007a; Grabowski et al., 2009) but also about the geometry of the basin before compression (Villalaín et al., 2003; Garcés et al., 2003; Soto et al., 2008). Sometimes, two secondary components of magnetization have been described, providing

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additional information about vertical axis rotations and development of deformation (Parés et al., 1994; Van der Voo et al., 1997; Weil et al., 2001; Zwing et al., 2002; Pueyo et al., 2007). Therefore secondary magnetizations can be very useful as kinematics indicators of intermediate stages of deformation.

The Mauléon basin registers the evolution of a sedimentary basin from its formation in a pull-apart setting under sinistral transtensional motion during Aptian–Albian times in the Northern Zone of the Pyrenees (Debroas, 1990; Choukroune, 1992; Bourrouilh et al., 1995; Canérot et al., 2005), to inversion of the extensional structures during the collision of Eurasia and Iberian–African plates from in the Late Cretaceous to the Miocene (Choukroune and E.C.O.R.S. Team, 1989; Choukroune, 1992; Roure et al., 1989; Muñoz, 1992; Daignières et al., 1994). Normal faults were then reactivated as reverse faults, with low-angle detachments cutting across the basement in the Axial Zone of the Pyrenees. During the tectonic inversion, hydrocarbon migration and cleavage development occurred. Over such a long, protracted history, anticlockwise vertical axis rotations related to the sinistral pull apart movements during the extensional regime (Ron et al., 1984) can be expected, as well as remagnetization events related to diagenesis (Katz et al., 1998), in addition to hydrocarbon migration (Elmore et al., 1987) or to fluid flow (McCabe and Elmore, 1989; Grabowski et al., 2009) related to crustal shortening.

In contrast to the southern Pyrenees, the North Pyrenean Zone has received very little attention from the point of view of paleomagnetic studies, except for some magnetostratigraphic studies in marine limestones that were deposited across the K/T boundary (Delacotte et al., 1985; Barchi et al., 1997; Le Callonnec et al., 1997; Galbrun, 1997; Thibal et al., 1999; Galbrun and Gardin, 2004) and some scattered sites in alkaline rocks (Storetvedt et al., 1999).

This paper focuses in the kinematic and thermo-chemical environment evolution during the inversion of the Mauléon transtensional basin (North Pyrenean Zone). The study is based on paleomagnetic and rock magnetic information from 37 sites distributed in the Aptian–Albian black marls of the Mauléon basin and evaluates these data in the context of possible deformation patterns in this part of the Pyrenees.

2. Geologic and structural setting

The Pyrenees is a mountain chain formed during the Tertiary at the junction between the European and Iberian plates. This plate border was extensional during Triassic and Jurassic times, then changing to a strike-slip regime during the eastwards movement of Iberia with respect to Europe during the Early Cretaceous (Boillot, 1984; Choukroune, 1992). Marine and terrestrial sedimentation developed during the Cretaceous–Tertiary transition. A turbiditic sequence in the northwest Pyrenees, and partly in the South Pyrenean Central Unit, was deposited during the Late Cretaceous. Foreland basin sedimentation began clearly from the early Eocene onward, with the development of the Southern Pyrenean basins, later transported in piggyback sequence toward the southernmost foreland basin, the Ebro basin.

The Mauléon basin is located between the North-Pyrenean fault, which is considered to be the limit between the European and Iberian plates, and the Late Cretaceous north-Pyrenean turbiditic basins (namely the Arzacq basin), partly covered at present by the Tertiary molasse of the Aquitaine basin. The principal deposits of the Mauléon basin consist of black marls accumulated in a deep, anoxic basin, and showing maximum thickness in the basin depocenter of about 1500 m, abruptly diminishing towards the basin margins (BRGM, 1969). The Mauléon basin shows at present a Pyrenean, WNW–ESE structural trend, resulting from crustal shortening during basin inversion. Structures show steeply-dipping fold limbs (Ternet et al., 2004; Dubos-Sallée et al., 2007), with a dominant southward vergence of asymmetric folds and thrusts. Anticlines are asymmetric, with faulted southern limbs, probably because they nucleated at inherited normal faults. Steeply-dipping thrusts can also be interpreted, with the Upper Triassic clays and evaporites as the main detachment level. Widespread foliation can be identified throughout the basin, in continuity with alpine cleavage developed in the Palaeozoic and Mesozoic sequences of the Axial Zone and the southern Internal Sierras. Cleavage typically is subvertical to steeply dipping, both to the south and to the north (Debroas, 1990; Choukroune, 1992), interpreted as the result of a continuous process of foliation development, folding, and later foliation.

The origin of the Mauléon basin has been linked to pull-apart zones within the overall left-lateral shear between the Iberian and European plates during the Early Cretaceous (Debroas, 1990; Choukroune, 1992; Barnolas et al., 1996), producing an extreme crustal thinning in the area (Jammes et al., 2009). However, the geometry of the extensional or transtensional faults limiting the basin is not accurately known, mainly because of the later deformation of normal faults. Most workers consider that a set of Early Cretaceous faults must be parallel to the present Pyrenean trend, and the other set can be either NE–SW (Debroas, 1990) or NNW–SSE (Bourrouilh et al., 1995; Canérot et al., 2005). This ambiguity results from the difficulty of identifying normal faults that are only recognizable from thickness changes in the Albian sequence. The faults with Pyrenean trend were reactivated as reverse faults under compression, and the other set probably re-activated as strike-slip faults during the Tertiary (Debroas, 1990).

3. Paleomagnetic methods

Most sites (31) were drilled in the field with a portable unit cooled with water. In addition oriented blocks were also taken at six sites (Fig. 1). An average of 8 specimens (one per independent sample) per site were paleomagnetically analyzed. Most of the remanence measurements were conducted using a 2 G Enterprises DC SQUID based superconducting magnetometer with an integrated 2 G AF demagnetization unit and an MMTD-60 furnace in the shielded room of the paleomagnetism laboratory at the University of New Mexico (UNM). A pilot laboratory set of demagnetizations was run in the paleomagnetic laboratory at the University of Michigan (UM) (2 G superconducting magnetometer, a SI-4 AF demagnetizer -Sapphire Instruments- and a TD-48 ASC furnace). Detailed stepwise demagnetization typically involved initial AF demagnetization up to 70 or 100 mT (every 5 to 10 mT steps) and then thermal demagnetization with 50° interval until 300° and then every 25–30° steps until 580° if needed (UNM measurements), and 50° interval until 300 °C and then 30° steps until 560° if needed (TH); 1 mT interval until 20 mT (UM measurements). Bulk susceptibility measurements were made with a KLY4S (AGICO Kappabridge) at UNM after every thermal demagnetization step to investigate the possible change in magnetic mineralogy with temperature. In total, 262 standard specimens were demagnetized in the laboratory (210 specimens by AF + TH and 52 by TH).

After the magnetic analyses, the components for every sample were calculated by means of PCA (principal component analyses, Kirschvink, 1980) with the Paleomag OSX v3.1b1 software (by Craig Jones) and the Paldir software (University of Utrecht). For three sites, great circles were also calculated and their intersections (INT) added to the PCA results to determine a more robust average component (Bailey and Halls, 1984). To validate some estimates of a site mean direction at the site scale, the Virtual Directions method (Ramón and Pueyo, 2008) was also used. Fisher (1953) averages for each component were calculated with Stereonet software (Allmendinger, 2005) at every site. Due to the structural setting of the Mauléon basin, the fold (McElhinny, 1964) and reversal (McFadden and McElhinny, 1990) tests were performed at regional scale using the SUPER-IAPD software (Torsvik et al., 1996). Rock magnetic (thermomagnetic curves, Magnetic Properties Measurement System – MPMS – measurements) and optical analyses (SEM and EDX qualitative chemical analyses) of the Black marls are reported in Oliva-Urcia et al. (2010). New acquisition curves of isothermal