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Quantification of mass transfers and mineralogical transformations in a thrust fault (Monte Perdido thrust unit, southern Pyrenees, Spain)

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ABSTRACT

In fold-and-thrust belts, shortening is mainly accommodated by thrust faults which are preferential zones for recrystallisation and mass transfer. This study focuses on a detachment fault related to the emplacement of the Monte Perdido thrust unit in the southern Pyrenees. The studied fault zone consists of a 10 m thick intensively foliated phyllonite developed within the Millaris marls, of Eocene age. The lithological homogeneity of the hanging wall and footwall allows us to compare the Millaris marls outside the fault zone with the highly deformed marls located in the fault zone and to quantify the chemical, mineralogical and volumetric changes related to deformation processes along the fault.

The Millaris marls are composed of detrital quartz, illite, chlorite, minor albite and pyrite, in a micritic calcite matrix. In the fault zone, the cleavage planes are marked by clay minerals and calcite ± chlorite veins attest to fluid–mineral interactions during deformation.

The mineral proportions in all samples from both the fault zone and Millaris marls have been quantified by two methods: (1) X-ray diffraction and Rietveld refinement, and (2) bulk chemical analyses as well as microprobe analyses to calculate modal composition. The excellent agreement between the results of these two methods allows us to estimate mineralogical variations using a modification of the Gresens' equation. During fault activation, up to 45 wt% of calcite was lost while the amounts of quartz and chlorite remained unchanged. Illite content remained constant to slightly enriched. The mineralogical variations were coupled with a significant volume loss (up to 45%) mostly due to the dissolution of micritic calcite grains. Deformation was accompanied by pressure solution and phyllosilicates recrystallisation. These processes accommodated slip along the fault. They required fluids as catalyst, but they did not necessitate major chemical transfers.

1. Introduction

In fold-and-thrust belts, major thrust faults have a strong impact on fluid flow and vice versa (e.g. McCaig et al., 2000). Fluid-rock interactions and fault activation might be responsible for chemical and mineralogical modifications in the fault zone. These modifications might have major impact on fault sealing potential but also on fault weakening (e.g. Byerlee, 1978; Carpenter et al., 2011; Gratier et al., 2013; Numelin et al., 2007). Quantifying mass transfers associated with deformation and fluid–rock interactions in faults affecting sedimentary rock is a difficult challenge because sedimentary rocks have generally heterogeneous composition and mineralogical quantification is hard because of the small size of the minerals.

In the Monte Perdido thrust fault, the mechanisms and the conditions of deformation have been well constrained in previous studies by Lacroix et al. (2011, 2012). These authors combined structural, geochemical and fluid inclusion analyses to determine the PT conditions of deformation and origin of the fluids in fault zones related to the emplacement of the Monte Perdido thrust unit (SW-Central Pyrenees). They showed that deformation in fault zones led to the development of a pervasive pressure solution cleavage as well as the formation of calcite-quartz shear and extension veins. The oxygen isotope analyses of syntectonic calcite

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and quartz veins combined with fluid inclusion microthermometry allowed the determination of the P-T conditions of deformation, i.e. ~208 °C/570 bar for the main shearing stage and ~240 °C/650 bar for the late shearing stage of the fault zones. Moreover, Lacroix et al. (2012) demonstrated through stable isotope analyses on carbonate veins that pressure solution with local mass transfer of calcite seems to be the major mechanism of this aseismic deformation. The pressure solution deformation mechanism might cause concentration of insoluble clay minerals and mechanical weakening within the fault zone (Lacroix et al., 2013). In the same fault zones, Buatier et al. (2012) demonstrated that clay minerals did not only act as passive insoluble mineralogical phases but that phyllosilicates dissolution and precipitation occurred during deformation in the most deformed sediments.

The aim of the present study is (1) to quantify the mass transfers during deformation and mineralogical reactions in a fault zone related to the emplacement of the Monte Perdido thrust unit and (2) to characterise the mineralogical reactions due to fluid–rock interactions in this fault zone. Mineralogical reactions have been deduced from electron microscopy and X-ray diffraction analyses, and quantified by Rietveld refinement. Mass transfers have been studied by bulk rock chemical analyses coupled with chemical point analyses and then quantified using mass balance calculation. Previous studies (e.g. Buatier et al., 2012; Lacroix et al., 2012, 2013) were realised on three selected outcrops, two outcrops corresponding to the Monte Perdido sole thrust with footwall and hanging wall of different lithologies (the Torla thrust) and the third one is a detachment fault inside the thrust unit (the Millaris fault). The latter fault was chosen for the present study because the similar marl lithology of the footwall and hanging wall is compatible with the assumption that the initial states of the sediments on both sides of the fault zone before deformation were identical.

2. Geological setting and outcrop description

The Pyrenean belt is a doubly-vergent orogenic wedge formed during the collision of the Iberian and European plates from the Late Cretaceous to the early Miocene (e.g. Muñoz, 1992; Roure et al., 1989; Teixell, 1998). The south-vergent thrust system comprises imbricated basement thrusts, which form the anticlinal stack of the Axial Zone and pass southwards to detachment levels below the cover thrust units of the South-Pyrenean Zone (Fig. 1).

The studied area is located in the South-Pyrenean Zone, in the northern part of the Jaca Basin (Fig. 1). Above the Triassic detachment level, the stratigraphy of the northern Jaca Basin comprises Cenomanian to Santonian platform limestones overlain by the syn-orogenic succession with, from bottom to top, Campanian to early Eocene (lower Ypresian) platform carbonates (divided in (i) Campanian–Maastrichtian sandy limestones and sandstones and (ii) Paleocene to lowermost Ypresian dolomites and limestones), lower Ypresian marls (the Millaris marls), the Ypresian–Lutetian turbidites of the Hecho Group and Bartonian to lower Oligocene coastal and continental deposits (e.g. Teixell, 1996) (Fig. 2). In the east, outer shelf carbonates are intercalated between the Millaris marls and turbidites. At the northern edge of the Jaca basin, the Triassic evaporites are absent and the Upper Cretaceous limestones rest directly on the Paleozoic basement of the Axial Zone.

The two major thrust units in the vicinity of the study area are the Monte Perdido and Gavarnie thrusts units with about 6 km and 10 km displacement respectively (Séguret, 1972; Teixell, 1996) (Fig. 2). To the north, the Monte Perdido sole thrust is a detachment located in the lower part of the Upper Cretaceous limestones. Southwards, the sole thrust cuts across the carbonate succession to reach an upper detachment in the early Eocene Millaris marls. Inside the Monte Perdido unit, an upper duplex system is located between a sole detachment in the upper part of the Campanian–Maastrichtian sandstone (Grès du Marboré Formation) and a roof detachment in the Millaris marls. To the north, the Monte Perdido thrust unit is folded by the hanging wall culmination of the underlying Gavarnie basement thrust, which passes southwards to the Triassic detachment level. Both the Monte Perdido and Gavarnie units are affected by a regional pressure-solution cleavage formed during their emplacement (Labaume et al., 1985; Oliva-Urcia et al., 2009; Séguret, 1972; Teixell, 1996). Both units are tilted southwards by the hanging wall culmination of another underlying basement thrust (Mutti et al., 1988). The Monte Perdido thrusting is dated to the mid-late Lutetian to end Bartonian (~46–38 Ma). The Gavarnie thrusting is dated to the Priabonian to Rupelian by stratigraphy (Teixell, 1996) and to Maastrichtian–Priabonian by Ar–Ar isotopic dating on authigenic illite (Rahl et al., 2011).

The studied fault zone (the Millaris fault) is located in the lower Ypresian Millaris marls, which are sub-horizontal along the studied outcrop. The fault zone is a 10 m thick shear zone sub-parallel to bedding bounded by major shear surfaces (Fig. 3). Outside the fault zone, the Millaris marls are affected by a north-dipping regional cleavage. Inside the fault zone, the fault-rock is intensely deformed and darker than the host marls, featuring a well-developed, closely-

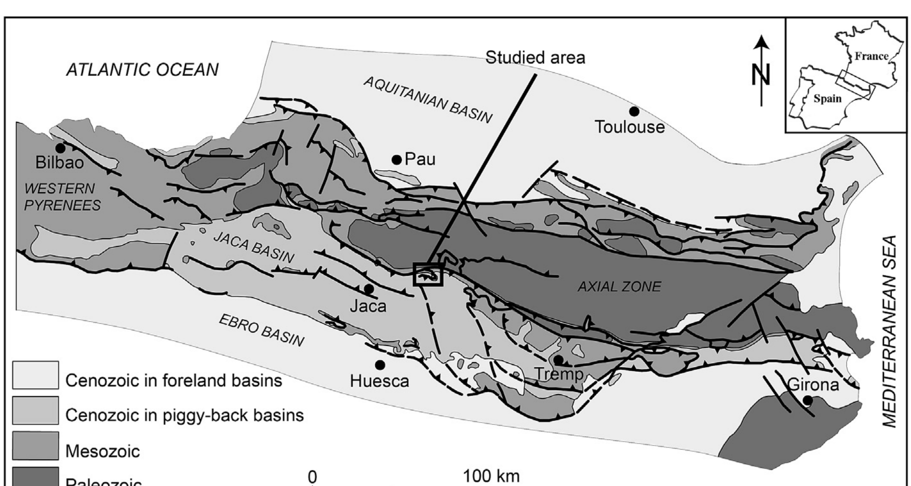

Figure 1. Structural map of the Pyrenees with the location of study area (modified from Teixell, 2000).