# Early record of tectonic magnetic fabric during inversion of a sedimentary basin
# Short review and examples from the Corbières transfer zone (France)

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*Key words*. – Magnetic fabric, Analysis of fault-slip data, Fold-and-thrust belt, Corbières, France

*Abstract*. – An integrated study combining anisotropy of magnetic susceptibility (magnetic fabric) and analysis of meso-scale structures is presented. The studied sites, which belong to the Corbières transfer zone (France), suffered a clear polyphase deformation. The magnetic fabric is of tectonic origin and records an early layer parallel shortening. In general, this primary fabric is not altered by later deformations including folding. However, secondary fabrics have been observed in the vicinity of major faults. They are probably related to tectonically driven fluids migrating along these planes. Consequences on interpretation and use of magnetic fabrics in inverted sedimentary basins are discussed.

# Enregistrement précoce de la fabrique magnétique au cours de l'inversion d'un bassin sédimentaire.
# Revue brève et exemples provenant de la zone de transfert des Corbières (France)

*Mots clés*. – Fabrique magnétique, Analyse microtectonique, Ceinture de chevauchement-plissement, Corbières, France

*Résumé*. – Une étude intégrée combinant des mesures d'anisotropie de susceptibilité magnétique (fabrique magnétique) et une analyse microtectonique est présentée. Les sites choisis qui proviennent de la zone de transfert des Corbières (France), ont subi une déformation polyphasée. La fabrique magnétique est d'origine tectonique et acquise précocement lors d'un épisode de raccourcissement parallèle aux couches. Dans le cas général, cette fabrique magnétique primaire n'est pas modifiée lors des déformations ultérieures, notamment par le plissement. En revanche, des fabriques magnétiques secondaires s'observent à proximité des failles majeures en liaison probable avec des circulations ascendantes de fluides le long de ces plans. Les conséquences sur l'interprétation et l'utilisation des fabriques magnétiques dans les bassins sédimentaires déformés à faible température sont discutées.

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## INTRODUCTION

Anisotropy of magnetic susceptibility (AMS) is now a standard tool for structural analysis [review *in* Borradaile, 1988; Rochette *et al.*, 1992; Borradaile and Henry, 1997]. In sedimentary basins deformed at low temperature, which is the topic of the present paper, this technique is used to complete or replace the analysis of meso-scale structures (stylolite, cleavage, tension gashes *etc*…) and, in particular, stress tensor reduction methods applied to fault-slip data [Carey and Brunier, 1974; review *in* Angelier, 1994] or to calcite twinning [review *in* Lacombe, 2001].

However, nature of information given by these methods is different. On one hand, the analysis of meso-scale structures or calcite twinning allows to distinguish the superimposition of different events and, with inversion methods, to establish an agenda of successive paleo-states of stress. On the other hand, AMS reflects the preferred orientation of grains and/or crystal lattice of minerals contributing to the susceptibility (essentially ferro- and paramagnetic minerals). Beyond the classical question of relationships between

AMS and strain [Borradaile and Henry, 1997], a key point is to know whether the calculated tensor is composite or, on the contrary, is related to a given tectonic event.

Within a sedimentary rock deformed at low temperature, an early record of the magnetic fabric is proposed by Graham [1966], who assumes that a change from sedimentary to tectonic fabric is easier within unconsolidated rocks. This point of view is reinforced by laboratory experiments of Borradaile [1988]. For natural deformations, integrated studies coupling AMS and analysis of meso-scale structures led to conflicting proposals that we present below.

In extensional context, Mattei *et al.* [1997] present AMS of sites situated close to major normal faults in the Ofanto piggy-back basin (southern Apennines). They show that AMS ellipsoid (the so-called magnetic fabric) is coaxial to the first of the three "tectonic events" defined by the analysis of meso-scale structures [Hippolyte, 1992].

In compressional setting, studies are more abundant following pioneering work by Kliegfield *et al.* [1981] in the "Dôme de Barrot" (French Alps), Kissel *et al.* [1986] in Greece, Lowrie and Hirt [1987] in Italy and Lee *et al.*

[1990] in Taïwan. The main purpose of these first studies was to demonstrate the usefulness of AMS to supply the scarcity of striated faults in siliciclastic sediments. So they aim at demonstrating that AMS and strain ellipsoids are co-axial. More precisely, work by Averbuch *et al.* [1992, 1993], Frizon de Lamotte *et al.* [1995; 1997] and Grelaud *et al.* [2000] in the Corbières (France) as well as by Sagnotti *et al.* [1998] in northern Apennines (Italy), Bakhtari *et al.* [1998] in Zagros (Iran), Grelaud [2001] in the Potwar basin (Pakistan) and Sanz *et al.* [2002] in the southern flank of the Pyrenees (Spain) show that magnetic fabric is, in general, recorded before folding. Accordingly, Weiler and Coe [1997] show that magnetic fabric is recorded before syn-thrusting vertical axis rotations defined by paleomagnetic data in a very recent sedimentary wedge of Papouasia-New Guinea.

However this timing, which relates magnetic fabric to the first stages of basin inversion, is not always confirmed. On the contrary, some authors underline that magnetic fabric acquisition is late. It is clearly the case where rocks are affected by metamorphism (even low) as shown by Housen and van der Pluijm [1991] and Robion *et al.* [1995; 1999] but metamorphism is out of the scope of our paper. In the Appalachian plateau, where sedimentary rocks have been deformed at low temperature, comparison between AMS and calcite twinning led Jackson *et al.* [1989] to consider that AMS is late. Showing that in alpine plutons AMS records a very late event, Henry [1974] is in line with such a timing. Accordingly, in the Calabrian Arc, it is suggested that AMS post-dates thrusting and related vertical axis rotations [Scheepers and Langereis, 1994].

So, even if the tectonic environment is relatively simple, chronological relationships between AMS record and development of meso-scale structures are not straightforward. The aim of this paper is to analyse typical sites where the sequence of mesoscale structures is well established. The presented sites, which belong to the Corbières transfer zone (France), are consistent with deformation observed elsewhere in the region. We will see in both cases that AMS is recorded early. In the discussion, we will examine the conditions allowing changes of the magnetic fabric. Consequences and recommendations will be presented in the conclusion.

## MESO-SCALE STRUCTURES AND AMS ANALYSIS OF SELECTED SITES

The two sites belong to the Corbières transfer zone (i.e. the arc joining the North Pyrenean zone and the Languedoc-Provence thrust belt, fig. 1A). This domain is characterised by a thin sedimentary pile formed by lacustrine limestone, sandstone and silt of Maastrichtian to Lutetian age supporting Bartonian molasses [Ellenberger, 1967; Plaziat, 1984]. This cover together with the Paleozoic substratum are involved in large ramp-related folds [Averbuch *et al.*, 1992; Frizon de Lamotte *et al.*, 1997; Grelaud *et al.* 2000]. At the regional scale the folds exhibit an "en-échelon" pattern relative to the North Pyrenean front, locally called "nappe des Corbières orientales" (fig. 1B).

Analysing meso-scale structures, Cluzel [1977] showed that the region was affected by two successive tectonic events characterised by NW-SE and WNW-ESE trends of shortening, respectively. These two events, labelled herein

after older and younger tectonic events, have been recognised everywhere in the Corbières transfer zone [Genna, 1989]. Such a polyphase evolution also exists in the Languedoc thrust-belt [Arthaud and Séguret, 1981; Arthaud and Laurent, 1995, fig. 1A] as well as in the Aquitaine basin [Gély and Sztràkos, 2000] (fig. 1A). However, out of the Corbières transfer zone, they are only defined by chronological considerations and not by change of the trends of shortening.

In the Lagrasse fold (fig. 2A & B), Frizon de Lamotte *et al.* [1997] discussed the relationships between the steps of folding and the regional tectonic events : the older tectonic event (NW-SE) began before and continued during folding whereas the younger tectonic event (WNW-ESE) is coeval with out-of-sequence thrusting.

The two sites presented below are situated in the footwall of the Lagrasse fold and in the forelimb of the Oupia fold, respectively (fig. 1B). The methods are classical and we refer the readers to recent reviews : Angelier [1994] for fault slip data analysis and Borradaile and Henry [1997] for AMS. We note K1 ≥ K2 ≥ K3 the three axes defining the tensor of magnetic susceptibility. In this paper we do not address the magnetic mineralogy, which is discussed elsewhere [Souque *et al.,* 2002]. At regional scale, the work by Averbuch *et al.* [1993] in the Lagrasse region and by Grelaud *et al.* [2000] in the Oupia region shows that the AMS signal is of tectonic origin. In order to avoid some difficulties discussed below, we use strain notation ($\lambda1 \geq \lambda2 \geq \lambda3$) rather than the more usual stress notation for the tensor deduced from inversion of fault-slip data. As under pure shearing strain axes relate directly to stress axes, this choice does not change anything.

### The "Ribaute bridge" site

This site is in the horizontal foreland of the Lagrasse fold (fig. 2 A and B) in a place where the Orbieu river cuts the upper flat and the marly limestone situated just below [Averbuch *et al.*, 1992]. The site exhibits numerous meso-faults bearing typical calcite fibre steps. On some fault planes, superimposed fibres allow to establish a chronology between the two events mentioned above (fig. 3).

During the older tectonic event, stylolitic joints, tension gashes and two sets of conjugate reverse faults developed (fig. 2C). The geometry of these latter obey the classical Anderson's model [*cf.* Angelier, 1994]. The mean 2θ angle between the conjugate faults is about 48°. This low value suggests an important effect of pore fluid pressure in agreement with abundance of fibrous calcite. Inversion of fault-slip data gives a tensor characterised by a λ3 axis trending N147 within the bedding and a λ1 axis perpendicular to bedding (fig. 2). One could note that SE-dipping faults are two times more abundant than the NW-dipping faults. According to Gapais *et al.* [2000], this could suggest a component of bed-parallel shearing consistent with slickensides observed on these planes.

During the younger event, the fault planes created previously are used again and new planes develop. This results in a greater dispersion in the azimuths of the fault planes bearing this second generation of calcite fibres. Tensor reduction leads to a λ3 axis trending N 123 and a λ1 axis perpendicular to bedding, here horizontal since data are corrected from the bedding (fig. 2C).
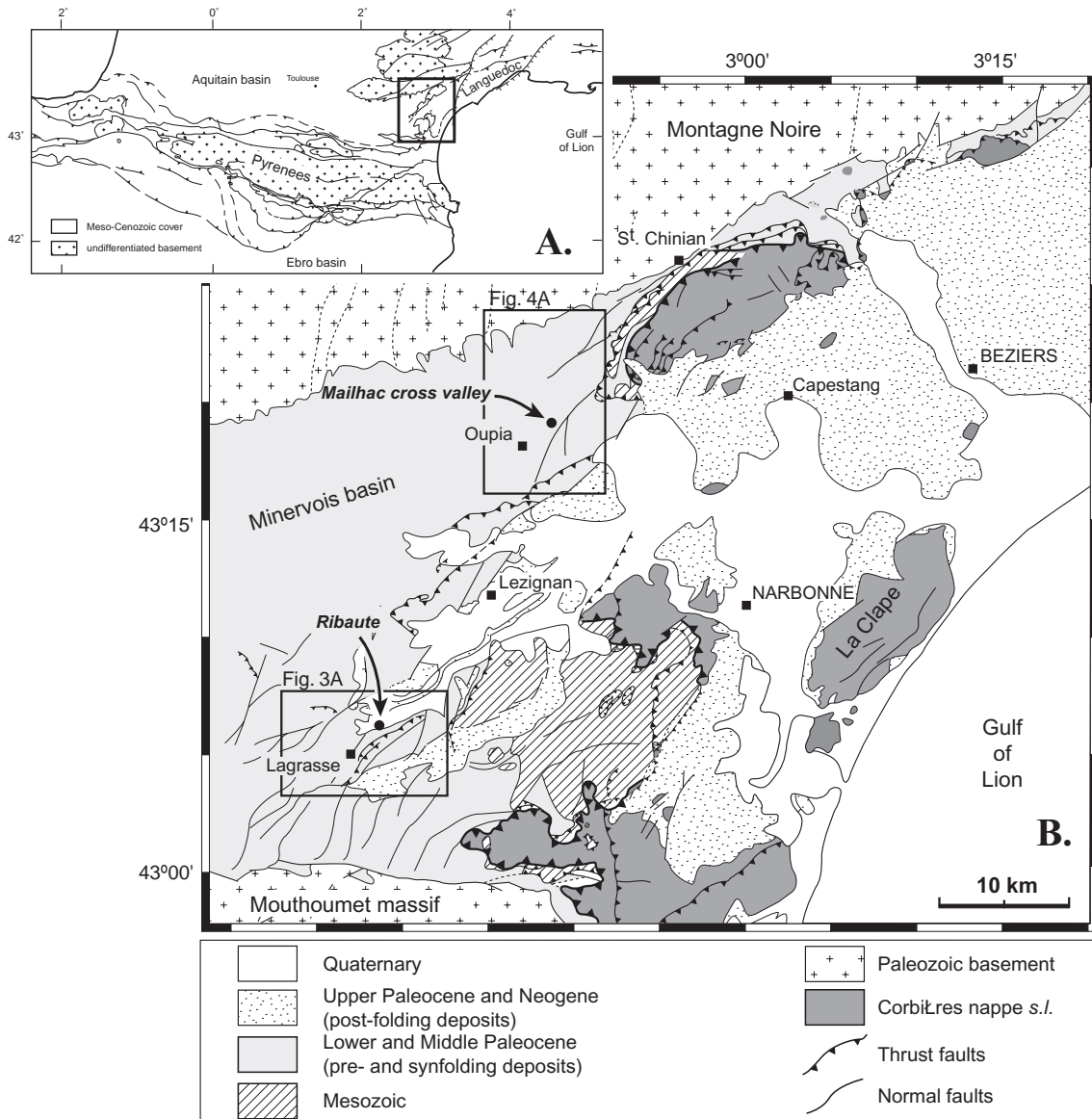
FIG. 1. – Structural sketch map of the Pyrenees (**A**) locating the Corbières transfer zone (**B**)
FIG. 1. – *Carte structurale simplifiée des Pyrénées* (**A**) *localisant la zone de transfert des Corbières* (**B**).

For AMS, the site is characterised by a K3 axis parallel to the pole to bedding and a K1 axis normal to the trend of shortening characterising the older event defined above. Following a classical method to enhance the fabric [Tarling and Hrouda, 1993], we observe that laboratory heating up to 500° and new measurement after cooling led to scattering of K3 axes within a great circle and clustering of K1 axes with a better definition of the magnetic lineation (fig. 2C). Coincidence between mean K1 and calculated λ2 axis is perfect. In other words, AMS is coaxial to the older tectonic event and is not changed by subsequent events.

**The Mailhac cross valley site**

This site is situated in the NW-SE Oupia anticline (fig. 4 A and B). Surface and subsurface data [Berger *et al*., 1990; Genna, 1989] allowed to propose a kinematic model in which the successive steps of the fold building are related to the sequential development of meso-scale structures

[Grelaud *et al*., 2000]. Among the numerous sites studied in the region [Grelaud, 2001], our choice is to present a site from the forelimb of the anticline where the set of mesoscale structures is complete. Samples have been collected and measurements performed in the Assignan formation made up of silt and sandstone of Cuisian age. Beds are overturned (dip 75° toward the SE). As elsewhere along the forelimb, a rough cleavage remains normal to bedding.

AMS data are typically of tectonic origin with a magnetic foliation parallel to the cleavage and a magnetic lineation parallel to the intersection between cleavage and bedding (fig. 4C). The trend of shortening deduced from AMS is N170. The attitude of magnetic foliation relative to bedding suggests that it records an early (pre-folding) layer parallel to the trend of shortening.

Meso-scale faults can be divided into two sets developed before and after folding. It is the reason why we present the first set after dip removed (fig. 4C). In this attitude, the geometry is that of conjugate reverse faults. Inversion
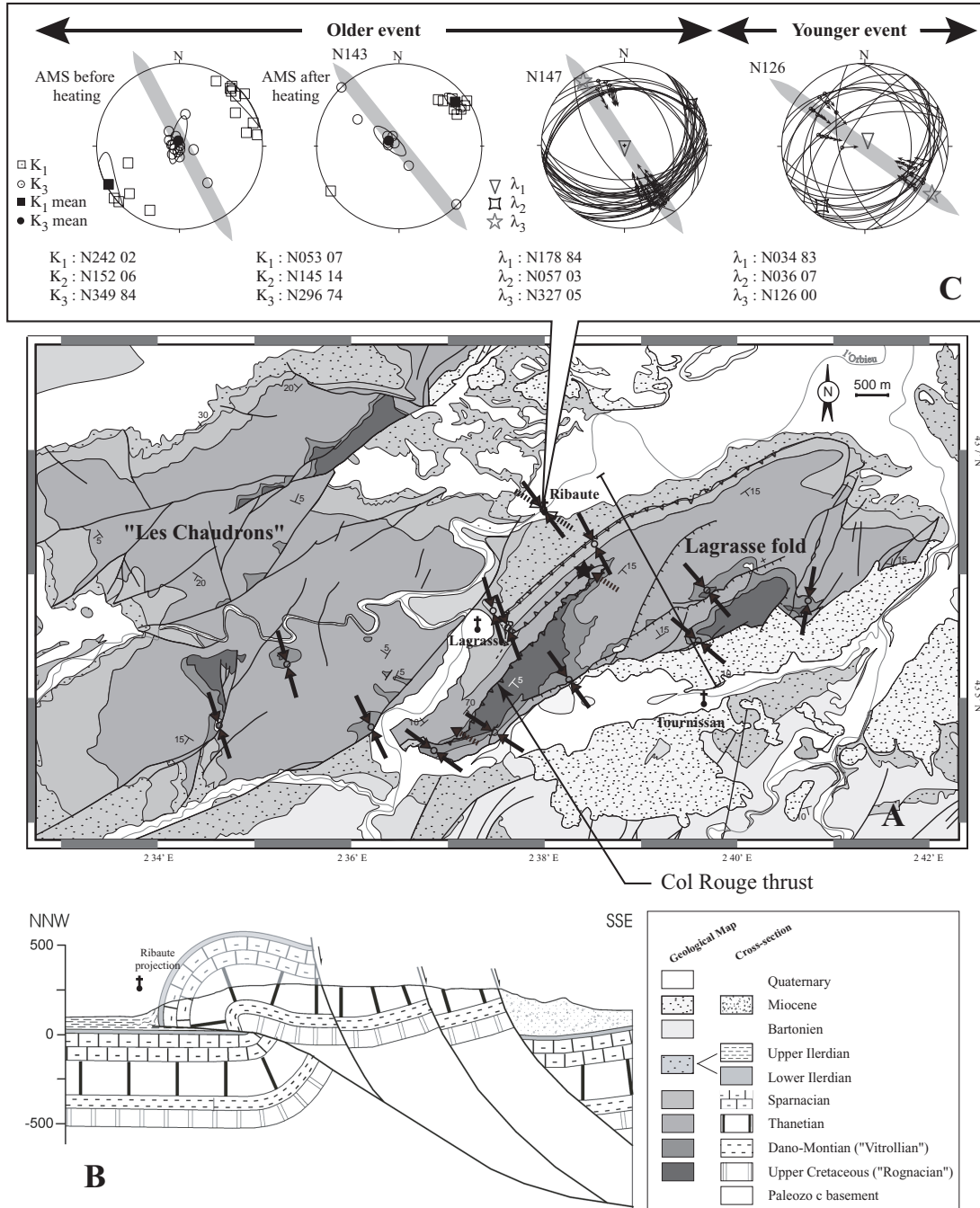
FIG. 2. – The "Ribaute" site in the foreland of the Lagrasse fold. (**A**) geological map of the Lagrasse fold [modified from Ellenberger *et al.*, 1985]. The double black arrows indicate the trend of shortening deduced from AMS data [partly from Averbuch *et al.*, 1992]. The other arrows (broken line) indicate either the tectonic transport direction along the "Col Rouge" thrust (simple arrow) or the trend of shortening related to the younger event (double arrow). (**B**) General cross section of the Lagrasse fold. The position of the section is indicated by the line east of Ribaute. (**C**) AMS and fault-slip data from the Ribaute site. All lower hemisphere stereonets are given after dip removed (few degrees). Stress tensor reduction has been made with an original software designed by S. Lallemant using the Angelier's method [1994].

FIG. 2. – *Le site du pont de Ribaute à l'avant du pli de Lagrasse [modifiée d'après Ellenberger* et al., *1985]. Les doubles flèches noires indiquent la direction de raccourcissement déduite des données ASM [partiellement d'après Averbuch* et al., *1992]. Les flèches en tirets indiquent soit la direction du transport tectonique le long du chevauchement de Col Rouge (flèche simple) soit la direction de raccourcissement associée à l'événement tectonique le plus jeune (flèche double). (**B**) Coupe à travers le pli de Lagrasse. La position de la coupe est donnée par la ligne à l'est de Ribaute. (**C**) Données ASM et micro-tectoniques. Tous les diagrammes stéréographiques sont présentés après remise de la stratification à l'horizontale (quelques degrés).*

of fault-slip data allows to define a $\lambda 3$ axis within the bedding plane and a $\lambda 1$ axis at right angle to it (fig. 4C). This strongly suggests that this faults set also developed during pre-folding LPS. However, the trend of shortening (N148) is different from the one defined by AMS (N170) suggesting that a counter-clockwise rotation of the trend of shortening occurred between AMS record and fracturing.
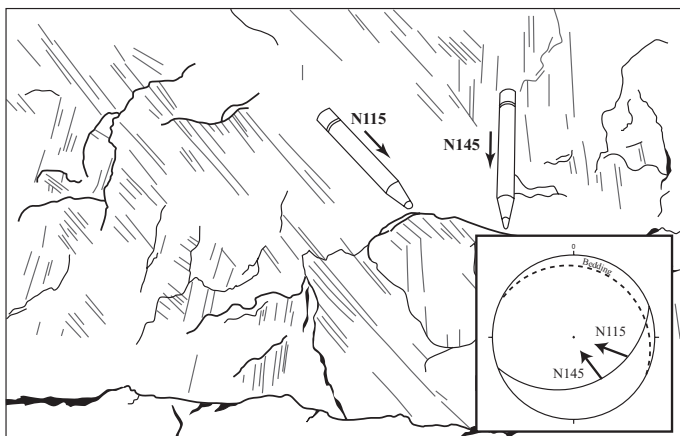
FIG. 3. – An example of superimposed slickensides on a minor fault plane from the "Pont de Ribaute" site.
FIG. 3. – *Exemple de stries superposées sur un plan de faille du site du Pont de Ribaute.*

The second set of meso-faults is more or less perpendicular to bedding. They bear calcite fibres, which are consistent with top to the NW shearing (N148) (fig. 4C). Such faults cutting through the overturned forelimb (i.e. "forelimb thrusts") are related to the late stages of folding.

## DISCUSSION

The "Ribaute bridge" and "Mailhac" sites are representative of the numerous other sites of the region, which were analysed by the same method coupling AMS and mesofaults measurements (fig. 2A and 4A) [Averbuch, 1993; Grelaud, 2001]. They both show that AMS characterising the region is recorded during the first increments of the Pyrenean shortening. In general, this first imprint is not modified by subsequent events including development of fold-thrust belt and grabens network [Ellenberger, 1967; Mascle *et al.*, 1996]. We will discuss first the origin of this primary magnetic fabric, then the conditions allowing the development of a secondary magnetic fabric.

### Origin of tectonic magnetic fabric

From a phenomenological point of view, it appears that AMS records internal deformation (strain) occurring before any development of fractures (fig. 5). New loading, after or without change of the trend of shortening, does not modify AMS. Accordingly, regional cleavage, if exists, is everywhere related to the older event.

From a physical point of view and in the context of low temperature deformation, the processes responsible for the magnetic fabric are quite complex. Three effects are generally considered : stress, grain rotation and crystallisation of new minerals [Borradaile, 1988; Jackson *et al.,* 1993; Borradaile and Henry, 1997].

The role of stress has been put forward by Kapicka [1984; 1988] who experimentally showed that an irreversible change of AMS occurred during a macroscopically elastic deformation. The effect of stress is consequently expected at the grain scale. For the studied sites, a stress effect is not required because there is a close relationship between AMS and the measured strain. In addition, potential stress effects acting during subsequent deformations do not change the magnetic fabric, which remains related to the oldest event. On the other hand, this effect could be advocated to explain the late AMS records presented in the introduction. It is frequent in the French literature to use fault slip data for inferring the orientation and relative magnitude of principal "paleo-stress" axes [see Angelier, 1994]. Some confusions originate from such an use. For instance, Borradaile and Henry [1997] quoted the work by Averbuch *et al.* [1992] and Kissel *et al.* [1995] in the section "AMS as a stress indicator" because these authors compare AMS to "paleo-stress" tensors calculated by inversion of fault slip data. However, in practice, the so-called "dynamic" analysis of fault-slip data consists to infer the orientation of "paleo-stress" axes from direction and sense of slip on faults but without using the amount of glide. So the measured effects do not result from stress in a context of elastic deformation as it has been supposed.

Grain rotation and recrystallisation are linked processes, which act during low-temperature deformation [see review *in* Groshong, 1988]. In the Corbières transfer zone, development of solution cleavage, abundance of stylolites and recrystallisation figures as well as low value of the 2θ angle (the angle between two conjugate faults) show that, among deformation mechanisms, pressure solution plays a major role. Pressure solution allows rotation of rigid grains [Borradaile and Tarling, 1984]. It is worth noting that AMS can record low reorientation with a great accuracy. Thus, small rotations (few degrees) of magnetic grains could explain the magnetic lineation parallel to the cleavage/bedding intersection observed at the Ribaute bridge (fig. 2C). By contrast, this process alone cannot explain the surface transposition leading to the development of a magnetic foliation perpendicular to bedding as observed at Mailhac (fig. 4C) and in numerous other sites of the region [Averbuch, 1993; Grelaud, 2001]. Such a change in the attitude of magnetic foliation requires important grain rotation (> 45°). We consider that such a rotation is inconsistent with the amount of shortening ratio, which is estimated less than 20 %. It is the reason why we emphasise syn-tectonic re-crystallisation of ferromagnetic and paramagnetic phases bearing the signal measured by AMS. This recrystallisation is certainly enhanced by iron release during diagenetic processes [Jackson *et al.,* 1988]. However, further work, including petrographic investigations, are required to progress in the understanding of such processes.
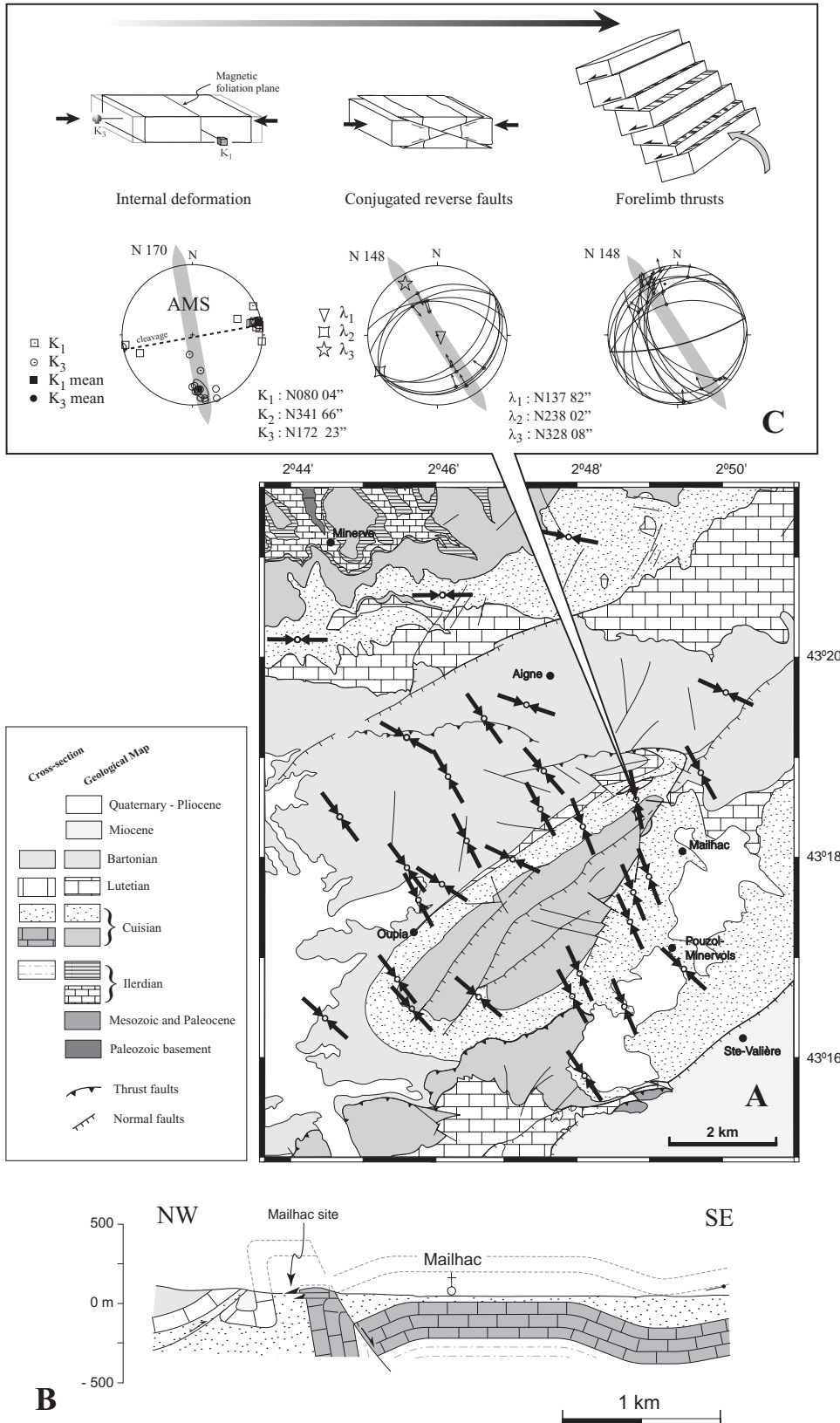
Fig. 4. – The "Mailhac cross-valley" site in the forelimb of the Oupia anticline. (A) geological map of the Oupia fold [modified from Berger *et al.* 1990]. The double black arrows indicate the trend of shortening deduced from AMS data [from Grelaud, 2001]. (B) General cross section of the Oupia fold [from Grelaud *et al.*, 2000]. (C) AMS and fault-slip data from the Mailhac site. The post-folding stereonet (right) is given in geographic coordinates (the bedding plane is the heavy line). The others are after dip removed.

FIG. 4. – *Le site de la cluse de Mailhac. (A) Carte géologique du pli d'Oupia [modifiée d'après Berger* et al., *1990]. Les doubles flèches noires indiquent la direction de raccourcissement déduite des données ASM [d'après Grelaud, 2001]. (B) Coupe à travers le pli d'Oupia [d'après Grelaud* et al., *2000]. (C) ASM et données microtectoniques. Les diagrammes pré-plissement sont donnés après remise de la stratification à l'horizontale. Le diagramme de droite (post-plissement) est donné en coordonnées géographiques (le trait fort figure la position du plan de stratification).*
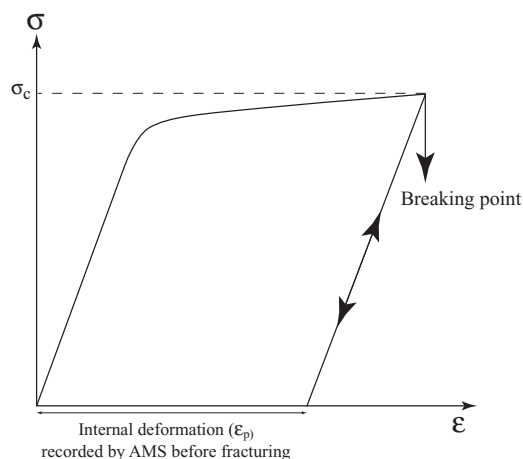
FIG. 5. – Not to scale stress-strain curve illustrating the strain (internal deformation) recorded by AMS.
FIG. 5. – *Courbe contrainte-déformation illustrant la déformation interne mesurée par ASM.*

## Conditions allowing alteration of early AMS imprint

Changes of magnetic fabric record occur in places where tectonic events are accompanied by crystallisation of new mineral phases. Large-scale fluids flow are usually advocated to explain such changes [Rochette and Vialon, 1984 ; Borradaile, 1988 ; Jackson *et al.*, 1988 ; Housen and van der Pluijm, 1991]. In the studied area three different cases occur : initial AMS is completely erased, only masked or "primary" (LPS-related) and "secondary" fabrics coexist.

Changes of the primary magnetic fabric has been observed in different places in the Lagrasse fold. Averbuch *et al.* [1993] show the development of a "secondary" magnetic fabric within the shear zone situated below the "Col Rouge" out-of-sequence thrust fault, which cuts out the Lagrasse forelimb (fig. 6). In this example the "new" magnetic lineation is parallel to the tectonic transport direction characterising the shear zone. This new fabric remains even after laboratory heating of the samples up to 500° (fig. 6).

Souque *et al.* [2002] describe "secondary fabric" occurring in different places along the frontal thrust of the Lagrasse fold and in the "La Cagalière duplex" situated at the lateral tip of this thrust. Contrarily to the secondary fabric described by Averbuch *et al.* [1992], this "primary magnetic fabric" is only masked (overprinted by the secondary one) and is revealed by heating. Possible mechanisms responsible for such changes are proposed by Souque *et al.* [2002].

For the purpose of this paper, we emphasise that, at the regional scale, these secondary magnetic fabrics are scarce : 9 in 62 sites in the Lagrasse region and none in 66 in the Oupia region where the thrust faults remain blind and buried at depth [Grelaud *et al.*, 2001]. Secondary fabric is always developed very close to thrust faults and, in general, in the shear zones associated to faults. Consequently, it is likely that the AMS changes are related to fluid flow along the faults acting as drains.
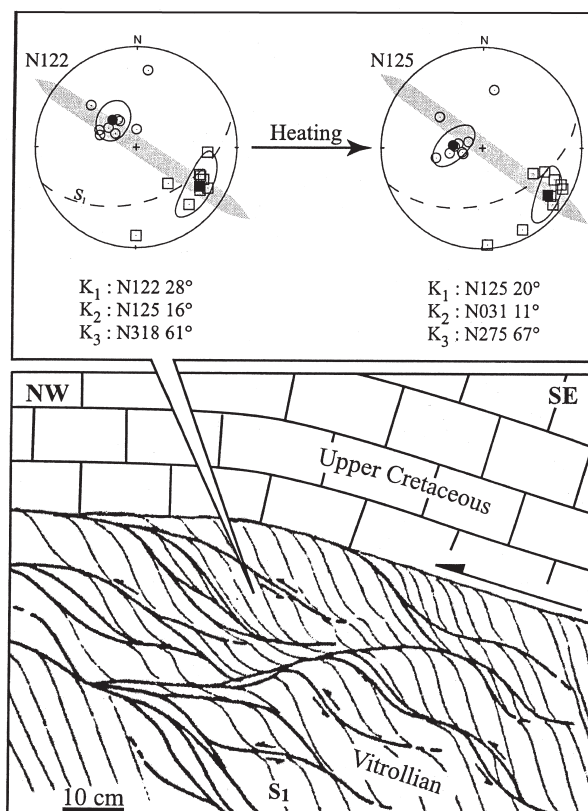


FIG. 6. – The shear zone below the « Col Rouge » thrust [sketch modified from Cluzel, 1976]. The site is located by a star on figure 2A. AMS data before (left) and after (right) laboratory heating at 500 °C. In both cases the magnetic lineation (K1 axis) is parallel to calcite fibres on shear planes.
FIG. 6. – *La zone de cisaillement sous le chevauchement de "Col Rouge" [dessin modifié d'après Cluzel, 1976]. Le site est localisé par une étoile sur la figure 2A. Données d'ASM avant (gauche) et après (droite) chauffage à 500 °C en laboratoire. Dans les deux cas la linéation magnétique (axe K1) est parallèle aux stries portées par les plans de cisaillement.*

## CONCLUSION

Work conducted in the Corbières and Minervois since ten years establishes that AMS measured in silt, sandstone and marly limestone records an early layer parallel shortening predating folding and fracturing. Such an early magnetic fabric can be modified if rocks are involved in shear zones related to major faults. So, according to the abundance of re-crystallisation, we assume that in the region and at the considered shallow depth, the thrust faults act as drains and not as barriers for fluids. In these cases, AMS interpretation is not straightforward because composition of magnetic sub-fabrics or vanishing of primary magnetic fabric have been observed. The use of appropriate tools is required for interpretation of such complex signals [see Souque *et al.*, 2002].

Within the Carcassonne basin (i.e. the north-eastern foredeep of the Pyrenees), AMS records the onset of the basin inversion (i.e. the transition between subsidence and uplift). At that time, the maximum of burial was reached and we can expect that subsequent erosion reduced both pressure and temperature and inhibited any change of the magnetic fabric. Along thrust faults, drainage of fluids enables new crystallisation consistent with this particular tectonic

context and responsible for the development of a new fabric.

More generally, we emphasise that AMS data provide information different from the one coming from analysis of meso-faults. These two methods must consequently be considered as complementary. Care must be paid to sampling. Sites situated away from the major faults are expected to preserve their primary magnetic fabric. On the contrary, a new magnetic fabric can be superimposed or even substituted to the primary one in the shear zones associated to faults. As a working hypothesis, which requires confirmation by studies of other regions, we suggest that development of secondary magnetic fabric could be related to fluid flow along faults.

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