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Palaeomagnetic dating of widespread remagnetization on the southeastern border of the French Massif Central and implications for fluid flow and Mississippi Valley-type mineralization

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SUMMARY

Palaeomagnetic dating techniques have been applied to determine the age of fluid migration that produced the Mississippi Valley-type (MVT) Pb–Zn–Ba–F deposits in the Cévennes region of southern France. 15 sampling sites in two gently deformed areas around the Largentière and Croix-de-Pallières mines on the Cévennes border were selected for palaeomagnetic study. They yielded a very well-defined direction of remagnetization corresponding to an Early-Middle Eocene age. This remagnetization cannot be related to the formation of magnetite as a result of the transformation of smectite to illite because the latter has been well dated as a Mesozoic event. The magnetic overprint in this area is related to a chemical phenomenon during fluid migration. The age of remagnetization corresponds to a major uplift in the Pyrénées mountains, located to the south of the Cévennes. This implies that fluid migration occurred from the south to the north as a result of hydraulic head established in the Pyrénées orogenic belt during orogenesis and suggests that the MVT deposits in the Cévennes region formed from a gravity-driven fluid system as described by Garven & Freeze (1984a,b).

Key words: fluid migration, Massif Central, mineralization, palaeomagnetism.

INTRODUCTION

Remagnetized rocks have been identified in fold belts and forelands adjacent to mountain ranges for at least 20 years. The remagnetization has usually been interpreted as resulting from fluid migration during orogenesis (e.g. Garven & Freeze 1984a,b; Oliver 1986, 1992; McCabe & Elmore 1989; McCabe *et al.* 1989; Symons *et al.* 1996). The geochemical properties of these fluids should be compatible with the formation or the transformation of ferrimagnetic minerals, thus allowing acquisition of remanent magnetization during fluid migration.

Carbonate-hosted lead–zinc (±barite and fluorite) mineralization of the Mississippi Valley type (MVT) are described in detail by Leach & Sangster (1993). These deposits are generally considered to have formed during the migration of enormous volumes of fluids (e.g. Garven & Freeze 1984a,b; Garven 1985; Bethke 1986; Leach & Rowan 1986) and are commonly located in foreland fold belts or their forelands. Radiometric dating of ore-stage mineralization in some MVT deposits has yielded ages (e.g. Nakai *et al.* 1993; Brannon *et al.* 1992, 1996; Christensen *et al.* 1995, 1996) that are coincident with that of the palaeomagnetic remagnetization (Symons *et al.* 1996). The general agreement between radiometric and palaeomagnetic age for many MVT districts suggests a similar origin for widespread carbonate remagnetization and MVT mineralization (Sangster 1986; Symons *et al.* 1996; Leach *et al.* 2001). The application of palaeomagnetic dating of MVT deposits has been successfully applied in most of the major MVT districts of North America (e.g. Symons & Sangster 1994; Lewchuk & Symons 1995; Symons *et al.* 1996; Leach *et al.* 2001) as well as the Silesian district in Poland (Symons *et al.* 1996) and the Navan deposit in Ireland (Smethurst *et al.* 1998). Thus, there is a good rationale for applying palaeomagnetic dating to the MVT deposits hosted by Mesozoic carbonate rocks of the Cévennes region of southern France.

The Pb–Zn–Ba–F deposits of the Cévennes region have many features that are typical of MVT deposits (Macquar *et al.* 1990; Leach & Sangster 1993). No reliable radiometric ages and no indisputable geological dating arguments have been obtained for the mineralization. Palaeomagnetic work began therefore 10 years ago to date these deposits. Unfortunately, the largest

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deposits are no longer accessible. The first studies were performed on minor deposits and apparently unmineralized host rocks in surface sites located at variable distances away from the most important ore deposits. Results from a preliminary study indicated that a magnetic overprint of about Eocene age affected the region (Rouvier *et al.* 1995), and so the study was enlarged to include numerous occurrences of barren rocks near mineralization at the Cévennes border. The large palaeomagnetic data set presented in this report is consistent with an event that produced a single magnetization direction in the rocks. Given the structural complexity of the region, the key to interpreting the palaeomagnetic data was the application of proper structural corrections for each site. Structural deformation includes more or less local vertical axis rotations that commonly affect areas around the Cévennes fault. The results presented here are intended to provide an initial reference direction on which further results can be based. Thus, they include barren rocks near mineralized areas, but only from those locations that belong to less deformed parts of this border. This should yield the most reliable reference direction for the area because it is free of local post-remagnetization structural complexities. Consequently, we can determine a precise age for the remagnetization by comparison with the European apparent polar wander path.

GEOLOGICAL SETTING

The Cévennes border (Fig. 1) is located at the western border (within a radius of about 50 km around 44.2°N, 4.1°E) of the large Southeast basin of France, which is bounded to the west by the crystalline basement uplift of the Cévennes (Baudrimont & Dubois 1977; Debrand-Passard & Courbouleix 1984; Arthaud & Laurent 1995; Mascle *et al.* 1996). The smaller Carboniferous (Alès) and Permian (Largentière) basins comprise the first sedimentary formations on the crystalline basement. These rocks are overlain by Triassic–Jurassic series consisting of six transgression–regression cycles with detrital or lagoonal facies separated by units deposited in a more or less open sea. These units consist mainly of marls in the centre of the basin, but grade towards carbonates on the Cévennes border. This change

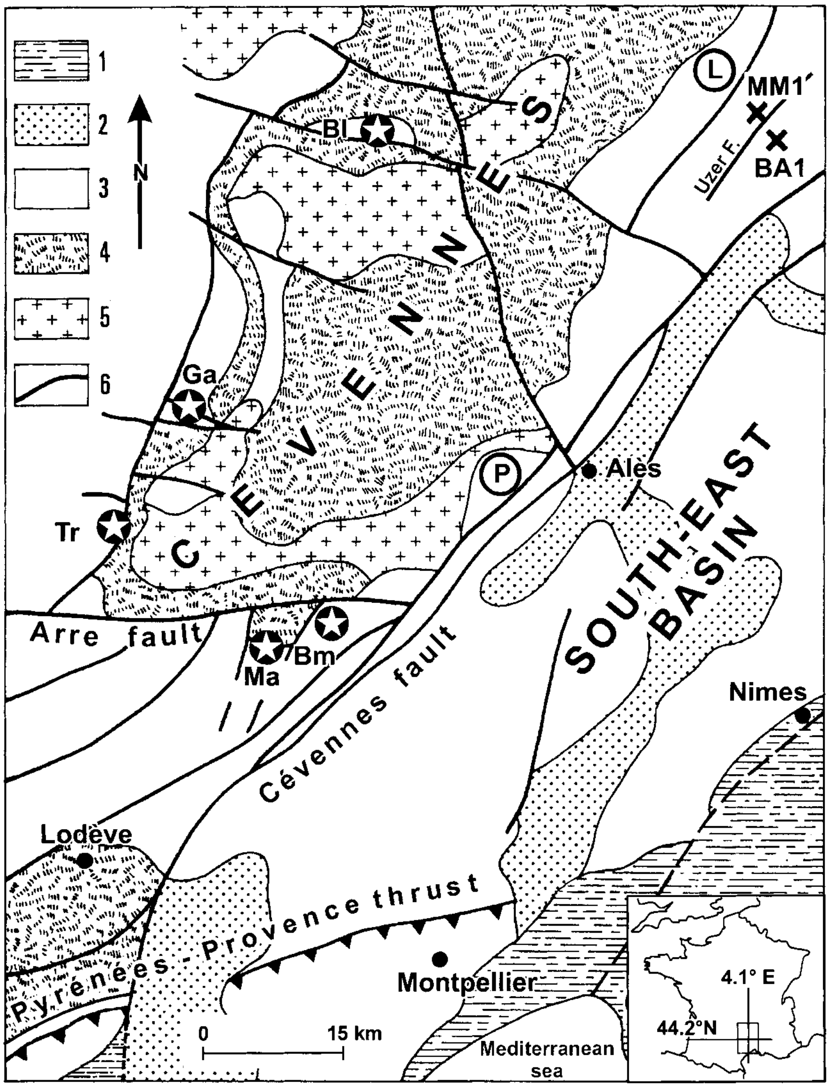

Figure 1. Structural map and locations of sampling sites. 1–Quaternary; 2–Oligo-Miocene; 3–Mesozoic to Eocene; 4–Palaeozoic; 5–Late Hercynian granites; 6–faults. Studied areas: L–Largentière; P–La Croix-de-Pallières. Boreholes GPF: MM1–Morte Mérie; BA1–Balazuc. Named ore deposits: Ma–Les Malines; Bm–Bois-Madame; Tr–Trèves; Ga–Gatuzières; Bl–Le Bleymard.

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of lithology has major consequences for the possibility of fluid migration as the carbonates are much more porous and therefore more likely to act as aquifers.

From a tectonic point of view, sinistral NE–SW and NNE–SSW and dextral E–W Late Hercynian faults affected the basement (Arthaud & Matte 1975). These faults were major structures involved in the tectonic evolution of this area because some of them were reactivated during and after the Mesozoic. They provided structural controls for sedimentation as well as for Cenozoic deformation. From the Liassic to the end of the Middle Jurassic, extension produced extensive block tilting (Gottis 1957; Bernard 1958; Bernier *et al.* 1970; Macquar 1980; Macquar *et al.* 1990). This resulted in the formation of the Cévennes ridge, the southwest extension of the Cévennes border, which is a basement uplift separating the Southeast basin and the small embayment called the Grandes Causses (Macquar 1980; Macquar *et al.* 1990).

The compressive Pyrenean phase of deformation was active from the end of the Cretaceous at least in the southern and axial zones of the Pyrénées, and until Late Eocene within the Pyrénées and their foreland margin to the north (Mattauer & Proust 1962). This compression (on average N15°E; Arthaud & Laurent 1995) affected both the basement and the cover, producing different effects according to the location relative to the axial Pyrenean zone. At the margin of the Gulf of Lion, at the front of the Pyrénées and on their westward submerged extension in the Mediterranean sea, this compression resulted in structures consisting of northward-thrust slices (Arthaud & Séguret 1981; Tempier 1987). In the foreland, early Pyrenean E–W folds were later affected by sinistral NE–SW to NNE–SSW transverse faults and, in particular, the Cévennes fault (Séguret & Proust 1965; Arthaud & Mattauer 1972; Macquar 1973; Bodeur 1976). This style of deformation is mainly restricted to the area southeast of the Cévennes fault. Northwest of this fault, the tabular zone is mainly affected by E–W reverse faults, sinistral transverse faults and minor folding.

The Cévennes mineralization is hosted in rocks of Triassic to Early Cretaceous age and in Palaeozoic dolostones under the Triassic unconformity at Les Malines. This mineralization predates the main deformation in the Cévennes as shown by Late Eocene faults and fractures that displace some ore deposits (Macquar 1973).

SAMPLING

The structural complexity of the Cévennes border, which resulted from the superimposition of multiple deformations, complicates the interpretation of palaeomagnetic results (Rouvier *et al.* 1995; Kechra 1997). The structure at each site depends on the relative influence of the different phases of deformation, which in turn varies as a function of local parameters such as the proximity to faults, localization in a rotated block, etc. To minimize the structural complications, sample sites were chosen within the less deformed areas in order to determine a palaeomagnetic reference direction for the remagnetization. Within these areas, some sites with significant dip allow us to perform a fold test.

Most samples were collected in the area of the Largentière mine (Fig. 1). Palaeomagnetic data obtained from Permian rocks in the Largentière basin and in Permian rocks from the Morte-Mérie deep borehole (Henry *et al.* 1999) demonstrated the tectonic stability of this area relative to stable Europe since the Permian.

Surface samples from the northern section (Fig. 1) of the study area were collected from three sites: (1) Anisian–Ladinian dolomites, close to Pb mineralization at Largentière (4.18°E, 44.32°N); (2) Sinemurian limestones at Laurac (4.18°E, 44.30°N); and (3) Callovian limestones at Morte-Mérie (4.20°E, 44.31°N). In addition, we obtained samples of Carboniferous, Permian, Triassic, and Liassic rocks from independently oriented (using a borehole special tool) cores from the two deep boreholes at Balazuc (4.22°E, 44.31°N) and Morte-Mérie (4.20°E, 44.31°N) that were drilled as part of the Géologie Profonde de la France program (Elmi *et al.* 1991; Giot *et al.* 1991; Bonijoly *et al.* 1996; Martin & Bergerat 1996; Steinberg *et al.* 1991; Pagel *et al.* 1997a,b; Clauer *et al.* 1997).

Several samples were also collected near the Croix-de-Pallières mine (Fig. 1). The Sinemurian limestones overlying the mineralized Hettangian dolostones were sampled at the mine site (3.57°E, 44.01 N). Hettangian dolostones were also sampled at Thoiras (3.56°E, 44.04°N) about 2 km away and Carixian limestones were collected at Saint Martin-de-Sossenac (3.59°E, 44.0°N) about 4 km away from the mine.

PALAEOMAGNETIC ANALYSIS

Initially all specimens were placed in a magnetically shielded space for more than two weeks in order to allow their viscous remanent magnetization (VRM), which is acquired *in situ* and after sampling, to decay. The intensity and the direction of the remanent magnetization were measured on an Agico JR-4 spinner magnetometer. Alternating magnetic field (AF) and thermal demagnetization techniques were performed using an AF demagnetizer that automatically cancels the parasitic anhysteretic remanence (Le Goff 1985) and a magnetically shielded furnace that were constructed at the Saint Maur Laboratory.

The main magnetic carrier in the carbonates of the Cévennes area is magnetite, sometimes with pyrrhotite (Ibouanga, personal communication in Kechra 1997). The very low value of the intensity of magnetization shows that the magnetization carrier is in very low concentration. In red beds from the Balazuc borehole, Curie curves were obtained using an Agico CS2-KLY2 Kappabridge that indicates the presence of haematite and possibly magnetite (Fig. 2).

Sulphides are unstable during heating at temperatures higher than 300 °C because of oxidation. Because of their presence in samples from some sites, the demagnetization process differed from site to site and was chosen depending on the analysis of the pilot specimens. Specimens with sulphides were thermally demagnetized up to 100–300 °C followed by AF treatment up to 35–40 mT. For the other specimens, only thermal demagnetization, up to 390–500 °C in carbonate facies and up to 550–650 °C in red beds, was used. A low-temperature magnetic component A, as well as a characteristic remanent magnetization (ChRM), can often be isolated (Fig. 3) during progressive demagnetization.

The A component was isolated in 133 samples (before dip correction, declination $D=-2°$, inclination $I=60.6°$, precision parameter $k=159$ and radius of cone of 95 per cent confidence $\alpha_{95}=1°$; Fisher 1953). It is usually removed during the first few thermal demagnetization steps up to 180–200 °C. It has been acquired after the main deformation as proved by a negative

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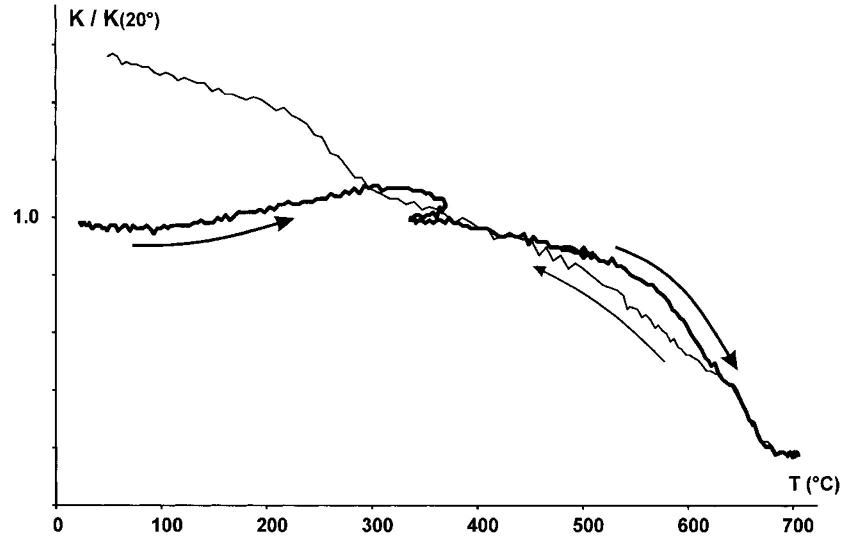

Figure 2. Variation of the susceptibility $K/K_{(20°)}$ as a function of the temperature T in a sample of red beds from the Balazuc borehole.

fold test, and it corresponds the present day terrestrial magnetic field (TMF) direction ($D=-1.7°$, $I=59.9°$). It is therefore a recent magnetic overprint.

The ChRM was obtained at higher fields up to 40 mT and sometimes at temperatures up to 650 °C. For the data from the Balazuc and Morte-Mérie boreholes, the ChRM can be split into two populations that vary according to lithology. In the Triassic red beds, both SSW reversed and antipodal NNE normal directions with a mean inclination of the order of 38°–48° were obtained, i.e. ChRM B (Table 1). In all other formations in the borehole, which are predominantly carbonates, and in all of the surface sites, the ChRM is only normal in polarity with a steeper inclination, i.e. ChRM C (Table 2). The characteristics of these ChRMs are detailed in the following sections.

STRUCTURAL CORRECTIONS

ChRM B

ChRM B, with normal and reversed polarity (Fig. 4), was only observed in some samples from less porous units in two boreholes. It was never observed in the surface samples. At Morte-Mérie borehole, the beds are horizontal. At Balazuc, in these detrital units the dip is unfortunately only roughly known by analysis of the facies containing cross-bedding. The stratification dip, be it bedding or cross-bedding, has a large uncertainty. Moreover, the apparent dip measurements are very irregularly distributed along the borehole and only representative of a few levels. The application of a precise dip correction could be meaningless in such a case.

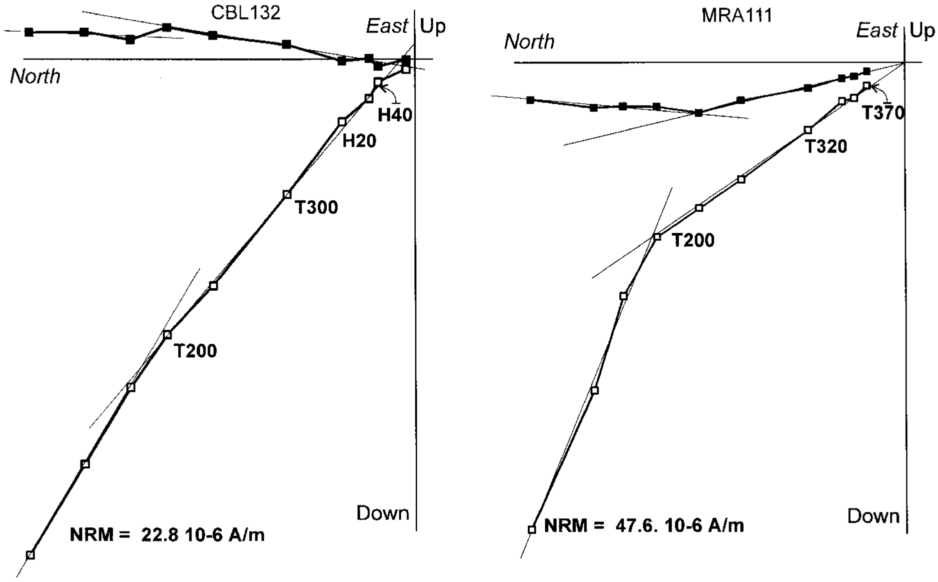

Figure 3. Examples of orthogonal vector plots: projections on the horizontal (filled squares) and vertical (open squares) planes: specimens CBL132 (Morte-Mérie–Callovian) and MRA111 (Saint-Martin–Carixian); T in °C, H in mT.

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Table 1. ChRM B: direction (declination *D*, inclination *I*) and associated Fisher scattering parameters (precision parameter *k*, radius of 95 per cent confidence cone α_{95}) for the Balazuc borehole, dominantly normal (1) or reversed (2) directions. Permian data after Henry *et al.* (1999).

Site	*N*	Before dip correction				After dip correction			
		D (°)	*I* (°)	*k*	α_{95} (°)	*D* (°)	*I* (°)	*k*	α_{95} (°)
Balazuc borehole									
Carnian-Norian 3	$15^{(1)}$	29.3	46.9	69	4.4	?	?		
Carnian-Norian 4	$17^{(2)}$	214.0	−40.8	54	4.6	?	?		
Carnian-Norian 5	$20^{(1)}$	23.6	48.1	83	3.4	?	?		
Morte-Mérie borehole									
Permian	9	197.0	2.5	34	8.0	194.1	−7.1	33	8.1
Carnian-Norian 2	4	200.1	−38.3	153	5.7	200.1	−38.3	153	5.7

ChRM C

The samples retaining the ChRM C (Fig. 5 and Table 2) are mostly from horizontal to very gently dipping beds. However, the dip is greater in two of the surface sites and in the deeper part of the Balazuc borehole, reaching 34° at the Saint Martin site. Progressive unfolding of the whole data set shows at once that the magnetization is 'synfolding', at about 40–80 per cent unfolding. A synfolding magnetization result can be obtained when the magnetization is acquired either during a phase of folding or between two distinct phases of folding. 'Synfolding' here means only that ChRM was acquired between the beginning of the first deformation and the end of the last deformation event. This area has been subjected to multiple phases of deformation and the relative effect of each phase at a given site depends on local structures. The use of the mean unfolding percentage obtained from the traditional fold test assumes that all the folds were subjected to the same percentage of deformation at the same time. Since such an assumption is not confirmed by geological evidence in this area, a more realistic approach to unfolding was used.

During progressive unfolding, the mean palaeomagnetic direction for a single site with a uniform dip will follow a small circle on the projection sphere, even in the case of a dipping fold axis. The best intersection of the small circles from several sites with differing dip directions corresponds therefore to the best estimate of a single common palaeomagnetic direction for all the sites. This is the actual direction of the 'synfolding' magnetization in an area that has been subjected to multiple deformation events (Surmont *et al.* 1990; Shipunov 1997). To determine this best intersection, the iterative method used by Surmont *et al.* (1990) has been chosen. For our study, small circles cross along the direction obtained in horizontal formations (Figs 5 and 6). Useful information is also given by the analysis of the shape of the confidence zone using elliptical statistics (Le Goff 1990; Le Goff *et al.* 1992). Fig. 6 shows that

Table 2. ChRM C direction: see caption to Table 1 for abbreviations. As approximate result, assuming the same dip as at Balazuc from Carnian to Hettangian formations, the mean direction after dip correction for the 15 sites should be $D=10.8°$, $I=59.0°$, $k=158$, $\alpha_{95}=2.9°$.

Site	*N*	Before dip correction				After dip correction			
		D (°)	*I* (°)	*k*	α_{95} (°)	*D* (°)	*I* (°)	*k*	α_{95} (°)
Largentière: Anis.-Ladin.	11	2.8	57.2	89	4.5	4.8	62.0	89	4.5
Laurac: Sinemurian	13	3.6	53.1	243	2.5	1.3	52.2	243	2.5
Morte-Mérie: Callovian	27	1.7	51.9	514	1.2	28.6	61.6	520	1.2
Croix-de-Pal. Sinemurian	16	1.6	53.0	700	1.3	0.1	53.7	591	1.4
Thoiras: Hettangian	31	0.1	58.2	485	1.1	6.1	60.6	473	1.2
Saint-Martin: Carixian	17	−13.0	34.5	351	1.8	12.0	58.8	351	1.8
Balazuc borehole									
Carboniferous.	13	1.3	55.6	440	1.8	32.7	67.0	440	1.8
Carnian-Norian 1	15	8.3	58.2	61	4.6	?	?	–	–
Carnian-Norian 2	9	15.0	57.2	113	4.4	?	?	–	–
Rhetian-Hettangian	22	3.2	56.1	216	2.0	13.4	58.7	216	2.0
Hettangian	22	−1.4	55.5	221	2.0	8.2	58.6	221	2.0
Morte-Mérie borehole									
Anisian-Ladinian	7	4.4	56.5	86	5.7	4.4	56.5	86	5.7
Carnian-Norian 1	7	6.8	55.1	151	4.3	6.8	55.1	151	4.3
Lower Hettangian	19	4.7	57.0	297	1.9	4.7	57.0	297	1.9
Middle-Upper Hettangian	19	6.2	54.8	337	1.7	6.2	54.8	337	1.7
Mean	15	2.5	54.4	140	3.1	–	–	–	–

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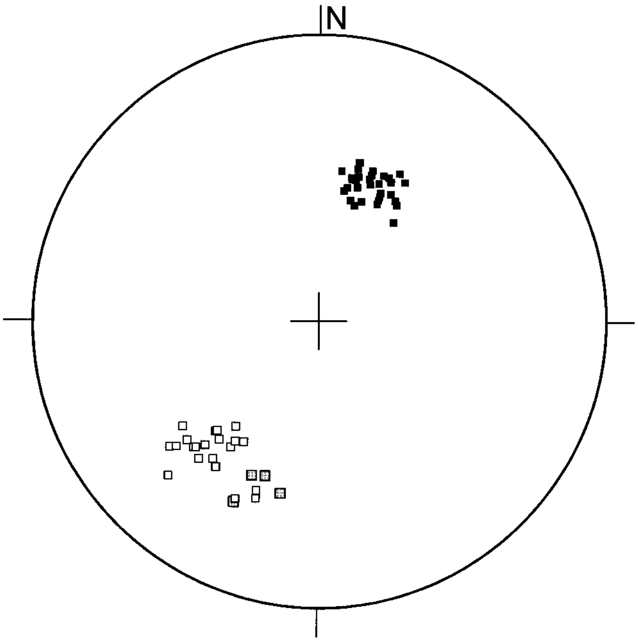

Figure 4. ChRM B directions (squares) without dip correction: equal-area plot, filled (open) symbols are plotted in the lower (upper) hemisphere. The four reversed directions of the Morte-Mérie borehole are shaded.

this shape is more elongated before and after dip correction than at optimal unfolding determined using the small-circles method. In addition to the obvious structural reasons, there are a number of converging arguments that also justify the use of this method.

Another advantage of this method is that it allows for the amount of unfolding at each site to vary independently of the other sites. For example, in our analysis (Fig. 6), the resulting optimal unfolding percentage is close to 20 per cent in Callovian beds east of Morte-Mérie and 75 per cent in the Carixian formation at Saint Martin, a situation that is not permitted in the progressive fold test. The optimal unfolding obtained at the other sites (Table 3) has to be carefully considered because of the very low dip values for the surface sites and of the uncertainty of the stratigraphic dip in the Balazuc borehole.

The mean direction for the remagnetization obtained in this method is therefore very well defined as $D=3.3°$, $I=55.6°$, $k=2155$ and $\alpha_{95}=0.8°$ (Fig. 6). It must be emphasized that the small-circles method is an optimization approach that gives the right mean direction but probably underestimates the confidence cone. However, the k-value obtained is very high (2155) compared to that before (140) and after (~ 158) 100 per cent unfolding. This shows the coherence of the data and confirms a common origin of the remagnetization at all the sites. The very high value of the k parameter results from the calculation widely used in palaeomagnetism of the Fisherian mean of the mean directions of the different sites. With such a calculation, the within-site scattering of the directions is lost, and it would be better to use statistics that keep this within-site scattering. For example, bivariate statistics (Le Goff 1990; Le Goff *et al.* 1992) yield the same direction ($D=3.1°$, $I=55.7°$, but precision parameters ($k=165$) similar to those of the individual sites, and $\alpha_{95}=0.8°$ with the whole set of 244 samples.

Table 3. ChRM C: retained directions, with recalculated dip value compared to present dip (assuming for each site the same horizontal axis of tilting during all tiltings). In the two sites with unknown dip values in the Balazuc borehole, we assume that the direction of the dip is the same as in the Hettangian units (the calculation was also made with slightly different dip directions, but the mean direction obtained appears not to be significantly different).

Site	Present dip	Calc. dip	*D* (°)	*I* (°)
Largentière: Anis.-Ladin.	5	6.7	2.3	55.5
Laurac: Sinemurian	2	3.2	5.1	53.6
Morte-Mérie: Callovian	20	16.4	5.3	54.3
Croix-de-Pal. Sinemurian	2	1.2	0.6	53.4
Thoiras: Hettangian	4	5.2	−0.7	57.7
Saint Martin: Carixian	34	8.3	2.0	56.0
Balazuc borehole				
Carboniferous.	20	19.4	1.9	56.0
Carnian-Norian 1	?	11.3	2.2	56.4
Carnian-Norian 2	?	14.7	4.3	54.5
Rhetian-Hettangian	7	7.4	2.7	56.0
Hettangian	7	4.5	1.8	56.7
Morte-Mérie borehole				
Anisian-Ladinian	0	0	4.4	56.5
Carnian-Norian 1	0	0	6.8	55.1
Lower Hettangian	0	0	4.7	57.0
Middle-Upper Hettangian	0	0	6.2	54.8
Mean direction			3.3	55.6

AGE OF THE TWO CHRMS

The palaeomagnetic results are compared in Fig. 7 to the new revised apparent polar wander path (APWP) for stable Europe (Besse & Courtillot 2001). In the lower part of the figure, the APWP includes the 95 per cent confidences ellipses for the Tertiary period. In the upper part, the declination–inclination path of the Earth's magnetic field since the Triassic is recalculated for the Cévennes area.

ChRM B

Only four reversed B directions were obtained at Morte-Mérie (Table 1 and Fig. 4). ChRM B was found in red beds from the Balazuc borehole (Fig. 4). It had both normal (without dip correction: $N=31$, $D=19.2°$, $I=48.3°$, $k=167$, $\alpha_{95}=1.9°$) and reversed (without dip correction: $N=20$, $D=216.7°$, $I=-40.4°$, $k=68$, $\alpha_{95}=3.8°$) directions with five intervals of normal polarity and four reversed. However, the samples were not regularly distributed along the core so that some polarity intervals could be missing. Such a reversal pattern suggests that ChRM B is a primary magnetization. However, the McFadden & McElhinny (1990) reversal test is not positive (critical angle 4.0°, actual angle 14.7°), suggesting that ChRM B actually results from the superimposition of a dual-polarity primary component and a secondary component.

An important observation is that the direction of ChRM C is very close to the great circle through the mean normal and mean reversed directions of ChRM B (see Fig. 7). The secondary component in the red beds is very likely to be ChRM C. ChRM B was usually defined at temperatures between 350 and 550 °C. At higher temperatures, its magnetization usually

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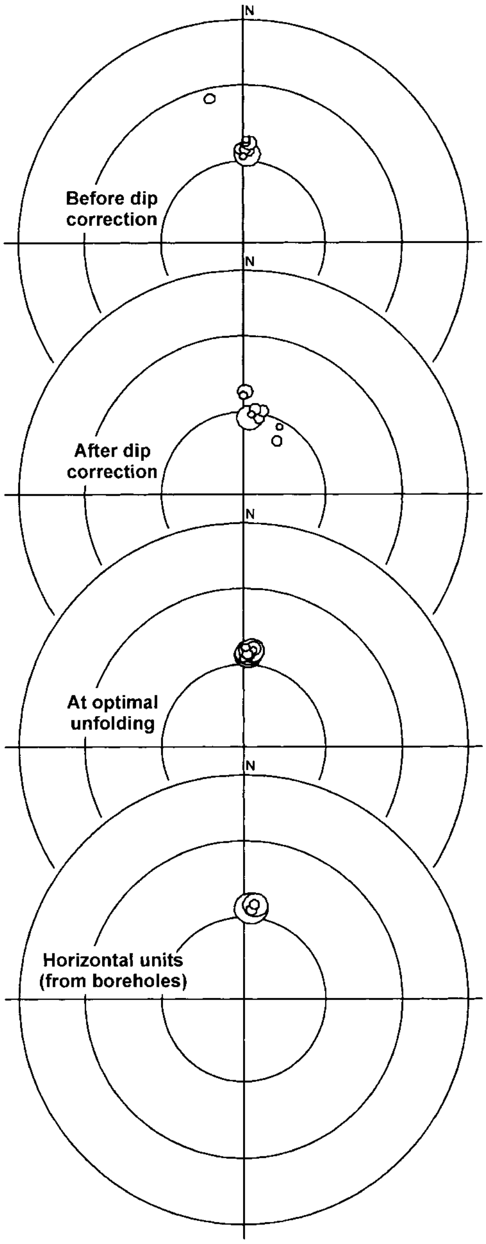

Figure 5. ChRM C cones of 95 per cent confidence for the 15 sites: equal-area lower-hemisphere plot.

became unstable, probably due to the formation of new magnetic carriers during the heating process. However, eight samples did retain stable magnetizations during treatment at temperatures higher than 600 °C. Their combined direction (ChRM B′), isolated between 580 and 650 °C, is poorly defined, but appears to be slightly different from ChRM B defined below 550 °C. The B direction falls between B′ and C, providing further evidence that B represents a combination of B′ and C over the 350–550 °C temperature range. Therefore, B′ probably represents the primary magnetization carried by haematite, while C is a secondary magnetization carried probably by magnetite. B results from the superimposition of the B′ and C components. The ChRM B direction ($N=51$, $D=26.9°$, $I=45.4°$) was calculated by combining the normal and reversed data. This is still a valid estimation of the actual orientation of the primary component because ChRM C has opposing effects for the normal and reversed directions thereby cancelling each other out when combined (this is valid when the angle between the B and C directions is greater than 90° and numbers of normal and reversed directions are about equal as well). Unfortunately, the dip is not known with sufficient accuracy to perform a significant dip correction that can allow the determination of the corresponding palaeomagnetic pole.

In the Fig. 7, where the expected inclinations and declinations are shown after the Besse & Courtillot (2001) and Van der Voo (1993) compiled data, together with a middle Triassic pole from France (Théveniaut *et al.* 1992), the ChRM B confidence ellipse shows correct agreement owing to the above-mentioned uncertainties.

ChRM C

Comparison (Fig. 7, bottom) of the palaeomagnetic pole for the ChRM C (165.5°E, 81.6°N, $K=1416$; $A_{95}=1°$) with the APWP for stable Europe (Besse & Courtillot, 2001) shows that, given the age of the rocks (>140 Ma), its direction is different from the expected direction for a primary magnetization. Therefore, ChRM C is a magnetic overprint with a direction that is exactly the Early-Middle Eocene (about 40–50 Ma) reference pole and not very far from the 100 Ma reference pole. The 100 Ma age must be rejected because the magnetization was acquired after most of the folding in the region; the main folding began in Late Cretaceous at the earliest but was mainly during the Eocene

Origin of the ChRM C

In the Balazuc borehole, the maximum burial temperature obtained from Rock-Eval pyrolysis data is about 130 °C in stratigraphic units at the present depth of ~ 1600 m (Pagel *et al.* 1997a). Locally, along the Uzer fault, maximum temperatures recorded in fluid-inclusion studies indicate that hydrothermal fluids reached a maximum temperature of 210 °C (Pagel *et al.* 1997a). The remagnetization was isolated using thermal demagnetization at temperatures as high as 550 °C. Thus, ChRM C cannot be a thermoremanent magnetization acquired at temperatures in the 130–210 °C range (Pullaiah *et al.* 1975) and thus it must be a chemical remagnetization.

Katz *et al.* (1998) found a secondary but pre-folding magnetization in Mesozoic carbonates closer to the centre of the Southeast basin, near Montclus. They proposed that the remagnetization was acquired by the formation of new magnetite during the transformation of smectite to illite (Deconinck *et al.* 1985) as a consequence of burial diagenesis without the influence of exotic hydrothermal fluids. They based their conclusions on three arguments.

(i) The measured ^{87}Sr/^{86}Sr values plot within the range of coeval seawater for corresponding stratigraphic intervals, and they should have had higher ratios if exotic fluids had affected the rocks.

(ii) The transition from units with smectite to those without smectite (Deconinck *et al.* 1985) corresponds to an important change in the magnetic properties.

(iii) The magnetic overprint was not observed at Berrias (Galbrun 1985) in the upper part of the Mesozoic series, where the smectite to illite transformation is not found.

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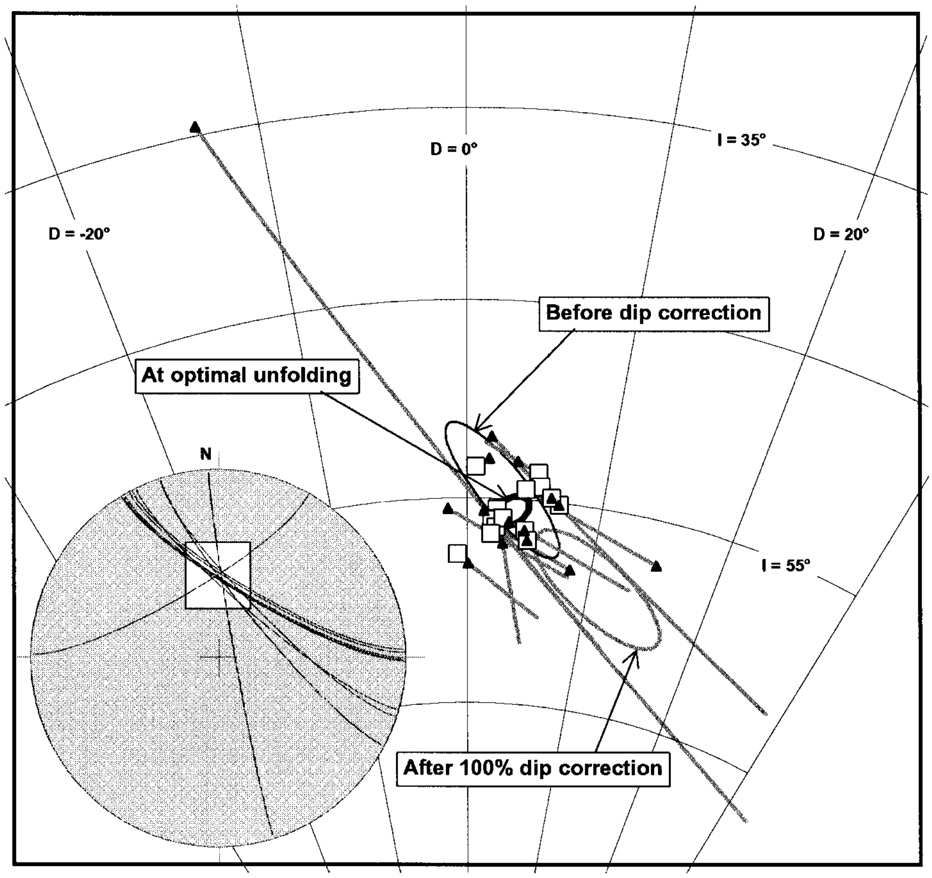

Figure 6. Determination of the ChRM C at optimal unfolding by the small-circles method: the filled triangles are the directions before dip correction; the grey lines are the portion of the small circle followed by the magnetization vector during 0–100 per cent dip correction (the two badly specified dip directions at Balazuc are taken as the same as for the Hettangian beds; see Table 2); the open squares are the retained directions for ChRM C. The three ovals are 95 per cent confidence cones around each mean direction. Equal-area lower-hemisphere plot.

In contrast to the conclusions of Katz *et al.* (1998), other observations suggest that the remagnetization of the Mesozoic carbonates near Montclus could not simply be due to the burial transformation of smectite to illite. These observations include the following.

(i) The ^{87}Sr/^{86}Sr values (Katz *et al.* 1998) were obtained from impermeable argillaceous carbonate in limestones. It is possible that the argillaceous carbonate was not affected by fluid migration and therefore the rocks would have ^{87}Sr/^{86}Sr ratios consistent with coeval Mesozoic seawater. In addition, a dominant part of the migrating fluid could be connate water with ^{87}Sr/^{86}Sr ratios that would be essentially the same as Mesozoic seawater.

(ii) Deconinck *et al.* (1985) specifically excluded the carbonates from their clay analyses. They argued that the change in smectite near Montclus does not correspond to a significant change in diagenetic processes, but rather to a substantial decrease of detrital chlorites, indicating the end of erosion in an emerged area. The occurrence of a large amount of smectite also suggests a climatic change (Paquet 1970; Deconinck *et al.* 1985). Therefore, the limit between facies with and without smectite is unlikely to be an indication of the level of diagenesis. In any event, the direction of the remanent magnetization above and below this transition is not statistically significantly different in the Katz *et al.* (1998) study. Similarly, near Morte-Mérie, Callovian beds show only the remagnetization ChRM C, but they correspond to units with a relatively high amount of smectite (Clauer *et al.* 1997).

(iii) At Berrias, Galbrun (1985) found a primary ChRM only after demagnetization of a presumably modern VRM at temperatures of up to 300–350 °C. However, these temperatures are high for a VRM, so it is possible that demagnetization below 350 °C removed a VRM and another magnetic overprint with a similar direction. The remagnetization direction found by Katz *et al.* (1998) as well as in this study is close to the VRM direction and thus it could have been present but not observed in the Galbrun (1985) study. The curved shape of the low-temperature range of the Zijderveld (1967) diagrams in Galbrun (1985) suggests the superimposition of the primary magnetization with another component between 225 and 350 °C. This unknown secondary component may correspond to our ChRM C.

It is therefore possible that the remagnetization in the Vocontian trough was related to burial diagenesis of smectite (Katz *et al.* 2000), but other origins of the magnetic overprint cannot be excluded.

The diagenetic transformation of smectite to illite during burial will affect all units containing clay minerals. However, Henry *et al.* (1999) found a primary magnetization in some units near the bottom of the boreholes and in surface samples in the Permian basin of Largentière. Either magnetite or haematite was the magnetic carrier, depending on the lithology.

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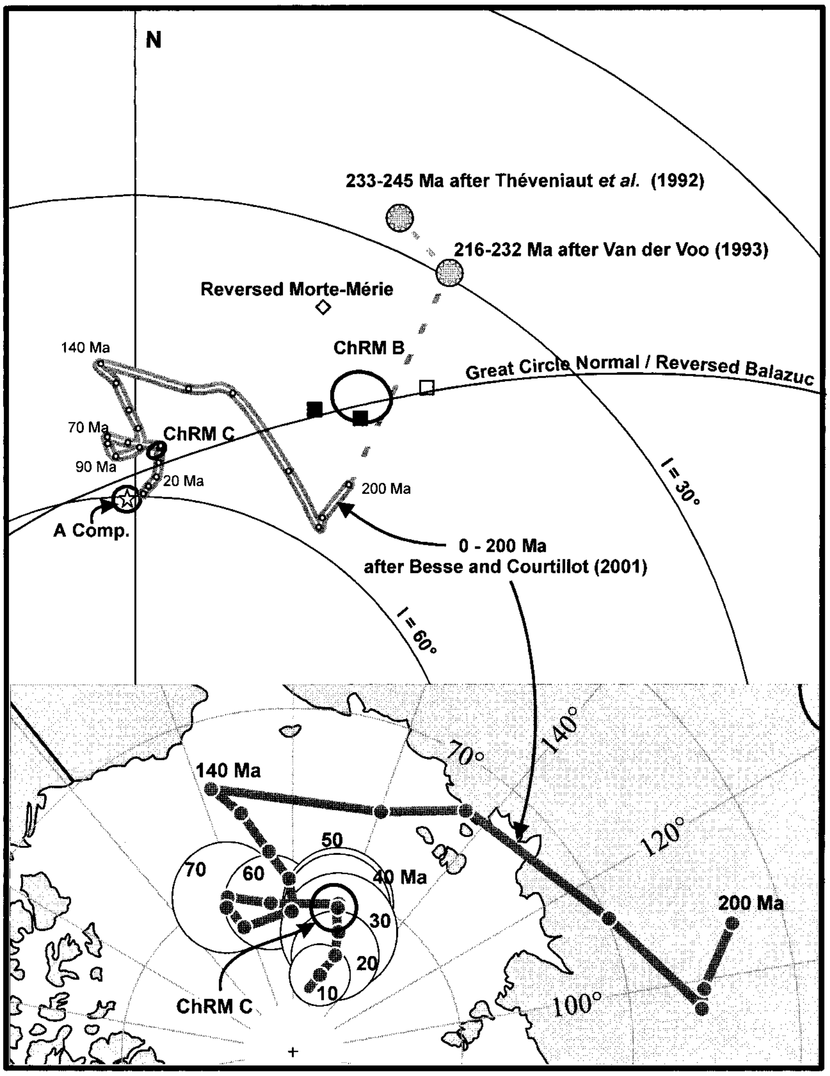

Figure 7. Summary figure of the palaeomagnetic analysis. Bottom: European APWP with confidence cones (Besse & Courtillot 2001), for clarity drawn only between 10 and 70 Ma, and palaeomagnetic pole for ChRM C at optimal unfolding (thick black circle). Top: calculated declination–inclination path of the Earth's magnetic field since the Triassic in the Cévennes region (equal-area lower-hemisphere plot) with the 95 per cent confidence zones of the three magnetizations A, B and C. The star is the present terrestrial magnetic field direction. The normal (filled symbols) and reversed (open symbols) ChRM B at Balazuc (squares) and Morte-Mérie (diamond) are all presented as being of normal polarity.

For the rocks with haematite as the main carrier, the intensity of the magnetization is relatively high. Therefore, the primary magnetization could be concealing the remagnetization, as found in the red beds from Balazuc borehole. However, this could not be the case for the rocks in which magnetite was the main remanence carrier because the intensity of the primary magnetization is similar to that of the remagnetization and could not conceal it. This provides further evidence that the remagnetization is not related to burial diagenetic processes because one would expect these units to be remagnetized as well by such a process. We also found remagnetization in units that were not deeply buried, where one would be most likely to find a primary magnetization.

In summary, we found the C remagnetization in some units that lack the important transformation from smectite to illite, and we found primary magnetizations in units that have undergone the transformation. In addition, we found the same direction and polarity in Hettangian, Triassic and Carboniferous units in the Balazuc borehole through ~1000 m of stratigraphy. If we were to assume that the magnetite formed during the diagenetic transformation of smectite to illite, this transformation must have occurred at the same time at all depths. This is an unrealistic scenario for diagenetic processes during burial.

Finally, Clauer *et al.* (1997) showed that K–Ar dating of illitization ranges from 121 to 190 Ma depending on the depth in the borehole. Since palaeomagnetic and structural relationships restrict the age of remagnetization to <65 Ma, it cannot be related to illitization. We suggest that the process responsible for illitization in the rocks of the Cévennes border as presented by Clauer *et al.* (1997) is independent of the process responsible for remagnetization. The Katz *et al.* (2000) assumption cannot be retained for the Cévennes border.

The other possible origin for the remagnetization is that it was produced by the migration of chemically active fluids. Such fluids can easily affect different stratigraphic units at the same time. Also, the existence of primary magnetizations in units at deeper levels can easily be explained by differences in the primary

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magnetic mineralogy and in the porosity and permeability from one stratigraphic horizon to the next. Impermeable units would not have interacted with the remagnetizing fluid, thus preserving their primary magnetic signature. In contrast, the remagnetized Carboniferous siltstones appear to have been subjected to intense fluid circulation (Aquilina *et al.* 1997) and therefore were permeable to the remagnetizing fluid.

According to Clauer *et al.* (1997), activity after 190 ± 20 Ma of the fault system at Balazuc probably did not induce major fluid movement, as suggested from the K–Ar dating of illite. Therefore, they assumed that the mineralizing fluid responsible for the ore deposits must have been related to a possible ~190 Ma Liassic hydrothermal event. However, fluid migration can occur without displacements on faults and illite formation may or may not occur with all hydrothermal fluid movements (Folger *et al.* 1996,1998). Furthermore, Clauer *et al.* (1997) admitted that the fluids involved in the interaction with the clay minerals seemed to have had at least two different origins. This directly conflicts with the Pb isotope ratios, which are similar for all deposits, even those in rocks much younger than 190 Ma (Sinclair *et al.* 1993). The small range in Pb isotope ratios for deposits in the region is best interpreted as the consequence of a single mineralizing event from fluid that acquired its lead content from a single reservoir of lead. Therefore, all of the ores must at least be younger than the youngest rocks hosting mineralization. Even ignoring the Pb isotope data, the mere presence of MVT ores in Early Cretaceous rocks proves that some fluid migration must have occurred after 190 Ma. Thus we believe that the K–Ar studies of Clauer *et al.* (1997) do not date the MVT mineralization.

Aquilina *et al.* (1997) showed that the interstitial fluids maintained the primary chemical characteristics of connate seawater in Hettangian limestones in the Balazuc borehole. This suggests that very little, if any, fluid migration occurred in these impermeable rocks after diagenetic cementation. In contrast, the remagnetized and faulted Hettangian dolostones were certainly subjected to fluid circulation related to the dolomitization of earlier limestones. Thus, the apparently higher permeability of the dolostones relative to limestones is possible support for fluid migration causing the remagnetization, which was observed only in the dolomitized lower part of the Hettangian units in the Balazuc borehole. Few samples were chosen in this study from the upper part of the Hettangian because of the unfavourable facies of these rocks and because they did not retain a stable magnetization. This could simply be due to the lack of fluid effects in these units.

Pagel *et al.* (1997b) obtained an Eocene age of 42 ± 4 Ma in the Balazuc borehole by studying apatite fission tracks. This age corresponds to cooling that is probably related either to uplift of the strata or to the end of a hot palaeofluid circulation. Their 42 ± 4 Ma age estimate is close to the younger age limit of the remagnetization, and it is consistent with cooling after the circulation of relatively hot fluids.

The fact that ChRM C is only of normal polarity seems to indicate a short duration of less than 1 Myr for the acquisition of the remagnetization, i.e. of fluid migration. However, due to the chemical origin of the magnetization, the total duration of acquisition of the magnetization could have been somewhat longer.

For specimens that had magnetic crystals formed or transformed during more than one polarity interval, both thermal and alternating field demagnetization methods may be inefficient at separating the normal and reversed components. Only the dominant polarity appears as both components are demagnetized simultaneously. For the Early-Middle Eocene, periods of reversed polarity represent a longer duration than that of normal polarity (Cande & Kent 1995). However, during the growth of new small crystals of the magnetic carrier or the progressive transformation of previous minerals, these individual crystals are at first paramagnetic, then superparamagnetic, and finally they can carry a stable remanence only when becoming single-domain crystals. The orientation of this remanence is then related to the ambient magnetic field when they grow large enough to exceed the superparamagnetic–single-domain threshold (McClelland 1996). As a crystal continues to grow, the interaction (exchange coupling) between the elementary magnetic moments in the original core and the new growth on the perimeter of the crystal would cause the new material to align its magnetic moments with those of the previous core rather than the ambient magnetic field. Therefore, the exclusively normal polarity that we see may simply indicate that most or all of the crystals passed through the single-domain threshold during a period of normal polarity, even though the entire process of development of the magnetic minerals may have taken much longer.

IMPLICATIONS

We interpret the ChRM C to be an Early-Middle Eocene remagnetization event that is related to widespread fluid migration. Two possible tectonic events were capable of generating large-scale fluid migration in the Cévennes area. They are the Pyrenean orogeny to the south and the Alpine orogeny to the east. The Alpine orogeny lasted mainly from ~30–10 Ma and is younger than the youngest tectonic events in the Cévennes area, so it cannot be the source of the fluids responsible for the remagnetization. The remagnetization post-dates the first orogenic event in the Pyrenean mountains, but pre-dates the last Pyrenean tectonic deformation in the Cévennes area.

The relationship between the remagnetization and Pyrenean tectonics has very important implications for the genesis of the ore deposits in the Cévennes area. Most previous research on the genesis of these deposits suggests that any fluids that may have migrated through the Cévennes border must have come from and through the Southeast basin to the east. Fluid migration northwards from the Pyrénées (Mascle *et al.* 1996) is more suitable hydrogeologically because the sedimentary sequence in the basin to the south of the Cevennes contains more porous carbonate rocks along its pathway. This migration pathway is even more plausible when one considers that the Pyrénées range extended eastwards into the present-day Gulf of Lion located ~200 km south of the Cévennes border during the Pyrenean orogeny. The eastern extension of the Pyrénées orogenic belt is now found as submerged zones in the Mediterranean Sea (Arthaud & Mattauer 1972) and the Corsica–Sardinia blocks that were rotated into their current positions mainly during the Miocene (Baudrimont & Dubois 1977; Vially & Trémolières 1996).

There are two commonly proposed hydrological models invoking the influence of orogenic belts on regional fluid migration. One model suggests that connate formational water is expelled and forced to migrate from sediments as a consequence of the squeezing of sediment layers during tectonic

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compression (Oliver 1986). The second model calls upon a topographic head, created during uplift of the orogenic belt, to establish a gravity-driven flow of meteoric water inboard from the orogen (Garven & Freeze 1984a,b). One important difference between these models is their prediction of the timing of fluid migration relative to the tectonic history. Fluid migration should peak early during orogenesis for the tectonic compression model of Oliver (1986), and late after the maximum uplift in the orogenic cycle for the Garven & Freeze model.

One major phase of uplift with metamorphism in the Pyrénées mountain range was during the Late Cretaceous. In the North Pyrenean zone, erosion of the relief due to this phase began before or during the Palaeocene (Mattauer & Proust 1967; Freytet 1970; Meurisse 1975). The Early-Middle Eocene age of the remagnetization corresponds to this major uplift in the Pyrénées. Thus, the palaeomagnetic age proposed for the MVT mineralization in the Cévennes region corresponds best to the time of fluid migration related to the topographic recharge mechanism of Garven & Freeze (1984a,b).

In the foreland of the Pyrénées, in Languedoc and Cévennes, the main thrusting and/or folding event occurred during the Late Eocene. Since this was the last major tectonic event in the Cévennes area, the synfolding remagnetization cannot postdate Pyrenean tectonics in the area. Assuming a similar age for all the MVT deposits (see Sinclair *et al.* 1993), the MVT mineralization is younger than the Early Cretaceous but predates the main deformation in the Cévennes (Macquar 1973). Both the remagnetization and mineralization therefore occurred within the same time window and both are very likely to be the product of topographically driven fluid migration, related to a major uplift of the Pyrénées orogenic belt (Rouvier *et al.* 2001; Lewchuk *et al.* 2001). We note that fluid flow responsible for the formation of MVT deposits near the Spanish Pyrénées has been constrained at 62.6 ± 0.7 Ma by means of U–Pb dating of cogenetic calcite and galena (Grandia *et al.* 2000).

CONCLUSIONS

Samples of carbonates obtained from selected sampling sites within two gently deformed areas around the Largentière and Croix-de-Pallières mines retain a single-polarity, syn- to post-folding remagnetization related to fluid migration. The mean remagnetization direction is very well defined. Comparison with the European APWP indicates an Early-Middle Eocene age, corresponding to a major orogenic event in the Pyrenean mountain range. This indicates that the fluids responsible for the remagnetization were driven from the south, and not from the east as previously believed. The age of the magnetic overprint relative to major uplift in the Pyrénées mountain range argues in favour of the Garven & Freeze (1984a,b) model that calls upon topographically driven fluid-flow as having formed the MVT deposits.

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