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Geophys. J. Int. (2004) **156,** 200–212 doi: 10.1111/j.1365-246X.2003.02106.x

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Accepted 2003 August 18. Received 2003 May 19; in original form 2002 July 29

SUMMARY

During remagnetization, chemical changes limited to moderate grain growth from pre-existing single domain (SD) grains do not modify the palaeomagnetic direction carried by these grains. Palaeomagnetic direction from new SD grains, on the contrary, is that of the magnetic field during remagnetization. The resulting direction becomes intermediate between the directions carried by previous and new SD grains, as it appears often in case of a partial magnetic overprint. If the growth of pre-existing grains is more important, these grains become large multidomain (MD) and loose the primary magnetization. Stable magnetization is then only related to the new SD grains, which carry the total remagnetization. In the Illizi basin (Saharan platform), these different cases of partial or total magnetic overprint have been observed, resulting from palaeomagnetic studies of different Palaeozoic and Mesozoic formations.

Key words: Cenozoic, chemical remagnetization, demagnetization, Permian, Sahara.

INTRODUCTION

In the Illizi basin (eastern Algerian Sahara), palaeomagnetic analyses were carried out in Silurian to Albian formations. Palaeomagnetic poles related to primary magnetization were obtained in the upper part of the series: Bashkirian (Derder *et al.* 2001a), Moscovian (Henry *et al.* 1992; Derder *et al.* 2001b), Stephano–Autunian (Henry *et al.* 1992; Derder *et al.* 1994), Upper Triassic – Lower Liassic (Kies *et al.* 1995) and Liassic (Derder *et al.* 2001c). Some of the samples from these sites also show Permian and Cenozoic secondary magnetizations. All the other studied levels (Silurian, Emsian, Givetian, Famenian, Strunian, Tournaisian, Namurian, Lower Bashkirian, and Albian) gave only Cenozoic secondary magnetization. The aim of this paper is to better understand acquisition processes and the history of these remagnetizations

SAMPLING AND ANALYSIS PROCEDURE

Formations of the Illizi basin (Figs 1 and 2) were sampled during several field trips mainly along a section Tamadanet (28°41′N, 9°11′E)—In Amenas (28°05′N, 9°30′E)—Illizi (26°29′N, 8°28′E)—Libyan border east of Illizi (26°13′N, 9°18′E). Another section was studied east of In Amenas at Zarzaïtine (28°18′N, 9°48′E) and Edjeleh (27°38′N, 9°50′E). Throughout this area, dip of the formations is very low (lower than 4°), except close to local structures and in the Edjeleh anticline. Most samples were drilled *in situ*, but oriented (with plaster cap) hand-samples were also collected, mainly in some clay or marl facies. Formations, with facies appropriate to palaeomagnetism, were extensively sampled: Strunian shelled limestone (in the Djebel Illirene Formation), Tournaisian red beds (in the Issendjel Formation), Upper Bashkirian and Moscovian limestone and clay (El Adeb Larache Formation), Stephano-Autunian sandy clay (Lower Tiguentourine Formation), Upper Triassic-Rhaetian sandstone and clay (Lower Zarzaïtine Formation), Liassic limestone and clay (Middle Zarzaïtine Formation) and Albian sandstone and clay (In Akhamil Formation). In the other formations, the sampling was mostly limited to site-tests in one or two stratigraphical levels: Silurian sandstone (Mederba Formation), Emsian sandstone, Givetian limestone, Strunian sandstone (all three in the Djebel Illirene Formation), Tournaisian gray sandy clay (in the Issendjel Formation), Visean sandstone (lower 'mushroom' level of the Assekaifaf Formation), Namurian limestone (Issaouane limestone of the Oubarakat Formation), Lower Bashkirian limestone and clay (Oubarakat Formation) and Permo-Triassic clay (Upper Tiguentourine Formation). In this last level, all the collected hand-samples were too soft to be drilled in the laboratory, even using forced air.

Selected samples from all localities have been subjected to rock magnetic studies in order to obtain information about main ferrimagnetic carriers, their domain state, and stability upon laboratory treatments, etc. Thermomagnetic analyses of low field magnetic susceptibility K(T) were done on an AGICO (Brno, Czech Republic) KLY-2 susceptibility bridge with high-temperature CS-2 attachment. Hysteresis loops were generated using a translation inductometer within electromagnet capable of reaching 1.6 T.

Samples for palaeomagnetic analysis were stored for at least one month in zero magnetic field, in order to eliminate the main part of the viscous remanent magnetization (VRM) acquired *in situ* or after sampling. The remanent magnetization was measured using a

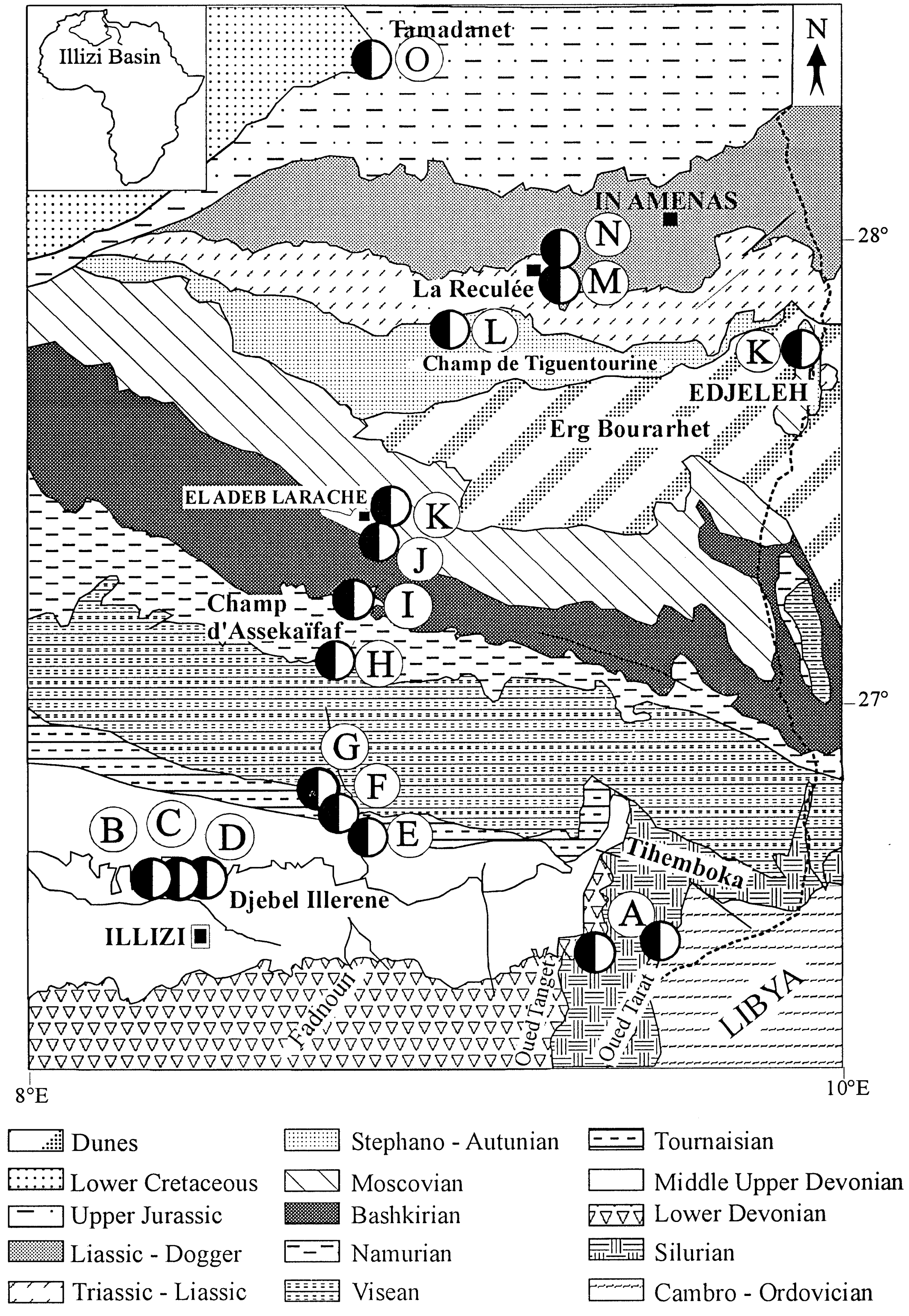

Figure 1. Map of the Illizi basin (after C.R.Z.A. 1964, 1965, modified), with the sampling areas in Silurian sandstone (A), Emsian sandstone (B) Givetian limestone (C), Strunian limestone (D), Strunian sandstone (E), Tournaisian red beds (F), Tournaisian sandstone (G), Visean sandstone (H), Namurian limestone (I), Bashkirian limestone and clay (J), Moscovian limestone and clay (K), Stephano-Autunian clay (L), Upper Triassic-Rhaetian sandstone (M), Liassic limestone and clay (N), and Albian sandstone and clay (O).

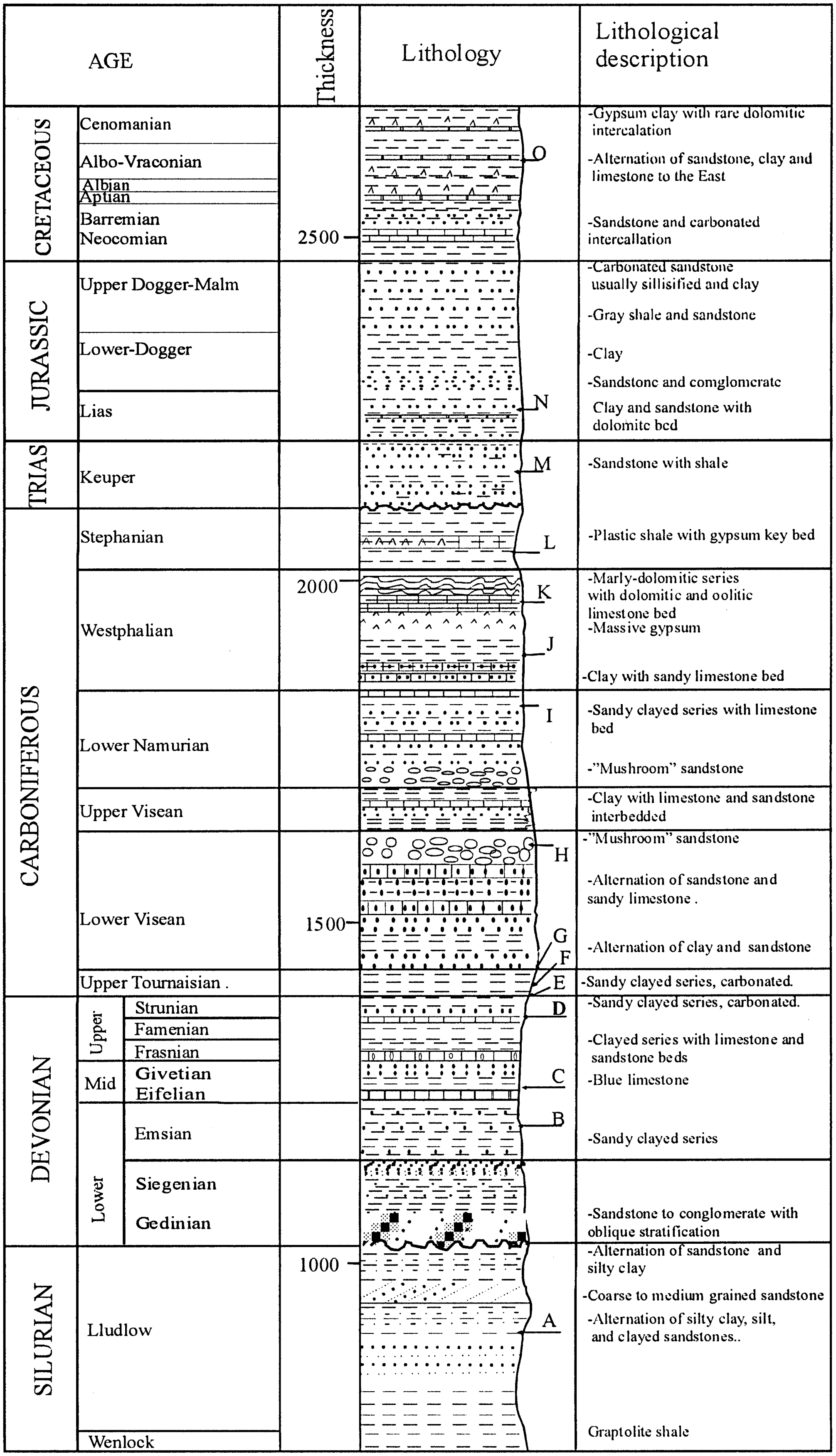

Figure 2. Cross-section of the series of the Illizi basin, with the sampled levels (see Fig. 1).

JR-4 magnetometer (AGICO, Geofyzika, Brno, Czech Republic). Preliminary study was carried out on at least two samples by site. Afterwards, all samples from sites allowing determination of magnetization with direction different from that of the Cenozoic field, sites-test and sites of Strunian limestone were then subjected to thermal demagnetization. The mean direction of the different components of natural remanent magnetization (NRM) in each specimen has been computed using principal component analysis (Kirschvink 1980). Fisher (1953) statistics and bivariate form of Fisher statistics (Le Goff 1990; Le Goff *et al.* 1992) were used to determine the mean direction of the NRM components within each site and for each formation.

PALAEOMAGNETIC ANALYSIS

Separation of the NRM components

Fig. 3 presents different magnetic behaviours observed during thermal demagnetization. The remaining part of VRM is eliminated after heating at temperature of 250 °C or lower.

In formations older than Upper Bashkirian age and in the Albian Formation, single characteristic remanent magnetization (ChRM), with normal or reversed polarity, has been mostly identified, after elimination of the VRM. In some cases, components of neighbouring directions, with the same polarity or of opposite polarities, have been separated. All the obtained palaeomagnetic directions are relatively close to that of the Cenozoic magnetic field (Fig. 4).

In the other formations, different cases have been observed after elimination of the VRM. In a few samples, a single ChRM of normal polarity and close to direction of the Cenozoic field has been isolated (Fig. 4) as in the previous formations. In the other samples, two components can often be determined. The component with lowest unblocking temperature, which is always of normal polarity, is relatively close to the present field. The other one is the ChRM. Fold test (Derder *et al.* 2001b) and evolution of palaeomagnetic direction according to formation age shows that this ChRM is the primary magnetization. That is confirmed for the Stephano-Autunian Formation by similar directions, dated by a fold test, obtained in the Bechar–Mezarif basins (Merabet *et al.* 2003). However, in some Bashkirian and Moscovian samples (Henry *et al.* 1992; Derder *et al.* 2001a,b), different directions can be observed. These directions correspond to that of the Permian overprint already observed in other studies in Africa (e.g. Daly & Irving 1983; Salmon *et al.* 1988; Aïfa 1993). In the Lower Stephano-Autunian Formation (sample TG18A on Fig. 3), the lowest unblocking temperature component is strongly dominant, and the primary component was

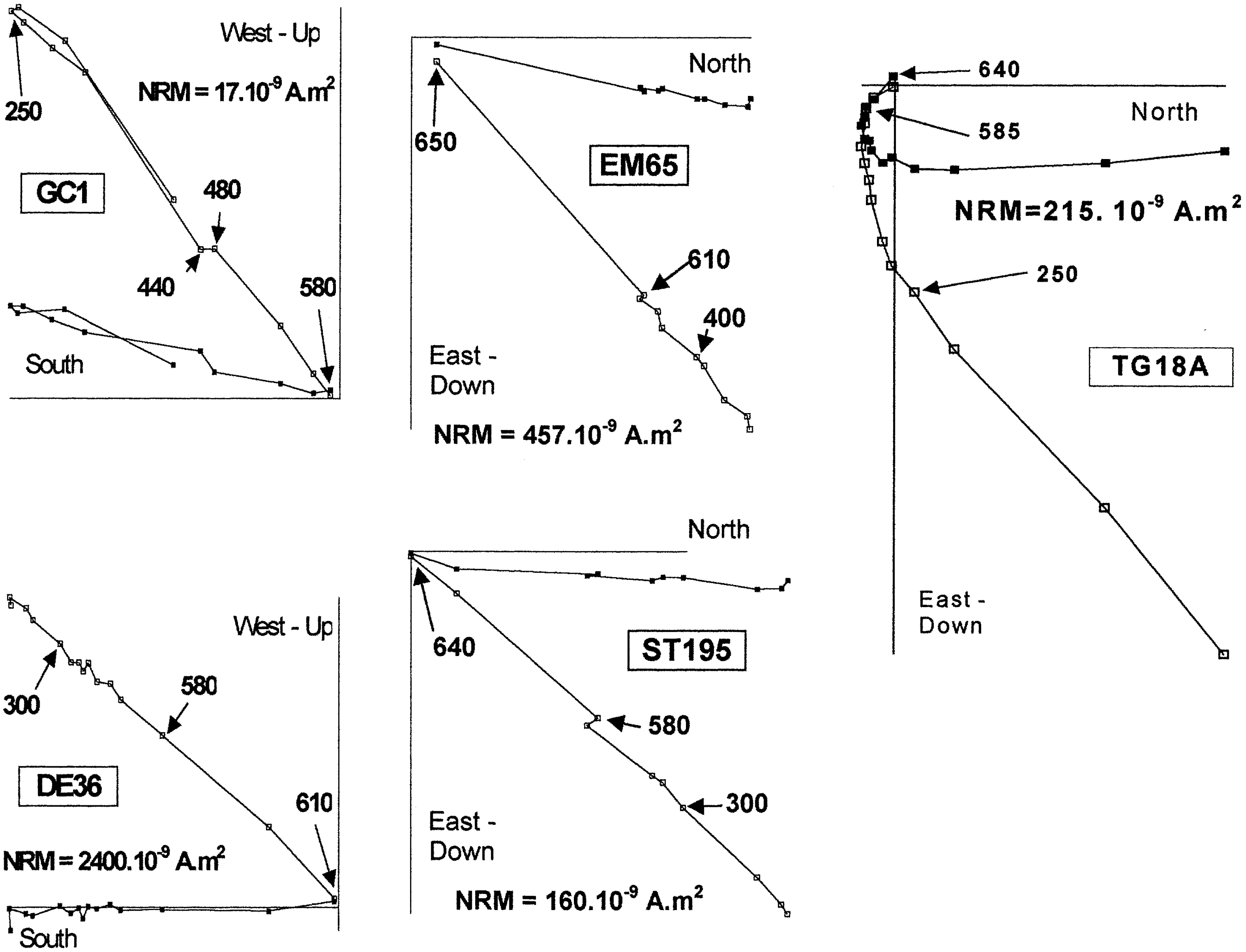

Figure 3. Orthogonal vector plots (filled symbols - horizontal plane, open symbols - vertical plane): Examples of: total remagnetization from Visean (GC1), Emsian (EM65), Strunian (DE36) sandstones, and Strunian shelled limestone (ST195); and, partial remagnetization from Stephano-Autunian clays (TG18A).

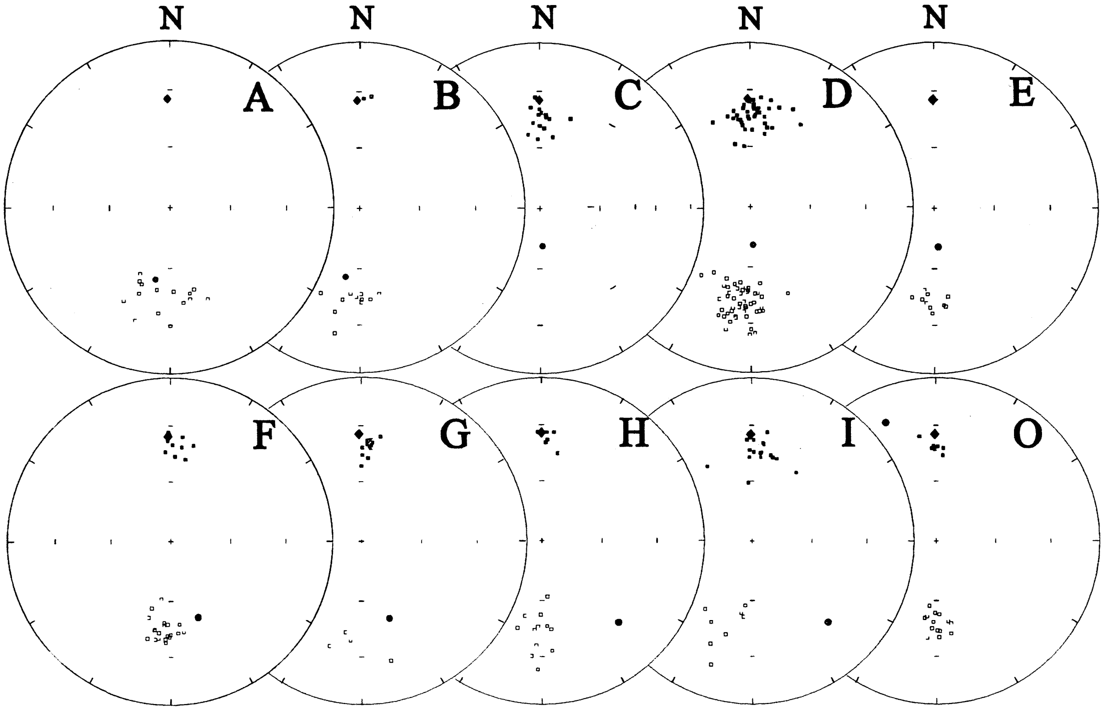

Figure 4. Palaeomagnetic direction of the Cenozoic remagnetization (squares) in the different formations (see Fig. 1). Diamond indicates the present day field and circle the field (lower hemisphere) during rock deposition (according to Van der Voo 1993). Stereographic projection, full (open) symbols correspond to the lower (upper) hemisphere. Results from the sites J to N, already published, are not presented.

hardly isolated (Derder *et al.* 1994). In part of Moscovian samples, the weak component is that of low unblocking temperature (Henry *et al.* 1992; Derder *et al.* 2001a,b). In Triassic and Liasic formations, the two components are of equal importance and can be relatively easily separated (Kies *et al.* 1995; Derder *et al.* 2001c). Results concerning the primary magnetization have been already published and are not the subject of this paper, which focuses on secondary components.

Permian component

The Permian magnetic overprint is well known, in particular in Northwestern Africa and in North America. Surprisingly, in the Illizi basin, it was recognized in a few samples only in the Moscovian Formation: at El Adeb Larache (Henry *et al.* 1992) in four different sites ($N = 22$, $D = 142.2°$, $I = 6.7°$, $k = 564$, $\alpha_{95} = 2.9°$), at Edjeleh (Derder *et al.* 2001b) in six sites ($N = 15$, $D = 146.5°$, $I = 9.2°$, $k = 64$, $\alpha_{95} = 4.8°$), and in the Bashkirian Formation (Derder *et al.* 2001a) in one site ($N = 12$, $D = 140.9°$, $I = 9.8°$, $k = 148$, $\alpha_{95} = 3.3°$). In all the cases, the Permian remagnetization is a total overprint clearly carried by haematite (Fig. 5a).

Components close to the Cenozoic magnetic field

These components have a relatively coherent orientation in the entire Illizi basin (Table 1 and Fig. 4). Their orientation is different from that of magnetic field during rock deposition (Van der Voo 1993). On the contrary, the corresponding palaeomagnetic poles are close (Fig. 6) to the Upper Cenozoic part of the African Apparent Polar Wander Path – APWP (Besse & Courtillot 2002). Although no fold, conglomerate or contact tests were possible, it is clear that these components are Upper Cenozoic remagnetizations.

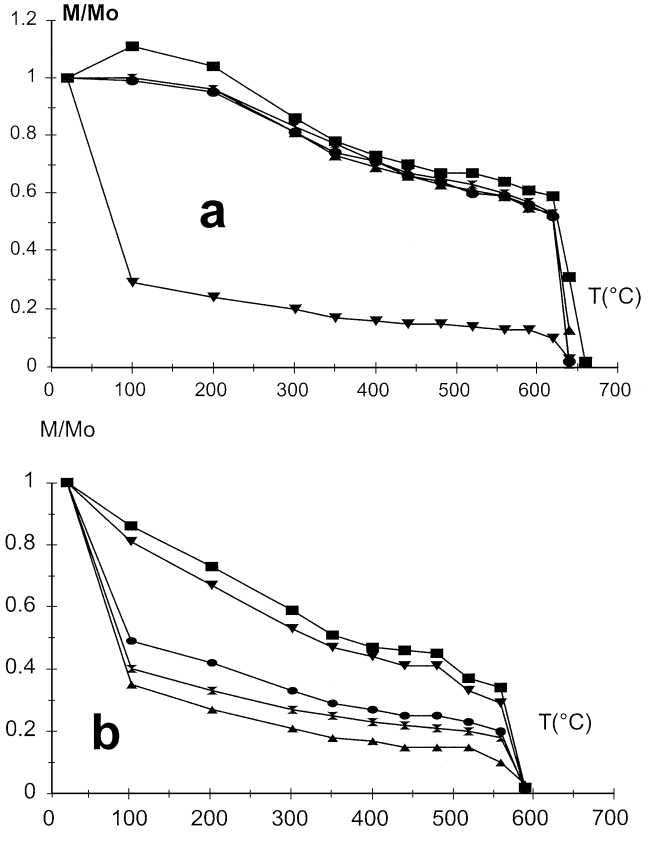

Figure 5. Demagnetization curves (M/Mo as a function of temperature) of the Permian (a) and Cenozoic (b) remagnetizations in the Moscovian Formation.

Table 1. Cenozoic magnetic overprint: number of samples of normal (N_n) and reversed (N_r) polarities; direction before dip correction (D and I) with associated Fisher parameters (k, α_{95}); latitude south (Lat); longitude east (Long); and, Fisher confidence angle (A_{95}) of the palaeomagnetic pole, critical (γ_c) and measured (γ_o) angles between the directions of opposite polarity for the reversal test (McFadden & McElhinny 1990). D, I, α_{95}, Lat, Long,. A_{95}, γ_c and γ_o in degrees. In the Stephano-Autunian Formation, the obtained direction is in intermediate position between the other Cenozoic remagnetizations and the primary magnetization, probably indicating that this direction results from a partial superposition of the actual Cenozoic remagnetization with this primary magnetization.

Formation	Normal polarity					Reversed polarity					Pole			Rev. test	
	N_n	D	I	k	α_{95}	N_r	D	I	k	α_{95}	Lat	Long	A_{95}	γ_c	γ_o
Silurian sandstone	0					15	181.0	−45.3	34	6.2	88.9	241.9	7.2		
Emsian sandstone	3	3.7	44.4	85	8.7	22	180.8	−46.6	100	3.0	88.3	227.1	4.9	9.0	3.0
						11	188.9	−36.0	33	7.4	79.7	314.2	6.8	16.2	9.3
Givetian limestone	15	0.7	46.4	111	3.4	0					88.5	212.0	3.9		
Strunian shelled limestone	41	0.6	44.9	71	2.6	49	182.3	−42.0	58	2.6	87.7	305.1	2.0	3.8	3.2
Strunian sandstone	0					6	181.0	−43.8	159	3.5	88.9	308.3	3.9		
Tournaisian red beds	9	2.7	41.9	162	3.7	20	181.7	−45.8	118	2.9	88.2	279.8	2.4	5.1	4.0
Tournaisian sandstone	12	3.3	42.7	247	2.6	4	181.2	−36.9	39	11.2	86.0	317.6	3.2	8.0	6.0
Visean sandstone	7	357.4	37.4	61	6.8	13	180.4	−42.8	40	6.1	86.2	7.0	4.0	10.3	5.9
Namurian limestone	18	3.4	45.4	59	4.3	8	195.0	−45.0	36	8.3	82.0	280.4	4.4	8.8	8.2
Bashkirian limestone and clay	7	5.6	26.3	38	8.5	0					75.3	351.5	8.0		
Moscovian limestone and clay	11	7.3	46.2	176	3.2	0					83.5	276.4	2.9		
Stephano-Autunian clays	66	16.6	52.8	67	2.1	0					74.6	253.3	1.9		
Upper Triassic-Rhaetian sandstone	19	2.3	37.9	547	3.0	0					83.0	351.3	3.5		
Liassic limestone and clay	26	358.2	34.5	506	2.8	0					80.7	24.5	2.2		
Albian sandstone and clay	8	358.0	43.0	339	2.7	15	178.6	−48.5	153	2.8	85.9	272.3	2.3	4.5	5.5

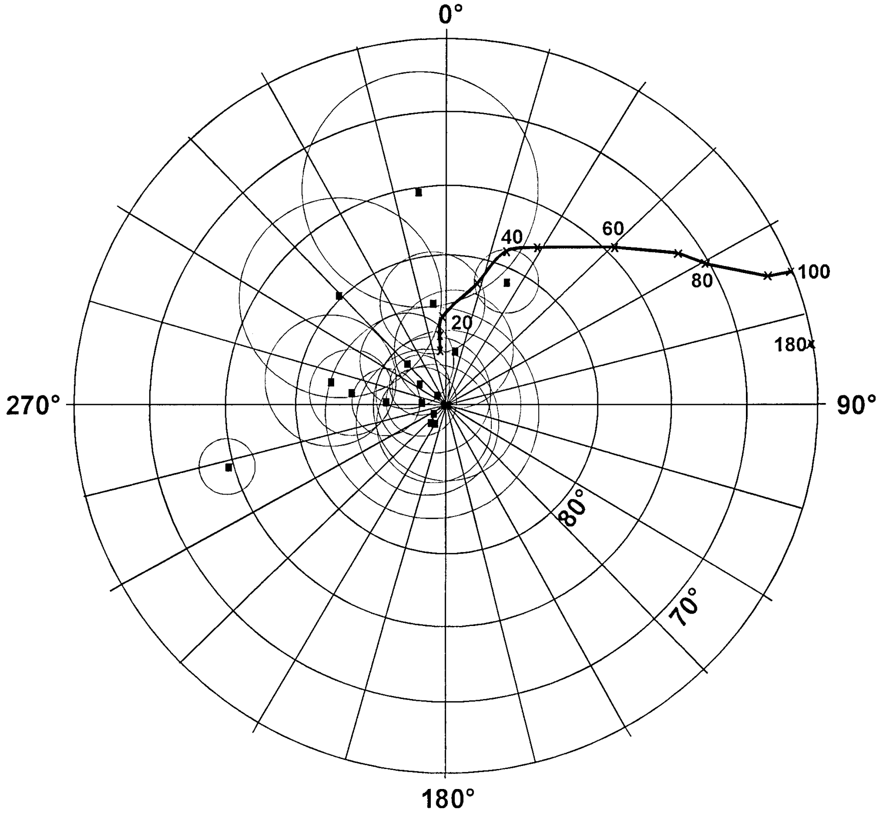

Figure 6. Palaeomagnetic poles corresponding to the Cenozoic remagnetization, and African APWP (Besse & Courtillot 2002). Southern hemisphere.

Magnetic carriers

To compare the acquisition process of the magnetic overprint in the different remagnetized samples, knowledge of the magnetic carriers provides key information.

Silurian sandstone, Strunian limestone and Tournaisian red beds

Weak mineralogical alterations occur only at the highest temperature during the thermomagnetic cycle. In Fig. 7a, magnetite and haematite are present, with a dominant effect of magnetite. However,

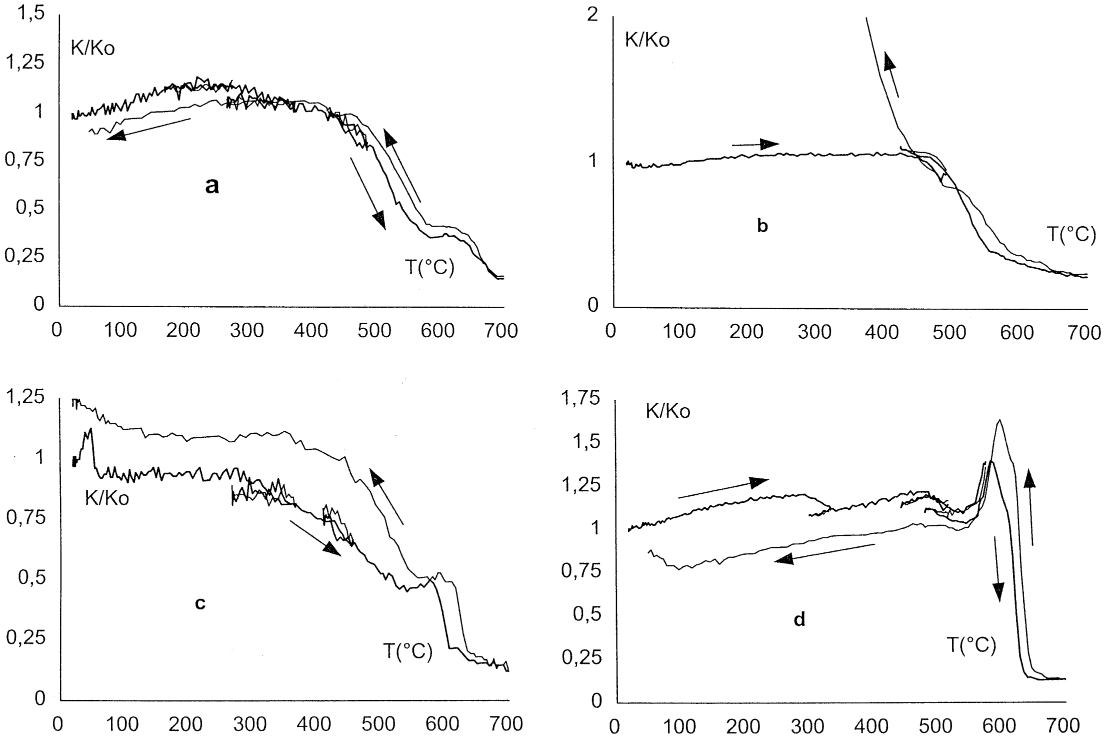

Figure 7. Thermomagnetic curves (susceptibility in low field as a function of temperature): (a) Silurian sample SN91, (b) Albian sample AL41, (c) Givetian sample GDE28, (d) Strunian sandstones sample DE39.

on hysteresis loops (Fig. 8a), the effect of magnetite does not appear and there is no wasp waist: magnetite is therefore probably represented by large multidomain (MD) grains, and this is confirmed by observed high maximum blocking temperatures, often above 600 °C. The remagnetization is carried, at least for the main part, by haematite.

Emsian sandstone

The thermomagnetic curve is reversible, with a clear dominant effect by magnetite. Magnetite also has a clear dominant effect for Albian clays and sandstone, but the thermomagnetic curve here is not reversible. This strong alteration occurs only at the highest

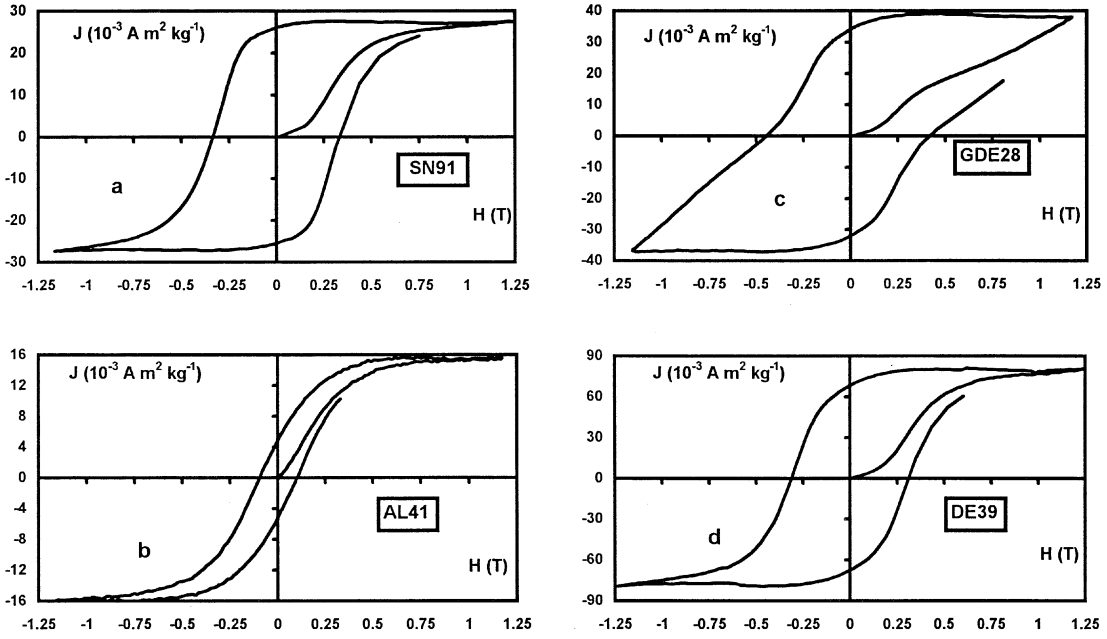

Figure 8. Hysteresis loops (corrected for the paramagnetism): (a) Silurian sample SN91, (b) Albian sample AL41, (c) Givetian sample GDE28, (d) Strunian sandstone sample DE39.

temperature (Fig. 7b). For Emsian and Albian formations, there is again no wasp waist on hysteresis loops (Fig. 8b), but remanent coercive force is lower than for the previous formations. The curve shape shows that part of magnetic minerals reaches saturation of their magnetization. Therefore, compared to the previous formations, there is more magnetite. Maximum blocking temperatures are, according to the samples, from 580 to 610 °C. Although the main carrier of the remagnetization is haematite, at least for some samples, the effect of magnetite remains possible.

Givetian limestone, Tournaisian and Visean sandstones

The thermomagnetic curve is reversible, with almost equivalent effect of magnetite and haematite (Fig. 7c). On hysteresis loops, the effect of magnetite does not directly appear, but there is visible small wasp waist (Fig. 8c). Magnetite therefore could be represented by large MD grains. This is confirmed by high maximum blocking temperatures, mainly around 600 °C (sometimes lower). The remagnetization is thus mainly carried by haematite.

Strunian sandstone

Only haematite appears on both thermomagnetic curves and hysteresis loops (Figs 7d and 8d). Maximum blocking temperatures are about 580–600 °C. The carrier of the remagnetization is haematite. The same observation was made on Stephano-Autunian sandy clays with, however, higher maximum blocking temperatures (Derder *et al.* 1994).

Triassic and Liasic formations

Haematite and, likely, magnetite are present (Kies *et al.* 1995; Derder *et al.* 2001c). Haematite with low blocking temperatures is the carrier of primary magnetization and probably of Cenozoic remagnetization.

Bashkirian and Moscovian formations

(Henry *et al.* 1992; Derder *et al.* 2001a,b). Haematite is the carrier of primary magnetization, and is the main magnetic mineral in most of the sites. Maximum blocking temperatures close to 670 °C (Fig. 5a) associated with Permian overprint, clearly indicate that this remagnetization has the same carrier. Cenozoic overprint has been observed, on the contrary, only in sites with mainly magnetite and few haematite. Its maximum blocking temperature is always lower than 580 °C (Fig. 5b). It is therefore probable that the carrier of this remagnetization is magnetite.

Polarity of the Cenozoic remagnetization

Only one remagnetization component per sample was obtained in some formations: (i) reversed in Silurian and Strunian sandstones; (ii) normal in Givetian, Bashkirian, Moscovian, Stephano-Autunian, Triassic and Liassic formations; (iii) normal or reversed in Strunian limestone.

Some of the samples from the other formations yield, after elimination of the viscous overprint, several components of different polarity.

Emsian sandstones

In seven sites, two components of reversed polarity can be distinguished during thermal treatment (temperature steps where the second component begins to be isolated: 400–500 °C), without evidence of normal polarity. These two components are significantly distinct, the angle separating the mean direction of these two components $\gamma_o = 12.2°$, being much larger than the critical angle $\gamma_c = 6.9°$ the maximum value for which two directions are not significantly different (McFadden & McElhinny 1990). In another site, direction has mainly normal polarity, but with evidence of reversed polarity for the highest treatment steps.

Tournaisian red beds

In two sites, polarity is mainly reversed, but evidence of normal polarity has been obtained for the highest temperatures steps of thermal analysis.

Tournaisian sandstone

In one site, some of the samples show normal polarity until 540 °C step of thermal analysis, and reversed polarity for higher temperatures.

Visean sandstone

During thermal analysis, remagnetization shows normal polarity until 350–400 °C step, and reversed polarity for higher temperature.

Namurian limestone

In one site, remagnetization is of normal polarity (or without significant demagnetization) until 550 °C, and reversed for the highest temperatures. In two other sites, polarity is always reversed, but there is no significant demagnetization from 400 ° to 550 °C.

Albian clay and sandstone

In one site, two samples show reversed (250–450 °C) and normal (450–580 °C) polarities. For three other samples, only normal polarity has been isolated, but there is no demagnetization from 250 to 450 °C. The other samples have low maximum blocking temperature (450 °C) and only reversed polarity has been obtained. In two samples from another site, several components have been obtained: Normal (up to 200 °C VRM), reversed (200–300 °C), normal (300–350 °C) and reversed (from 350 °C to maximum blocking temperature 450 °C).

In almost all the formations with two polarities, reversal test of McFadden & McElhinny (1990) is positive (Table 1), of class B ($5° < \gamma_c \leq 10°$) or C ($10° < \gamma_c \leq 20°$). The single exception is the Albian Formation, where the test is non-conclusive (angle between mean normal and reversed polarity is however only 5.5°, but the test is of class A: $\gamma_c \leq 5°$). These normal and reversed components were therefore acquired during neighbouring periods. The two reversed components in Emsian Formation are on the contrary significantly distinct, and may be corresponding to two distinct periods of acquisition.

DISCUSSION

Origin of the Cenozoic remagnetization

Petrographic criteria have been searched in the different facies to distinguish remagnetized and non-remagnetized samples. In some facies, no significant petrographic difference appears between these samples. Fine grained limestones carry mainly primary magnetization (Moscovian), total overprint (Namurian) or both magnetizations (Liassic). The same remark can be made for fine-grained sandstones (total remagnetization in Emsian sandstone and only primary magnetization or both magnetizations in Upper Triassic Formation). However, red pelites, which carry primary magnetization in Bashkirian Formation and total remagnetization in Tournaisian Formation, are a little more sandy in the latter. In one site of the Moscovian Formation, different magnetizations have been obtained in carbonated sandstones (Cenozoic and Permian remagnetizations) and marls (primary magnetization). It is then possible that increase of the sandy fraction rather has favoured remagnetization acquisition and that, on the contrary, increase of the argillaceous fraction is more favourable for preservation of primary magnetization. In one site of the Moscovian Formation, limestone, much more porous than in the other limestone sites that kept primary magnetization, carries Permian overprint. Higher porosity could also be a factor favouring remagnetization. However, primary magnetization has also been found in Upper Triassic porous sandstone, and these petrographic and physical criteria cannot be generalized. Concerning permeability, only one marls bed corresponding to impermeable facies has been studied (Moscovian), yielding primary magnetization. The other sampled impermeable beds gave too soft samples to be studied. Stephano-Autunian sandy clay, which contains a significant amount of quartz grains, is not actually impermeable and carries partial overprint. Pelites are indurate but strongly fractured, allowing water circulation. They gave primary magnetization and remagnetization according to the formation.

In the Illizi basin, no strong strain or thermal event affected the series. Owing to observed high blocking temperatures, thermoviscous effect cannot be at the origin of remagnetization. Coherence of the directions excludes lightening effect. Magnetic overprint is therefore related to chemical phenomenon.

Several mechanisms have been proposed for the origin of chemical remanent magnetizations (CRM). They can be broadly divided into two categories: the first one corresponds to remagnetization related to internal processes alone, like *in situ* alteration of clays (Katz *et al.* 1998, 2000) and maturation of organic material (Elmore *et al.* 1993) related to burial or weathering; the second one requires fluid migrations leading sometimes to dolomitization (Lewchuk *et al.* 1998, 2000; Elmore *et al.* 2000), hydrocarbon pooling (Oliver 1986) or base metal mineralization (Lewchuk & Symons 1995). Warm fluids could also act similarly as burial on internal processes, simply by thermal effect.

Here, there was almost no cover (i.e. no burial) during remagnetization acquisition. In addition, samples from deep (greater than 3000 m) boreholes (Pozzi 1967; Bucur 1971) do not show Cenozoic remagnetization, contrary to surface samples. Ankerite has been found only in part of the remagnetized formations and there is no significant metal mineralization in the studied area. Part of limestone is dolomitic in the Illizi basin (Moscovian and Liassic formations), but they mostly carry primary magnetization. Hydrocarbon pooling was finished prior to Cenozoic. The samples do not contain significant amount of organic matter, contrary to samples from boreholes. Organic matter however could have been leached since remagnetization times, but no burial could give maturation of organic matter at remagnetization time. If maturation of organic matter or clay alteration occurred, it was only possible by a process other than burial, such as interaction with fluids or weathering. Another important remark is that remagnetization here is mostly carried by haematite. Most of the process indicated above corresponds to production of magnetite. If magnetite was produced, it was then oxidized in most formations.

With only the exceptions of two Tournaisian sites, magnetic polarity is the same within each site. In the two Tournaisian sites, the different polarities correspond to slightly different stratigraphical levels. It seems therefore that a magnetic polarity—stratigraphy relationship could exist. An observation made in the Strunian shelled limestone shows that it is not always the case. The southern cliff of the Djebel Illirene (26°37N, 8°21E) is one of the locations with slightly higher dip (reaching locally 10°). Detrital shells within hematitic–ankeritic carbonated cement are here disposed in few thin levels interbedded in Strunian sandy clay and sandstone. Two such levels, moderately dipping to the north, appear in discontinuous outcrops. They have been studied in 10 sites along an E–W section. On the same level, polarity is different according to the sites. However, comparing obtained polarities in the two levels in neighbouring sites, it appears that polarity is always the same at the same altitude. That could be a mere chance, but also an indication of a relation to altitude (also then explaining the magnetic polarity—stratigraphy relationship in sub-horizontal beds). Topography being irregular, the phenomenon acting in a horizontal plane is probably not weathering. That rather suggests relation to ground-fluids. The relationship between remagnetization and ground-fluids is not always very simple (Evans *et al.* 2000). Here different polarities have been observed according to altitude and that could be explained by variation of the level of migrating fluids. Pozzi (1967) and Bucur (1971) showed that the same formation is remagnetized in surface outcrops, but has no magnetic overprint in deep borehole. Remagnetization then occurred only in part of ground-fluid, probably in the upper part. That could be related for example to stratification of different fluids or to interaction with atmosphere.

Fluids at origin of remagnetization could have been tectonically migrating fluids (Oliver 1986; Leach *et al.* 2001). The main tectonic events during the Upper Cenozoic are, on the northern border of the Sahara, uplift and deformation in the Alpine chain, and, south of the Illizi basin, in the Hoggar area the emplacement of thick (100 to 250 m) basaltic trapps, phonolitic and trachytic lavas during important uplift. This uplift probably produced fluids migration (Garven & Freeze 1984a,b). Moreover, due to volcanism, fluids from the Hoggar could have been enriched with chemically active components.

An alternative explanation could be related to climatic effect on ground-fluids. During the Upper Villafranchian, occurrence of ferruginous cuirasses and carbonated incrustations is a widespread phenomenon in Sahara (Conrad 1969) and also could be the origin of remagnetizations. Such occurrence is also related to fluids migration, but along a vertical direction. Perhaps, organic matter was still present at this time and interacted with the fluids, but regardless it is clear that the fluids giving ferruginous cuirasses carried iron.

No definitive arguments allow choosing, for origin of remagnetizations, between fluids migration related to tectonic event and to occurrence of cuirasses and incrustations. The first assumption should agree with the effect of altitude, assuming level variations of ground-fluids. For the second one, iron was clearly present in fluids during occurrence of cuirasses, but vertical fluids migration does not simply explain the relation between polarity and altitude. It is also possible that both fluid circulations acted in remagnetization acquisition (for example, climatic effect related to the level of ground-fluids). We cannot exclude the hypothesis of another single unknown phenomenon, possibly even related to internal processes alone, as weathering (though this would hardly explain the presence of different polarities).

The presence of two different remagnetization carriers according to the formations (magnetite in Bashkirian and Moscovian formations, and haematite in the others) should imply that the acquisition process of remagnetization was not a simple crystallization of ferrimagnetics from exotic fluids. Even assuming that haematite results from oxidation of newly formed magnetite, rock initial composition has an effect because magnetite was not oxidized in all the formations. For fluid migration, remagnetization could be related either to alteration of rock component(s) under the effect of fluids (for example, by simple thermal effect), or to interaction with exotic element(s) carried by fluids. For internal processes alone, the importance of the rock composition becomes obvious. However, as indicated before, no general petrographic criterion to distinguish remagnetized and non-remagnetized facies is reliable. Magnetite and haematite as carriers of remagnetization have been found both in sandstone and limestone. No petrographic criterion yields determination of the carrier of remagnetization.

'Apparent' magnetostratigraphy

Table 1 gives polarity(ies) of remagnetization according to the studied level. It is clear that the sampling is not representative of all the series. The important observation is the existence of a succession of different polarities according to the formations in a cross-section of the series of the Illizi basin. The result is a kind of magnetostratigraphy of this series, but only related to magnetic overprints (Henry *et al.* 1991). In relatively old series as in this basin, there is no ambiguity concerning the non-primary character of the magnetization, because magnetic field direction during remagnetization was very different from that during the rock's deposition. Similar phenomenon occurring relatively few times after emplacement of the series could be, on the contrary, responsible for magnetostratigraphic fully erroneous interpretations of a succession of polarities according to stratigraphy.

It can be noticed that a similar 'apparent magnetostratigraphy', more limited, has been observed in tabular Triassic series of southern Tunisia (Ghorabi & Henry 1991). The magnetic overprint is also Cenozoic in age. In the Lower and Middle Triassic, its polarity is mixed. Samples of Lower Carnian age show reversed polarity, Middle Carnian age show mixed polarity, and Upper Carnian and Rhaetian ages show normal polarity.

Theoretical remarks about chemical remagnetizations

Acquisition of a stable chemical remagnetization (see McClelland 1996; Dunlop & Özdemir 1997 and included references for complementary information about CRM) implies either increase (grain growth) or decrease (alteration) of the size of magnetic grains to reach a size with stable magnetization, or formation of new grains, as a new crystal or from transformation of a non-magnetic grain.

New very small grains of magnetic mineral are superparamagnetic (SP) at nucleation state. During their growth, they can acquire stable remanence when becoming single domain (SD) grains (Néel 1949, 1955). The orientation of this remanence is then related to ambient magnetic field when the grains grow large enough to cross the threshold SP–SD. As the grains continue to grow, interaction (exchange coupling) between the elementary magnetic moments in the original core and the new thin growth perimeter of the grain, would cause the new material to align its magnetic moments with those of the previous part rather than with ambient magnetic field. In fact, one SD grain cannot carry two different magnetization directions. If the grain continue to grow, it becomes pseudo-single domain (PSD), then small MD, then reaching a large MD size with unstable magnetization (similarly, a decrease of size from large MD grain can allow acquisition of a stable magnetization).

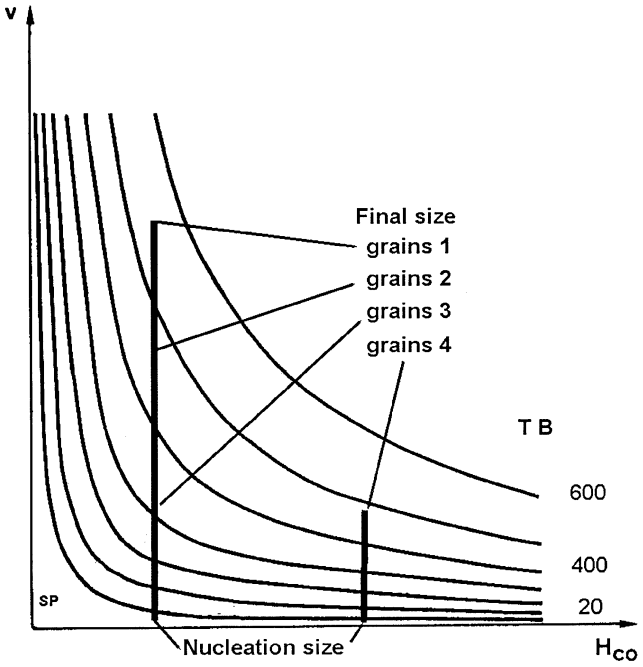

Figure 9. Evolution of the magnetic characteristics of a SD grain during its growth on the Néel (1949, 1955) diagram, assuming no change of microscopic coercive force (Dunlop & Özdemir 1997). Magnetization, of grains with different volume (V) 1 to 3 but same Coercive force (H_{co}), can be separated during thermal treatment (different unblocking temperatures TB). Magnetization of grains 2 and 4 corresponds to the same unblocking temperature though different volume because of their different coercive force. For the same reason, magnetizations of grains 3 and 4 have different unblocking temperature though the same volume. SP: superparamagnetics.

This implies that, during grain growth, magnetization direction acquired by newly formed part of pre-existing SD grains, does not correspond to that of ambient magnetic field. If there is no formation of new grains, the effect of grain growth on SD grains (Fig. 9) is only an increase in stability (Fig. 9, see Néel 1949, 1955) of the previous magnetization at the beginning (notice that such an increase modifies the magnetic characteristics, yielding, for example, wrong data in palaeointensity determinations). However, if grains size becomes that of large MD, these grains will loose this stable magnetization. If there is also formation of new SD grains, the magnetization of these new grains will be related to ambient field, but the acquired total new magnetization will result from that in new and old SD grains and will have an intermediate orientation between those carried by the two families of grains. So, the more new SD grains are formed, the more the resulting direction will be closer to this ambient field. However, as shown by the Néel (1949, 1955) diagram, if the microscopic coercive force is not too different for the two families of grains, progressive demagnetization could lead to separation of the two directions (Fig. 9).

Complete and partial remagnetizations

Complete magnetic overprint indicates, either that rock did not acquire any primary stable magnetization (or only one too weak), or that primary magnetization disappeared. This disappearance can be related to mineralogical alteration or to change of grain size.

Partial overprint can be related to two different minerals, one carrying primary magnetization and the other remagnetization. At least the component carried by the mineral with the highest blocking temperature is then mostly isolated during thermal treatment (Henry *et al.* 1999; Merabet *et al.* 1999). This component can be the primary or the secondary component. If the same mineral carries primary and secondary magnetizations, the possibility of separation depends on homogeneity of the microscopic coercive force of the grains. An interesting remark is that the magnetization with the highest blocking temperature will be then the primary one if the grains, all of neighbouring microscopic coercive force, keep SD size.

Application to the Cenozoic remagnetizations

In the Illizi basin, partial overprint, with haematite as carrier for both the primary and secondary magnetizations, has been found in the Stephano-Autunian Formation. During thermal treatment, the direction of difference-vectors of the magnetization progressively evolves towards primary magnetization. The microscopic coercive forces of the grains are therefore not perfectly homogeneous. The component with the highest blocking temperature is the primary magnetization in all the cases. Consequently, growth of the grains carrying the primary magnetization was limited and the spectrum of microscopic coercive forces for most of the grains is then not very large.

In formations affected by total remagnetizations, magnetite and haematite have been observed everywhere, except in Strunian sandstones which (only haematite). In the Bashkirian and Moscovian formations, magnetite is probably the carrier of the Cenozoic remagnetization. In the other formations, magnetite appears as relatively large MD grains and cannot carry stable magnetization. If this magnetite resulted from evolution of primary small grains, these would grow sufficiently to reach such a large size, which would lead to loss of primary magnetization in these formations. It is possible that this growth of magnetite occurred during the period of magnetic overprinting, because we know that magnetite formed at least in two formations during remagnetization.

In formations with one remagnetization component per sample, this component was isolated with a relatively regular demagnetization curve. It is very probable that the SD size of new grains has therefore been mainly acquired during a single polarity interval. That does not exclude continuation of growth of these SD grains during a longer period (Henry *et al.* 2001).

Except for the two Emsian reversed components that have significantly distinct directions, remagnetization in samples with different polarities was acquired over a relatively long duration including part or totality of several polarity intervals. New grains reached SD size during this entire period. In samples with grains having homogeneous microscopic coercive forces, the different polarities clearly appear on the Zijderveld plot and the demagnetization curve (Fig. 10a), as for the thermal remagnetization acquired during very slow cooling (Crouzet *et al.* 1997). In the other samples, changes of polarity are only indicated by a change of the slope on the demagnetization curve, often corresponding to almost no demagnetization (Fig. 10b). Similar change during thermal demagnetization can be often observed (see for example Fig. 3). An irregular slope of a demagnetization curve is usually interpreted as reflecting the presence of several families of grains with different

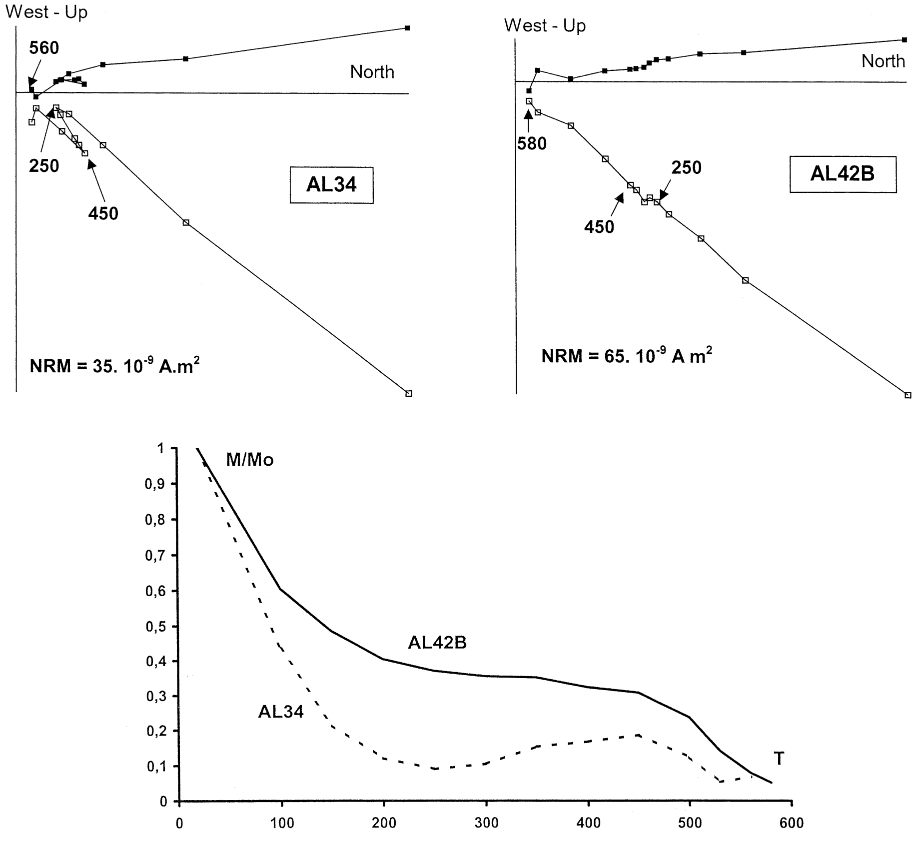

Figure 10. Orthogonal vector plots (filled symbols - horizontal plane, open symbols - vertical plane) and corresponding demagnetization curves (M/Mo as a function of temperature) for Albian samples AL34 and AL42B.

characteristics. It appears here that such a shape can sometimes be an indicator of the existence of several polarity intervals during remagnetization.

Implications for the magnetic 'story' of the Illizi basin

The surprising fact in the Saharan basins is that all presently studied formations older than the Namurian have been affected by complete magnetic overprinting, except in depth. In the Illizi basin, the stratigraphical limit between complete or partial overprint is within the Bashkirian. In the Ahnet and Tindouf basin, this limit is the same (Bayou *et al.* 2000; Bouabdallah 2000). Some of the studied facies are however very similar in formations over and under this limit (for example, red beds in the Tournaisian and part of the Upper Bashkirian Formation in the Illizi basin). It is therefore not excluded that an event (fluid migration?), having occurred during the end of the Hercynian deformations, affected the entire Saharan craton and led to erasing most of the primary magnetizations. In addition, Aïfa *et al.* (1990) and Aïfa (1993) assume that remagnetization occurred locally during Carboniferous in the northwestern Sahara.

The first sure magnetic overprinting in the southern Sahara occurred during Permian times, but its effect is limited to only the Bashkirian and Moscovian formations in the Illizi basin and Moscovian Formation in the Ahnet basin (Daly & Irving 1983). The fact, that this Permian overprint was not indicated in any of the older formations, again underlines the limit within the Bashkirian. Assuming an event having erased mostly the primary magnetization in the old formations, this event could have led to a change of rock composition precluding the acquisition of the Permian overprint. Another possibility is that the Permian remagnetization was completely overprinted in the Illizi basin during the Cenozoic times, except locally in the Bashkirian and Moscovian formations.

The last remagnetizing event is precisely the Cenozoic overprinting.

CONCLUSION

In the Illizi basin, total and partial magnetic overprints of chemical origin have been observed. Partial remagnetization indicates that the primary small grains did not grow sufficiently to loose the primary stable magnetization. The latter often becomes more stable than at the time of its initial acquisition. On the contrary, total remagnetization could indicate that these grains transformed into large MD unable to retain stable magnetization.

Even for chemical remagnetization, analysis of the demagnetization data can yield information about duration of remagnetization phenomenon by occurrence of new magnetic SD grains. Decreases of slope of the demagnetization curve sometimes corresponds to existence of opposite polarity intervals during remagnetization. In favourable cases, different components acquired during neighbouring periods can be separated. The demagnetization data are then very similar to that obtained for thermal remagnetization due to very slow cooling.

ACKNOWLEDGMENTS

The authors are very grateful to D. Elmore and B. Katz for constructive comments, to T. E. Abdelatif for help with the manuscript, to M. Le Goff, J. Seilhan, and R. Benjelloul for assistance during field trips, and to the SONATRACH for logistic support in the field. This work was supported by the Algerian Direction de la Post-Graduation et de la Recherche Universitaire of the Ministère de l'Enseignement Supérieur et de la Recherche Scientifique and the French Centre National de la Recherche Scientifique.

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