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JUXTAPOSED AND SUPERIMPOSED MAGNETIZATIONS IN CARBONIFEROUS FORMATIONS OF THE TINDOUF BASIN

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ABSTRACT

In the Tindouf basin, two well defined juxtaposed magnetizations B and C have been determined in two Carboniferous formations using principal component analysis. The B component, corresponding to the lowest unblocking temperatures of magnetization, results of the superimposition of the primary component C to a chemical remagnetization D (here a Permian overprint). Such a superimposition could have been pointed out by analyzing the relations in orientation between B and C components.

Keywords - Juxtaposed magnetizations - Superimposed magnetizations - Chemical Remagnetization- Tindouf basin.

AIMANTATIONS JUXTAPOSÉES ET SUPERPOSÉES DANS LES FORMATIONS CARBONIFÈRES DU BASSIN DE TINDOUF

RÉSUMÉ

Dans deux formations carbonifères du bassin de Tindouf, deux aimantations juxtaposées B et C, bien définies, ont été déterminées par analyse en composantes principales. La composante B, qui correspond aux basses températures de blocage de l'aimantation, résulte de la superposition de l'aimantation primaire C avec une réaimantation chimique D (d'âge permien). Une telle superposition a pu être mise en évidence par l'analyse des relations en orientation entre les composantes B and C.

Mots clés - Aimantation juxtaposées - Aimantations superposées - Réaimantation chimique - Bassin de Tindouf.

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VERSION FRANCAISE ABREGEE

Deux études paléomagnétiques ont été réalisées dans le bassin de Tindouf, dans les formations argilo-gréseuses rouges de Reouina d'âge Namurien et celles de Merkala d'âge Stéphanien inférieur (Bouabdallah, 1999; Henry *et al.*, 1999; Merabet *et al.*, 1999). Les analyses de magnétisme de roches (courbes thermomagnétiques, méthode de Lowrie -1990- et courbes de désaimantation) avaient montré la présence d'hématite et très probablement de magnétite. Durant le traitement thermique et après élimination d'une faible aimantation A proche du champ magnétique actuel (aimantation visqueuse ou réaimantation récente portée par de la goethite), deux composantes B et C avaient clairement été le plus souvent séparées (fig. 1): B isolée entre 200-300°C et 550-580°C, et C à des températures plus élevées jusqu'à 670°C. Le but de ce travail est de préciser les relations entre ces composantes B et C. Rappelons (voir Bouabdallah, 1999; Henry *et al.*, 1999; Merabet *et al.*, 1999) que l'aimantation C a été acquise pendant ou juste après la diagénèse de ces formations, et que l'orientation de la composante B est intermédiaire entre celle de l'aimantation C et celle de la réaimantation permienne. Les résultats des paléodirections ont été résumés dans le tableau 1 pour la formation namurienne et dans le tableau 2 pour la formation stéphanienne. Les cycles d'hystérésis (fig. 2) des spécimens contenant les composantes B et C montrent "une taille de guêpe" plus prononcée que ceux des spécimens avec seulement la composante C.

Les composantes B et C sont très bien définies et semblent représenter un bon exemple d'aimantations juxtaposées. Cependant, d'un échantillon à l'autre (fig. 3a) comme d'un site à un autre (fig. 3b et c), l'angle entre la direction moyenne de la composante B et celle de la composante C apparaît remarquablement constant, en valeur et en orientation (en moyenne, 8.7° +/- 3.3° pour Reouina et 9.9° +/- 2.8° pour Merkala). Une relation existe donc entre l'orientation des composantes B et C. Or des aimantations acquises indépendamment ne devraient pas avoir une telle relation, au moins dans une zone non déformée. Pour une aimantation donnée, la disposition (écart angulaire en valeur *et en direction*) de la direction moyenne de chaque site par rapport à celle de la moyenne pour l'ensemble des sites est liée essentiellement à la variation séculaire du champ magnétique terrestre et à la dérive continentale. Il n'y a aucune raison que, comme dans les formations de Merkala et de Reouina, cette disposition soit la même pour deux aimantations acquises indépendamment. Il est donc alors important de rechercher l'origine de cette relation. L'aimantation C n'a été isolée que pour des grains magnétiques avec des températures de blocage supérieures à 580°C, mais, comme elle n'est pas une aimantation thermorémanente, d'autres grains peuvent aussi être porteurs de l'aimantation C pour des températures de blocage inférieures à 580°C. La composante B doit alors être interprétée comme le résultat de la superposition de la composante C avec une composante inconnue D. La bonne définition de la composante B sur les diagrammes de projection orthogonale implique que les spectres de températures de blocage de C et D sont similaires pour les températures où B est définie.

Pour rechercher cette composante D, l'intersection des grands cercles (Halls, 1976) contenant la direction moyenne pour chaque site des composantes B et C (et donc celle de la composante D) a été déterminée (fig. 4a et c). A Reouina, la meilleure intersection (D=126,3°, I=15,9° avant correction de pendage) correspond à la composante C (D=125,2°, I=16,2° avant correction de pendage). La composante D reste donc indéterminée car les vecteurs aimantation C sont dans ce cas mieux regroupés que ceux correspondant à l'aimantation D. En revanche, pour la formation de Merkala, la meilleure intersection (D=133,4°, I=-5,0° avant correction de pendage) est différente de la composante C

(D=128,2°, I=13,1° avant correction de pendage). Cette dernière n'est pas incluse dans la zone de confiance (Henry, 1999) associée à cette intersection (fig. 4d). La direction obtenue de la meilleure intersection correspond à celle de la réaimantation permienne, bien connue dans tout le Nord Ouest de l'Afrique. Cette réaimantation serait donc la composante D. Connaissant l'orientation des composantes B, C et D, il est possible d'estimer, grâce aux valeurs des angles séparant B et D d'une part et B et C d'autre part, les proportions des composantes C et D existantes dans l'aimantation B (ici la composante C représente en moyenne environ 20%). La figure 5 montre les proportions des températures de blocage des composantes C et D en fonction des fenêtres de température. Le spectre de température de blocage de chacune de ces deux composantes apparaît très semblable à ceux généralement obtenus pour des aimantations dues à une seule composante.

Lorsqu'une réaimantation chimique partielle coexiste avec l'aimantation primaire, une pseudo-composante très bien définie peut donc apparaître. L'interprétation de telles réaimantations partielles doit être faite avec beaucoup d'attention pour mettre en évidence de telles éventuelles données paléomagnétiques composites.

INTRODUCTION

Thellier (1938) showed, for Thermo-Remanent Magnetizations (TRM), that Partial TRM acquired in different windows of temperature can be separated using thermal treatment. Néel (1955) theory confirmed that, similarly, Viscous Remanent Magnetization (VRM) can be isolated during thermal demagnetization and Isothermal Remanent Magnetization (IRM) or Piezo-Remanent Magnetization (PRM) during alternating field treatment. However, Natural Remanent Magnetization (NRM) in sediments can be of chemical origin (recrystallization or grain growth) and there is no specific demagnetization mode for these Chemical Remanent Magnetizations (CRM). Some attempts were made using acid leaching for CRM related to grain growth, but this method is strongly limited by the rock porosity. Thermal or alternating field treatment applied to magnetizations of chemical origin sometimes yields juxtaposed components (Cogné *and al.*, 1990) though mostly at least partially superimposed components were found (Derder *and al.*, 1994). Another illustration of this question of CRM demagnetization is given by Cenozoic chemical remagnetizations obtained in many different places (Witte and Kent, 1991; Morris and Robertson, 1993; Villalain *and al.*, 1994; Rouvier *and al.*, 1995; Aubourg and Chabert-Pelline, 1999; Thomas *and al.*, 1999). These remagnetizations are mostly of single polarity, though acquired during a period with frequent reversals. This has been explained by the chemical origin of the remagnetization and by the lack of separation of remagnetization of opposite polarity during demagnetization (Henry *and al.*, 2001); only the dominant polarity can be observed. Recently, juxtaposed components of chemical origin have been isolated in several sites in two Carboniferous formations of the Tindouf basin (Henry *and al.*, 1999; Merabet *and al.*, 1999). The aim of this paper is to try to better understand the actual meaning of such juxtaposed magnetizations.

MAGNETIZATION COMPONENTS IN THE TINDOUF BASIN

The already published paleomagnetic results (Bouabdallah, 1999; Henry *and al.*, 1999; Merabet *and al.*, 1999) obtained in the Tindouf basin (West Algerian Sahara) will not be detailed here. For precise location of the sampling sites and geological information about these red beds, refer to these papers. 12 sites (108 samples) in the Namurian formation of Reouina and 9 sites (92 samples) in the Stephanian formation of Merkala have been selected along crosssections of the whole series. Rock magnetism analyses (thermomagnetic curve of the susceptibility in low field as a function of the temperature and Lowrie's -1990- method) and demagnetization curves point out the presence of hematite and of another carrier, possibly magnetite. 10 samples (6 from Namurian formation and 4 from Stephanian formation) were eliminated during treatment, because of the lack of stable magnetization or of softness of the specimens. In the other specimens, NRM consisted of 2 or 3 components which were thermally separated and determined by the means of principal component analysis (Kirschvink, 1980). They are clearly juxtaposed and each one is very well determined (fig. 1).

- Component A has been isolated at temperature values up to 200°C. Before dip correction, it is close to the present day field direction and represents likely a viscous or chemical (goethite) recent magnetic overprint. It will be therefore not considered further in this paper.

- Component B has been isolated in most of the samples (60% in Reouina formation and 90% in the Merkala formation) at temperatures ranging between 200-300°C and 550-580°C.

- Component C has been obtained at temperatures ranging between 550-580°C and 670°C. It is carried by hematite.

Nevertheless, for 40% of Reouina specimens, a single component has been obtained between 300 and 670°C. The direction obtained in this case is similar to that of the C component. This argues rather for a lack of the B component. Paleodirectionnal results have been summarised in table 1 for the Namurian formation and in table 2 for the Stephanian formation. The single difference of the magnetic properties between the different samples is that the hysteresis loops (Bouabdallah, 1999) are often a little less wasp wasted in samples showing only C components than in those with B and C components (fig. 2). In these last samples, the magnetic carriers are therefore less homogeneous, probably allowing the distinction of two different magnetization components.

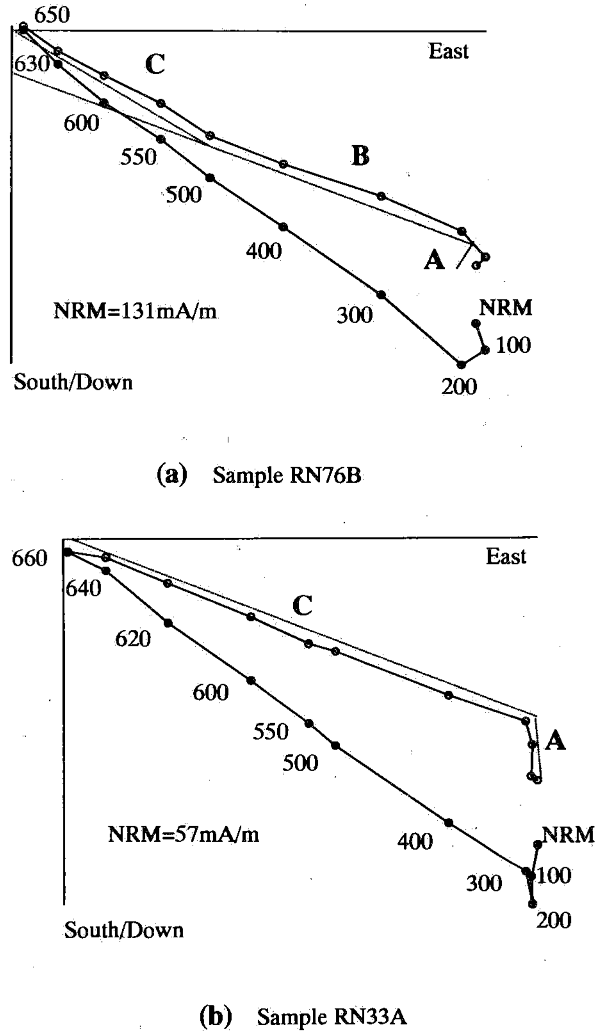

Fig. 1 - Examples of orthogonal vector plot: projections on horizontal (open circles) and vertical (full circles) planes: separated B and C components (a) and single C component (b).

Exemples de projection orthogonale sur les plans horizontaux (cercles vides) et verticaux (cercles pleins): composantes B et C séparées (a) et composante C unique (b).

Table 1 - Namurian mean characteristic directions (D, I) after dip correction.
N is the number of directions, and k and α_{95} are the Fisher's (1953) statistics parameters

Directions caractéristiques namuriennes moyennes (D, I) après correction de pendage.
N est le nombre de directions, et k et α_{95} sont les paramètres de la statistique de Fisher (1953)

	Low Temperatures (Component B) After dip correction					High Temperatures (Component C) After dip correction				
Site	**N**	**D(°)**	**I(°)**	**k**	**α_{95}(°)**	**N**	**D(°)**	**I(°)**	**k**	**α_{95}(°)**
2	8	134.3	3.7	286	2.9	19	126.5	8.2	208	2.2
3	5	129.9	10.0	74	7.3	19	121.7	12.0	75	3.7
4	9	133.1	8.3	107	4.5	13	124.1	11.8	150	3.2
5	4	143.1	11.6	32	12.5	14	128.3	18.1	224	2.5
6	14	133.0	6.7	185	2.8	22	130.6	10.7	215	2.0
7	9	130.7	12.7	62	5.9	18	127.7	18.0	65	3.4
8	11	132.2	0.4	96	4.3	17	127.1	3.4	100	3.4
9	12	132.7	2.1	72	4.8	18	126.6	7.8	115	3.1
10	11	132.7	4.3	129	3.7	20	128.1	7.8	206	2.2
11	15	137.3	5.8	66	4.5	19	127.4	9.7	165	2.5
12	17	135.5	7.4	78	3.9	14	127.4	10.8	181	2.8

Mean direction of sites (Before dip correction)

11	133.0	12.9	285	2.5	11	125.2	16.2	375	2.2

Mean direction of sites (After dip correction)

11	134.0	6.6	235	2.8	11	126.9	10.8	276	2.5

Table II - Stephanian mean characteristic directions (See Table 1).

Directions caractéristiques stéphaniennes moyennes (Voir Tableau 1)

	Low Temperatures (Component B)					High Temperatures (Component C)				
Site	**N**	**D(°)**	**I(°)**	**k**	**α_{95}(°)**	**N**	**D(°)**	**I(°)**	**k**	**α_{95}(°)**
1	18	131.2	-3.6	134	2.9	18	126.8	11.4	107	3.2
2	12	132.4	-5.2	185	3.0	09	131.1	6.1	275	2.8
3	22	133.9	-6.3	284	1.8	22	131.7	1.1	274	1.8
4	18	130.9	-6.9	292	1.9	18	128.2	-0.1	356	1.7
5	16	132.3	-3.2	324	1.9	14	123.4	6.7	229	2.5
6	20	133.3	-2.9	254	2.0	18	131.4	5.2	320	1.8
7	14	130.7	4.6	414	1.8	14	129.6	12.1	329	2.1
8	17	134.6	-4.4	551	1.4	17	132.8	2.7	514	1.5
9	14	136.5	2.8	164	2.9	17	133.7	13.1	132	3.0

Mean direction of sites (Before dip correction)

9	132.8	4.5	436	2.2	9	128.2	13.1	197	3.3

Mean direction of sites (After dip correction)

9	132.9	-2.8	342	2.5	9	129.9	6.5	195	3.3

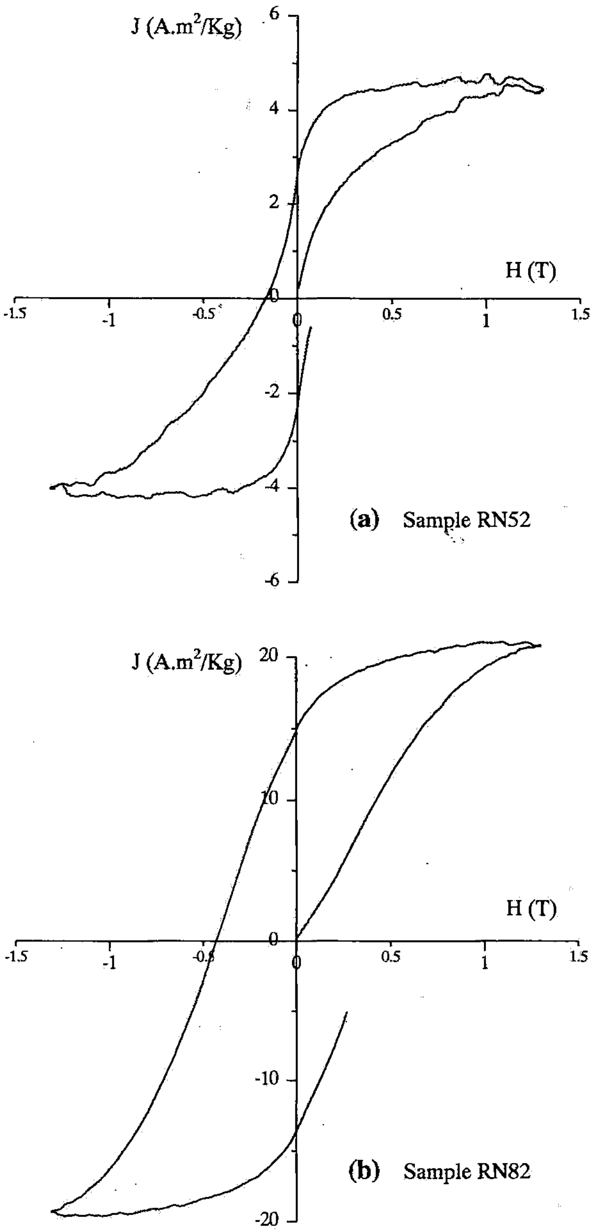

Fig. 2 - Hysteresis loop after correction of the paramagnetism in samples showing the components B and C (a) or only the component C (b)

Cycle d'hystérésis après correction du paramagnétisme dans des échantillons dans lesquels ont été isolées les deux composantes B et C (a) ou seule la composante C (b)

Unfortunately, these two formations crop out only on the northern limb of the Tindouf syncline, and no paleomagnetic test was available to constrain the age of magnetization acquisition. However, the orientation of the C component is significantly different in the Namurian formation and in the Stephanian one. This difference shows that the C component cannot correspond to a single remagnetization having affected this whole area during a same period of time. In each formation, this orientation after dip correction is similar to that obtained for the primary magnetization of rocks of the same age in the Saharan craton (Henry *and al.*, 1999; Merabet *and al.*, 1999). This confirms that the magnetization C has been acquired during or just after the diagenesis of these red beds.

The component B in both formations has orientation slightly different, roughly in intermediate position between that of the C component and that obtained in northwestern Africa for the widespread Permian remagnetization.

The presence of two magnetization components clearly indicates that at least one of these components is related to a remagnetization phenomenon. Because of the lack of strong thermal event, this magnetic overprint is therefore of chemical origin.

RELATION BETWEEN B AND C COMPONENTS

In both formations, the angular difference between B and C components is of the order of few degrees, but statistically significant (in average, 8.7° +/- 3.3° for Reouina and 9.9° +/- 2.8° for Merkala). A key observation was that the directions B and C appear not independent. For example, in a site, the sample giving the B direction with the lowest declination mostly also gives the C direction with the lowest declination. Within each site (fig. 3a) as for the mean site directions (fig. 3b and c), the angular deviation from C to B is in fact remarkably constant, in orientation as in angular value. A relation therefore exists between B and C components. Magnetizations acquired independently should not have such a relation, at least in a non-deformed area. For a single component, the orientation of the mean direction for a site relative to the mean direction for all the sites is mainly related to the secular variation of the magnetic terrestrial field and the continental drift. There is no reason to have a same relative orientation for two independent magnetizations, and such similar relative orientations have been precisely obtained in the Tindouf basin.

JUXTAPOSED OR SUPERIMPOSED MAGNETIZATIONS ?

Any interpretation based on wholly independent magnetization acquired during different periods of time has therefore to be excluded.

A first hypothesis, to explain this relation, is that B and C were acquired at the same time, but that only the B component was affected by an inclination error. It has to be rejected because B and C inclinations for some samples have opposite signs, and that the difference between B and C concerns also declination. B and C

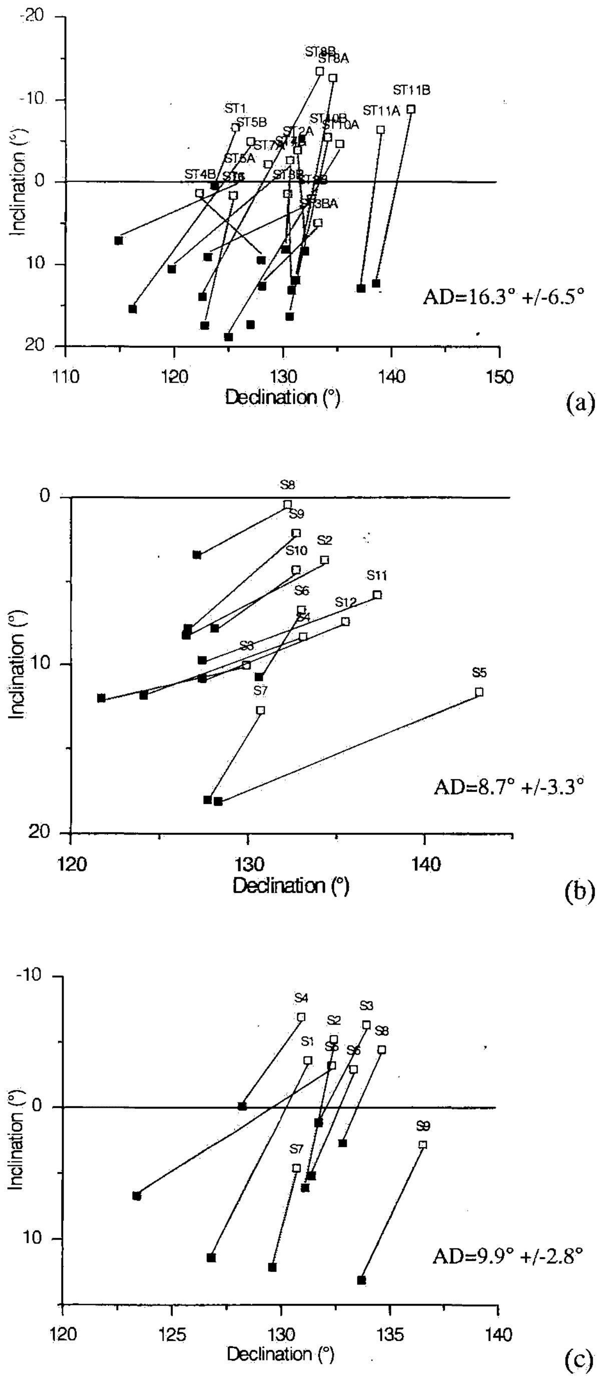

Fig. 3 - Angular deviation (AD) between B (open squares) and C (full squares) components presented on Inclination-Declination diagram (diagram usable here without significant distortion because of the low values of the inclination), using samples data within a site - example of site 1 of Merkala Formation - (a) and mean site directions for Reouina (b) and Merkala (c) formations.

Déviation angulaire (AD) entre les composantes B (carrés vides) et C (carrés pleins) présentée sur un diagramme Inclinaison-Déclinaison (ce diagramme est utilisable sans distorsion significative à cause des faibles valeurs de l'inclinaison), utilisant les données des échantillons à l'intérieur d'un même site - exemple du site 1 de la formation de Merkala - (a) et les directions moyennes par sites pour les formations de Reouina (b) et de Merkala (c).

were therefore, at least for a part, acquired at different time.

Secular variation like effect of continental drift does not give such relation between two wholly independent magnetizations. The relation between B and C then can only be explained if B component results from the superimposition of C component with another unknown component D (underprinting - Miller and Kent, 1988). In practice, C component was defined for temperatures higher than 580°C (fig. 1a), but part of the grains carrying this component has probably maximum blocking temperature lower than 580°C (fig. 1b). The well determination of the B component on orthogonal projection diagrams implies that the blocking temperature spectra of C and D components have a similar look for the windows of temperature where B is defined, the main difference being related to the proportion of C and D components. For CRM overprint and primary magnetization, a superimposition of these components is not surprising. It should be in fact much more unexpected that blocking temperature spectra are not overlapping, because this would mean that there is none of the blocking temperature for the hematite under 580°C. The remarkable thing here is the similar look of the blocking temperature spectra. Such overprinting has been already pointed out, but with one largely dominant magnetization component (Witte and Kent, 1991; Diego-Orozco and Henry, 1993).

THE HIDDEN COMPONENT D

The B component resulting from the superimposition of the C component with an unknown D component let us try to determine this D component. The later must be in the half-plane (half great circle on the projection sphere) including B and C components and limited by C. It must necessarily be beyond B component relatively to C component. This half-great circle contains none of the directions of the field in the Tindouf area since the Carboniferous, except during the Permian times. To extract the D component, great circles including B and C (and therefore D) mean directions were determined for each site. These great circles are strictly equivalent to remagnetization circles (i.e. including the two superimposed components of magnetization). Their best intersection has been determined using the Halls (1976) method (fig. 4a and c). Such intersection of great circles, associated with the superimposition of both components C and D, is assumed to correspond to the direction of the component with the less scattered direction (except if the scattering for the two components is similar - Schmidt, 1985).

For the Reouina formation, the best intersection (D=126.3°, I=15.9° before dip correction) has the same orientation as the C component (D=125.2°, I=16.2° before dip correction). The C component is then the less scattered and thus the D component remains unknown. On the contrary, for the Merkala formation, the best intersection (D=133.4°, I=-5.0° before dip correction) is different from the C component (D=128.2°, I=13.1° before dip correction) and beyond B component (D=132.8°, I=4.5° before dip correction) relatively to C component. The confidence zone, estimated using bootstrap method (Henry, 1999), associated with this intersection (fig. 4d) moreover does not include the C component. Since the C component is known, we can compare the precision parameter k for C and D in order to check if the obtained intersection is biased or not (Schmidt, 1985). In order to have comparable values, the k parameter (k_C and k_D) for each magnetization component (C and D) has been calculated using, on each great circle, the closest direction of the mean direction of the component. The parameter ratio k_C/k_D is then 0.56 and the bias is probably weak. The intersection obtained therefore corresponds to the D component. Its orientation corresponds to that of the widespread Permian magnetic overprint in Northwestern Africa. The D component in the Merkala as likely in the Reouina formation corresponds to this Permian remagnetization.

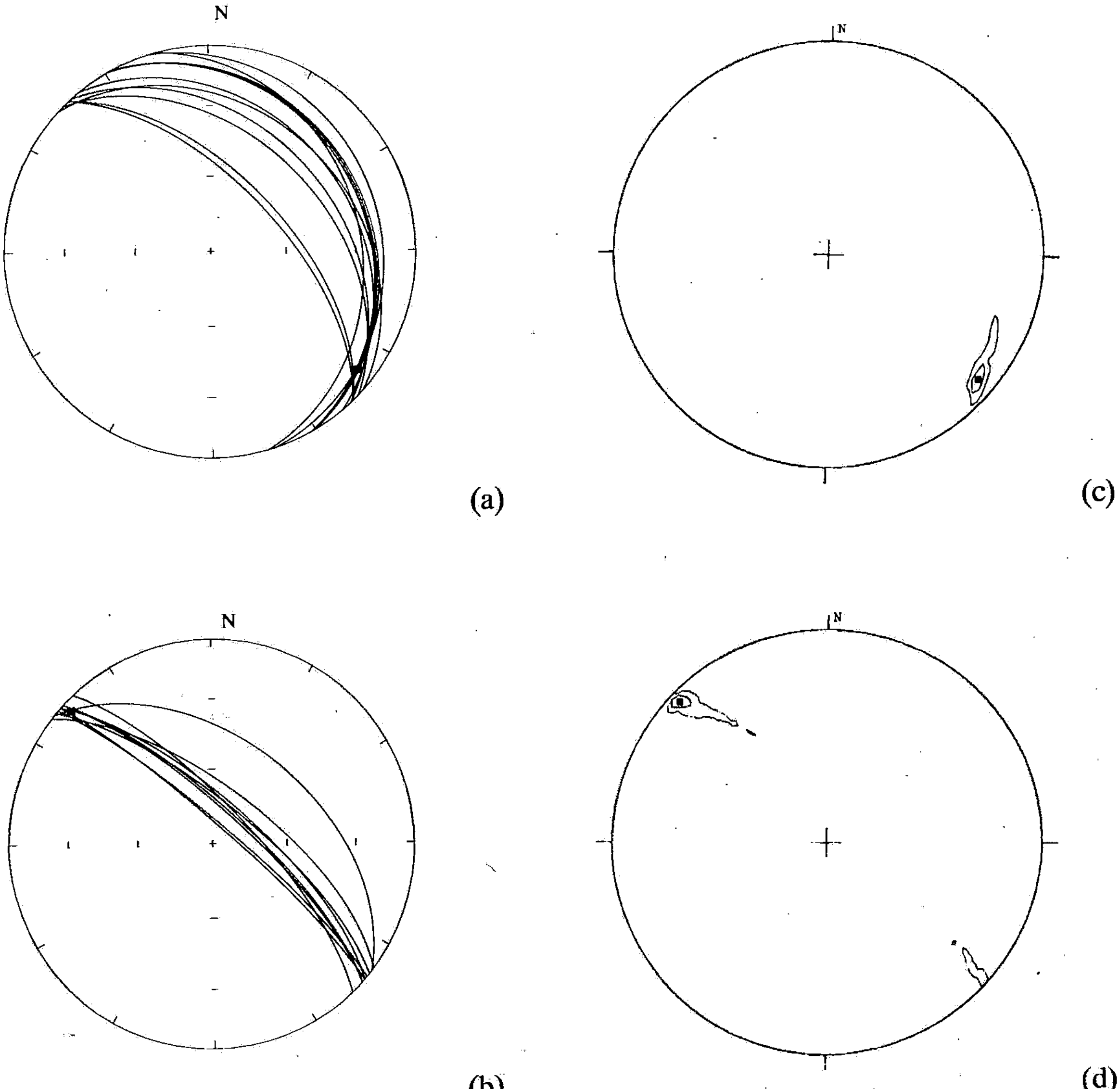

Fig. 4 - Each great circle includes the mean B and C directions for a site: Reouina (a – 11 sites) and Merkala (b – 9 sites) formations and corresponding confidence zone at 95% for the best intersection of great circles in Reouina (c) and Merkala (d) formations. Stereographic projection in the lower hemisphere.

Chaque grand cercle inclut les directions moyennes B et C d'un site : formations de Reouina (a – 11 sites) et de Merkala (b – 9 sites) et zones de confiance à 95% de la meilleure intersection des grands cercles associées des formations de Reouina (c) et de Merkala (d). Projection stéréographique dans l'hémisphère inférieur.

For the Merkala formation, the C and D component and their resulting B component are known. It is therefore easy to estimate the proportion of C and D components existing in the B one. We have therefore to keep in mind that the direction of D component is not well specified, and that this proportion is not accurate. The percentage of C component in the B magnetization should be of the order of 20%. Figure 5, given only as a rough illustration, shows the unblocked magnetizations of C and D components as a function of the window of temperature for one sample, assuming that C component represents 20% of the B magnetization. It appears a regular variation of the unblocking temperature spectra for C and D components, in each case similar to that mostly obtained for single component magnetization.

CONCLUSION

Though well defined using principal component analysis, the component B is not a single magnetization component, but results from the superimposition of the primary magnetization with a chemical remagnetization. The chemical overprint does not directly appear during demagnetization, but can be determined in favorable conditions. Such a superimposition is probably mostly the case if chemical remagnetization is acquired in addition to the primary magnetization, thus giving sometimes a well defined pseudo-component. Interpretation of partial CRM has therefore to be made very carefully, to avoid paleomagnetic data reflecting no actual paleodirection of the Earth magnetic field.

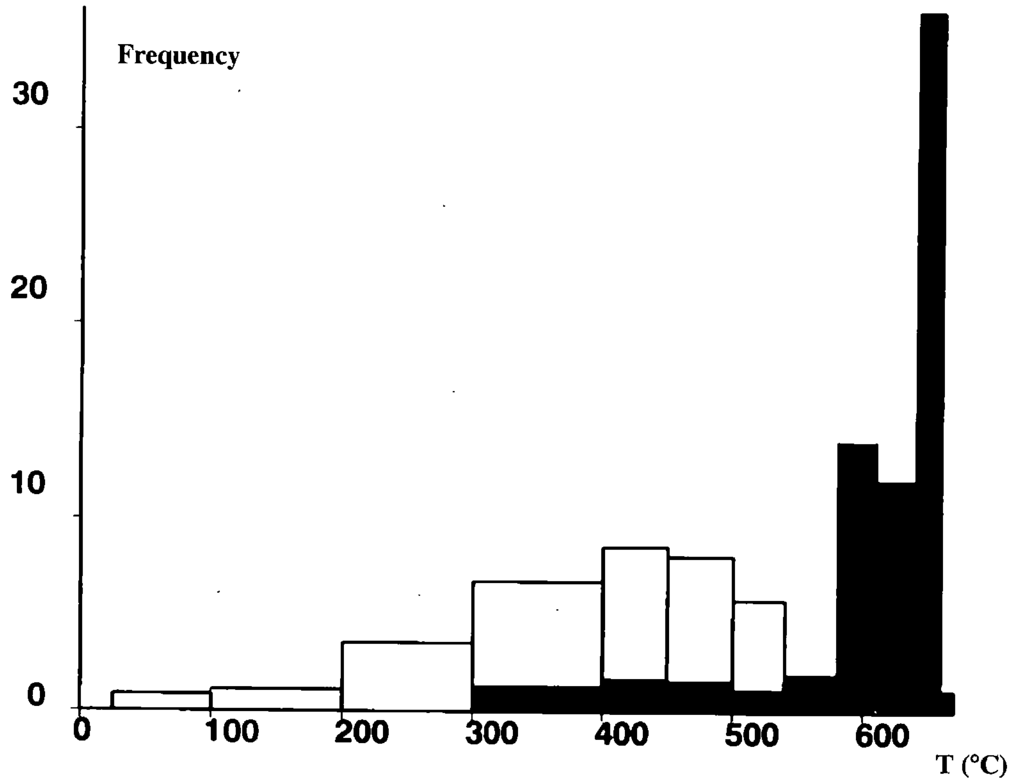

Fig. 5 - Spectrum of blocking temperatures as a function of windows of temperature for components C (in black) and D (in white). Separation has not been made for temperatures lower than 300°C (likely mainly VRM).

Spectre des températures de blocage en fonction des fenêtres de température pour la composante C (en noir) et D (en blanc). La séparation n'a pas été faite pour les températures inférieures à 300°C (probablement une ARV pour l'essentiel).

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