Syn-folding remagnetization events in the French-Belgium Variscan thrust front as markers of the fold-and-thrust belt kinematics

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Key words. – Ardennes, Paleomagnetism, Variscides, Fold test, Remagnetizations, Tectonic rotations.

Abstract. – New paleomagnetic studies have been carried out within the Ardennes segment of the N France - S Belgium Variscan fold-and-thrust belt to set constraints on the fold-thrust belt kinematics and reveal the casual relationships between vertical-axis rotations and major strike deviated zones localised along the general trend of the belt. Magnetite-bearing Devonian and Carboniferous limestones yielded two characteristic, secondary components of the natural remanent magnetization : a low temperature component recorded most probably during the late stages of folding and a high temperature component, acquired during incipient stages of deformation. Both post- and synfolding magnetizations were identified in the Lower Devonian hematite bearing sandstones. Ages of magnetization, inferred from the analysis of characteristic remanence inclinations compared to the reference curves for the stable parts of the Old Red Sandstones Continent (ORC), suggest the previous remagnetization event to be due to the burial of sedimentary rocks under the thick molassic foreland basin of Namurian-Westphalian age and the second to the final out-of-sequence activation of the thrust front in Stephanian times. Irrespective of the age of the magnetizations, orientations of paleomagnetic directions are dominantly governed by second-order structural trends. Clockwise rotations are observed in relatively narrow zones featuring deviated orientations of fold axes, other sites show paleomagnetic directions akin to those known from the ORC. We interpret this feature as a result of local transpressive deformations and related rotations, which occurred at lateral borders of propagating thrust-sheets. The latter deformation zones are suggested to be controlled by deep-seated discontinuities inherited from the Devonian Rheno-hercynian basin development. The Ardennes thrust belt was thus not rotated as a whole unit with respect to the ORC after the Namurian, preserving the initial orientation of the continental margin.

Réaimantations syn-cinématiques au front de la chaîne varisque franco-belge : apports à la cinématique des structures plissées-faillées

Mots clés. – Ardennes, Paléomagnétisme, Varisque, Test du pli, Réaimantations, Rotations.

Résumé. – De nouvelles données paléomagnétiques ont été acquises dans le massif des Ardennes (N France-S de la Belgique), au front septentrional de la chaîne varisque, afin d'établir des contraintes temporelles sur les déformations plissées-faillées et mettre en évidence d'éventuelles rotations autour d'axes horizontaux associées à l'existence de virgations majeures le long de la chaîne.

Les calcaires dévoniens et carbonifères présentent deux composantes de réaimantation portées par de la magnétite : une composante de relativement basse température enregistrée très probablement au cours des dernières phases de plissement et une composante de haute température acquise au tout début des déformations plissées. Des réaimantations post-pli et syn-pli sont également observables dans les grès rouges du Dévonien inférieur à hématite. L'âge des réaimantations, établi à partir des inclinaisons caractéristiques mesurées comparées aux courbes de référence pour les zones stables du Continent des Vieux Grès Rouges, suggère que le premier épisode régional de réaimantation résulte de l'enfouissement des séries sous l'épais bassin molassique d'avant-pays d'âge Namurien-Westphalien et que le second soit enregistré lors de l'activation finale du front de chaîne (Stéphanien d'après les données d'inclinaison) lors de la reprise hors-séquence des chevauchements majeurs.

Indépendamment de l'âge des réaimantations, les directions des vecteurs paléomagnétiques sont principalement contrôlées par l'orientation des structures. Des rotations horaires d'une amplitude maximale de 40° sont localisées le long des virgations des structures chevauchantes. Les zones, présentant l'orientation classique du segment ardennais, ne montrent aucune rotation par rapport aux domaines stables du continent des Vieux Grès Rouges. Il est suggéré que la torsion des structures se développent au sein de zones transpressives dextres mises en place aux limites latérales d'écailles chevauchantes majeures, ces dernières étant probablement contrôlées par des discontinuités profondes héritées de la géométrie du bassin rhéno-hercynien. La chaîne de chevauchements des Ardennes n'a ainsi pas subi de rotation d'ensemble par rapport au continent des Vieux Grès Rouges postérieurement au Namurien, conservant l'orientation initiale de la paléo-marge continentale.

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INTRODUCTION

The northern rim of the Variscan orogenic belt extends from eastern Europe to the Iberian Peninsula, displaying a distinctly curved trend [Perroud, 1986 ; Eldredge *et al.*, 1985 ; Bachtadse and Van der Voo, 1986 ; Dias and Ribeiro, 1994 ; Weil *et al.*, 2000 ; Matte, 1991, 2001]. One of the basic problems concerned with the curved shape of the outer Variscides is to what extent the present-day structural pattern is governed by the original shape of the Devonian - Carboniferous sedimentary basins, and what impact does oroclinal bending have on the shape of the Variscan fold belt. In this study, we applied the paleomagnetic method to set time-constraints on the different stages of tectonic development in the northern France - Belgium segment of the belt, focusing on a better understanding of the origin of strike variations in a context of oroclinal bending/primary basin shape alternatives. Special attention is given to regional-scale tectonic rotations related to the process of thrusting [e.g. Allerton, 1998], as well as to the nature of the locally observed strike disturbances with respect to the general trend of the belt. We also used information from structural geology, attempting a more interdisciplinary approach. Providing new information, our results are complementary to the outcomes obtained so far.

Previous paleomagnetic studies in the N France-S Belgium part of the Variscan fold belt (FBVB) have been performed by Nowaczyk and Bleil [1985] ; Edel and Coulon [1987] ; Thominski *et al.* [1993] ; Molina Garza and Zijderveld [1996] and Marton *et al.* [2000]. They were concentrated mainly in the eastern part of this orogen i.e. the Ardennes thrust belt. All these authors reported on the presence of characteristic secondary components of the natural remanent magnetization (NRM), recorded at different stages of the tectonic evolution. Described pre-, syn- or post-folding components were generally dated between late Carboniferous and Permian in age. In sites situated in the Brabant Massif and the Namur Syncline (Parautochthonous units *sensu* Meilliez and Mansy [1990]), directions akin to those known from stable Europe were observed. In turn, in the Dinant Syncline (Allochthonous unit *sensu* Meilliez and Mansy [1990]), most of the authors noted paleomagnetic rotations [Edel and Coulon, 1987 ; Thominski *et al.*, 1993 ; Molina Garza and Zijderveld, 1996].

A two components nature of NRM in Ardennes was described so far only by Edel and Coulon [1987], and Molina Garza and Zijderveld [1996]. In these studies most of the paleomagnetic sampling sites were localised in the vicinity of the Meuse and Ourthe river valleys. However, since these rivers cut through the thrust units along specific zones of strike deviation [Lacquement, 2001], the obtained data cannot be considered as representative for the entire Ardennes segment of the FBVB.

GEOLOGICAL OVERVIEW

Paleozoic structures of northern France and Belgium show a multi-stage tectonic development. At the Silurian/Devonian boundary, the region was situated at the southern margin of the Old Red Sandstones Continent (ORC) [e.g. Cook *et al.*, 1997, Meilliez *et al.*, 1991] that formed by collage of the Laurentia, Avalonia and Baltica continents in mid-Paleozoic times. An early Devonian rifting event generated extensional deformations in this area [Meilliez *et al.*, 1991 ; Franke, 1992, 2000 ; Lacquement, 2001] and resulted in the formation of a rifted sedimentary basin (the Rheno-Hercynian basin) characteristic for a continental passive margin. Subsidence and deposition were controlled by normal faulting of the Lower Paleozoic basement and led to the formation of several independent blocks bordered by a set of NW-SE and NE-SW fault zones [Meilliez *et al.*, 1991].

Development of the southward dipping subduction of the Rheno-Hercynian domain initiated the Variscan orogenic wedge, with a progressive northward propagation of thrusting and folding [e.g. Plesch and Oncken, 1999]. In Upper Carboniferous times, sedimentary rocks from the Rheno-Hercynian margin were transported towards the north-northwest and formed a typical thrust weddge upon a major crustal scale, southward dipping, décollement zone (fig. 1) [e.g. Lacquement *et al.*, 1999]. The frontal zone of the main Variscan basal thrust is represented by the Midi Fault zone, that separates the so-called allochthonous units (Ardennes thrust belt) to the south from the parautochthonous units to the north on top of which lie the residual parts of a molassic coal-bearing Namurian-Westphalian foreland basin (see cross-section in figure 1, definition of units after Meilliez and Mansy, 1990]. The parauthochthonous unit, that was only partially mobilised and deformed, forms the cover of the Caledonian Brabant Massif [e.g. Lacquement *et al.*, 1999].

Thrusting within the Ardennes belt was influenced both by the basement geometry, inherited from the extensional period of basin development, and differences in thickness of sedimentary series [Meilliez *et al.*, 1991]. Variscan shortening in the region under study led to gently dipping thrusts and asymmetric folds with a general north vergence [Mansy *et al.*, 1995]. Despite the general NNW direction of the tectonic transport and shortening in the allochthonous units, related structural trend, expressed by cleavage and fold axes orientations, displays distinct local variations. Magnitude of these deviations reaches up to 70 degrees in some places. Along the general NE-SW regional tectonic trend, we can thus observe local E-W to NW-SE aberrant orientations of structures in the region of Meuse and Ourthe rivers (fig. 1a).

At the scale of the whole Ardennes thrust-belt, strain markers as well as fold-thrust relationships document a general migration of the deformation towards the foreland [Mansy *et al.*, 1995 ; Lacquement *et al.*, 1997]. The frontal parts of the belt display however a conspicuous out-of-sequence dislocation of the primary thrust structures [e.g. Averbuch and Mansy, 1998] that possibly implies a final buttress effect of the Brabant Caledonian massif. Nevertheless, structures display generally younger ages towards the Midi Fault, as it is indirectly evidenced by radiometric data obtained for the chlorite minerals grown within the cleavage. Their estimated ages vary between 315 Ma in the southern region up to 297 Ma in the northern one [Piqué *et al.*, 1984]. Migration of the deformation front toward the N-to-NNW is also attested by paleontological dating within the Namurian-Westphalian synorogenic deposits [Meilliez *et al.*, 1991 ; Engel and Franke, 1983].

The sequence of tectono-thermal events in the allochthonous units can be reconstructed on the basis of the low-grade metamorphic evolution [see Fielitz and Mansy,

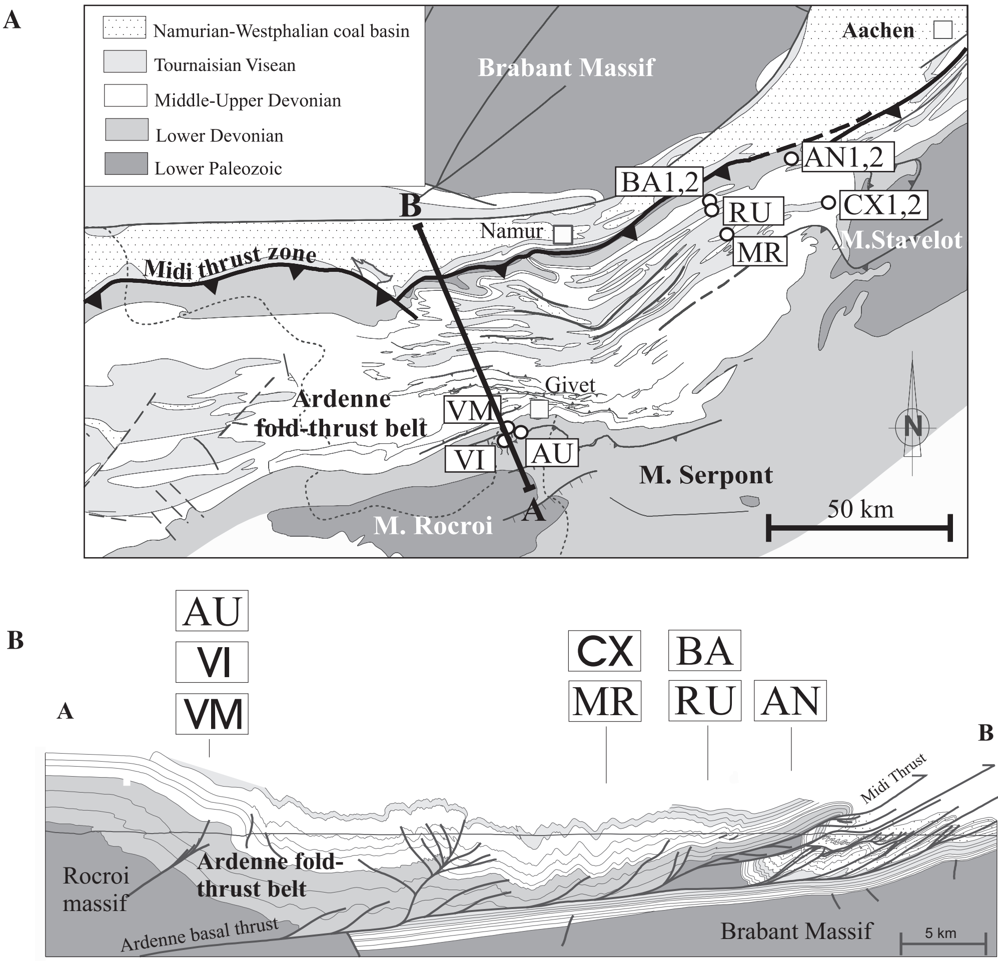


FIG. 1. – A. Geological map of study area showing location of paleomagnetic sampling sites (for abbreviations see table I).
B. Structural cross-section [after Lacquement, 2001] throughout the FBVB ; labels refer to site localities (see table I for explanations).
FIG. 1. – A. *Carte géologique de la zone d'étude montrant la localisation des sites d'échantillonnage pour le paléomagnétisme (pour les abbréviations voir table I).*
B. *Coupe géologique du front chevauchant varisque franco-belge [d'après Lacquement, 2001] reportant la position structurale des sites échantillonnés (descriptions en table I).*

1999 ; Kenis *et al.*, 2000]. The first thermal event was related to the general burial of the sedimentary cover during basin subsidence. Its magnitude, controlled by extensional faults, increased generally towards the south [e.g. Meilliez *et al.*, 1991]. The Devonian-Carboniferous rocks of the allochthonous units situated north of the Lower Paleozoic Massifs [Dinant synclinorium according to Fourmarier, 1922], show a maximum degree of metamorphism in its southern part, locally reaching anchi-metamorphic conditions [e.g. Fielitz and Mansy 1999 ; Robion *et al.*, 1999].

The second phase of metamorphism, developed during the main Variscan orogenic deformations when the foreland basin accumulated molasse-type sediments, originated from the already uplifted zones to the south. As a consequence of the northward foreland basins migration, a variation in the time of acquisition of the metamorphic overprint is recorded [Han *et al.*, 2000]. Within the Ardennes belt, the highest thermal overprint is observed in the central part of the allochthonous complex (up to 200-300 ^{o}C, dated around 300 Ma), probably as the result of maximum burial under the thick molassic cover [see Chamley *et al.*, 1997 ; Han *et al.*, 2000].

SAMPLING AND LABORATORY METHODS

A total of 58 oriented hand samples were collected. The samples were set in plaster of Paris and drilled to give cores of 24 mm diameter. These were sliced into standard specimens of 22 mm length. Smaller 8 mm right-cylindrical cores were drilled for thermomagnetic analysis prior to demagnetization.

Identification of the magnetic minerals in the rocks was done by thermomagnetic analysis [e.g. Kadzialko-Hofmokl and Kruczyk, 1976]. The specimen was saturated in a magnetic field of ca. 1T to produce a saturated induced remanent magnetization (SIRM). It was then continuously heated in a zero magnetic field in a furnace combined with a spinner magnetometer. During the experiment, the unblocking temperature spectrum (Tub) was plotted against the decaying SIRM.

Thermal demagnetization was carried out using a magnetic measurements MM-1 furnace. Each specimen was heated stepwise up to 650 ^{o}C and cooled in a zero magnetic field. After each demagnetization step, the remaining remanence was measured with a 2G SQUID cryogenic magnetometer with a residual internal of < 3 μA/m and noise level of about 5 µA/m. Both the furnace and magnetometer were operated inside Helmholz coils, diminishing the ambient geomagnetic field by ~ 95 %. The experiment continued until the remanence intensity dropped down to magnetometer noise level unless a spurious magnetization appeared in the specimen. Alternating field (AF) cleaning was performed by means of demagnetization coils integrated with the 2G SQUID magnetometer. Magnetic susceptibility was monitored after subsequent steps of thermal cleaning in order to identify mineralogical changes. Specimens which displayed strong change in magnetic susceptibility combined with significant shift in remanence orientation were rejected from further analysis.

Orthogonal projections of the remanence vector endpoints during stepwise demagnetization were plotted for each specimen. Paleomagnetic data analysis (PDA) software by Lewandowski *et al.* [1997], employing principal component analysis (PCA [Kirschvink, 1980]), was used to calculate characteristic NRM components (ChRM) from the demagnetization data and to plot the demagnetization diagrams. Standard Fisher [1953] statistics were used to calculate characteristic mean directions for each sub-populations.

We used the fold test of McFadden and Jones [1981] as well as inclination-only test using procedure of Enkin and Watson [1996]. The softwares by McFadden [1990] and Enkin [1994] were used for performing the tests. Reference paleomagnetic data for the Old Red Sandstones Continent were taken from Van der Voo [1993].

All sampling sites of rocks for paleomagnetic study are situated within the allochthonous units. We preferred locations that had not been yet investigated paleomagnetically and we avoided areas of uncertain structural coherence. Special attention was given to sampling different limbs of kilometric to hectometric folds in the sites representative for the different structural trends along the allochthonous unit (fig. 1a).

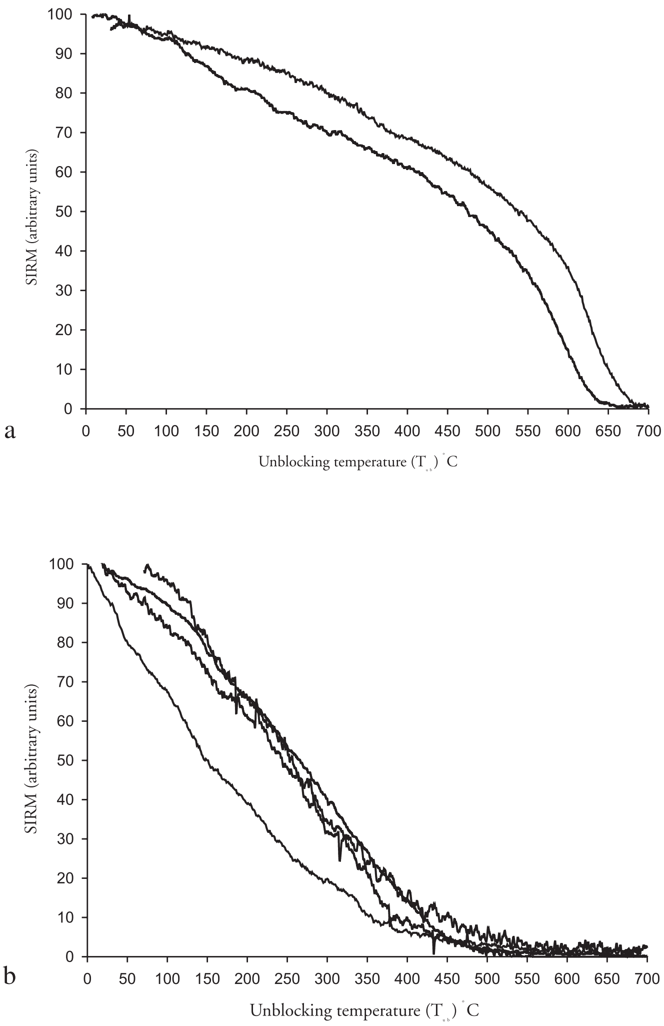


FIG. 2. – Thermomagnetic analysis of carbonates (a) and red beds (b). SIRM = saturation isothermal remanent magnetization. Each curve corresponds to a single sample.
FIG. 2. – *Analyse thermomagnétique des carbonates* (a) *et des niveaux clastiques rouges* (b) *étudiés. SIRM = aimantation rémanente isotherme à saturation. Chaque courbe correspond à un échantillon.*

PALEOMAGNETIC RESULTS

Devonian and Carboniferous limestones

Six sites have been investigated in carbonate rocks of Givetian and Visean age (CX1, CX2, BA1, BA2, RU, MR – see fig. 1a and table I for details). Thermomagnetic curves for carbonates (fig. 2a) show a progressive decrease of the magnetic signal, with maximum unblocking temperatures (Tub) around 500 °C-550 °C. Such Tub range is characteristic for magnetite [Lowrie and Heller, 1982], which was the only magnetic carrier identified in the rocks.

NRM of the carbonates displays a multicomponent behaviour during demagnetization and shows a strong variation of the initial intensity between 0.1 and 15 mA/m. AF method of demagnetization in spectrum fields up to 20 mT (fig. 3a) removes a weak, northerly directed, normal polarity component with moderately high positive inclination. While this component, most probably of recent origin, is being removed, the resultant vector moves along a great-circle plane towards a reversed polarity component with shallow inclination, the remanence intensities gradually increasing (fig. 3a). In AF fields ranging from 30 to 50 mT the reversed polarity component decays to the origin of Zjiderveld diagram, suggesting the univectorial nature of this remanence. More detailed analysis indicates, however, that for most of the samples the inclination displays small, but successive changes in progressive demagnetization

TABLE I. – Summary of paleomagnetic sites.
Dir/dip – is direction of the dip and dip ; N/n ratio of rock samples and specimens.
TABL. I. – *Description synthétique des sites paléomagnétiques. Dir/dip : azimut de la ligne de plus grande pente et valeur du pendage ; N/n : nombre de blocs orientés sur le nombre total d'échantillons.*

Site	Locality	Lithology	Age	Dir/dip	N/n
CX2	Chanxhe	crinoid limestone	Visean	171/61	6/15
CX1	Chanxhe	crinoid limestone	Visean	350/58	7/17
RU	Roiseux	crinoid limestone	Visean	157/41	6/11
MR	Petite Avins	crinoid limestone	Visean	334/67	4/12
BA2	Barse	lamin. limestone	Givetian	350/15	5/9
BA1	Barse	lamin. limestone	Givetian	157/47	5/14
VM	Vireux-Molhain	red sandstone	Emsian	350/105	7/12
VI	Vireux	red sandstone	Emsian	150/25	4/7
AU	Aubrives	red sandstone	Emsian	320/77	4/10
AN2	Angleur	red sandstone	Emsian	11/53	5/10
AN1	Angleur	red sandstone	Emsian	170/80	5/8

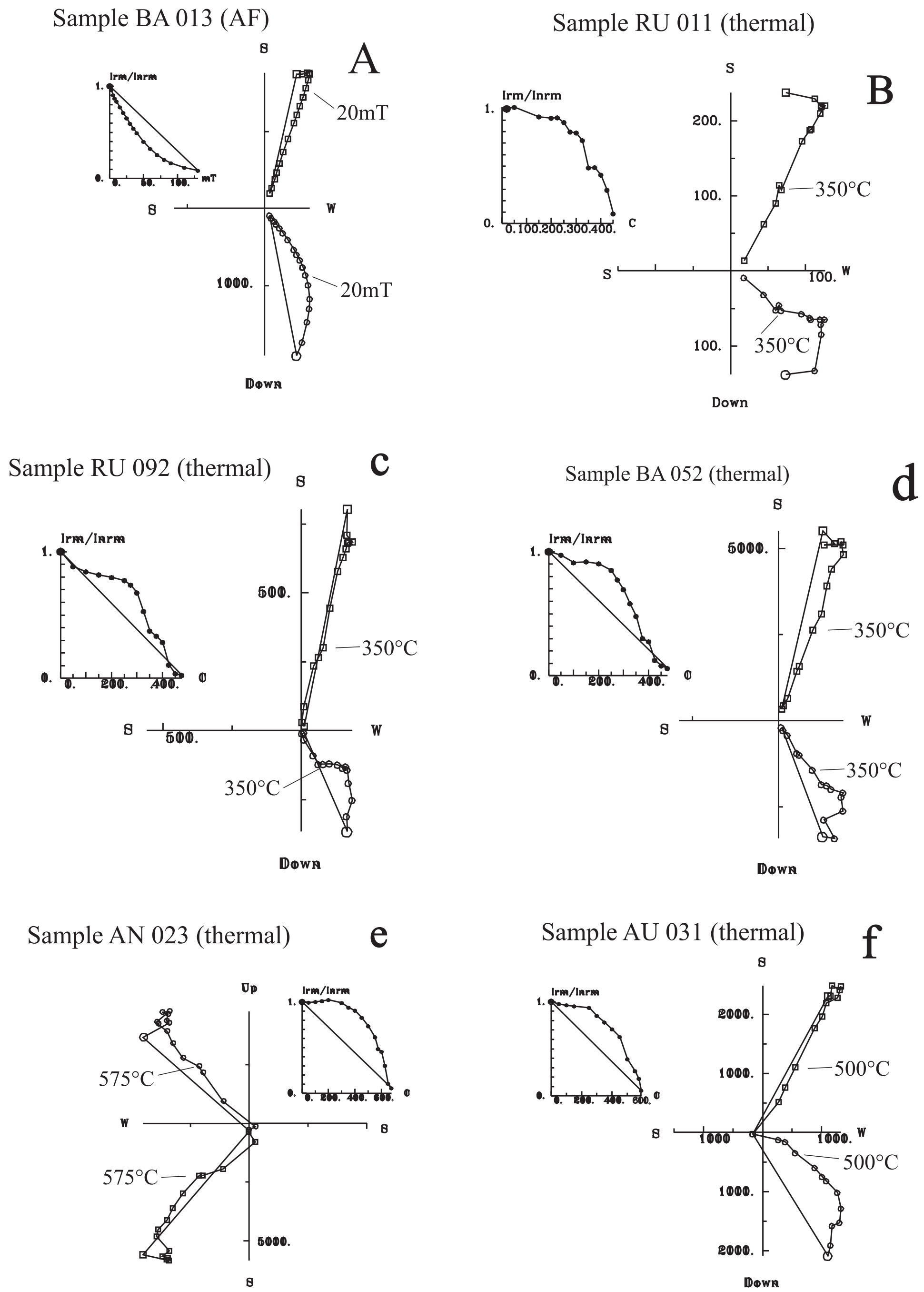


FIG. 3. – Thermal (b, c, d, e, f) and alternative field (AF) (a) demagnetization results. Specimens of limestones (a, b, c, d) and clastics (site AN – e ; AU – f). Units at Zijderveld diagrams expressed in μA/m. Irm/Inrm = normalized intensity of remanent magnetization/intensity of initial NRM. In situ position.
FIG. 3. – *Résultats des désaimantations thermiques* (b, c, d, e, f) *et en champ alternatif* (a). *Échantillons carbonatés* (a, b, c, d) *et clastiques (site AN* - e *; AU* - f*). Les unités des diagrammes de Zijderveld sont exprimées en μA/m. Irm/Inrm = intensité normalisée de l'aimantation rémanente/intensité de l'aimantation rémanente naturelle initiale. Report en position in situ.*

(fig. 3a). This observation suggests that the investigated reversed polarity remanence is in fact composed of two characteristic components with strongly overlapping coercivity spectra.

The multicomponent nature of the ChRM is confirmed by the results of thermal cleaning (fig. 3b, c, d), which proved to be more efficient in separation of the NRM components. Low temperatures of demagnetization effectively remove the component directed towards the recent magnetic field, akin to the one observed in the low fields of AF cleaning. At higher temperatures, usually two characteristic components were observed. The low temperature component (LT), demagnetised between 250 °C and 350 °C, is characterised by generally SSW declination and horizontal inclination (before tectonic correction). In temperatures over 375 °C, when the LT component is finally removed, the remaining component (high temperature component - HT) exhibits an univectorial behaviour, going to the origin of the Zijderveld diagram. The HT component, with Tub ca. 550 °C, shows generally SW to SSW declinations with shallow positive to horizontal inclinations after bedding correction.

Devonian clastic red beds

Five sites have been investigated in clastic rocks of Lower Devonian age (AN1, AN2, VI, VM, AU). Their location is reported in figure 1a and their geological characteristics are listed in table I.

The red beds of Lower Devonian age contain hematite as the main magnetic carrier. The presence of hematite can be inferred from the thermomagnetic analysis, which points to a magnetic phase with Tub as high as 650 °C (fig. 2b), as well as from a weak response of NRM to AF demagnetization.

The structure of the NRM record is different in investigated localities. In the Emsian sandstones from the Angleur anticline (sites AN1, AN2, fig 3e), a soft component is removed after cleaning up to 300 °C. A single, stable component is demagnetised in subsequently higher temperatures, showing trends towards the origin of the Zijderveld diagram up to 550 °C, when artificially induced magnetization prevents further thermal cleaning. In turn, the Emsian sandstones from the Chooz Formation (sites VM, VI, AU fig. 3f) yielded a characteristic component that could be defined up to 600 °C. Generally, the magnetic record from the red beds is of moderate-to-low quality, frequently showing saw-shaped demagnetization paths. Although in several cases the presence of two components with strongly overlapping blocking temperatures cannot be excluded, in most specimens high Tub ChRM display univectorial behaviour.

Apart from the red beds, greenish to grey Devonian clastics containing magnetite were also investigated, but no reliable results were obtained.

FOLD TESTS, RELATIVE AGE AND ORIGIN OF REMAGNETIZATIONS

Devonian and Carboniferous limestones

It should be mentioned first that in both carbonate and clastic rocks we have observed a relatively low degree of anisotropy of magnetic susceptibility. Therefore we postulate that tectonic deformation had little influenced on CHRM which is a necessary condition for the fold tests to be performed [see Stamatakos and Kodama, 1991].

We have applied a fold test for a kilometric scale fold with parallel striking limbs (sites CX1, CX2 in Chanxhe locality) and a local, small scale anticline (sites BA1, BA2 in Barse locality), within the southern limb of a regional-scale anticlinal structure. Results are shown in the figure 4 a, b and 4 c, d respectively. In both cases the HT component indicated an early synfolding origin, displaying a maximum k parameter [Fisher, 1953], as well as a minimum f parameter [McFadden and Jones, 1981] for 80 % (CX1, CX2) and 70 % (BA1, BA2) of unfolding. In turn, the LT component displays best grouping in the initial stage of unfolding for both sites. In this case, however, the variability of statistic parameters is smaller.

In cases where sampling sites were situated in structures featuring different tectonic trends, we applied an inclination-only test using the Enkin and Watson [1996] procedure. The inclination-only test was performed under the assumption, that the axes of the tectonic rotations were vertical so that tectonic dips and paleomagnetic inclinations remained unchanged. For data combined from sites CX1, CX2, BA1, BA2, MR, RU we have found (fig. 5 a) that the best grouping, expressed by maximum value of precision parameter k appeared after 83 % and 12 % of unfolding for HT and LT, respectively. For these optimal degrees of untilting we have found a 95 per cent confidence intervals : 78 % to 88 % of untilting for HT component and 12 % to 26 % of untilting for LT component. We observed also similar results including data of Molina Garza and Zijderveld [1996] (sites characterised by significant plunging of the fold axes are not considered) (fig. 5 b). In this case, the maximum k occurs at 89 % of unfolding for HT and 8 % for LT with 95 per cent confidence intervals 86 %-91 % and 5 %-12 %, respectively.

This outcome is in line with previously published data [Molina Garza and Zijderveld, 1996], where the classical McElhinny [1964] fold test was performed at the site level giving a maximum for κ at 90 % and 10 % of unfolding for the HT and LT components, respectively. However maximum κ for HT and LT components did not pass the test at the 95 % significance level and therefore both components were interpreted as pre-and postfolding origin, respectively [see Molina Garza and Zijderveld, 1996].

In our study, paleomagnetic results indicate the early synfolding (HT components) and late synfolding (LT components) character of the magnetizations. It is worth noting however that for the LT component, estimated optimal degrees of untilting are very close to zero. Therefore, we postulate that the HT and LT components are of secondary origin. The HT component, being older, had been acquired at the incipient stage of structural development, while the LT component (younger) has been recorded during the final stage or just after the deformations.

For our final tectonic interpretation, we have taken into account also the site-mean directions presented by Molina Garza and Zijderveld [1996], which were formerly considered of pre- and postfolding origin. Following the results presented above, we have finally considered them of synfolding origin and therefore we calculated the paleomagnetic directions with the tectonic corrections, deduced from the fold test performed by these authors (i.e. 90 % and 10 % of untilting for HT and LT respectively).

Some evidences for the age of the remanence can be obtained by comparing measured inclinations with reference data recalculated from the apparent polar wander path (APWP) for the Old Red Sandstones Continent at the geographic position of the study sites. For both HT and LT components (see table II), observed inclinations range typically from -10^{o} to $+10^{o}$ (reversed polarity), being typically somewhat shallower for the LT component. This suggests an Upper Carboniferous age for both HT and LT components acquisition. The reversed polarity of both components points to Kiaman reversed polarity superchron. Taking into account that values of paleomagnetic inclinations generally decrease with age for ORC in the Carboniferous-Permian time interval, we may only estimate the time of the

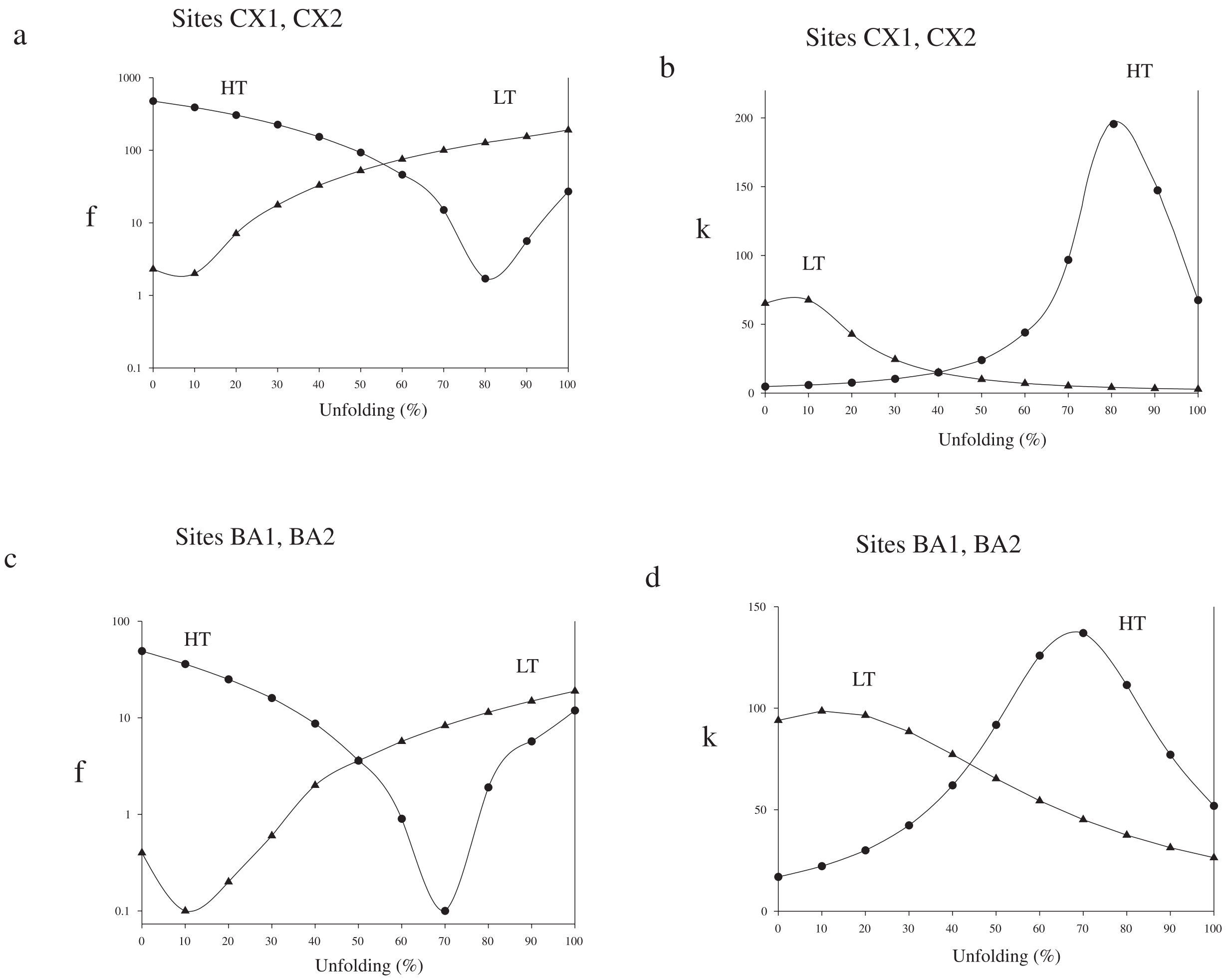


FIG. 4. – Fold test results for Devonian and Carboniferous limestones : (a, c) – following McFadden and Jones's procedure [1981] ; (b, d) – kappa versus per cent of untilting plot ; (a, b) – local fold test for sites CX1 and CX2 (Chanxhe fold). (c, d) – local fold test for sites BA1, BA2 (Barse fold). f = observed value of F distribution, k = fisherian precision parameter. HT = high temperature component ; LT = low temperature component.

FIG. 4. – *Résultats des tests du pli pour les calcaires dévoniens et carbonifères : (*a, c*) – suivant la procédure de McFadden et Jones [1981] ; (*b, d*) – diagramme reportant k en fonction du pourcentage de débasculement ; (*a, b*) – test du pli local pour les sites CX1 et CX2 (pli de Chanxhe). (*c, d*) – test du pli local pour les sites BA1 et BA2 (pli de Barse).* f = *valeur observée de la distribution F,* k = *paramètre de précision de la statistique fisherienne.* HT = *composante haute température ;* LT = *composante de relativement basse température.*

remanence acquisition to be Namurian/Westphalian for HT and Stephanian for LT components, bearing in mind that the latter is younger and displays slightly shallower inclinations.

It is worth noting that this method of remanence dating is very sensitive to even small errors in inclination estimations. In our fold test, we have unfolded two limbs of a fold symmetrically with respect to the axial plane, which may not mimic real kinematics of these structures [Shipunov, 1997 ; Setiabudidaya *et al*., 1994]. Moreover, we cannot exclude small-scale tilting of the whole of the structure during thrusting. This and the unfolding procedure may have some bearing on observed between-site dispersion of inclination, while in-site clustering of NRM components is very good.

Assuming that the process of unfolding did not imply a significant inclination error, then a Namurian-Westphalian age is very likely for the early folding HT component and a Stephanian one can be proposed for the late folding LT component. Taking into account the tectono-thermal evolution of rocks involved in the Ardennes thrust belt, we can relate the first event to the general burial of the Devonian-Carboniferous limestones under the 3-4 kilometers thick [Han *et al*., 2000] Namurian-Westphalian molassic foreland basin and the second to the final activation of the frontal thrust zone in early Stephanian times. The precise mechanisms by which the Ardennes limestones have been remagnetized are however poorly constrained. Chemical as well as thermo-viscous remanent overprints can commonly operate in fold-thrust belts during foreland basin-induced burial (first event) and frontal thrust-sheet stacking (second event) [see for example Enkin *et al*., 2000]. Based on SEM observations, Molina-Garza and Zijderveld [1996] suggested a chemical origin of both Ardennes limestones remagnetization events due to the formation of secondary "diagenetic" magnetite. Enkin *et al*. [2000], in the southern Canadian Cordillera, interpreted the same scenario of remagnetizations that we observed in the Variscan frontal thrust belt (e.g, an early folding and a late folding overprint) as the result of successive chemical and thermo-viscous remagnetization events. In the absence of more precise petrological and geochemical data on the Ardennes Devo-

TABLE II. – (a, b) Paleomagnetic data from carbonates.
D_0/I_0 - declination and inclination of ChRM *in situ* ; % - percent of untilting that yields best grouping direction in terms of McFadden and Jones (1981) test; D/I – mean declination and inclination in synfolding position from McFadden and Jones [1981], * - from inclination only test [Enkin and Watson 1996] ; κ, α - statistical parameters calculated at the sample level, N – number of independently oriented hand samples employed for calculations.
TABL. II. – (a, b) *Données paléomagnétiques pour les sites carbonatés.* D_0/I_0 *- déclination et inclinaison de l'aimantation rémanente caractéristique in situ ; % - pourcentage de débasculement donnant le meilleur groupement au sens de McFadden et Jones (1981) ;* D/I *– déclinaison et inclinaison moyenne après débasculement optimal suivant McFadden et Jones [1981], * - à partir uniquement du test d'inclinaison [Enkin et Watson, 1996] ; κ, α - paramètres de quantification de l'analyse statistique, N – nombre de blocs orientés indépendants utilisés lors du calcul.*

CARBONATES HT

Site	D_0/I_0	N	κ	α	%	D/I	κ	α
CX2	222.7/40.7	6	139.4	5.7	80	**209.5/2.7**	195.8	3.0
CX1	220.3/-32.1	7	355.9	3.2				
RU	212.4/24.5	6	215.8	4.6	-	**205.6/4.0***	215.8	4.6
MR	210.3/-37.2	4	96.6	9.4	-	**195.5/-0.2***	96.6	9.4
BA2	194.2/-0.8	4	69.7	11.1	70	**193.6/8.6**	137.5	4.4
BA1	201.4/34.5	5	277.8	4.6				

CARBONATES LT

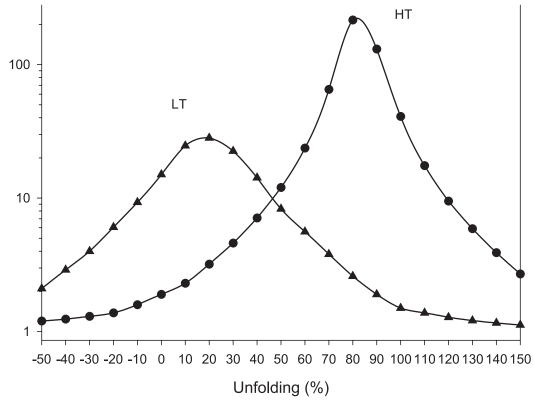
Site	D_0/I_0	N	κ	α	%	D/I	κ	α
CX2	193.8/4.4	5	91.9	8.0	10	**197.1/0.9**	67.6	6.3
CX1	201.2/-1.5	4	61.5	11.8				
RU	203.8/3.3	6	82.4	7.4	-	**203.7/-2.4***	82.4	7.4
MR	199.0/-28.5	4	51.9	12.9	-	**195.0/-18.7***	51.9	12.9
BA2	197.0/1.8	4	92.9	9.6	10	**196.9/2.3**	97.9	5.2
BA1	197.0/5.2	5	82.1	8.5				

nian and Carboniferous limestones, we cannot discriminate between these two mechanisms for the sites studied in this paper. However, as proposed for other foreland thrust belts [Setiabudidaya *et al.*, 1994 ; Enkin *et al.*, 2000], we subscribe to the idea that hot fluid flows expelled ahead of the deformation front are likely to contribute to the process of remagnetization in the French-Belgium Variscan thrust belt. Pervasive dolomitization events observed in the carbonate rocks from the Ardennes thrust belt are also likely to reflect such regional fluid migrations during thrust belt development as suggested by petrological and fluid inclusion studies [e.g. Goudalier, 1998].

Devonian clastic red beds

A fold test was performed in two distant locations : the Angleur anticline situated close to the Midi Fault (fig. 1 a, site AN1, AN2) and in the northern forelimb of the Rocroi culmination (sites VM, VI and AU, fig. 1 a), characterised by various bedding strikes and dips. Results from Angleur indicate synfolding magnetization (fig. 6a, b), while within sites VM, AU, VI, the best grouping of paleomagnetic directions was observed without tectonic correction (fig. 6c, d).

Analysis of paleomagnetic inclinations (see table III) and their comparison with Devonian-Carboniferous inclinations for ORC suggest an older age for the postfolding than for the synfolding component of NRM. Such an apparent paradox, however, may be explained by the progressive migration of the thrusting towards the foreland (see isochrones



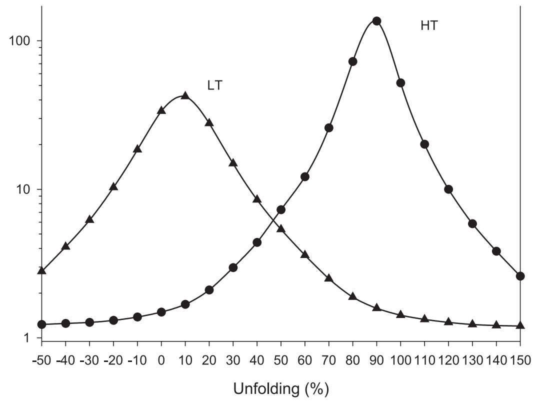


FIG. 5. – Inclination-only tilt tests following Enkin and Watson's procedure [1996]. (a) – taking into account only carbonate sites of this study (CX1, CX2, BA1, BA2, RU and MR), (b) – including carbonate sites of Molina-Garza and Zijderveld [1996]. Other explanations are the same as in the figure 4.
FIG. 5. – *Tests de débasculement d'inclinaison suivant la procédure d'Enkin et Watson [1996]. (*a*) – prenant en compte uniquement les sites carbonatés de cette étude (*CX1, CX2, BA1, BA2, RU et MR*), (*b*) – incluant les sites carbonatés de l'étude de Molina-Garza et Zijderveld [1996]. Autres explications identiques à la figure 4.*

TABLE III. – Paleomagnetic data from clastics.
D_0/I_0 - declination and inclination of ChRM in situ; % - percent of untilting that yields best grouping direction in terms of McFadden and Jones [1981] test; D/I – mean declination and inclination in synfolding/postfolding position from McFadden and Jones [1981]; , α - statistical parameters calculated at the sample level, N – number of independently oriented hand samples employed for calculations.
TABL. III. – *Données paléomagnétiques pour les échantillons clastiques.* D_0/I_0 *- déclinaison et inclinaison de l'aimantation rémanente caractéristique in situ; % - pourcentage de débasculement donnant le meilleur groupement au sens de McFadden et Jones [1981] ;* D/I *– déclinaison et inclinaison moyenne après débasculement optimal suivant McFadden et Jones [1981] ; κ, α - paramètres de quantification de l'analyse statistique*, N *– nombre de blocs orientés indépendants utilisés lors du calcul.*

CLASTICS

Site	D_0/I_0	N	κ	α	%	D/I	κ	α
VM	205.2/13.8	7	44.6	9.1				
AU	203.5/3.3	4	67.4	11.3	0	**207.2/11.0**	32.3	6.8
VI	214.9/13.7	4	18.7	21.8				
AN2	214.1/-40.7	5	114.8	7.2	60	**209.4/-10.4**	67.0	5.9
AN1	215.2/26.3	5	40.7	12.1				

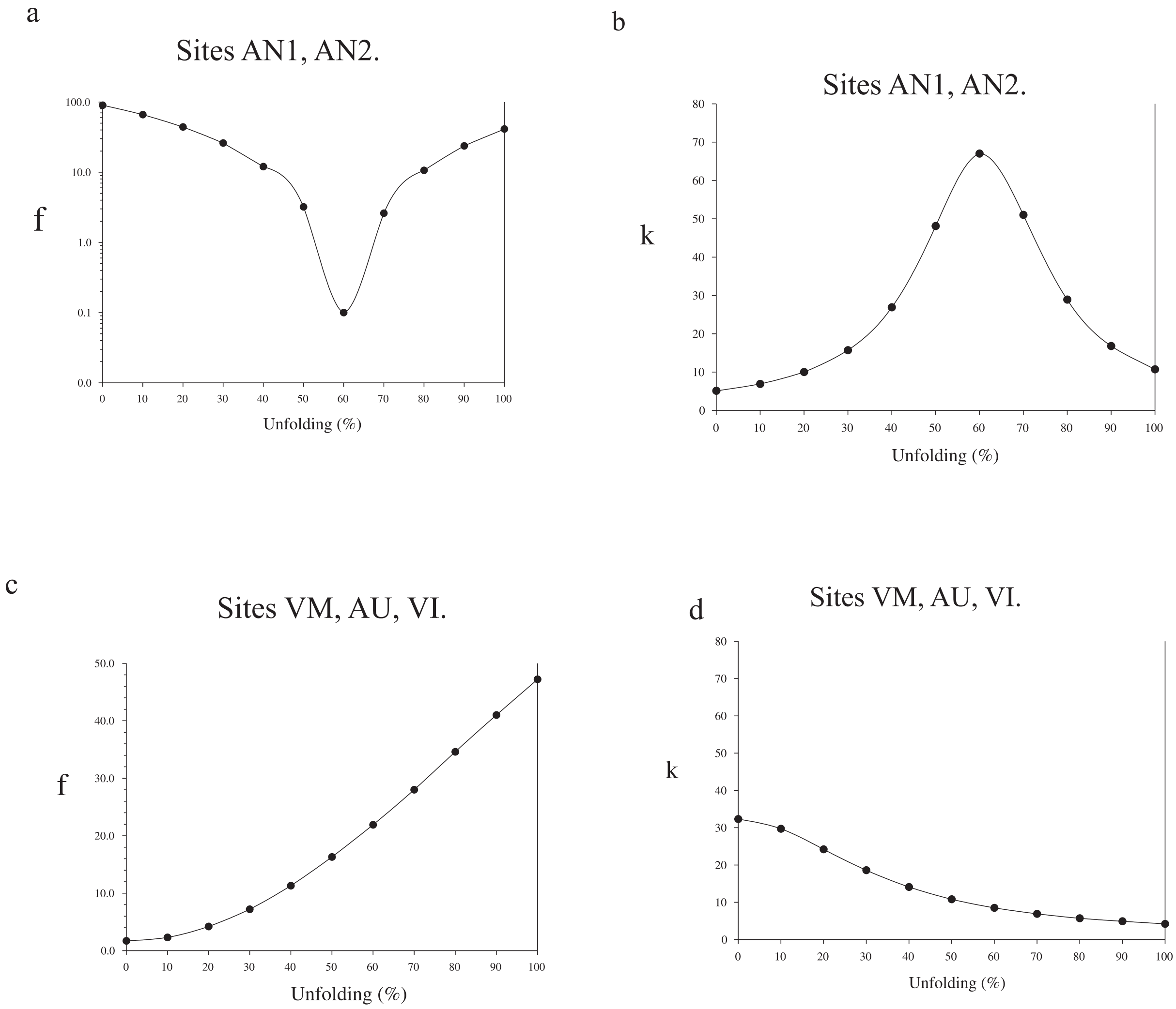


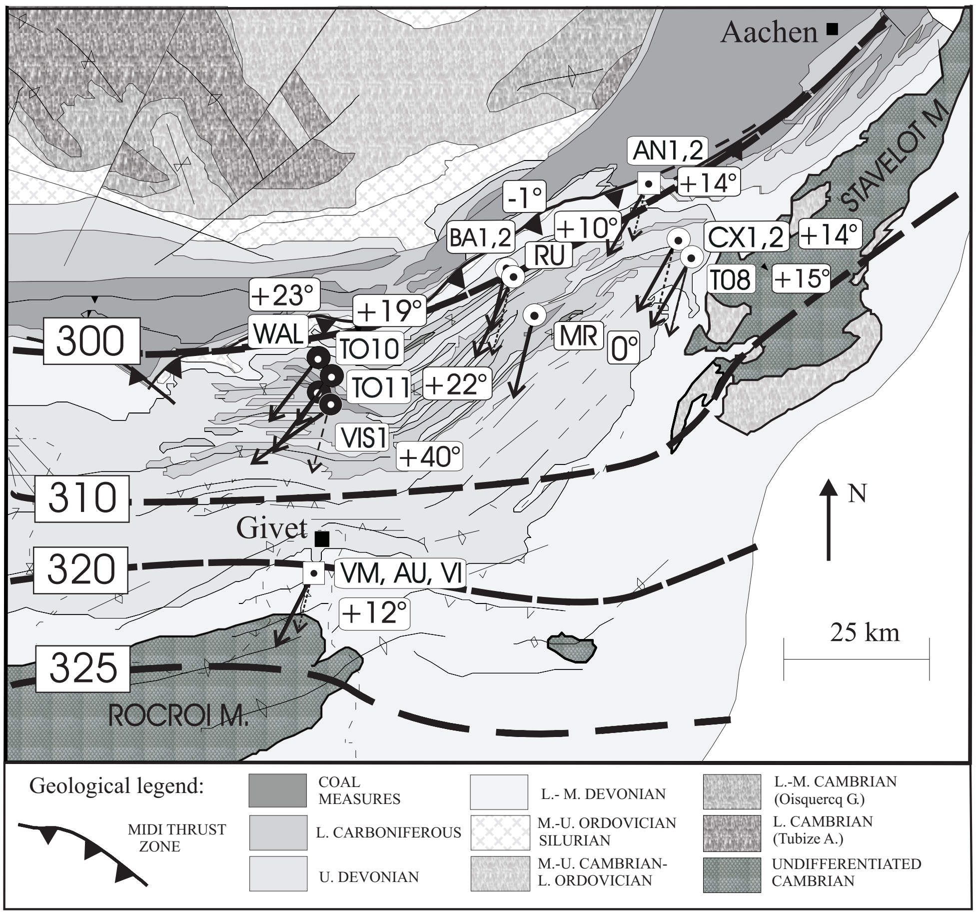
FIG. 6. – Fold test results for Lower Devonian clastic sites. (a, c) – following McFadden and Jones's procedure [1981], (b, d) – kappa versus per cent of untilting plot. (a, b) – local fold test for sites AN1 and AN2 (Angleur fold). (c, d) – local fold test for sites VM, AU, VI (forelimb of the Rocroi anticline). Other explanations are the same as in the figure 4.

FIG. 6. – *Résultats des tests du pli pour les sites clastiques du Dévonien inférieur (*a, c*) – d'après la procédure de McFadden et Jones [1981], (*b, d*) – diagramme reportant* k *en fonction du pourcentage de débasculement (*a, b*) – test du pli local pour les sites AN1 et AN2 (pli d'Angleur). (c, d) – test du pli local pour les sites* VM, AU, VI *(retombée avant de l'anticlinal de Rocroi). Autres explications identiques à la figure 4.*

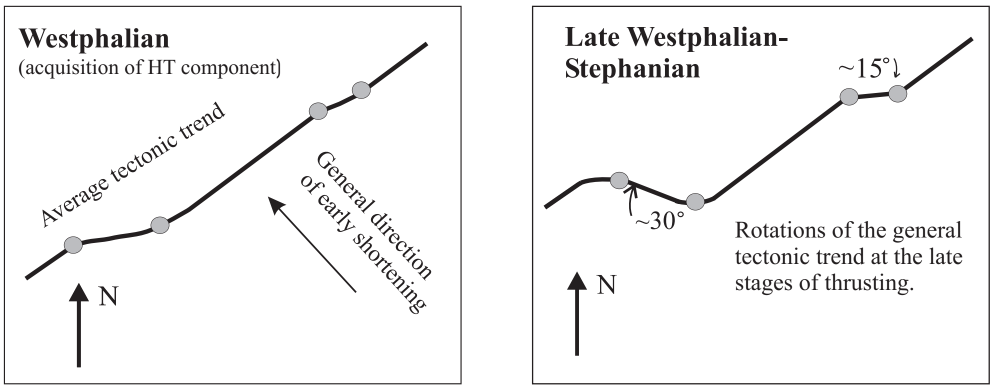
from fig. 7). Structural data suggest that the sampling area situated to the south of the allochthonous units (sites VM, VI, AU) had already been folded and uplifted when the regions located to the north (site AN1, AN2) were still undeformed and covered by molasse. This scenario of tectonic development is also reflected in the burial history and patterns of radiometric and paleontological dating [Chamley *et al.*, 1997 ; Han *et al.*, 2000 ; Plesch and Oncken, 1999]. Devonian and Carboniferous limestones investigated in this study as well as the Angleur clastic rocks were sampled along the youngest isochrone of deformations (circa 300Ma – see fig. 7). The Angleur synfolding magnetization can thus be dated as late Westphalian to early Stephanian. The Lower Devonian sandstones sampled in the southern parts of the fold-belt did not record however the same deformation history. The latter are involved in the forelimb of the Rocroi thrust ramp anticline (fig. 1) [e.g. Lacquement, 2001] and were deformed very likely in Upper Visean times. They are the only one in our data set to have experienced anchi-metamorphic conditions due to tectonic burial under the thick Rocroi massif thrust wedge [e.g. Robion *et al.* 1999]. In this zone, remagnetizations thus probably occurred during this process (i.e. in late Visean times).

TECTONIC INTERPRETATION OF PALEOMAGNETIC DECLINATIONS

Combined together, the ChRM declinations of this study and the results of Molina Garza and Zijderveld [1996] are shown on a geological map (fig. 7) in order to compare obtained paleomagnetic declinations with structural trends in the FBVB. It is clear that declinations for HT component are similar to directions known for the Upper Paleozoic of the ORC in regions of NE-SW orientation of fold axes. Conversely, areas characterised by E-W to WNW-ESE trends show ChRMs rotated clockwise. Similar dependence can be



a



b

FIG. 7. – a. Geological map of the study area [after Lacquement, 2001] showing the paleomagnetic declinations for HT components at different sites. The horizontal projection of the paleomagnetic vector is shown by a black arrow, the reference direction for stable ORC is shown by a dashed arrow, the angular deviation at each site is reported (see text for more explanations).
Paleomagnetic data:
this study: ⊙ – carbonates, ⊡ – clastics;
study of Molina Garza and Zijderveld [1996] : ● – carbonates
300 – Isochrones (Ma) of progressive deformation [after Plesch and Oncken,1999].
b. Schematic diagrams illustration the evolution of the general tectonic trend during the different stages of shortening.

FIG. 7. – a. Carte géologique du secteur d'étude [d'après Lacquement, 2001] montrant la déclinaison paléomagnétique pour la composante de haute température au niveau des différents sites. La composante horizontale du vecteur paléomagnétique est reportée par une flèche noire, la direction de référence pour le continent stable (ORC) est reportée en pointillée, la déviation angulaire à chaque site est reportée (voir le texte pour plus d'explications).
Données paléomagnétiques :
Cette étude : ⊙ – carbonates, ⊡ – niveaux clastiques;
Etude de Molina Garza et Zijderveld [1996] : ● – carbonates
300 – Isochrones de déformation (Ma) montrant la migration du front chevauchant [d'après Plesch et Oncken, 1999]
b. Diagrammes schématiques illustrant la torsion localisée des structures au cours du raccourcissement.

observed for the LT component, but in this case magnitude of the deviation of paleomagnetic declination from the reference directions for ORC is generally smaller and correlation of strike and declinations more dispersed (fig. 8a, b). Paleomagnetic declinations obtained for clastics display orientations deviated from the reference directions from ORC in the same way going with a corresponding pattern for carbonates (fig. 7). It should be pointed out, that such correlation of paleomagnetic declinations from carbonates with structural trends was noted also by Thominski *et al.* [1993]. However, using AF method for paleomagnetic cleaning, these authors did not discriminate between HT and LT components.

Presented declination data thus support the local oroclinal bending origin of strike deviations observed in the Ardennes thrust-belt (fig. 7b). However, as shown by the slope of the linear correlation estimated between declination anomalies and strike deviations (fig. 8), observed rotations do not account for the total fold axes deviations. We suggest that clockwise rotations of the structures occur as the result of distributed dextral transpressive deformations, that took place within the lateral boundaries of propagating thrusts sheets (fig. 9) [Lacquement, 2001 ; Averbuch *et al.*, 2002]. HT and LT components, acquired at different steps of structural development and exhumation process, recorded successive stages of bending within the developing fold belt. Notable rotations within the thrust-sheet, inferred from declinations of the presumably late-synfolding LT component, indicate that evidenced shear zones were active late in the process of thrusting. Geometry in cross-sections and depth map of the basal décollement zone [Lacquement, 2001 ; Averbuch *et al.*, 2002] moreover suggest that such narrow shear zones are localized by a system of NW-SE trending deep-seated basement discontinuities inherited from the Lower Devonian Rheno-Hercynian basin geometry (fig. 9).

GENERAL CONCLUSIONS

Paleomagnetic results from FBVB indicate the existence of two main episodes of regional remagnetization acquired at different stages of the deformation process. Fold tests applied for sites situated at different distances from the main frontal thrust (Midi thrust) evidenced a first episode of remagnetization which is coeval with the onset of deformation within the central and northern part of the allochthonous unit. Based on inclination data compared with reference directions for ORC [recalculated from Van der Voo, 1993], we suggest a Namurian-Westphalian age for this remagnetization event. Taking into account only reversed polarity for ChRM components in our studies and those of Molina Garza and Zijderveld [1996], we can furthermore constrain a time of remanence acquisition to the Kiaman reverse superchron. We relate the remagnetization event to the general burial of the FBVB under a thick molassic foreland basin (up to 4 km thick), as evidenced by fluid inclusions [Kenis *et al.*, 2000] and illite cristallinity data [Han *et al.*, 2000].

The second remagnetization event affected FBVB carbonates at a late stage of folding, as could be evidenced in the central and northern part of the thrust-and-fold belt. Inclination data indicate a Stephanian age for this remagnetization episode. We suggest this second event to be related with the final activation of the Midi frontal thrust zone which has been shown to occur as an out of sequence thrust system when the frontal parts of the belt were almost completely emplaced [e.g. Averbuch et Mansy, 1998 ; Lacquement *et al.*, 1999].

The distribution of paleomagnetic directions implies the existence of localized domains of tectonic rotations associated to strike deviated zones along the belt. Within these narrow zones, declination data evidence clockwise rotations of maximum 40 degrees whereas the zones trending NE-SW

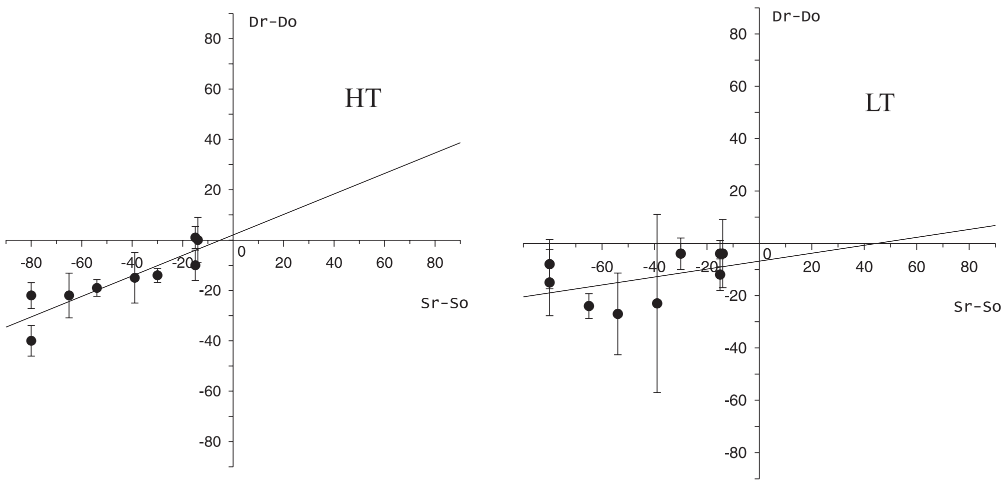


FIG. 8. – Diagram reporting strike deviations (Sr-So) with respect to declination deviations (Dr-Do) for HT and LT components. Reference strike (Sr) is 50ºE for both diagrams, while reference declination Dr for ORC is 195ºE for HT (Namurian-Westphalian) and 193ºE for LT (Stephanian). Do – measured declination, So – observed strike. Solid line is the best fitted line for the data sets. Note the poor correlation of LT component directions with structural trends.

FIG. 8. – *Diagramme reportant la déviation d'orientation des structures (*Sr-So*) en fonction de la déviation de déclinaison (*Dr-Do*) pour les composantes de haute température (*HT*) et de basse température (*LT*). La direction de référence (*Sr*) est 50ºE pour les deux diagrammes, la déclinaison de référence (*Dr*) pour ORC est 195ºE pour la composante de haute température* HT *d'âge namurien-westphalien et de 193ºE pour la composante de plus basse température* LT *d'âge stéphanien.* Do – *déclinaison mesurée,* So – *direction des structures observée. La droite en trait plein est la droite de corrélation optimale pour les deux ensembles de données. A noter une moins bonne corrélation pour les composantes de basse température* LT.

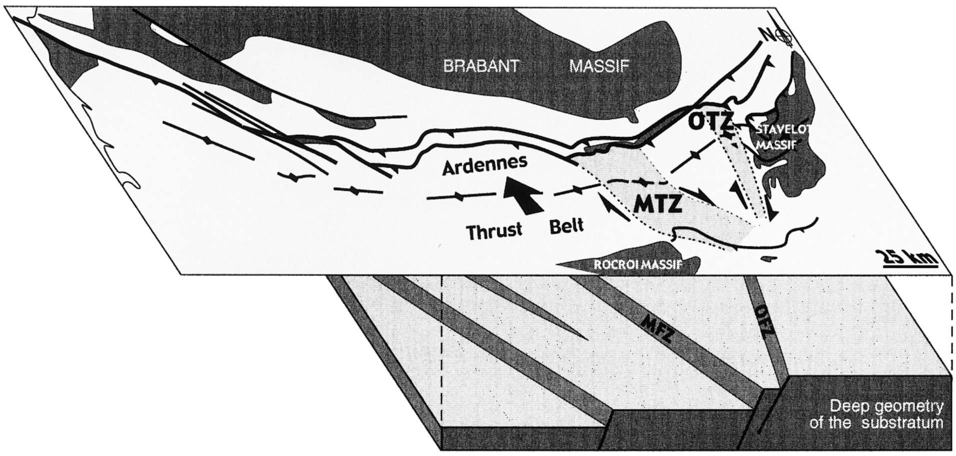


Fig. 9. – Schematic 3D view illustrating the development of clockwise rotated corridors due to distributed dextral transpressive deformation at lateral borders of propagating thrust-sheets. Note that this zones are controlled by deep-seated footwall discontinuities inherited from the Lower Devonian basin development [modified from Lacquement, 2001 and Averbuch *et al*., 2002]. MTZ : Meuse Valley transpressive zone ; OTZ : Ourthe Valley transpressive zone ; MFZ : Meuse Valley footwall fault zone ; OFZ : Ourthe Valley footwall fault zone.

FIG. 9. – *Vue 3D schématique illustrant le développement de couloirs de rotation en sens horaire associés à une déformation distribuée à caractère transpressif dextre en bordure latérale d'écailles chevauchantes. Il est à noter que ces zones sont contrôlées par des discontinuités profondes du substratum héritées du développement du bassin au cours du Dévonien inférieur [modifié de Lacquement, 2001 et Averbuch* et al., *2002].* MTZ *: zone transpressive de la Vallée de la Meuse;* OTZ *: zone transpressive de la Vallée de l'Ourthe;* MFZ *: zone faillée au mur des chevauchements associée à la zone de la vallée de la Meuse;* OFZ *: zone faillée au mur des chevauchements associée à la zone de la vallée de l'Ourthe.*

exhibit no rotations compared to the ORC. Rotation magnitude correlates well with the degree of strike deviation but does not account for the entire shape of the bent structures. We suggest that these rotations occurred within dextral transpressive zones located at lateral borders of thrust-sheets. The latter are likely to be controlled by pre-existing discontinuities inherited from the early Devonian basin evolution as shown by drastic variations in the depth of the base of the Devonian-Carboniferous cover [Lacquement, 2001 ; Averbuch *et al*., 2002]. On the other hand, as parts of these rotations are recorded by the late remagnetization event, we may infer that the transpressive system was active until late in the deformation history.

At a more regional scale, it is worth noting that the zone displaying the general NE-SW trend of the Ardenno-Rhenish segment of the Variscan arc preserved the original orientation of the sedimentary basin. This indicates that the study area was not rotated as a whole unit with respect to the ORC since the high temperature component was acquired (i.e. Namurian/Westphalien). This result contrasts with previous paleomagnetic interpretations [Edel and Coulon, 1987 ; Thominski *et al*., 1993 ; Molina Garza and Zijderveld, 1996] and has thus to be considered regarding the origin of the arcuate shape of the western European Variscan belt (Ibero-Armorican arc).

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Communiqué de presse

Sahara

Sous le sable... des lacs

Un voyage dans le temps

Nicole PETIT-MAIRE

Parution : 16 janvier 2003

On sait maintenant assez précisément que le climat actuel de la Terre n'est qu'un état transitoire, un point mobile sur la courbe d'une évolution toujours en marche. Les véritables archives que constituent les données emmagasinées dans les couches géologiques montrent en effet que les climats ont eu, dans le passé, une formidable variabilité.
Comment le Sahara a-t-il réagi à ces bouleversements ?
Vingt-cinq ans de missions dans les régions les moins accessibles de ce désert ont permis à Nicole Petit-Maire, aidée sur le terrain et en laboratoire par une équipe multidisciplinaire d'une vingtaine de spécialistes, de reconstituer l'évolution des environnements sahariens depuis 130 000 ans, en relation avec les changements climatiques globaux. Les puissantes interactions entre les processus astrophysiques, géologiques, biologiques et humains sont ainsi mises en lumière. Sur la base de photographies de terrain, les méthodes de recherche et leurs résultats sont ici expliqués de manière simple.
Au cours d'une promenade en images dans les magnifiques paysages du Sahara, nous découvrons, au bord d'anciens lacs asséchés, toute une flore et une faune fossiles, ainsi que des sites archéologiques, témoins de temps où le désert actuel était une savane ou une steppe herbeuse. Enfin, des photos rares des mines de sel de Taoudenni, exploitées depuis le xvie siècle, illustrent les rapports entre un lac depuis longtemps disparu et un commerce moderne toujours vivant.
La face cachée du désert, qui gît, toute proche, sous le sable, derrière le rocher, au creux des ergs, est encore là. Il faut savoir la reconnaître, la déchiffrer : elle nous livrera son histoire et peut-être, si nous la comprenons bien, son avenir...

Nicole Petit-Maire, Docteur ès Sciences, récemment encore Présidente du Comité français de l'Union Internationale pour l'Étude du Quaternaire (INQUA), est actuellement Directeur de Recherches émérite au CNRS. Elle a été, de 1987 à 1994, Vice-Présidente de l'Union Internationale des Sciences Géologiques et Chef de deux Programmes internationaux de l'UNESCO.

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