Paleomagnetic direction obtained by strain removal in the Pyrenean Permian redbeds at the “Col du Somport” (France)

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In order to investigate the possibility and limitations of paleomagnetic works within strained regions, a paleomagnetic study, related with strain analysis has been conducted in the deformed Pyrenean Permian redbeds in the “Col du Somport” area. Paleomagnetic sampling together with strain estimates have been conducted in 6 sites through a fold. The results obtained by measuring the orientation and axial ratios of elliptical reduction spots show that (1) the shale beds have undergone a penetrative strain, (2) the sandy beds can be regarded as tectonically unstrained with reduction spots flattened in the bedding, showing that they recorded the compaction. It is shown that the total strain recorded in the slate beds probably results from the superimposition of tectonic strain upon the compaction fabric. The paleomagnetic study shows that the primary pre-tectonic magnetization is widely overprinted by a secondary syn- or post-tectonic magnetic component. As both components appear to be carried by hematite pigment, their separation using classical demagnetization procedures has been difficult. A characteristic remanent magnetization (ChRM) has however been determined, when possible, as the hardest component in demagnetization curves. Then, the ChRM direction distributions are represented in stereographic density plots. Although these ChRM directions exhibit a clear tendency towards SE declinations and shallow inclinations, characteristic of Permian paleomagnetic field direction for the Iberian plate, the tilt correction does not induce a clustering of these directions. Strain is inferred to be responsible for this situation. Assuming that both pre-tectonic magnetization directions and bedding planes closely follow the material plane and line strain response model of March [1], an attempt has been made to remove the effect of strain upon the remanent magnetization. It is shown that when using a reconstructed tectonic strain tensor (i.e., the total strain tensor as measured in the field, corrected for an estimated compaction) we obtain a significant clustering of ChRM directions. The computation of the relevant VGP, gives a pole position (210.5° E, 42.1° N) compatible with the reference APWP for the Iberian plate. It is therefore inferred that the strain removal technique is a usable tool in order to obtain paleomagnetic results within such strained rocks.

1. Introduction

The use of paleomagnetic methods to help the understanding of ancient plate motions as well as of geodynamic evolution of some orogenic zones, is based upon the assumption of a time stability of the remanence acquired at a given age until now. The deformation, sensu-lato, whose effects are especially crucial in orogenic belts, is well admitted to cause deviations of primary (pre-tectonic) magnetization direction in folded or fractured rocks. Since Graham [2] has proposed the fold test to determine pre- or post-tectonic acquisition age of remanence in folded series, some developments of the simple tilt correction have been done, to take into account plunging axis folds [3], non-cylindrical folds [4] or superposed folds [5]. However, all the proposed techniques consist of more or less complicated rotations, assuming only a rigid-body rotation part in the total deformation, and cannot deal with internally deformed, or strained, rocks [6,7].

In order to investigate rock magnetism properties and remanent magnetization behaviour in naturally deformed series, we recently conducted some studies in deformed red slates. The first one dealt with the Permian red shales and slates of the Alpes Maritimes (France). In these rocks, we showed a nearly material-line behaviour of the deviated pre-tectonic direction of magnetization under strain [8]. It has been shown that these deviations are controlled by progressive hematite platelets reorientation during the cleavage development in these rocks [9] and, with the help of a...
numerical simulation, that passive rotation of platelets bearing micromoments may induce an actual material line-like behaviour of resultant magnetization [10]. In these series, we made an attempt to remove strain, using the strain data measured in the field. This allowed a reliable Permian paleomagnetic direction to be recovered, even though in-situ and tilt corrected directions were too scattered to be consistently interpreted.

In order to verify the assumptions of a material line behaviour of primary paleomagnetic vectors in such strained rocks, other paleomagnetic investigations related with structural analysis have been carried out in a fold from the Permian red beds of the Pyrenean chain.

2. Geological setting and sampling sites

The studied area is situated at the “Col du Somport” (0.5° W, 42.8° N), at the southern border of the “Axial Primary Zone” of the Pyrenean chain (Fig. 1a). An Autunian age is inferred from the paleontologically based age of lateral equivalent formations at the “Sierra del Cadi” [11]. Here, the red series show ESE-WNW trending asymmetrical folds, slightly recumbent to the south, characteristic of the fan-shaped cross-section of the chain (Fig. 1b) [12]. The location of this area, southwards of the North Pyrenean Fault System, which is suspected to be the limit between the Iberian and European plates during the Cretaceous opening of the Bay of Biscay [14], points to its Iberian belonging. These structural observations are controlled by the paleomagnetic data obtained by Schwarz [15] on the Permian andesites of the Rio Aragon, a few kilometers south of the Col du Somport area. Paleomagnetic vectors have a shallow inclination with a SSE declination, characteristic of Permian and Permo-Triassic data.

Fig. 1. (a) Schematic structural map of the Pyrenean chain (after Choukroune [12]). The Somport area is circled, and the emplacement of the cross-section of Fig. 1b is indicated. Pointed area: Hercynian basement. Hatched area: Secondary Eocene “décolleté”. (b) Schematic N-S cross-section through the axial zone (after Choukroune [13]). The Somport structural emplacement is indicated.
for the Iberian plate [16,17]. The major Pyrenean phase is responsible for the axial planar northerly dipping slaty cleavage development in these red beds.

66 cores were drilled and oriented in 6 sampling sites (A to F; Fig. 2), along the N157 roadside on about 500 m of cross section under the Col du Somport. Three sites (A, B, C) are situated in a southern steeply dipping limb, the others in a northern long slightly dipping limb. Samples of site B were drilled in a fine-grained red sandstone bed, about one meter thick, the others from the slaty mudstones. The area of the sites, generally 1–10 m², was chosen in order to ensure a good homogeneity of the strain (see Ramsay [18]) within each site.

3. Strain estimates

The red series studied are mainly mudstone slates with alternance of some sandstone beds which underlie the bedding plane. The well-developed slaty cleavage which affects the muddy beds, exhibits a large refraction at the sandy beds interface. In these beds, cleavage becomes of fracture type and the sedimentary fabric appears to remain unaffected by the tectonic strain. At each site, a mean strain tensor has been estimated by measuring in the field the orientation and axial ratios of elliptical green reduction spots and little quartz pebbles, on natural fracture planes as close as possible to the principal strain planes. It is to be noted that when both strain markers are present in the same measurement plane, their mean axial ratios are, on the average, identical. From the measurements on at least two sets of perpendicular strain planes, and assuming no volume change (i.e. \( \lambda_1\lambda_2\lambda_3 = 1 \)), the principal strains \( \lambda \), and related strain parameters are computed. The results are listed in Table 1 and shown in Fig. 3.

In the slates, the ellipsoids are flattened in the cleavage plane, with the maximum elongation axis \( \lambda_1 \) parallel to the stretching lineation which has, on the average, a 90° pitch in the cleavage. The ellipsoids are triaxial, with a shape parameter \( K [19] \) lower than 1, and intensities \( r [20] \) ranging from 1.9 to 3.7. In contrast, the sandstone bed of site B shows oblate ellipsoids (\( \lambda_1 = \lambda_2 > \lambda_3 \)), flattened in the bedding, which underline the preserved sedimentary fabric. The shape and orientation of elliptical reduction spots as well as the non-penetrative fracture-type cleavage, show that these sandy beds can be regarded as tectonically unstrained and that only the compaction is responsible for the shape of the reduction spots.

A very important observation arises from these results: one can note that strain intensities and ellipsoid shapes show variations with the site location in the southern (A, C) or northern (D, E, F)
TABLE 1
Mean structural data for the sites of the Somport area

<table>
<thead>
<tr>
<th>Site</th>
<th>$S_o$</th>
<th>$S_t$</th>
<th>$a$</th>
<th>$X$</th>
<th>$\lambda_1$</th>
<th>$\lambda_2$</th>
<th>$\lambda_3$</th>
<th>$K$</th>
<th>$r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>160</td>
<td>287</td>
<td>110</td>
<td>17</td>
<td>66</td>
<td>1.395</td>
<td>0.670</td>
<td>0.558</td>
<td>1.9</td>
</tr>
<tr>
<td>B</td>
<td>297</td>
<td>277</td>
<td>49</td>
<td>4</td>
<td>51</td>
<td>1.678</td>
<td>0.533</td>
<td>0.464</td>
<td>2.6</td>
</tr>
<tr>
<td>C</td>
<td>166</td>
<td>292</td>
<td>95</td>
<td>22</td>
<td>70</td>
<td>1.633</td>
<td>0.609</td>
<td>0.886</td>
<td>2.3</td>
</tr>
<tr>
<td>D</td>
<td>254</td>
<td>274</td>
<td>33</td>
<td>4</td>
<td>51</td>
<td>1.715</td>
<td>0.408</td>
<td>0.145</td>
<td>3.7</td>
</tr>
<tr>
<td>E</td>
<td>274</td>
<td>282</td>
<td>62</td>
<td>12</td>
<td>62</td>
<td>1.890</td>
<td>0.421</td>
<td>0.369</td>
<td>3.5</td>
</tr>
<tr>
<td>F</td>
<td>278</td>
<td>277</td>
<td>52</td>
<td>27</td>
<td>52</td>
<td>1.809</td>
<td>0.421</td>
<td>0.369</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Notes: $S_o$ and $S_t$ are the bedding and cleavage planes; their orientations are defined by strike and dip. $a$ is the angle between pole to cleavage and pole to bedding. The orientation of the principal elongation axis $X$ is defined by $D$ (declination) and $I$ (inclination). $\lambda_1$, $\lambda_2$, $\lambda_3$ are the eigenvalues of the strain tensor, with $\lambda_1 > \lambda_2 > \lambda_3 > 1$. $K$ and $r$ describe the shape [19] and intensity [20] of the strain ellipsoid.

limb of the fold. More precisely, the lower the angle between pole to cleavage and pole to bedding, the greater the strain intensity and the lower the shape parameter (Table 1). In other words, when compaction and tectonic shortening axes are close to each other, the total strain ellipsoid recorded by the elliptical markers are more flattened, and with a greater intensity, than when this angle is higher. It is thus inferred that the strain measured in the field results from the superimposition of the tectonic strain upon a noticeable compactional fabric. It will be shown that recovering the tectonic part of total strain is a critical point in order to remove its effects upon pre-tectonic remanent magnetization.

4. Paleomagnetic analysis

All the magnetic measurements have been done with a computer-assisted Schonstedt DSM-1 spinner magnetometer of sensitivity $10^{-9}$ A m$^{-2}$. Progressive IRM acquisition experiments were done with a Brucker BE-10 electromagnet (maximum field 1.25 T). A Schonstedt TSD-1 non-magnetic furnace was used for thermal demagnetization procedures. Chemical demagnetizations were carried out following the classical procedures [21, 22]: samples immerged in HCl in individual closed recipients were prepared by drilling a 1 cm diameter hole in order to increase the leaching surface, and let in a field-free space during increasing time steps. This was performed at room temperature and required a total leaching time ranging from 500 to 1000 hours.

The 127 specimens of this study were submitted to a short-period viscosity test [23]. 94% have a viscosity coefficient lower than the 20% value we have chosen as the maximum allowed for our paleomagnetic investigations. The NRM intensities are rather low, ranging from $10^{-3}$ to $10^{-1}$ A m$^{-1}$. The NRM directions are widely scattered. The density plots of the in-situ directions (Fig. 4, up) reveal a bipolar distribution, with one northerly steeply dipping maximum and one subhorizontal southeast maximum. Tilt-correcting these directions (Fig. 4, down) induces a scattering of
the first group, that can thus be thought to be post-tectonic remagnetizations. On the other hand, this does not improve the SE directions distribution, although they can be thought to be characteristic of the Iberian Permian paleomagnetic direction, and therefore, antetectonic in age. We can thus suspect both effects of remagnetization, and of strain upon the pre-tectonic magnetization directions.

Both thermal and chemical stepwise demagnetization techniques were used as an attempt to separate the contributions of the two groups of magnetization. 80 specimens were demagnetized thermally and 36 specimens by hydrochloric acid leaching. The NRM evolution during demagnetization can be summarized site by site as follows:

- All the specimens of the sandy bed of site B exhibit linear demagnetization paths in the Zijderveld [24] diagrams (Fig. 5a) in thermal as well as in chemical demagnetization. The unblocking temperatures are high, near the Curie point of hematite (Fig. 5a, left). This reveals a single magnetization component, whose southeasterly striking is characteristic of the Iberian Permian paleomagnetic direction.

- In sites A and F (Fig. 5b), a north to north-easterly steeply dipping component predominates. Although in some cases, the demagnetization curves do not converge towards the origin (see, for example, Fig. 5b specimen PA 07), they suggest a nearly total overprinting of the pre-tectonic magnetization by a secondary magnetization component. Such directions appear consistent with the Cretaceous and Lower Tertiary remagnetizations as described by Schott [17] through the whole Pyrenean chain.

- In the three other sites (C, D, E; Fig. 5c), the demagnetization curves clearly show the presence of at least these two components. Thermal demagnetization was the most successful mean of separating them (Fig. 5c, specimen PE 50A). However, the least stable component has unblocking temperatures as high as 600°C, sometimes higher, which may partially overlap the high unblocking temperature spectra of the hardest component. This results in some cases in an incomplete separation of the components, as can be seen in Fig. 5c, specimen PE 49A. In most cases, the chemical demagnetization by acid leaching did not allow a good separation of the components (Fig. 5c, specimen PC 23B). This kind of situation could arise either from a bad penetration of HCl into the specimen, or from identical magnetic carriers for both magnetization components.

Isothermal remanent magnetization (IRM) acquisition experiments were performed on pairs of leached and unleached specimens from the same core. The curves obtained (Fig. 6) are typical of red series, with the predominance of high coercivities in the fresh specimen, which are thought to be characteristic of the ultrafine red hematite pigment [25]. After acid leaching, this phase tends to disappear, and a lower coercivity phase (0.1 0.3 T) remains, which seems to be unaffected by leaching in HCl. The low coercivities could be due either to magnetite or to large specularite hematite. However, the comparison of the magnetization intensities acquired at 1.25 T, shows that the dissolved phase, the pigment, bears more than 98% of the IRM acquired by the fresh specimens. Since a similar NRM percentage is carried by the
dissolved phase (Fig. 5), it is thought that the lower coercivity phase has probably a negligible contribution to the total NRM of these rocks.

From these experiments, as well as from the similarities between chemical and thermal demagnetization curves, it is thus inferred that NRM is predominantly carried by a single magnetic mineral, the red hematite pigment. This explains the difficulties encountered in separating NRM components which show a nearly to complete overlapping of both unblocking temperature and solubility spectra.

5. Results of the paleomagnetic analysis

From the above comments, it appears that the straight portions of demagnetization curves in Zijderveld [24] diagrams are not necessarily well resolved single NRM components, and that there exists a real possibility of measuring the vectorial sum of two components simultaneously demagnetized. It is therefore unappropriate to classify the isolated components in groups depending upon their unblocking temperature ranges or solubility spectra, and to treat them following the classical Fisher [26] analysis. Another reason to avoid the Fisher's statistics is that the strain can disperse data initially clustered, and a population can loose its Fisherian distribution. A classical Fisherian analysis could lead to reject some data which show anomalous direction, although the anomaly itself is significant with respects to the strain. In the present study, this is complicated by the fact that magnetization components are suspected to be poorly separated, and it was often impossible to decide if one component direction resulted from a strain-induced deviation or from a partial overprint, or a composition of both effects. Therefore, in order to avoid an a-priori interpretation of the components, we have preferred to define, whenever possible, a characteristic remanent magnetization (ChRM) as the last component in the demagnetization curves. The ChRM are then interpreted, not on a site-by-site basis, but all together in the same projections. It is assumed that if the whole strain removal technique is valid, only the part of pre-tectonic directions should cluster, all the other directions (secondary and overprinted components) should be dispersed by the treatment. To have a better vision of the distributions of points, density plots of these directions are used. From the 116 demagnetized specimens, 38 were rejected, since it was not possible to determine a stable ChRM component. The following analysis is thus done on 78 magnetization directions.

The density plots of the ChRM directions are shown in Fig. 7, as in-situ (up) and tilt corrected
Fig. 7. Density plots of the 78 ChRM directions isolated by demagnetization. Upper: in-situ (IS); lower: tilt-corrected (TC); left: lower hemisphere (LH); right: upper hemisphere (UH). Same contours and projections as in Fig. 3. In the upper left projection, star is the normal present-day dipole field direction, open triangle is the mean strain λ1 axis of the five slates sites.

(down). The in-situ directions show a large scatter which draws approximately a great circle containing the present-day dipole field axis. A first group of data clusters near the normal dipole field direction, as shown by a submaximum of density. The tilt correction using the classical procedure as described by Graham [2], disperses the data of this first group (Fig. 7, down), which are thus inferred to be post-tectonic in age. Furthermore, one can note that, in the in-situ projection, the maximum of this first group is slightly deviated from the dipole towards the λ1-axis of the strain (see Fig. 7). This could illustrate the effect of anisotropy due to the cleavage development upon the post-tectonic magnetization acquisition.

At the other end of the girdle drawn in the in-situ projections (Fig. 7, up) by intermediate (probably unresolved) magnetization directions, a more important group of directions shows south-easterly declinations, with shallow, negative and positive inclinations. The classical tilt correction does not induce any significant improvement in the distribution of this population, and submaxima which are observable in-situ, remain scattered after this procedure. However, such declinations and inclinations are only compatible with Permian paleomagnetic directions known for the Iberian plate, and therefore should be pre-tectonic in age. The absence of effects of tilt correction could be partly explained by the fact that the fold axis trends subhorizontal in an ESE direction, that is, close to the remanent magnetization directions. Nevertheless, even in this case, unfolding should appreciably cluster pre-tectonic magnetization directions if they are dispersed by rigid rotations only.

As in the case of the Alpes Maritimes redbeds, where a similar situation was described [8], the strain is inferred to be responsible for the failure of the fold test. A further observation may be done about the remanent magnetization declinations. As a matter of fact, if the magnetization were Permian, it should present a declination around 160°. But we observe that remanent magnetization declinations trend 120–140°, as well in-situ as tilt corrected, that is between the expected declination (160°) and the cleavage plane direction (100–110°). This is in good agreement with the expected behavior of remanent magnetization vectors in such strained rocks [10].

6. Strain removal

Here as in the case of the Alpes Maritimes redbeds, an attempt has been made to correct the magnetization vectors using the inverse strain tensor determined from field measurements. Assuming that both ChRM vectors and bedding plane closely follow the material lines and planes strain response model of March [1], strain removal is done in two steps [8]. First, each ChRM direction is corrected by using the inverse strain tensor of the relevant site. On the other hand, the bedding plane tilt, as observed in the field is decomposed into two parts, a rigid-body rotation, and a strain-induced rotation; the strain is therefore removed from the bedding plane in a similar way. The strain removal of the paleomagnetic vectors is then achieved by a tilt correction using the unstrained bedding plane. Some remarks must be done about this treatment. First, the final orientation of a material line within a homogeneously strained volume does not depend upon the strain history, but only upon the initial orientation of the line and the finite strain tensor. Therefore the
folding style does not interfere with the strain removal technique, providing that corrections are made at a scale where strain is homogeneous, and that the total strain itself is accurately determined. This accuracy is limited by the fact that the treatment is made at the site scale, in a discrete manner. In particular, the rigid-body rotation within a site, which is estimated from the tilt of the undeformed bedding plane, is not fully constrained for the rotations about vertical axes. To summarize, we can say that, compared to an ideal undeforming method, the strain removal applied here is of the same simplifying level as the classical tilt correction of Graham [2] with respect to more elaborated unfolding methods [3–5] taking into account the fold geometry.

Results of this treatment are shown in Fig. 8, where the density plots are drawn in vertical E-W projections for a better visualization, since the changes in the distributions of points are expected to be around the horizontal plane. For comparison, Fig. 8a shows the tilt corrected directions as in Fig. 7 (lower). The strain removal technique, applied by using the strain tensor directly determined from the elliptical markers measurements in the field, leads to the results of Fig. 8b. It is clear from this figure, that the treatment does not bring any improvement in the dispersion of the ChRM’s. Thus, in a first approach, this could be interpreted as a failure of the procedure. However, a more careful analysis of the dispersion of Fig. 8b has shown that the southernmost directions belong to the northern limb sites of the studied fold, and the easternmost directions to the southern limb sites. And, whereas the first group seems to be overcorrected, the latter is undercorrected. Two main reasons for this situation can be evoked: (a) a bad estimation of the rigid body rotation part of the total deformation, in particular, as it was noted above, of the rotations about vertical axes, which are not recovered by the unstraining method we propose; (b) a bad estimation of the tectonic strain which induces the ChRM deflections. This last hypothesis is corroborated by the remarks we made about the strain distribution within the fold limbs: it has been shown that there is a relation between the total strain intensity (greater in the northern limb than in the southern one) and the angle between \( \lambda_3 \) and the pole to bedding in each site. This has been interpreted as resulting from the superimposition of the tectonic strain upon a noticeable compactional fabric. Since ChRM is carried by ultrafine pigment which is generally believed to form in-situ, during or after diagenesis [27], it can be thought that the time of primary magnetization acquisition is situated between the two main strain events of compaction and deformation. On the other hand, reduction spots appear to have recorded both events. Therefore an estimation of the tectonic part of the total strain tensor has been made by removing its compactional part.

Formally, if we express the total strain tensor \( S \) (determined from elliptical markers measurements in the field) as:

\[
S = T \cdot C
\]

where \( T \) is the tectonic strain tensor, and \( C \) the compaction tensor, we estimate \( T \) as

\[
T = S \cdot C^{-1}
\]

then \( T \) is used to correct ChRM, as described above. In each site, the tensor \( C \) has been constructed with eigenvalue ratios \( \lambda_1/\lambda_2 = 1 \) and \( \lambda_2/\lambda_3 = 2 \), the order of magnitude of eigenvalue ratios of site B, with the compaction direction...
normal to the bedding plane.

Another problem is to improve the corrections applied to site B data. As described, the sandy bed does not show any internal deformation induced by the folding of the rock unit. Therefore, ChRM directions have not been changed with respect to the bedding reference frame and in the previous treatment, site B data were only corrected by a simple tilt correction. However, in all the other sites, bedding tilt was always measured at sandy and pelitic beds interface as it was for the site B. The bedding plane of site B can thus be considered as a passive material plane, like in the other sites, and its actual attitude, as resulting from a rigid body rotation and a rotation induced by the strain of the plastically deforming pelitic matrix in which it is embedded. In order to remove this strain induced rotation an estimated strain tensor was constructed at this place by averaging the nearly homogeneous strain data (intensity and direction; see Fig. 3) of sites A and C which are the nearest to site B. Then the rigid body inverse rotation was done by a classical tilt correction, by using the undeformed bedding plane tilt, as in the other sites. During these rotations, ChRM directions remain fixed within the bedding reference frame.

The results obtained by correcting ChRM directions using the estimated tensor T are illustrated in Fig. 8c. It is clear from this figure that the paleomagnetic directions cluster to form a single density maximum. It is thus inferred that the most significant part of the dispersion observed in Fig. 8b was actually induced by a bad estimation of the tectonic strain in each site, and the insufficiency of a simple tilt correction for site B data.

The density contours of the maximum in Fig. 8c show that these directions have a nearly Fisherian distribution. We can thus calculate their mean direction and compare it with the mean of the same specimen directions in the in-situ and simply corrected situations. We obtain:

in-situ:
\[
D_m = 140.0° \quad I_m = -2.5° \\
N = 50 \quad k = 12
\]
tilt-corrected:
\[
D_m = 142.0° \quad I_m = 7.5° \\
N = 50 \quad k = 12
\]
undeformed:
\[
D_m = 157.5° \quad I_m = 1.5° \\
k = 28 \quad \alpha_{5%} = 4° \quad N = 50
\]

These results can be summarized as follows: (a) there is no change in grouping induced by tilt correction; (b) tilt corrected data strike too much to the east with regards to the known Iberian Permian paleomagnetic directions; (c) the removal of tectonic strain induces a clustering of directions. The computation of the relevant VGP's gives:

tilt-corrected: 226.5° E, 32.0° N
undeformed: 210.5° E, 42.0° N

As a final control on the recovered paleomagnetic direction, these VGP's are compared with the available apparent polar wander path (APWP) of the Iberian plate from the Upper Carboniferous to the Lower Jurassic (after the compilation by Schott [17]) (Fig. 9). The VGP calculated after the classically tilt corrected data is broadly away from this APWP. In contrast, the undeformed ChRM directions give a VGP which appears compatible with the Lower Permian published results. Overall, the strain removal technique not only improves the clustering of the paleomagnetic mean direction at the formation scale (which could have been interpreted as being only a computing effect), but also allows us to obtain results of geodynamic significance.

7. Summary and conclusion

The analysis of the results obtained by structural and paleomagnetic studies on 6 sites distributed in both limbs of the fold shows that at least two magnetization components are carried by the red hematite pigment. The recovering of primary pre-tectonic magnetization by the mean of demagnetization techniques has been difficult, due to the large remagnetization of these rocks, probably when or shortly after the Carboniferous deformation occurred. However, the characteristic remnant magnetization directions distribution has been globally interpreted by analysing their density path. This shows a grouping of ChRM's towards SE directions, which can be a-priori thought to be Permian, and therefore pre-tectonic in age. The effect of strain upon these directions is two-
fold: first, they show a non-positive fold test, mainly due to a significant scatter of the directions in inclination, after tilt correction. This strain-induced change in angular relationships between magnetization and bedding has already been described in previous studies in such red beds. Secondly, ChRM declinations appear deviated towards the east by a significant amount of about 20-40°. This is in good agreement with expected sense and amount of magnetization deviations, when the initial angle between the pre- tectonic magnetization and the strain shortening axis is in the range of 40-50°. Although the relationships between strain and deviated magnetization directions are less precise and less well documented than in the Alpes Maritimes red beds, it has been assumed that global behaviour of remanent magnetization closely approaches the material line strain response model of March [1], as it has been shown in other natural series [8] and in analogic simulations [28], as well as numerical ones [10].

We therefore decided to use the strain removal technique we previously proposed [29,30], in order to test the hypothesis of a passive line behaviour of remanent magnetization vectors. Applied to the paleomagnetic directions of this study, this technique did not bring an improvement in the vectors distribution, when using the strain tensors directly derived from the elliptical markers measurements. Nevertheless, it has been shown that the observed anomalies in the corrected directions can be explained by a bad estimation of the actual tectonic strain undergone by each site. The strain tensors have thus been corrected from a compactional part estimated from the measurements of site B elliptical reduction spots.

The strain removal, using these corrected tensors, induces a clustering of the paleomagnetic directions. Although they can appear as somewhat complicated, the proposed improvements do not question the basic hypothesis of a nearly material line behaviour of ChRM. However, they put forward the need of an extreme care in analysing the deformation and paleomagnetic vectors relationships. The recovered mean paleomagnetic direction then gives a VGP which well fits the Permian part of the Iberian APWP. It is thus concluded that the strain removal technique has proven helpful in recovering a mean pre-tectonic direction of magnetization in a series which has suffered a significant strain, and where the structural corrections classically used in mountain belts should have given a non positive fold test and, without other controls, false geodynamic results. It is therefore argued that paleomagnetic studies are possible within strained regions, under the condition of a careful analysis of strain, NRM components and directions, and their interrelationships. Although the limitations of the method are not currently known, such results, if verified on other examples, should open new fields of paleomagnetic investigations within strained regions of orogenic belts.

References

5 N. Bonhomme, P.R. Cobbold, H. Perroud and A. Richardson, Paleomagnetism and cross-folding in a key area of the Asturian Arc (Spain), J. Geophys. Res. 86, 1873–1887, 1981.