Paleomagnetism and magnetic fabric of the deformed redbeds of the Cap de la Chèvre formation, Brittany, France

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ABSTRACT


We present the results of a palaeomagnetism and magnetic fabric study in six sampling sites of the lower Ordovician redbeds of the Cap de la Chèvre formation, Crozon Peninsula, France. Measurement of anisotropy of magnetic susceptibility (AMS) shows that these beds are affected by a weak but significant tectonic strain during the Hercynian folding of the Armorican Palaeozoic cover. Samples containing small elliptical reduction spots allowed us to check the control of strain on AMS. Site mean AMS data were then used to provide strain estimates at each site. Analysis of remanent magnetization through thermal and chemical stepwise demagnetization procedures allowed us to isolate three magnetic components. Component A, defined in the lower unblocking range, is a recent overprinting which clusters around the present-day dipole field direction. Components B and C, defined respectively in the intermediate and higher unblocking temperature ranges, appear to be pre-tectonic in age. The fold test, however, is inconclusive for both, because of the significant dispersion still remaining after the simple tilt correction. Assuming that at least a part of this dispersion is due to strain, we have applied the strain removal technique using AMS-derived strains at each site. This results in a clustering of component C from four sites, allowing recovery of the primary Ordovician paleomagnetic direction (D = 261°, I = 71°, α95 = 11°). In contrast, unstrained component B shows a small circle distribution, containing the formation mean of unstrained component C. The hypothesis that component B and C distributions arise from beds being tilted during a long-term magnetization acquisition in the Ordovician field is discussed, taking into account the extensional geodynamic context during deposition of lower Palaeozoic redbeds in Brittany.

1. Introduction

Palaeomagnetic studies of geological units from orogenic zones classically come up against problems of magnetic memory stability, arising from physical and chemical events taking place during mountain building processes. These problems can be set into two main groups. The first group deals with the problems of magnetic memory resetting under thermal or alteration conditions, leading to partial or total remagnetizations. All the techniques (stepwise demagnetizations and components analysis, rock magnetism experiments, etc.) and tests (fold test, contact test, conglomerate test) that have been developed and improved during the last two decades, generally provide arguments on the nature, origin, age and carriers of natural remanent magnetization (NRM) of a given rock formation.

A second kind of magnetization instability is the result of deformation, in a large sense, and particularly of the deviating effects of folding processes in orogenic zones. Until now, structural corrections of palaeomagnetic directions have relied on the classical bedding tilt correction (Graham, 1949). The comparison of vector distribu-
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This correction allows a test of pre-, syn-, or post-tectonic age of magnetization. However, this correction has proved inadequate when working within the interior of orogenic belts, where strain processes may be important during folding of sedimentary units. In effect, when a plastic deformation occurs, preferred orientations of platey minerals are developed by mechanisms such as grain deformation, dynamic recrystallization, or grain rotation. When such a mechanism of mineral rotation affects magnetic carriers (e.g. Cogné and Gapais, 1986), it does not change the magnetic memory of each grain. The pre-tectonic remanent magnetization at the measurable scale, however, will be rotated within the bedding reference frame, thus resulting in anomalous paleomagnetic vector populations with respect to the classical tilt correction. In order to characterize some aspects of these strain effects, several studies have recently been conducted either by numerical and analogical simulations (e.g. Cogné et al., 1986; Anson and Kodama, 1987; Cogné, 1987a; Van Der Pluijm, 1987; Kodama, 1988) or through paleomagnetic studies of deformed redbeds (Kligfield et al., 1981, 1983; Cogné and Perroud, 1985; Hirt et al., 1986; Cogné, 1987b, 1988).

We present here the results of a study of anisotropy of magnetic susceptibility and palaeomagnetism of an Ordovician redbed formation from the Armorican Massif, W. France. The aims of this work are (1) to provide a further example of paleomagnetic properties of deformed redbeds, and (2) to check the usefulness of the strain removal technique proposed by Cogné and Perroud (1985) in order to correct palaeomagnetic vectors for strain-induced deviations.

2. Geological setting and sampling sites

The Ordovician redbeds of the Cap de la Chèvre formation are situated in the western central part of the Armorican Massif (Fig. 1; mean position: 48.2° N, 4.5° W). This formation is one of coarse redbeds (conglomerates, sandstones and siltstones)
that marks the beginning of the Palaeozoic sedimentation in the Armorican Massif during Arenigian (middle Ordovician) times. They rest disconformably on a basement of fine-grained metasediments classically attributed to the Brioverian (Upper Proterozoic) (Cogné, 1962). They are conformably overlain by the Grès Armoricain formation which has been given a palaeontologically based age of Middle Arenigian (Paris and Skevington, 1979). A 465 ± 1 Ma age has been obtained by Bonjour et al. (1988), by U–Pb zircon dating of interbedded volcanoclastic rocks within the Cap de la Chèvre formation. Recent studies by Ballard et al. (1986) and Brun et al. (1991) have shown that redbed formations of Central Brittany were probably deposited during an Ordovician extensional event on series of Brioverian tilted blocks. This point is very important, as we shall discuss later, because initial deposition of redbeds may have taken place on non-horizontal planes.

Both Brioverian and Palaeozoic rocks have undergone one single phase of folding during the Carboniferous (Le Corre, 1978), associated with dextral wrenching at the crustal scale (Gapais and Le Corre, 1980; Percevault and Cobbold, 1982). For the Cap de la Chèvre formation, this results in a northwesterly dipping monoclinal structure, bounding the southern flank of the Chateaulin Synclinorium (Fig. 1).

After the preliminary results obtained by Duff (1979), paleomagnetic investigations have been conducted on several Ordovician formations in the Armorican Massif: the intrusive Thouars Massif (Perroud and Van der Voo, 1985), some dolerite sills of the Crozon Peninsula (Perroud et al., 1983), the Moulin de Chateaupanne redbed formation (Perroud et al., 1986), the Pont-Réan redbed formation (Cogné et al., 1986; Cogné, 1988). The above are lateral equivalents of the Cap de la Chèvre formation. All these formations reveal a highly inclined primary magnetization component, characteristic of the Ordovician magnetic field in the Armorican Massif (Perroud, 1985).

Seventy cores (25 mm in diameter, 50 to 100 mm long) were drilled and oriented in situ at six sites distributed in the two main outcrops of the formation (Fig. 1); four in the western outcrop (C1, C2, C4, C5), and two in the eastern outcrop (C3, C6). The structure is monoclinal, with all the beds dipping northwesterly. The bedding planes of the western sites dip with 10–30°, whereas sites from the eastern outcrop dip with 50–60°. This should allow a pre-tectonic magnetization component, if present, to cluster upon unfolding.

### 3. Strain and magnetic fabric

The Hercynian folding of Palaeozoic cover in Central Brittany generally induces the development of a penetrative axial planar cleavage. In contrast, the Cap de la Chèvre formation does not clearly exhibit such a penetrative deformation. However, a rough cleavage plane was observed in sites C1, C2 and C6, which are more pelitic than sites C3, C4 and C5. Unlike in other redbed formations, conventional strain markers have not been found at the sites. Such markers enable an estimate of the amount of internal deformation. Two hand-samples containing millimetric reduction spots (e.g. Graham, 1978; Kligfield et al., 1981; Cogné, 1988) were, however, collected at an outcrop near site C3. As we shall see later, they were used to control the strain estimates.

Because of the lack of strain indicators, we attempted to check for the deformation state in these beds by measuring the anisotropy of magnetic susceptibility (AMS). Measurements were made on standard palaeomagnetic specimens (21 mm long, 25 mm in diameter) using the Digico Anisotropy Delineator at Rennes. Experimental procedures and statistical processing of the data (Jelinek, 1978) have already been described (Cogné, 1988).

Site mean AMS and structural data are given in Table 1. Anisotropy values are illustrated in a Flinn (1965) diagram on Fig. 2. One can see that AMS is very low, with susceptibility ratios generally lower than 1.05. However, the most significant fact is that the points are distributed on the line separating oblate and prolate fields of the diagram, and not along the axis $k_2/k_3$ (pure oblate shape), which would be the case if AMS was of compaction or sedimentary origin (e.g. Hrouda, 1982). Directions of principal susceptibilities are shown, after bedding tilt correction, in the
weak but significant tectonic strain within these beds.

4. Palaeomagnetic analysis

4.1. Natural remanent magnetization (NRM)

NRM directions are shown in the density plots of Fig. 4. In the in situ projection they show a roughly great-circle distribution from the present-day field direction towards slightly inclined southerly directions, and through to highly inclined SW directions. The bedding tilt correction (Graham, 1949) does not cluster the data. NRM intensities range from 0.001 to 0.01 Am\(^{-1}\) which, although weak, allow the analysis of magnetization components through demagnetization procedures, and measurements with the Schonstedt DSM-1 spinner magnetometer.

4.2. Demagnetizations

Most of the specimens (61 out of 94) have been treated by stepwise thermal demagnetization, using a Schonstedt TSD-1 oven system, while chemical demagnetization by hydrochloric acid leaching has been used for few of them (13). Magnetic vector behaviour has been analyzed through the vector end-point orthogonal projection technique (Zijderveld, 1967).

### Table 1

Mean-site structural and anisotropy of magnetic susceptibility (AMS) data in the Cap de la Chèvre formation

<table>
<thead>
<tr>
<th>Site</th>
<th>S(_b)/Di</th>
<th>Pole to S(_d)</th>
<th>(k_1)</th>
<th>(k_3)</th>
<th>Bulk ((\times 10^{-3} \text{ Sl}))</th>
<th>(N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>191/13</td>
<td>341/48</td>
<td>1.019</td>
<td>0.979</td>
<td>0.136</td>
<td>15</td>
</tr>
<tr>
<td>C2</td>
<td>218/29</td>
<td>310/44</td>
<td>1.032</td>
<td>0.965</td>
<td>0.1444</td>
<td>11</td>
</tr>
<tr>
<td>C3</td>
<td>249/58</td>
<td></td>
<td>1.035</td>
<td>0.970</td>
<td>0.1230</td>
<td>15</td>
</tr>
<tr>
<td>C4</td>
<td>203/28</td>
<td></td>
<td>1.024</td>
<td>0.973</td>
<td>0.2106</td>
<td>29</td>
</tr>
<tr>
<td>C5</td>
<td>250/27</td>
<td></td>
<td>1.010</td>
<td>0.991</td>
<td>0.1239</td>
<td>8</td>
</tr>
<tr>
<td>C6</td>
<td>255/63</td>
<td>321/31</td>
<td>1.031</td>
<td>0.974</td>
<td>0.0814</td>
<td>16</td>
</tr>
</tbody>
</table>

\(S_b\), S\(_d\)/Di, strike/dip of bedding plane; S\(_d\), D/I, declination/inclination of the unit normal to cleavage; \(k_1\), \(k_3\), maximum and minimum mean susceptibilities, normalized to \((k_1 + k_2 + k_3)/3\) (see Jelinek, 1978; Cogné, 1988); Int, D/I, normalized intensity, declination/inclination; Bulk, bulk susceptibility computed as \((k_1 + k_2 + k_3)/3\) of the unnormalized mean tensor; \(N\), number of specimens measured. \(k_2\) is not given, but it is orthogonal to \(k_1k_3\) plane, and its normalized intensity can be computed as \(k_2 = 3 - (k_1 + k_3)\).
Three magnetization components, A, B and C, have been defined in thermal demagnetizations. Typical examples of orthogonal plots for thermal treatment are shown in Fig. 5.

Component A is defined by low unblocking temperatures, lower than 300°C (Fig. 5, C4–52, C6–63a). It has northerly declination, and high positive inclination. Owing to a probable overlapping of unblocking temperature spectra, the complete separation of component A from the following is not always achieved. This can be seen in Fig. 5, specimen C6–64.

Component B is unblocked in the 300–630°C temperature range (Fig. 5). It has southwesterly declinations and positive intermediate inclinations.

Component C is isolated at the end of thermal demagnetizations, in the temperature range 600–670°C, which is close to the Curie point of haematite. As can be seen on the diagrams of Fig. 5, the direction of this component is very close to that of component B. It also has a south-southwest declination and a positive intermediate inclination. Here too, problems caused by overlap-

![Fig. 3. Equal-area density plots of tilt corrected susceptibility directions in the Cap de la Chèvre formation: $k_1$, maximum; $k_2$, intermediate; and $k_3$, minimum susceptibility.](image)
Fig. 4. Equal-area density plots of (a) in situ and (b) tilt corrected natural remanent magnetization directions.

Fig. 5. (a)–(d). Orthogonal projections of magnetic vector and end-points for four samples obtained by thermal demagnetization. Closed (open) symbols: projection onto the horizontal (vertical) plane. Temperature steps are indicated in °C.

The results of chemical demagnetizations were difficult to interpret because of the frequent overlapping of different components, and also because of the problem of non-uniform leaching of the samples. However, where the results are clear, they tend to indicate that B and C demagnetize in a reverse order with respect to thermal demagnetization. This is illustrated in Fig. 6. The orthogonal plots of Fig. 6(a) show that thermal demagnetization of specimen C3–35b isolates first a horizontal component and then an inclined component, both trending south. Although incomplete, the chemical demagnetization of specimen C3–35a of the same core first isolates the inclined component. The curve does not converge towards the origin, but rather towards lower inclinations. Another example is given in Fig. 6(b). In Fig. 6(b), right, the component B is highly inclined at the beginning of the thermal demagnetization; during progressive demagnetization, the magnetic direction progressively converges towards the shallower component C. The chemical demagnetization shows exactly a reverse order with first a deviation towards shallower inclination and then an evolution towards the higher inclined component B at the end of
Fig. 6. Comparison of thermal and chemical demagnetization results. (a) Orthogonal projections; same conventions as in Fig. 5. (b) Equal-area projections of magnetic vector evolution during demagnetizations. All the points are projected onto the lower hemisphere. Open symbols; chemical demagnetizations (Ch.); closed symbols, thermal demagnetizations (Th.); arrows indicate the sense of evolution with increasing temperature or leaching time.

Fig. 7. Isothermal remanent magnetization (IRM) acquisition curves for a non-leached (a) and a leached (b) specimen of the core C4-041. Bar diagrams: coercivity spectra indicating the percentage of total IRM acquired by 0.1 T steps.
Fig. 8. Equal-area projections of magnetic components isolated through thermal demagnetizations. Left, in situ; right, tilt corrected. (a) and (b), specimen component A; (c) and (d), site mean component B with 95% confidence intervals; (e) and (f), site mean component C. In (c)–(f), stars are for sites from the western outcrop (C1, C2, C4, C5), circles and dotted 95% confidence circles for sites of the eastern outcrop (C3, C6). Closed (open) symbols: projection onto the lower (upper) hemisphere.
demagnetization. This can also be seen in Fig. 6(b), left, where the end of thermal and chemical demagnetizations diverge. These observations suggest that component C demagnetizes first in chemical demagnetization, whereas B is the hardest one with respect to acid leaching.

Isothermal remanent magnetization (IRM) acquisition on couples of leached and unleached specimens has been done. Typical IRM acquisition curves are given in Fig. 7. They show that for fields up to 1.2 T, saturation is reached neither for the fresh specimen (Fig. 7(a)) nor for the leached specimen (Fig. 7(b)). The IRM coercivity spectra show a maximum at 0.2–0.3 T, which is typical for haematite (Dunlop, 1972) or iron hydroxides such as goethite. One can further note that this maximum is displaced towards lower fields after acid leaching, suggesting that carriers with the higher coercivity are removed by leaching. This together with the disappearance of the red coloration during chemical leaching, suggests that the beginnings of chemical demagnetization curves should display information about the magnetic components carried by ultrafine haematite (pigment).

The comparison of thermal and chemical demagnetizations, together with the results of IRM acquisition experiments, suggest that B and C are carried only by haematite: in coarse grains (specularite) for component B, and in finer grains (pigment) for component C. For component A, its low unblocking temperature range indicates that it is carried by hydroxides such as goethite.

Finally, owing to the bad separation of components, the results of the chemical demagnetizations have not been used in the following analysis of component directions.

4.3. Results

Component A. In situ specimen directions clearly cluster around the present-day field direction (Fig. 8(a)) and are scattered by the classical tilt correction (Fig. 8(b)). This scattering is significant at the 95% probability level (McElhinny, 1964), with the ratio of in situ to tilt corrected Fisher's (1953) $k$ parameters $k_{15}/k_{TC} = 2.27$, $N = 21$. This component is thus interpreted as a recent overprinting of probably weathering origin.

Component B. The within-site consistency of the mean-site directions of component B is not very good (Table 2 and Fig. 8(c)–8(d)). This may be partly owing to a bad separation from other magnetization components during demagnetization. The conventional tilt correction (Graham, 1949) induces a clustering, and a more Fisherian distribution of these directions at the formation scale. However, the $k$ ratio is not high enough for this fold test to be significant at the 95% probability level. Nevertheless, data from sites C3 and C6, from the more dipping beds, clearly join the other group upon unfolding (dotted circles of confidence in Fig. 8(c) and 8(d)). The failure of the fold test could result from the low number of data, and

<table>
<thead>
<tr>
<th>Site</th>
<th>$n/N$</th>
<th>In situ</th>
<th>Tilt corrected</th>
<th>$k$</th>
<th>$\alpha_{95}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$D$</td>
<td>$I$</td>
<td>$D$</td>
<td>$I$</td>
</tr>
<tr>
<td>C1</td>
<td>9/10</td>
<td>244.0</td>
<td>62.5</td>
<td>254.5</td>
<td>51.5</td>
</tr>
<tr>
<td>C2</td>
<td>10/10</td>
<td>225.0</td>
<td>38.0</td>
<td>244.0</td>
<td>29.0</td>
</tr>
<tr>
<td>C3</td>
<td>9/11</td>
<td>195.5</td>
<td>12.0</td>
<td>226.0</td>
<td>50.5</td>
</tr>
<tr>
<td>C4</td>
<td>7/11</td>
<td>243.0</td>
<td>64.0</td>
<td>266.0</td>
<td>41.0</td>
</tr>
<tr>
<td>C5</td>
<td>4/8</td>
<td>210.0</td>
<td>60.0</td>
<td>266.0</td>
<td>66.0</td>
</tr>
<tr>
<td>C6</td>
<td>8/11</td>
<td>200.0</td>
<td>27.0</td>
<td>263.0</td>
<td>59.0</td>
</tr>
<tr>
<td>Mean</td>
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<td>214.5</td>
<td>45.5</td>
<td>252.0</td>
<td>50.5</td>
</tr>
<tr>
<td>$k$</td>
<td></td>
<td>10</td>
<td></td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>$\alpha_{95}$</td>
<td>22</td>
<td></td>
<td></td>
<td>14</td>
<td></td>
</tr>
</tbody>
</table>

$n/N$, number of entries in the statistics/number of treated specimens; $D$, $I$, declination, inclination; $k$, $\alpha_{95}$, parameters of Fisher's (1953) statistics; mean, formation mean computed from the site-mean directions.
the low angle between bedding dip of the sites. However, we consider component B to be pre-
tectonic.

Component C. The small size of the circles of
confidence (Table 3 and Fig. 8(e)–8(f)) show that
this component is better defined at the site scale
than is component B. However, although compo-
nents B and C can be clearly separated by demag-
netization procedures at the specimen scale, the
distributions of B and C magnetizations are very
similar at the rock formation scale. Here, as in the
previous case, the classical tilt correction induces a
clustering of data from sites C3 and C6 with the
others, but the overall dispersion of data remains
high. As in the previous case, it can be assumed
that this component is pre-tectonic, although the
fold test is inconclusive.

Finally the tilt-corrected directions of both
components B and C are roughly consistent with
the known Ordovician magnetic field direction in
the Armorican Massif, which has a high inclina-
tion in a SW direction (Perroud, 1985).

Two main questions arise from the results ob-
tained in this study.

(1) Why are these pre-tectonic magnetization
directions so scattered after the tilt correction?
This is especially crucial for component C, since
its good within-site definition shows that the for-
mation mean dispersion does not result from a
bad separation of components during stepwise
demagnetization.

(2) What is the mechanism responsible for the
acquisition of two pre-tectonic magnetization com-
ponents which, moreover, are so close to each
other that they are not distinguishable at the rock
formation scale?

Taking into account the evidence of internal
deformation provided by AMS results, and the
analysis of strain effects upon pre-tectonic rema-
nent magnetization in redbeds given by Cogné
and Perroud (1987) and Cogné (1988), it can be
suspected that at least a part of the anomalous
dispersion of C magnetization directions arises
from a deviating effect due to strain at each site.
We therefore decided to apply the strain removal
technique as described by Cogné and Perroud
(1985) to both B and C pre-tectonic remanent
magnetizations.

5. Correction of strain-induced deviations of mag-
etization

5.1. Technique of strain removal and strain esti-
mates

The technique is based on the observation that
strain-induced deviations of palaeomagnetic vec-
tors within redbeds are similar to the deviations of
material lines (or 'passive lines'). This allows the
use of the tensor of homogeneous strain de-
termined at each sampling site to correct for these
deviations, as proposed by Cogné et al. (1982) and
discussed by Cogné and Perroud (1985, 1987) and
Lowrie et al. (1986). Briefly, the technique is ap-
plied in two steps: (1) the inverse strain tensor

<table>
<thead>
<tr>
<th>Site</th>
<th>$n/N$</th>
<th>In situ $D$</th>
<th>$I$</th>
<th>Tilt corrected $D$</th>
<th>$I$</th>
<th>$k$</th>
<th>$a_{95}$</th>
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<td>C1</td>
<td>9/10</td>
<td>202.0</td>
<td>53.0</td>
<td>217.0</td>
<td>49.0</td>
<td>42</td>
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</tr>
<tr>
<td>C2</td>
<td>8/10</td>
<td>166.0</td>
<td>47.0</td>
<td>202.5</td>
<td>64.0</td>
<td>34</td>
<td>9.5</td>
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<td>C3</td>
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<td>57.5</td>
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<tr>
<td>C4</td>
<td>10/11</td>
<td>198.0</td>
<td>73.0</td>
<td>259.0</td>
<td>59.0</td>
<td>21</td>
<td>11</td>
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<tr>
<td>C6</td>
<td>9/11</td>
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<td>54.0</td>
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<tr>
<td>$k$</td>
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expressed in the in situ (geographic) reference frame is applied to the magnetic vectors; (2) the bedding plane is also corrected for distorsional strain, by applying the strain tensor to the plane unit-normal and then a tilt correction from this unstrained bedding plane is performed.

The major problem in the present study is that conventional strain markers have not been found at the sites. We therefore attempted to empirically estimate strains from AMS measurements. These estimates are based upon the following assumptions.

(1) Where both strain and AMS tensors can be determined in redbed formations, they generally show identical principal directions (e.g. Kligfield et al., 1981, 1983; Cogné, 1988). Therefore, the direction of $k_3$ is the finite strain shortening ($\lambda_3$) direction, and the direction of $k_1$ is the stretching ($\lambda_1$) direction.

(2) The shape of the ellipsoids of strain and AMS, expressed for example by the Flinn (1965) $K$ parameter, $K = (\lambda_1/\lambda_2 - 1)/(\lambda_2/\lambda_3 - 1)$, are generally similar, and variations of strain intensities give rise to similar variations in AMS intensities. There is, therefore, some correlation between principal strain and principal susceptibility magnitudes. Following Kligfield et al. (1983), we use the linear regression $\epsilon_i = a + b M_i$, ($i = 1, 2, 3$), where $\epsilon_i$ are the natural strains and $M_i = (k_i - k_0)/k_0$ with $k_0 = (k_1 k_2 k_3)^{1/3}$, where $k_i$ are the principal susceptibilities. It is generally recognized that coefficients $a$ and $b$ depend on the lithologies studied (e.g. Borradaile, 1988). However, they may appear similar between different formations having similar lithologies (e.g. Rathore, 1988). Having no other means for estimating strain, we therefore assumed that strain to AMS correlation for the Crozon redbeds is similar to the one determined in the lateral equivalent Pont-Réan formation (Cogné, 1988); the best-fit line over these points is shown.

at each site, and the regression coefficients determined in the Pont-Réan formation.

5.2. Results and discussion

Component C (Fig. 10(a)). Application of the strain removal technique induces a clustering of the site mean component C directions. However, these directions cluster into two groups: one (sites C4 and C5) has northwesterly declination and about 50° downward inclination, and the other (sites C1, C2, C3, and C6) has westerly declination and 70° downward inclination. The formation mean direction, computed for these four sites (Table 4), is consistent with the known Ordovician magnetic field direction in the Armorican Massif (Perroud, 1985), and it is thus assumed to be the
primary magnetization of the Cap de la Chèvre formation. Consequently, the direction of sites C4 and C5 can be considered as anomalous. If we draw a small circle with a horizontal pole (Fig. 10(a)), we see that this pole has a direction similar to the average strike direction of the beds. This means that the observed distribution may result from an inadequate bedding tilt correction. Two reasons may be evoked for this as follows.

(1) We could first think of an under- or an over-correction for strain in sites C4 and C5, especially because strain values have been roughly estimated from AMS. This would imply that strain intensities in both sites are either the lowest or the highest. This is not the case, since from AMS results (Fig. 2) it can be seen that deformation intensities are different in sites C4 and C5. Moreover, the AMS derived strain of site C5 is very weak, and we can see that site mean component C of this site changes very slightly after the application of strain corrections (Tables 3 and 4). This means that strain corrections are not responsible for the anomaly, for this site at least.

(2) The second explanation of the failure of the tilt corrections deals with the admitted assumption that beds are deposited horizontally. It is now well

**TABLE 4**

<table>
<thead>
<tr>
<th>Site</th>
<th>Component B</th>
<th>Component C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D</td>
<td>I</td>
</tr>
<tr>
<td>C1</td>
<td>281.5</td>
<td>50.5</td>
</tr>
<tr>
<td>C2</td>
<td>276.0</td>
<td>30.0</td>
</tr>
<tr>
<td>C3</td>
<td>201.5</td>
<td>63.0</td>
</tr>
<tr>
<td>C4</td>
<td>291.0</td>
<td>41.0</td>
</tr>
<tr>
<td>C5</td>
<td>275.0</td>
<td>63.0</td>
</tr>
<tr>
<td>C6</td>
<td>242.0</td>
<td>74.0</td>
</tr>
<tr>
<td>Mean ($n = 4$)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Number of data per site, same as in Tables 2 and 3; mean is the formation mean computed from unstrained mean-site component C of sites C1, C2, C3 and C6; D, I, k, $\alpha_{95}$, as in Table 2.
known that normal faulting induced by crustal extension may give a formation a tilted-block geometry. This is believed to be the case in the Lower Palaeozoic sedimentary formation of Central Brittany, as demonstrated in the Pont-Réan redbed formation by Ballard et al. (1986) and Brun et al. (1991). These authors have shown that the redbeds were deposited on tilted Brioverian blocks, in basins with triangular cross-sections. Owing to this geometry, the bedding plane could locally have had an initial synsedimentary dip of 10–20° towards the centre of the basin. If we now use such bedding surfaces as palaeohorizontal indicators, corrected palaeomagnetic vectors can be significantly affected by an error of 10–20° of rotation around a horizontal axis. Such an error has already been suspected and discussed for the palaeomagnetic directions of the Pont-Réan formation (Cogné, 1988), where a bimodal distribution of directions was observed as in the present case.

In the Cap de la Chèvre formation, no detailed study has yet been conducted in order to identify specific structures of normal faulting. However, what was observed in the Pont-Réan formation is thought to be of regional significance (Brun et al., 1991), and could characterize the geodynamic environment of Palaeozoic sedimentation in Central Brittany. It seems reasonable, therefore, to infer such a local initial dip for the beds of the Cap de la Chèvre formation during magnetization acquisition of component C in the Ordovician magnetic field.

Component B (Fig. 10(b)). Obviously, the applied corrections are insufficient to give these directions a Fisherian distribution at the formation scale. However, as in the case of component C, it is possible to fit a small circle to the data, the horizontal axis of which strikes in a direction similar to that of the previous one drawn on C directions. Furthermore, this small circle contains also the mean direction of component C (star with circle of confidence in Fig. 10(b)), which has been interpreted as the Ordovician magnetic field direction. Assuming the validity of the unstraining technique, the small-circle distribution could result from an insufficient structural correction, at each site, of a magnetization component acquired in the same field direction as C. The only solution for B and C being acquired in the same field direction, but having different directions at each site, is to suppose that some tilting process of the beds took place before or during the recording of the field. Indeed, these tilting processes are to be connected with the extensional geodynamic context during the sedimentation of the redbeds.

To summarize, we can propose the following scheme. The redbeds of the Cap de la Chèvre formation are deposited upon a Brioverian basement which presents a geometry of blocks tilted by normal faults. The deposition plane may have had a slight initial synsedimentary dip. An early magnetization component (C) is acquired parallel to the Ordovician magnetic field during or shortly after deposition when the beds were subhorizontal or slightly tilted. A second magnetization component (B) is acquired in the same magnetic field, but later than C, by beds already deposited and involved in the continuing tilting of the blocks produced by normal faulting processes. In this interpretation, component C would be the primary magnetization component, while B would be a secondary one.

6. Conclusions

From the above discussion, the main results of this study can be summarized as follows.

(1) The Cap de la Chèvre formation carries two pre-tectonic magnetization directions, both having been acquired in the Ordovician magnetic field. The first direction, carried by fine haematite particles, was probably acquired very early in the diagenetic history of the sediments and shows a reasonably good cluster at the formation scale. Owing to the extensional geodynamic event taking place during the sedimentation, the end of magnetization acquisition is thought to be achieved in tilted beds. This secondary component, probably carried by larger haematite grains, therefore shows a small-circle distribution when bedding surfaces are restored to a horizontal position. If this interpretation is correct, it further indicates that this component is of chemical origin, carried by haematite in large grains or specularite. This tends to
show that a large size of haematite grains is not necessarily an indication for the detrital origin of magnetization in redbeds.

(2) The Hercynian folding of the Palaeozoic cover of Central Brittany is accompanied by a weak internal deformation in the Cap de la Chèvre formation. This induced the development of a rough cleavage plane. Anisotropy of magnetic susceptibility has shown to be a good strain marker, allowing an accurate estimate of strain principal directions at each site. On the assumption that strain-to-AMS relationships are similar to the those observed in the lateral equivalent Pont-Réan formations, AMS further provided estimates of strain values at each site.

(3) Although weak, strain has induced deviations of pretectonic palaeomagnetic vectors, leading to problems in recovering the true initial direction of magnetization by using the classical tilt correction. The use of AMS derived strains in order to correct strain-induced deviations enabled us to recover pretectonic directions of magnetization and to interpret the presence of two pretectonic magnetization components. We thus point to the usefulness of strain removal techniques as the best current means of correcting strain effects in moderately deformed redbeds.

Finally, we point out that the magnetic history of the Cap de la Chèvre was quite difficult to decipher. This is mainly owing to the superimposition of internal deformation upon two magnetization components, acquired in a complex geodynamic environment. However, this analysis shows that a careful analysis of both palaeomagnetic and structural data allows to draw consistent interpretations.

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References


