Anisotropy of magnetic susceptibility as a strain gauge in the Flamanville granite, NW France

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The relationship between strain and anisotropy of magnetic susceptibility (AMS) has been investigated in the Carboniferous Flamanville granite in the Armorican Massif, NW France. We measured the axial ratios of elliptical inclusions and the orientation of cleavage planes at eight sites around the granite margin. Measurements of AMS were made on 73 specimens using a Schonstedt spinner magnetometer. AMS measurements are shown to provide accurate predictions of cleavage and lineation direction, even where these structures are difficult to measure in the field. The strain and AMS ellipsoids show similar regional variations in shape and intensity, and a good correlation between the lengths of the principal axes. Finally, our data are consistent with the hypothesis that the Flamanville granite was syntectonically emplaced during the late stages of the Hercynian Orogeny.

1. Introduction

The Flamanville granitic pluton was intruded into an Upper Proterozoic–Lower Paleozoic basement during the late phases of the Hercynian Orogeny. Whereas the pluton shows no sign of deformation in its central part, there is a clear structural foliation parallel to the margins, suggesting these were severely deformed during emplacement. The pluton has been the subject of structural studies by Martin (1953), Ledru and Brun (1977) and Brun (1981). A paleomagnetic reconnaissance by Van der Voo and Klootwijk (1972) yielded anisotropy of magnetic susceptibility (AMS) results with a good fit between principal directions of AMS and strain. This encouraged us to perform a more detailed study. The occurrence of deformed xenoliths (Martin, 1953) allowed us to estimate strain intensity and thus to attempt to correlate the strain and susceptibility ellipsoids quantitatively, following similar work by others (e.g., Kneen, 1976; Wood et al., 1976; Hrouda, 1979; Rathore, 1979; Kligfield et al., 1981, 1983). The purpose of this paper is therefore to report new structural and magnetic data that we have obtained on this pluton and to discuss their relationships and implications with respect to its emplacement.

2. Geological setting and sampling sites

Being intrusive in the Paleozoic formations of the Siouville syncline in Normandy, France (Fig. 1), the granite massif of Flamanville was at first considered to mark the end of the Hercynian structural history of the region (Martin, 1953). However, a detailed study of cleavage development in the Siouville syncline (Ledru and Brun, 1977) has shown that it is controlled by the thermal anomaly due to granite intrusion. Regionally, the cleavage trajectories trend E–W in the country rocks, but locally they bend around the margins of the Flamanville pluton. The locally subcircular cleavage pattern grades into the regional schistos-
Fig. 1. (a) Location map of the Flamanville area in the Armorican Massif, Normandy, France. (b) Schematic geological map of the Flamanville massif. A–I are the sampling sites of this study.

3. Strain estimates

At each site (except G), xenoliths systematically show ellipsoidal shapes, their long axes lying within the foliation surface. The xenoliths were used to estimate a mean finite strain at site scale. As noted by Martin (1953), long axes of inclusions tend to lie at random in the flattening plane ($\lambda_1\lambda_2$) and it is therefore difficult (at some sites, impossible) to determine the stretching direction in this plane. Nevertheless, since the lineation in the country rocks is almost horizontal (Brun, 1981), and the granite appears to be syntectonic, the stretching lineation in the granite was assumed to have the same shallow plunge for the purposes of field measurement. We generally considered subhorizontal joint planes, perpendicular to the foliation planes ($\lambda_1\lambda_2$), as being the $\lambda_1\lambda_3$ planes and the mutually perpendicular subvertical ones as the $\lambda_2\lambda_3$ planes. Moreover, the foliation plane was not always a plane of easy splitting (particularly at site G) and a measurement of the orientation of this plane may not be as accurate as desirable. Mean axial ratios of the elliptical inclusions have been estimated from arithmetic means of the measurements within each of the principal planes. Declination and inclination of stretching ($\lambda_1$) and shortening ($\lambda_3$) directions, mean axial ratios and strain parameters are listed in Table I. Foliation planes, represented by their poles in Fig. 2(a), strike parallel to the wall of the body and systematically dip towards the centre of the massif.

Fig. 2. Strain data: (a) Lower hemisphere stereographic projections showing the orientation of the mean poles to cleavage ($\lambda_3$). (b) Flinn diagram (1965) of the mean strains of sites A–I. $k = (\lambda_1/\lambda_2 - 1)/(\lambda_2/\lambda_3 - 1)$. 

TABLE I
Mean site strain data for the Flamanville granite

<table>
<thead>
<tr>
<th>Site</th>
<th>Shortening ($\lambda_1$)</th>
<th>Stretching ($\lambda_3$)</th>
<th>Principal strains</th>
<th>Shape</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$D$</td>
<td>$I$</td>
<td>$D$</td>
<td>$I$</td>
<td>$\lambda_1$</td>
</tr>
<tr>
<td>A</td>
<td>328.0</td>
<td>10.0</td>
<td>237.0</td>
<td>7.0</td>
<td>1.725</td>
</tr>
<tr>
<td>B</td>
<td>327.0</td>
<td>14.0</td>
<td>57.0</td>
<td>0.0</td>
<td>1.704</td>
</tr>
<tr>
<td>C</td>
<td>268.0</td>
<td>10.0</td>
<td>358.0</td>
<td>0.0</td>
<td>1.552</td>
</tr>
<tr>
<td>D</td>
<td>247.0</td>
<td>6.0</td>
<td>337.5</td>
<td>0.0</td>
<td>1.434</td>
</tr>
<tr>
<td>E</td>
<td>252.0</td>
<td>13.5</td>
<td>342.0</td>
<td>0.0</td>
<td>1.361</td>
</tr>
<tr>
<td>F</td>
<td>229.5</td>
<td>11.0</td>
<td>323.0</td>
<td>17.0</td>
<td>1.561</td>
</tr>
<tr>
<td>G</td>
<td>213.5</td>
<td>9.0</td>
<td>303.5</td>
<td>0.0</td>
<td>--</td>
</tr>
<tr>
<td>H</td>
<td>209.5</td>
<td>19.0</td>
<td>299.5</td>
<td>0.0</td>
<td>1.437</td>
</tr>
<tr>
<td>I</td>
<td>199.5</td>
<td>18.0</td>
<td>100.0</td>
<td>27.5</td>
<td>1.569</td>
</tr>
</tbody>
</table>

Shortening and stretching down-plunge directions are given by their declination ($D$) and inclination ($I$). Principal strains $\lambda_i$ are $1 + e_i$, where $e_i$ is the elongation along each axis. Strains are computed assuming no volume change (i.e., $\lambda_1\lambda_2\lambda_3 = 1$). Shape (Flinn, 1965) is $k = (\lambda_1/\lambda_2 - 1)/(\lambda_2/\lambda_3 - 1)$. Intensity (Watterson, 1968) is $R = \lambda_1/\lambda_2 + \lambda_2/\lambda_3 - 1$.

At all the sites, the strain ellipsoid is of the flattening type with low values of the shape parameter $k$ (Flinn, 1965), close to an oblate strain ellipsoid.

4. Anisotropy of magnetic susceptibility (AMS)

4.1. Measurements of AMS

The AMS measurements were made with a Schonstedt spinner magnetometer, in the manner described by Collinson (1983): a 40 A m$^{-1}$ vertical field is applied to the spinning sample, whilst the horizontal fluxgate measures the component of magnetization perpendicular to the field and the spinning axis. The magnetization measured is due to both remanent magnetization and anisotropic induced magnetization. The periodic signal is sampled eight times during each spin and the data are transferred to a PDP 11 microcomputer for processing. By combining the eight readings, both remanent and induced magnetization components can be estimated since they have different periodicities. Accumulation of results from several spins controls the signal to noise ratios for both magnetizations. In order to determine fully the susceptibility tensor, $K_{ij}$ (i.e., the susceptibility along the Z axis of the sample) is measured with a susceptibility meter (Digico or Bartington).

A more difficult problem is the calibration of the Schonstedt magnetometer; especially since electronic amplification and filtering produce phase offset and amplitude attenuation which are frequency dependent. For our study, the magnetometer was calibrated using an artificial sample, composed of Fe needles, carefully oriented along the sample axes of a wooden cylinder. The sample was measured along these axes using the Bartington susceptibility meter, and the values obtained

![Fig. 3. Stereographic projections of the principal susceptibility axes of two individual specimens (from different localities) measured after successive steps of A.F. demagnetization. (a) this study, measurements made with a spinner magnetometer. (b) results obtained by Van der Voo and Klootwijk (1972, fig. 6b) measuring with an astatic magnetometer. Filled symbols: projection in the lower hemisphere. Open symbols: projection in the upper hemisphere.](image-url)
were used to calibrate the Schonstedt magnetometer.

Finally, to check the influence of remanent magnetization on our results, we have progressively demagnetized some samples using alternating fields up to 100 mT and measuring AMS at each step. We have observed no variation of AMS during each entire experiment (Fig. 3) and we conclude, therefore, that AMS measurements with the Schonstedt magnetometer are not significantly perturbed by the second harmonic of the remanent magnetization signal, as suggested by Collinson (1983). This was not the case for the results of Van der Voo and Klootwijk (1972) (Fig. 3(b)) who used an astatic magnetometer, and we can therefore consider our apparatus as being at least as accurate as the astatic magnetometer when dealing with fairly intense anisotropic induced magnetization. However, the measurement of low susceptibilities or low anisotropy has proved to be impossible, due to the effect of sample shape when the sample is too close to the fluxgate sensor. The measured signal should be strong enough to be detectable when the sample is at a distance of at least two or three times its diameter from the fluxgate.

4.2. Results

At the nine sites distributed around the granite body, 66 cores with a diameter of 25 mm and length of 60–100 mm were drilled and oriented in situ, using magnetic and sun compasses. The cores were cut in the laboratory to yield 93 samples, with standard shapes of 25 mm diameter × 24 mm length. The Kzz component of the susceptibility tensor of these specimens was measured using a Digico bulk susceptibility meter. Twenty specimens were eliminated from the AMS measurements because their low volume susceptibility (< 10⁻⁵ SI = 10⁻⁴ G Oe⁻¹ CGS) was too weak to be measured with the spinner magnetometer. All the specimens of site H are in this category, and we have no results for this site. For the 73 remaining samples, the Kzz component is in the range 0.3–0.8 × 10⁻² SI. The eigenvectors of the susceptibility tensor give the orientation of the maximum (Kmax), intermediate (Kint) and minimum

<table>
<thead>
<tr>
<th>Site</th>
<th>N</th>
<th>Kmax_D</th>
<th>Kmax_I</th>
<th>Kmin_D</th>
<th>Kmin_I</th>
<th>P1</th>
<th>P2</th>
<th>An (%)</th>
<th>Principal susceptibility difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>7</td>
<td>65.0</td>
<td>14.4</td>
<td>332.1</td>
<td>11.2</td>
<td>1.078</td>
<td>1.221</td>
<td>31.6</td>
<td>0.124, 0.042, -0.146</td>
</tr>
<tr>
<td>B</td>
<td>4</td>
<td>62.7</td>
<td>-3.8</td>
<td>333.6</td>
<td>13.3</td>
<td>1.082</td>
<td>1.169</td>
<td>26.5</td>
<td>0.110, 0.026, -0.122</td>
</tr>
<tr>
<td>C</td>
<td>11</td>
<td>9.9</td>
<td>33.2</td>
<td>274.5</td>
<td>8.1</td>
<td>1.066</td>
<td>1.128</td>
<td>20.3</td>
<td>0.087, 0.019, -0.097</td>
</tr>
<tr>
<td>D</td>
<td>8</td>
<td>3.4</td>
<td>36.1</td>
<td>267.3</td>
<td>8.4</td>
<td>1.047</td>
<td>1.158</td>
<td>21.2</td>
<td>0.083, 0.034, -0.107</td>
</tr>
<tr>
<td>E</td>
<td>10</td>
<td>357.4</td>
<td>38.2</td>
<td>259.6</td>
<td>9.7</td>
<td>1.069</td>
<td>1.143</td>
<td>22.2</td>
<td>0.093, 0.023, -0.105</td>
</tr>
<tr>
<td>F</td>
<td>10</td>
<td>340.5</td>
<td>45.0</td>
<td>234.8</td>
<td>15.2</td>
<td>1.060</td>
<td>1.125</td>
<td>19.3</td>
<td>0.081, 0.020, -0.093</td>
</tr>
<tr>
<td>G</td>
<td>14</td>
<td>342.2</td>
<td>34.5</td>
<td>238.6</td>
<td>18.8</td>
<td>1.042</td>
<td>1.107</td>
<td>15.3</td>
<td>0.063, 0.020, -0.078</td>
</tr>
<tr>
<td>I</td>
<td>9</td>
<td>296.2</td>
<td>54.7</td>
<td>196.8</td>
<td>6.6</td>
<td>1.040</td>
<td>1.212</td>
<td>26.1</td>
<td>0.094, 0.052, -0.132</td>
</tr>
</tbody>
</table>

N is the number of susceptibility ellipsoid determinations at each site. Direction of principal susceptibility axes (Kmax, Kmin) is given by declination (D) and inclination (I). P1 = Kmax/Kint, P2 = Kint/Kmin. An = (Kmax/Kmin - 1)×100. M1 = (K1 - K0)/K0 with K0 = (KmaxKintKmin)^1/3, i = 1, 2, 3 - Kmax, Kint, Kmin.

Fig. 4. AMS data: (a) Flinn diagram (1965) for all measured specimens; P1 = Kmax/Kint, P2 = Kint/Kmin. (b) Frequency plot of the anisotropy percentages for the 73 specimens; An = (Kmax/Kmin - 1)×100.
(\(K_{\text{min}}\)) susceptibility axes, and its eigenvalues give the magnitude of \(K_{\text{max}}, K_{\text{int}}, K_{\text{min}}\), from which are derived the shape and intensity parameters of the ellipsoid. At each site, a mean susceptibility tensor has been computed by summation of the \(n\) tensors measured. Diagonalization of this tensor provides the mean directions and parameters which are shown in Table II.

In all specimens, the susceptibility ellipsoid is triaxial and oblate (Fig. 4(a)). There is a measurable ellipticity in the \(K_{\text{max}}-K_{\text{int}}\) plane and, thus, there is a magnetic lineation in this plane. The total degree of anisotropy, expressed as a percentage, \(\text{An} = (K_{\text{max}}/K_{\text{min}} - 1) \times 100\), is high, ranging from 10% to 35% (Fig. 4(b)). These results are in good agreement with those obtained by Van der Voo and Klootwijk (1972). The principal directions of susceptibility from each site are shown in Fig. 5. They show good within-site consistency. The \(K_{\text{min}}\) axes are systematically inclined down to the west (NW–SW). The corresponding \(K_{\text{max}}-K_{\text{int}}\) planes dip steeply towards the centre and strike parallel to the margins of the pluton. The magnetic lineation is well defined within each site, with a good cluster of \(K_{\text{max}}\) directions in the \(K_{\text{max}}-K_{\text{int}}\) plane. The plunge of the within-site mean \(K_{\text{max}}\) axes progressively increases from north (15°) to south (55°).

Forty specimens out of these 73 were also measured using the Bartington magnetic susceptibility meter. The measurements were made in six different positions (three sample axes plus three diagonals), sufficient for the susceptibility tensor to be estimated. No significant differences were observed between the two data sets, on the basis of either shape and intensity of susceptibility ellipsoids or directions of their axes.

5. Correlation of strain ellipsoid and magnetic susceptibility ellipsoid

As expected, both ellipsoids have similar orientations. The angle between the pole to cleavage (\(\lambda_3\), Table I) and the pole to the mean magnetic foliation (\(K_{\text{int}}\), Table II) is generally < 10°, except at sites D and G where this angle is > 20°. This is not surprising, since greater difficulties were encountered at these sites in estimating the strike and dip of the cleavage plane.

Although no clear stretching lineation is observable in the field, owing to the low \(\lambda_1/\lambda_2\) ratio displayed by the elliptical xenoliths, AMS measurements show a weak but well-defined magnetic lineation. The within-site cluster of the \(K_{\text{max}}\) directions (obvious in Fig. 5), together with the non-random between-site distribution of these axes, suggest they are related to a structural lineation.

Following other studies, an attempt has been made to express the magnetic anisotropy in quantitative terms of finite strain. From the published case histories on this subject, two main expressions have been used to correlate AMS with strain. On the one hand, Kneen (1976), Wood et al. (1976), Rathore (1979) and Rathore et al. (1983) favour the following relationship

\[
K_1/K_2 = \left[\frac{1 + e_1}{1 + e_2}\right]^x
\]

\[
K_2/K_3 = \left[\frac{1 + e_2}{1 + e_3}\right]^x
\]
where $e_1$, $e_2$ and $e_3$ are the three principal extensions and with various results for the value of exponent, $x$. On the other hand, Hrouda (1979) and Kligfield et al. (1981, 1983) favour a relationship of the form

$$(K_1 - K_2)/K_0 = y \ln[(1 + e_1)/(1 + e_2)]$$

$$(K_2 - K_3)/K_0 = y \ln[(1 + e_2)/(1 + e_3)]$$

(2)

where $K_0$ is either $(K_1 + K_2 + K_3)/3$ (Kligfield et al., 1981), or $(K_1 K_2 K_3)^{1/3}$ (Kligfield et al., 1983).

The choice between these two sets of formulae is not straightforward, since there does not appear to be any theoretical reason for preferring a log-log relation rather than a linear-log relation or even a linear-linear one. Furthermore, since we usually deal with anisotropy < 30%, we have $(K_1 - K_2)/K_0 = \ln(K_1/K_2)$ and $(K_2 - K_3)/K_0 = \ln(K_2/K_3)$ (Hrouda, 1982). Thus, both expressions are equivalent in the range of experimental error. We follow Kligfield et al. (1983) in computing the linear regression between the logarithmic strains ($\epsilon_i = \ln(1 + e_i); i = 1, 2, 3$) and the related principal susceptibility differences ($M_i = (K_i - K_0)/K_0$; $K_0 = (K_{max} K_{int} K_{min})^{1/3}; i = 1, 2, 3$) (Fig. 6). A strong positive correlation is obtained, $\epsilon = 5.358 M - 0.022$, with a correlation coefficient $r = 0.986$ ($n = 21$). In the ideal case, the residual term $(-0.022)$ should be zero, but it appears small enough to be neglected. This correlation strongly suggests that AMS ellipsoid shape and intensity variations are directly related to strain variations. On the strength of this correlation, it therefore seems possible to estimate the strain in any other point of the granite body even if there are no direct strain markers.

Finally, the correlation between strain and AMS intensities is illustrated in Fig. 7, where strain intensity, $R$ and total degree of anisotropy, $A_n$, are plotted for the various site locations around the quasi-circular western border of the Flamanville granite. Strain intensity increases, from the western border of the body, towards either the north or the south. This strain gradient is accompanied by a similar variation in AMS percentages. Note the lack of AMS data at site H and of strain data at site G. Although the two sites are different, each shows AMS or strain values intermediate to those of western and southern sites.

6. Conclusions

From our study, we draw conclusions at two levels. First, strain tensors and AMS tensors may be correlated not only in the directions of their eigenvectors but also in the variations in magnitude of their eigenvalues. The AMS technique is probably more accurate in the determination of
the flattening strain plane direction. Moreover, a consistent magnetic lineation is found at each site, although it was not possible to find a well-defined stretching lineation in the field. The good correlation that exists between the logarithmic strains and the principal susceptibility differences, shows that the degree and shape of susceptibility anisotropy is controlled by strain. It therefore seems possible to derive strain from AMS measurements at all points in the granite body. All these fit the accepted idea that AMS not only provides a complementary tool in structural analysis but may be considered itself as a good strain marker, providing there is a minimum number of classical strain markers to allow the correlation to be established and controlled.

The geological interpretation of our data with respect to the emplacement of the Flamanville granite also supports the idea of a syntectonic diapir proposed by Ledru and Brun (1977). The strain and anisotropy percentage, as they increase from the western sites towards the northern and southern borders of the pluton, probably result from the superimposition of a N–S regional shortening (E–W regional schistosity) upon a radial shortening due to ballooning during pluton emplacement (Brun, 1983). The dip of the cleavage towards the centre of the Flamanville pluton shows that the current erosion surface is situated slightly below the plane of maximum width of the body. The effect of diapiric emplacement alone should have produced down-dip stretching lineations in this zone (Brun, 1983). Here too, the intermediate inclination of magnetic lineations may be the result of the superimposition of a shallow regional stretching in the country rocks (Brun, 1981) upon the down-dip stretching produced by diapiric emplacement. The structural and AMS studies reported here, thus provide additional arguments for the synchronism between granite intrusion and region Hercynian deformation in the Flamanville area.

References

Rathore, J.S., Courrioux, G. and Choukroune, P., 1983. Study of ductile shear zones (Galicia, Spain) using texture go