PALEOMAGNETIC EVIDENCE FOR CRUSTAL AND THIN-SKINNED ROTATIONS IN THE EUROPEAN HERCYNIDES

Valerian Bachtadse and Rob Van der Voo
Department of Geological Sciences, University of Michigan, Ann Arbor, MI 48109

Abstract. Devonian and Carboniferous paleomagnetic data from the European Hercynides show a coherent trend in inclination but significant dispersion in declination. The declination anomalies with respect to expected declinations for stable Europe indicate a strong correlation with the regional changes in the structural trend of the mountain belt. Detailed analysis of the paleomagnetic and structural data revealed the highest degree of correlation between changes in strike and declination anomalies for external parts of the orogen, where thin-skinned nappes have been most prevalent. The correlation between changes in strike and declination anomalies from interior parts of the Hercynides is less well defined and displays a greater degree of scatter. Nevertheless, the partly secondary character of the arcuate shape can be demonstrated. Thus the internal Hercynides are at least in part a true orocline with secondary bending in the sense of S.W. Carey. We infer that the bending of the European Hercynides resulted from the combination of multiple deep-reaching deformations of the European lithosphere as well as the effects of thin-skinned rotations. The decreasing degree of rotations toward the crystalline interior of the belt appears to favor a geodynamic model involving indentations and/or buttressing effects. The indentation of Hercynian Europe by a microplate or an African promontory during the Hercynian orogeny might be one of the principal causes for the secondary bending and the associated nappes rotations.

Introduction

Stretching from Poland in the northeast to Portugal in the southwest, the Hercynides form the dominant geological structure of extra-Alpine Europe. They consist of a central crystalline ridge bordered on both sides by fold belts consisting of low-grade or non-metamorphic Paleozoic sediments and volcanics. Though there is geological evidence for a localized orogenic phase of Devonian age (Acadian), the main deformation has been shown to be Carboniferous, i.e., Late Visean to Namurian in age (Hercynian). The final stages of this deformation phase are Westphalian in age [Lorenz and Nicholls, 1984 and references therein]. Despite the large number of publications there is still no comprehensive tectonic model available which defines the type of the Hercynian orogeny or the location of any such orogeny [see Windley, 1984 and references therein].

The curvature of the Hercynian belt around the Bay of Biscay, its bending in Central Europe as defined by the change from the western European Armorican to the central European Variscan structural trend (Figure 1) and its potential importance for geodynamics is only one aspect of this plate tectonic enigma. The bending around the Bay of Biscay (the Ibero-Armorican arc), originally recognized and discussed by Argand [1924] and Carey [1958], totals at least 165° [Ries and Shackleton, 1976] in a pre-Mesozoic reconstruction [Van der Voo, 1969], whereas the curvature of the orogen in central Europe is approximately 40°.

To test the validity of several possible models proposed to explain the curvatures [e.g. Perroud and Bonhommet, 1981, 1983], it is very important to reconstruct the direction of the regional stress field during Variscan times. One possible approach is the determination of structural geometries involved in possibly bent fold belts and a test of primary versus secondary origin as proposed by Carey [1958] in his orocline concept. Paleomagnetic data, especially declinations, are ideal for such a determination.

The paleomagnetic declinations

A substantial paleomagnetic data base (Table 1) now exists for Devonian and Carboniferous rocks from different parts of the Hercynian mountain belt. Positive fold tests and/or inclination values, in agreement with the apparent polar wander path for stable Europe [Duff, 1980, French, 1976], constrain the ages of magnetization to the Devonian-Carboniferous. To calculate...
TABLE 1. Devonian and Carboniferous paleomagnetic data for western and central Europe

<table>
<thead>
<tr>
<th>Structural setting</th>
<th>Strike</th>
<th>Decl.</th>
<th>Incl.</th>
<th>(\alpha_{95})</th>
<th>(S_r - S_o)</th>
<th>(D_r - D_o)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bugaco &quot;C&quot;</td>
<td>180(^1)</td>
<td>179(^1)</td>
<td>+36(^2)</td>
<td>11</td>
<td>+30</td>
<td>+4</td>
</tr>
<tr>
<td>Bugaco &quot;D&quot;</td>
<td>180(^1)</td>
<td>184(^1)</td>
<td>+5(^2)</td>
<td>6</td>
<td>+30</td>
<td>-5</td>
</tr>
<tr>
<td>San Pedro</td>
<td>135(^1)</td>
<td>144(^1)</td>
<td>+34</td>
<td>9</td>
<td>+75</td>
<td>+41</td>
</tr>
<tr>
<td>San Emiliano</td>
<td>125(^1)</td>
<td>137(^1)</td>
<td>+13</td>
<td>2</td>
<td>+85</td>
<td>+48</td>
</tr>
<tr>
<td>Atienza</td>
<td>160(^1)</td>
<td>194(^1)</td>
<td>+19</td>
<td>12</td>
<td>+50</td>
<td>-8</td>
</tr>
<tr>
<td>Laval syncline tuffs</td>
<td>307</td>
<td>217</td>
<td>+19(^2)</td>
<td>6</td>
<td>-97</td>
<td>-28</td>
</tr>
<tr>
<td>Laval syncline sediments</td>
<td>307</td>
<td>224</td>
<td>+25(^2)</td>
<td>18</td>
<td>-97</td>
<td>-35</td>
</tr>
<tr>
<td>Cambro-Ordovician red beds</td>
<td>259</td>
<td>207</td>
<td>+6(^2)</td>
<td>14</td>
<td>-49</td>
<td>-18</td>
</tr>
<tr>
<td>Bray-Cap Freshel red beds</td>
<td>272</td>
<td>195</td>
<td>+2(^2)</td>
<td>12</td>
<td>-62</td>
<td>+6</td>
</tr>
<tr>
<td>Zone Bocaine</td>
<td>290</td>
<td>203</td>
<td>+8(^2)</td>
<td>13</td>
<td>-80</td>
<td>-14</td>
</tr>
<tr>
<td>Cabo de Peñas</td>
<td>265(^1)</td>
<td>203(^1)</td>
<td>+19(^2)</td>
<td>8</td>
<td>-55</td>
<td>-18</td>
</tr>
<tr>
<td>Carteret Group B</td>
<td>272</td>
<td>216</td>
<td>+28(^2)</td>
<td>14</td>
<td>-62</td>
<td>-27</td>
</tr>
<tr>
<td>Rozel Group B</td>
<td>255</td>
<td>203</td>
<td>0(^2)</td>
<td>7</td>
<td>-45</td>
<td>-14</td>
</tr>
<tr>
<td>Crozon dolerites</td>
<td>240</td>
<td>217</td>
<td>+29(^2)</td>
<td>10</td>
<td>-30</td>
<td>-28</td>
</tr>
<tr>
<td>Thouars</td>
<td>270</td>
<td>219</td>
<td>+20(^2)</td>
<td>18</td>
<td>-60</td>
<td>-30</td>
</tr>
<tr>
<td>Montmartin red beds</td>
<td>270</td>
<td>206</td>
<td>-3(^2)</td>
<td>12</td>
<td>-60</td>
<td>-17</td>
</tr>
<tr>
<td>Flamanville granite</td>
<td>270</td>
<td>203</td>
<td>+14(^2)</td>
<td>15</td>
<td>-60</td>
<td>-14</td>
</tr>
<tr>
<td>Plourivo red beds</td>
<td>275</td>
<td>213</td>
<td>+17(^2)</td>
<td>12</td>
<td>-65</td>
<td>-24</td>
</tr>
<tr>
<td>Tregastel-Ploumanac'h granite</td>
<td>275</td>
<td>200</td>
<td>+9(^2)</td>
<td>7</td>
<td>-65</td>
<td>-11</td>
</tr>
<tr>
<td>Jersey dolerites</td>
<td>275</td>
<td>199</td>
<td>+16(^2)</td>
<td>9</td>
<td>-65</td>
<td>-10</td>
</tr>
<tr>
<td>North Brittany dykes</td>
<td>275</td>
<td>212</td>
<td>+10(^2)</td>
<td>6</td>
<td>-65</td>
<td>-23</td>
</tr>
<tr>
<td>Mill Haven sediments &quot;P-C&quot;</td>
<td>280</td>
<td>251</td>
<td>+10(^2)</td>
<td>8</td>
<td>-70</td>
<td>-62</td>
</tr>
<tr>
<td>Freshwater sediments &quot;C&quot;</td>
<td>280</td>
<td>222</td>
<td>-11(^2)</td>
<td>7</td>
<td>-70</td>
<td>-33</td>
</tr>
<tr>
<td>Freshwater sediments &quot;D&quot;</td>
<td>280(^6)</td>
<td>278</td>
<td>+20</td>
<td>16</td>
<td>-70</td>
<td>-55</td>
</tr>
<tr>
<td>Massif Central</td>
<td>365</td>
<td>258</td>
<td>+2</td>
<td>12</td>
<td>-55</td>
<td>-65</td>
</tr>
<tr>
<td>Franconian Forest &quot;C&quot;</td>
<td>240</td>
<td>203</td>
<td>-2</td>
<td>8</td>
<td>-30</td>
<td>-9</td>
</tr>
<tr>
<td>Franconian Forest &quot;D&quot;</td>
<td>240</td>
<td>186</td>
<td>+30</td>
<td>9</td>
<td>-30</td>
<td>+8</td>
</tr>
<tr>
<td>Harz Mountains &quot;C&quot;</td>
<td>240</td>
<td>183</td>
<td>-4</td>
<td>18</td>
<td>-30</td>
<td>+11</td>
</tr>
<tr>
<td>Harz Mountains &quot;D&quot;</td>
<td>240</td>
<td>189</td>
<td>+24</td>
<td>20</td>
<td>-30</td>
<td>+5</td>
</tr>
</tbody>
</table>

Devonian and Carboniferous paleomagnetic directions (Decl. and Incl.) for western and central Europe. \(\alpha_{95}\) is the radius of the circle of confidence at the 95% probability level, \(S_r\) the reference strike, \(S_o\) the regional strike, \(D_r\) the expected magnetic declination and \(D_o\) the observed magnetic declination. For references see Eldredge et al. [1985].

1 regional strike and magnetic declination after the closing of the Bay of Biscay [Van der Voo, 1969].

2 remagnetized data, indicating late Hercynian overprint.

expected declinations (\(D_o\)) for the different regions investigated we either the Carboniferous or Devonian reference pole position for stable (northern) Europe. Deviations of the observed declinations (\(D_o\)) from the expected reference directions (\(D_r\)) can be compared with the regional trend anomalies (\(S_r - S_o\)) which have been calculated by taking the difference between observed regional strike (\(S_o\)) and an arbitrary average structural trend of 210°, selected as a reference strike (\(S_r\)). The error bars of the declination data as shown in Figure 2 for the 95% confidence interval have been determined according to Beck [1980]. Allowing for the opening of the Bay of Biscay in Mesozoic times, structural and paleomagnetic data from the Iberian peninsula have been corrected by adding 35° [Van der Voo, 1969].

Oroclinal bending sensu stricto [Eldredge et al., 1985] affects any pre-existing structural trends, as well as those paleomagnetic directions that predate the bending event. If the arcuate shape of the fold-system is primary, then paleomagnetic directions from any geographical position along the trace of the arc should not show any deviations from the expected declination (\(D_r\)). On the other hand ideal oroclinal bending would result in a linear dependence between the two variables (\(D_r - D_o\) and \(S_r - S_o\)). This inter-dependence of declination and structural trends can be tested by simple mathematical or graphical methods [Schwartz and Van der Voo, 1983] such as illustrated in Figure 2. Linear regression of the data set provides an estimate of the internal distribution of the data points (correlation coefficient, \(r\)) and the slope of the regression line indicates whether both variables are inter-dependent (oroclinal bending) or not (no oroclinal bending). Linear regression for the data from the exterior (mostly allochthonous) parts close to the northern (Wales) and southern (Cantabria) edges results in a well-defined best fit line (\(r=0.96\) significant at the 95% probability level) with a slope of 31° (line "A" and open symbols in Figure 2). A very strong correlation between the regional changes in structural trend and the changes in declination can therefore be deduced for the external parts of the mountain belt. Analysis of the data from the more interior parts of the mountain belt shows somewhat different picture. Linear regression yields a fairly well-
late to post-orogenic strike-slip movements may have led to large-scale draping or drag-fold-
ing (Figure 3a),

(2) squeezing or buckling of the Armorican mi-
croplate in a NE-SW directed compressional stress
may have occurred during final suturing between
Gondwana and northern Europe [Perroud and Bonhom-
et, 1981] (Figure 3b),

(3) structural trend changes could reflect het-
erogeneities of pre-collision cratonic margins
[Lorenz, 1976; Lorenz and Nicholls, 1984], which
acted as buttressing zones that molded the inter-
vening, deformable Southern European plate into
oroclines during a Hercynian Gondwana-Laurussia
continent-continent collision (Figure 3c),

(4) northwest ward indentation of western Europe
by an African promontory [Matte and Ribiero,
Fig. 2. Declination anomalies (Dr-Dr) plotted as
a function of strike anomalies (Sr-Sr) for west-
ern and central Europe. Open symbols: data from
thin-skinned parts of the orogen. Sr: reference
strike; Sr: observed strike; Dr: expected mag-
netic declination; Dr: observed magnetic declina-
tion. Error bars calculated according to Beck
[1980]. Lines A and B are the best fit for the
data sets from allochthonous resp. autarchonous
parts of the mountain belt, respectively.

defined correlation coefficient, r, of 0.47
(significant at the 95% probability level). Al-
though the regression line (labeled "B" in Figure
2) is significantly different from the x-axis of
Figure 2, its rather shallow slope angle (12°)
indicates much less intense bending than expected
from the strongly curved structural trends. This
suggests that the present-day curvatures are the
product of both primary (initial) curvature and
secondary, oroclinal bending.

Geodynamic Models

Substantial changes in magnetic declinations
as a function of regional structural trends have
been demonstrated for several orogens [e.g., El-
dredge at al., 1985]. However in many of the
cases the inferred rotations seem to be related
to pure thin-skinned tectonics (thrusting) rather
than to deep-reaching mechanisms involving the
entire crust. The findings of this study demon-
strate the effect of thrust rotations in the ex-
ternal parts of the European Hercynides. This in-
troduces an extra nuance to the interpretation of
previous analyses [Perroud and Bonhomme, 1983;
Eldredge et al., 1985], which did not address the
particular contribution of thin-skinned rotations
of low-angle thrust faults to the overall bending
of the European Hercynides. Nevertheless the
analysis of paleomagnetic and structural data
from probably autochthonous massifs of the orogen
still indicates systematic changes in declination
as a function of changes in structural trend.
Since thin-skinned rotations are not considered
to have occurred in the interior parts of the
orogen it is argued that the rotations displayed
by our data probably represent crustal bending.
Along the margins of the orogen, on the other
hand, deformation has largely been taken up by
thrusting and thrust rotation.

At least four geodynamic models may explain
this curvature and are compatible with the re-

Fig. 3. Different models to explain the arcuate
shape of the European Hercynides. A: Sinistral
shear; B: Paleo-Southwest-Northeast directed com-
pression; C: Deformation along salients and re-
cesses [modified after Lorenz, 1976]; D: Indenta-
tion of Western Europe by the hypothetical Ibero-
Pyrenean micro-continent. Symbols as in Figure 1.
Curved arrows in Figure 3c indicate sense of ro-
tation.
thrusting and wrenching [Brun and Burg, 1982] lead to some bending during the Acadian orogeny. Following model 4 (Figure 3d) subsequent north-westward impingement of an Ebro-Pyrenean microplate or an African promontory into Europe during the Carboniferous provoked secondary tightening of the already existing Ibero-Armorican arc and initialized bending of the Central-European arc. Whereas the interior parts of the orogen responded to the deformation by moderate orocline bending sensu stricto [Eldredge et al., 1985], in the outer parts of the orogen the strain has partially been taken up by thin-skinned tectonics (thrusting and thrust rotation). Thus deep reaching crustal deformation combined with thin-skinned deformation caused by continental indentation appears to be a viable mechanism for orocline bending of the Hercynides.

Acknowledgments. The manuscript benefited from valuable suggestions and discussions with our colleagues N.L. Bogen, R. Johnson and B.A. van der Pluijm. This research was supported in part by the Division of Earth Sciences, the National Science Foundation, grant EAR 84-07007.

References

Carey, S.W., A tectonic approach to continental drift, in Continental drift a symposium, edited by S.W. Carey, pp. 177-155, Tasmania University, Hobart, 1958.
Lefort, J.P. and Van der Voo, R., A kinematic model for the collision and complete suturing between Gondwanaland and Laurussia in the Carboniferous, J. Geol., 89, 537-550, 1981.
Van der Voo, R., Paleomagnetic evidence for the rotation of the Iberian peninsula, Tectonophysics, 7, 5-56, 1969.

V. Bachtadse and R. Van der Voo, Department of Geological Sciences, University of Michigan, Ann Arbor, MI 48109-1063.

(Received November 14, 1985; Accepted December 2, 1985.)