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

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Abstract. Devonian and Carboniferous paleomagnetic data from the European Hercynides show a coherent pattern 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 nappe emplacement has 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 nappe 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 suture(s) [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 Devono-Carboniferous. To calculate

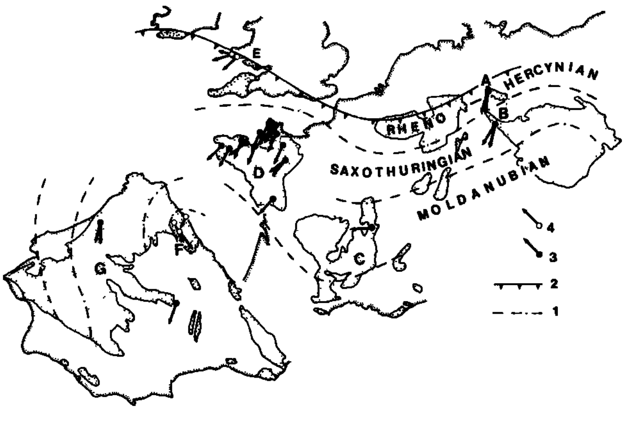

Fig. 1. Geological sketch map of the European Hercynides after closing the Bay of Biscay [Van der Voo, 1969]. The direction of the structural trends (1), the northern overthrust (2) and the directions of Devonian to Carboniferous magnetic declinations from presumably autochthonous (3) and allochthonous (4) areas are shown. A: Harz Mountains; B: Franconian Forest; C: Massif Central; D: Britanny; E: Wales; F: Cantabria; G: Galicia-Castilla. Open symbols: data from thin-skinned parts of the orogen.

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TABLE 1. Devonian and Carboniferous paleomagnetic data for western and central Europe

Structural setting	Strike	Decl.	Incl.	α_{95}	S_r-S_o	D_r-D_o
Buçaco "C"	180^1	179^1	$+36^2$	11	+30	+4
Buçaco "D"	180^1	188^1	$+5^2$	6	+30	-5
San Pedro	135^1	144^1	+34	9	+75	+41
San Emiliano	125^1	137^1	+13	2	+85	+48
Atienza	160^1	194^1	+19	12	+50	-8
Laval syncline tuffs	307	217	$+19^2$	6	-97	-28
Laval syncline sediments	307	224	$+25^2$	18	-97	-35
Cambro-Ordovician red beds	259	207	$+6^2$	14	-49	-18
Erquy-Cap Frehel redbeds	272	195	$+2^2$	12	-62	+6
Zone Bocaine	290	203	$+8^2$	13	-80	-14
Cabo de Peñas	265^1	203^1	$+19^2$	8	-55	-18
Carteret Group B	272	216	$+28^2$	14	-62	-27
Rozel Group B	255	203	0^2	7	-45	-14
Crozon dolerites	240	217	$+29^2$	10	-30	-28
Thouars	270	219	$+20^2$	18	-60	-30
Montmartin red beds	270	206	-3^2	12	-60	-17
Flamanville granite	270	203	+14	15	-60	-14
Plourivo redbeds	275	213	$+17^2$	12	-65	-24
Tregastel-Ploumanac'h granite	275	200	+9	7	-65	-11
Jersey dolerites	275	199	+16	9	-65	-10
North Brittany dykes	275	212	+10		-65	-23
Mill Haven sediments "P-C"	280	251	$+10^2$	8	-70	-62
Freshwater sediments "C"	280	222	-11^2	7	-70	-33
Freshwater sediments "D"	280	278	+20	16	-70	-55
Massif Central	265	258	+2	12	-55	-65
Franconian Forest "C"	240	203	-2	8	-30	-9
Franconian Forest "D"	240	186	+30	9	-30	+8
Harz Mountains "C"	240	183	-4	18	-30	+11
Harz Mountains "D"	240	189	+24	20	-30	+5

Devonian and Carboniferous paleomagnetic directions (Decl. and Incl.) for western and central Europe. α_{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_r) for the different regions investigated we used 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 interdependent (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-

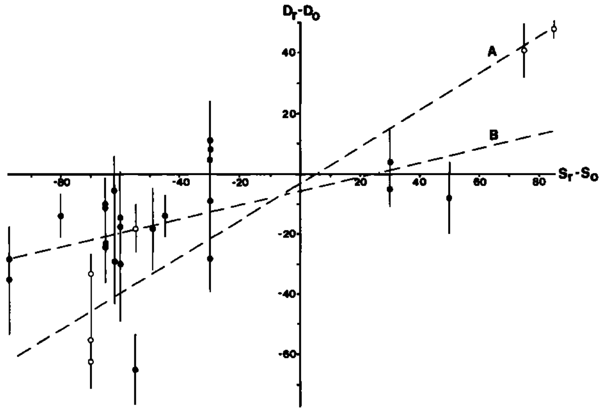

Fig. 2. Declination anomalies (D_r-D_o) plotted as a function of strike anomalies (S_r-S_o) for western and central Europe. Open symbols: data from thin-skinned parts of the orogen. S_r: reference strike; S_o: observed strike; D_r: expected magnetic declination, D_o: observed magnetic declination. Error bars calculated according to Beck [1980]. Lines A and B are the best fit for the data sets from allochthonous resp. autochthonous parts of the mountain belt, respectively.

defined correlation coefficient, r, of 0.47 (significant at the 95% probability level). Although 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., Eldredge 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 demonstrate the effect of thrust rotations in the external parts of the European Hercynides. This introduces an extra nuance to the interpretation of previous analyses [Perroud and Bonhommet, 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 results of this study:

(1) late to post-orogenic strike-slip movements may have led to large-scale draping or drag-folding (Figure 3a),

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

(3) structural trend changes could reflect heterogeneities of pre-collision cratonic margins [Lorenz, 1976; Lorenz and Nicholls, 1984], which acted as buttressing zones that molded the intervening, 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 Ribeiro, 1975; Matte and Burg, 1981] or by a microplate [Lefort and Van der Voo, 1981, Badham, 1982, Ziegler, 1983], (Figure 3d).

Discussion

The results of this study show that the bending of the European Hercynides and especially the Ibero-Armorican arc is at least in part a secondary feature showing both lithospheric and thin-skinned deformation. Though paleomagnetic data alone do not allow to distinguish between the different dynamic scenarios briefly described in the previous section, it should be pointed out that secondary bending of the Ibero-Armorican arc as a consequence of squeezing an already slightly bent fold system (model 2, Figure 3b) contradicts the sense of movement along the Ibero-Armorican shear zones [see Matte and Burg, 1981].

Structural data from the Ibero-Armorican arc [Brun and Burg, 1982] strongly suggest a first deformation of the Ibero-Armorican arc during the Devonian collision of Armorica with the northern continents [Perroud et al., 1984]. Combined

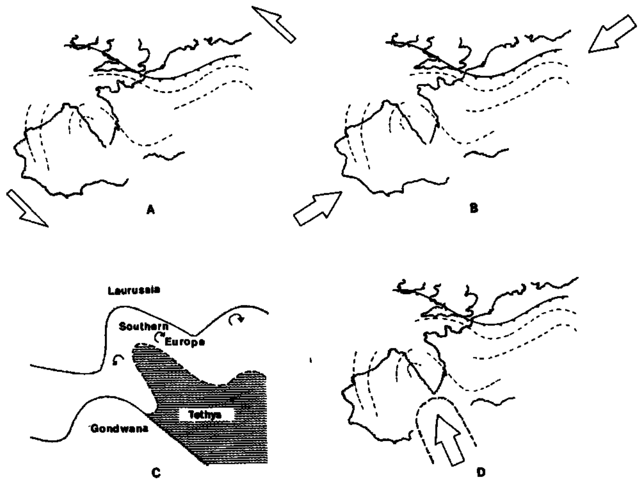

Fig. 3. Different models to explain the arcuate shape of the European Hercynides. A: Sinistral shear; B: Paleo-Southwest-Northeast directed compression; C: Deformation along salients and recesses [modified after Lorenz, 1976]; D: Indentation of Western Europe by the hypothetical Ebro-Pyrenean micro-continent. Symbols as in Figure 1. Curved arrows in Figure 3c indicate sense of rotation.

thrusting and wrenching [Brun and Burg, 1982] lead to some bending during the Acadian orogeny. Following model 4 (Figure 3d) subsequent northwest ward 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 oroclinal 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 oroclinal bending of the Hercynides.

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