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Late Devonian to Early Carboniferous palaeomagnetic poles from the Armorican Massif, France

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Summary. In order to test plate tectonic hypotheses for the Hercynian orogeny in western Europe, Late Devonian and Cambro-Ordovician redbeds and volcanics have been palaeomagnetically studied. The Late Devonian redbeds show nearly univectorial remanent magnetizations during stepwise thermal, chemical and alternating field demagnetization and yield a pole position at 19.8° N, 144.2° E. All three Cambro-Ordovician units studied yielded characteristic directions of magnetization that are interpreted as remagnetizations of Late Devonian–Early Carboniferous age on the basis of negative fold tests, similarities with the directions of the Late Devonian redbeds, reset K/Ar ages of 345 MA, or the occurrence of significant high-temperature magnetizations. A comparison of a mean Late Devonian–Early Carboniferous pole for all four formations (28.1° N, 146.4° E, $dp = 3.87°$, $dm = 7.50°$) from the Armorican Massif with contemporaneous poles from stable ('extra-Hercynian') Europe indicates that there was little or no separation between Hercynian and stable Europe in that time. A significant separation between the Armorican Massif and Gondwanaland, on the other hand, suggests that an intervening middle Palaeozoic ocean existed which subsequently was consumed by subduction somewhere to the south of the Armorican Massif. Those high-temperature directions from the Cambro-Ordovician redbeds and volcanics that are relatively well grouped are interpreted as original Cambro-Ordovician magnetizations. They show shallow inclinations and north-westerly declinations, but are not sufficiently substantiated to give more than the tentative interpretation that their palaeolatitudes also are roughly in agreement with the data from stable Europe for that time.

Introduction

Interpretation of past orogenies in a plate tectonic context is valuable in expanding knowledge of plate tectonic theory and of specific orogenic processes. Some orogenies readily lend themselves to a tectonic subduction and/or collision interpretation. Others, such as the Late Palaeozoic Hercynian orogeny of western Europe, are enigmatic. The Hercynian orogenic belt lacks many of the typical tectonic indicators of subduction and collision and has characteristics not easily explained in plate tectonic terms. The Hercynian belt has few or no high-pressure, low-temperature metamorphic indicators, ophiolites or ultrabasites. Nappe structures are rare. Metamorphism is shallow. In addition, the orogenic belt is very wide (approximately 1000 km) and contains abundant granites and migmatites (Zwart 1967). The difficulty in placing the Hercynian orogeny into a plate tectonic model can be seen in the number of locations of proposed subduction zones (Fig. 1) and the suggested styles and timing of closure.

The plate tectonic models can be divided into three groups: (1) those proposing the closure of an ocean to the north of the Armorican Massif separating stable or northern Europe from Hercynian or central and southern Europe ending in a continent–continent collision (Johnson 1973, 1974; Dewey & Burke 1973; Burrett 1972; in part, McKerrow & Ziegler 1972; in part, Burne 1973), (2) those proposing the closure of an ocean to the south of Hercynian Europe in an Andean-type subduction, later the site of the Alpine orogeny (Nicolas 1972; Floyd 1972), and (3) those proposing the existence of more than one ocean where Hercynian Europe or parts of it acted as microplates between or attached to stable Europe and the Gondwana continents (Laurent 1972; Riding 1974; Badham & Halls 1975; in part, Floyd 1972). In general, proponents of subduction maintain that closure of an intervening ocean or oceans was occurring during the Late Devonian and/or Early Carboniferous with final collision in the early Late Carboniferous. Krebs & Wachendorf (1973) and Ager (1975) dispute the palaeontological, structural, geochemical and sedimentological arguments and maintain that the Hercynian orogeny did not involve any large-scale

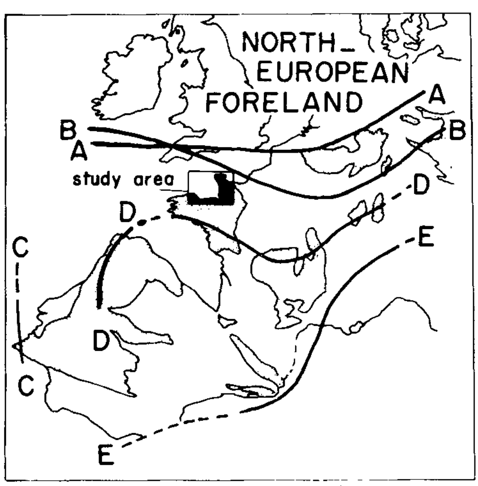

Figure 1. Approximate locations of proposed subduction zones in a plate tectonic interpretation of the Hercynian belt. Zone A: Johnson (1973, 1974); Zone B: Burrett (1972), Dewey & Burke (1973), Laurent (1972), in part Burne (1973); Zone C: Burrett (1972), Bard *et al.* (1973); Zone D: Riding (1974); Zone E: Floyd (1972), Nicolas (1972), Laurent (1972) and Riding (1974). The major Hercynian massifs and uplands are indicated as well as our study area.

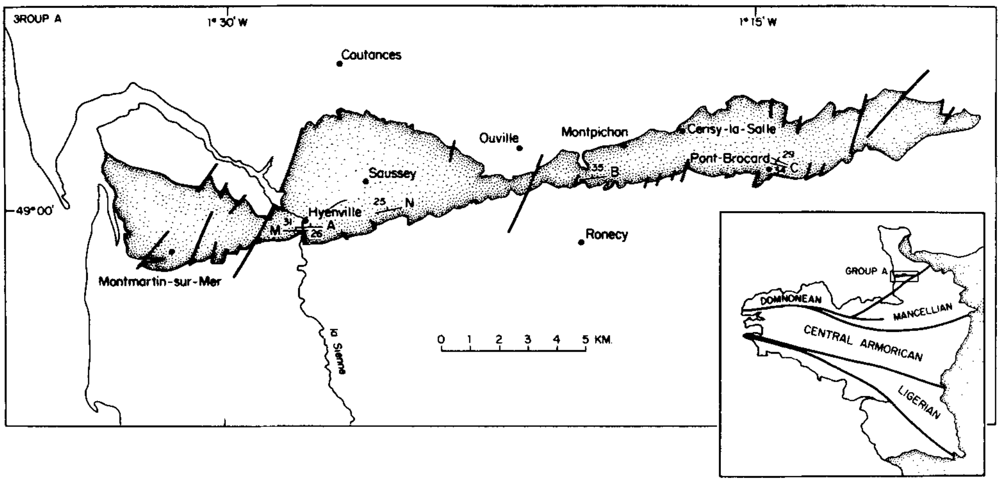

Figure 2. Schematic map with the sampling sites of the samples of Group A from the Syncline of Montmartin, Normandy. The strike and dip symbols indicate the site locations, the numbers represent the dip and the letters refer to the site-code used in the text and tables. The inset gives the main domains of the Armorican Massif after Cogné (1974) and the location of the Syncline of Montmartin.

plate motions but was of ensialic nature, i.e. an orogenic event probably of thermal origin occurring within the already unified European continental plate.

The existence of an ocean or oceans separating Hercynian Europe from stable Europe and/or the Gondwana continents during the Middle to Late Palaeozoic is testable palaeomagnetically. Comparison of the palaeolatitude of Hercynian Europe with respect to stable Europe and Gondwanaland during a given time in the Palaeozoic can show the latitudinal extent of any such oceans at that time. Although sparse within certain ages, enough palaeomagnetic data exist for stable Europe and the Gondwana continents for such a comparison through most of the later Palaeozoic. The present study was undertaken to obtain palaeomagnetic data for Hercynian Europe to complete the comparison.

The Armorican Massif was selected for sampling due to prevalence of relatively unmetamorphozed Palaeozoic sediments preserved in the synclines of Normandy and Brittany. The Massif is divided into a series of domains separated by fault systems trending E–W to ESE–WNW (Fig. 2, inset). The two northernmost domains, the Domnonean domain and the Mancellian domain, are thought to have been virtually unaffected or only moderately affected respectively by the Hercynian deformation and metamorphism (Cogné 1974), and thus they appeared to be well suited for palaeomagnetic investigation. Devonian redbeds were sampled from the Syncline of Montmartin (Group A) in Normandy, Cambro-Ordovician redbeds and trachyandesites were sampled in the areas of Paimpol–Bréhec (Group B) and Erquy–Cap Fréhel (Group C) in northern Brittany. Samples of Late Cambrian to Early Ordovician redbeds were taken from the Syncline of the Zone Bocaine (Group D) in Normandy. The geology and relative ages of the individual areas will be discussed with the results.

Sampling and laboratory techniques

All sites but one were drilled in the field and oriented with a standard geological compass. For two sites within the trachyandesite, orientation errors increased from $\pm 2^{\circ}$ to a maximum of ±30° on strike and ±15° on dip because the flow structure was difficult to determine. Consequently the strike and dip had to be approximated from nearby sedimentary strata and map outcrop pattern. The one site not drilled in the field was collected as hand-samples and had an approximate orientation error of ±4°. All samples were demagnetized in a stepwise fashion thermally, chemically and in alternating fields or various combinations thereof. The procedure for chemical leaching followed that of Roy & Park (1974) with the following two exceptions: (1) the normality of HCl was increased from 8N to 10N at 600 hours, and (2) samples were leached and stored in a magnetic field of approximately 200 nanoTesla (nT) ± 200 nT after effects of the Earth's field were observed when samples were treated in unshielded space. Measurements were made on either a Schonstedt SSM-1A Magnetometer or a Super-Conducting Technology 1–½ inch Cryogenic Magnetometer. Demagnetizations were plotted using Zijderveld (1967) diagrams and analysed by vector subtraction. All directions so obtained as well as sampling localities and lithologies are given in more detail in Jones (1978).

Results

GROUP A – LATE DEVONIAN OF THE SYNCLINE OF MONTMARTIN, NORMANDY

Five redbed sites were sampled on the south limb of the Syncline of Montmartin (Fig. 2). Three sites are within the redbeds of Hyenville which are assigned a Late Devonian age by Doubinger & Poncet (1964) and Doubinger, Drot & Poncet (1966) on the basis of microfossils. The remaining two sites (B and C) are within the finer-grained layers of the basal conglomerate in the eastern portion of the Syncline. The age of these beds is questionable since some authors claim the fault separating the eastern and western portions of the Syncline (and the two sets of sites from each other) to be a delineation between Late Devonian to the west and Late Ordovician or Early Silurian to the east (Cogné 1974; Robardet 1973). In addition, there is controversy about a conformable versus tectonic contact in the east between the (sampled) basal conglomerate and the (unsampled) overlying sandstone which contains fossils of tentative Ordovician/Silurian age (Robardet 1973; Doubinger *et al.* 1966). Because of the uncertainty of the age determination of the basal conglomerate, we are following Graindor & Roblot (1966) in taking the entire sampled portion of the Syncline of Montmartin as Late Devonian. The mean direction for the redbeds is given with and without these two possibly Ordovician sites. It can be seen in Table 1 that this does not make any appreciable difference.

Thermal, chemical and alternating field demagnetizations were performed on the Late Devonian redbeds. The demagnetization curves are generally of good quality and show nearly univectorial decay (Fig. 3). In almost all cases the chemical demagnetizations agree well with thermal and alternating field demagnetizations in both the component removed and the final 'stable' component (the endpoint at which direction and intensity changes cease). The direction and coercivity of this final component was determined by further demagnetization in alternating fields of one of the chemically demagnetized samples (following the technique used by Park (1970)). The direction obtained by vector subtraction of the final component was very similar to the characteristic direction seen in all other samples from Group A that were thermally or chemically demagnetized. The final component was of low coercivity since approximately 50 per cent of the remaining magnetization was removed by peak alternating fields of 50 milliTesla (500 Oe). The low coercivity and resistance to acid leaching would imply that the final component was carried by magnetite of relatively large grain size.

High-temperature directions were observed in some samples. The high-temperature component was seen either as an over-shoot of the origin at intensities above machine noise level (as in sample A 7b, Fig. 3) or as a small final component decaying to the origin but barely above machine noise level (as in sample A 10 of Fig. 3). When statistically analysed the high-temperature directions are very poorly grouped (with a Fisher precision parameter of 2 (Table 2)) and consequently are taken to be insignificant.

Fig. 4 is an equal-area plot of the characteristic directions of magnetization after structural correction. Due to the similarity of bedding corrections a fold test of these characteristic directions of magnetization is not significant at the 95 per cent confidence level. However, the nearly univectorial decay during thermal, chemical and alternating field demagnetizations (excluding the scattered high-temperature magnetization) documents the existence of only one significant direction of magnetization recorded in the redbeds, regardless of the blocking temperature, solubility and coercivity of the carriers of magnetization. Since no conclusive evidence for remagnetization is seen, the resulting pole position of 19.8° N, 144.2° E is taken to be the Late Devonian pole for the Syncline of Montmartin.

GROUP B – CAMBRO-ORDOVICIAN OF PAIMPOL-BRÉHEC, BRITTANY

Three sites of redbeds and five sites of trachyandesites were sampled in the Paimpol-Bréhec area (Fig. 5, top). The three redbed sites were sampled from the redbed of la Roche-Jagu, one of which was quartzitic (site D). Three of the trachyandesite sites are within a flow intercalated with the redbeds. Of these three, sites F and G appear weathered in outcrop. The remaining two trachyandesite sites (I and Y) were sampled from two dikes cutting the redbeds.

The redbeds contain no fossils; therefore an age assignment is made on the basis of radiometric dating of the intercalated trachyandesite flow and dikes. Recently these have been assigned a Rb/Sr whole-rock isochron age of 472 ± 8 MA (Macé *et al.* 1979). In addition, two much younger Late Devonian K/Ar ages have been found (Macé *et al.* 1979; Rochette-Pinel, Giot & Dumesnil 1965) for the trachyandesite flow; these appear to record a younger thermal event which has affected these rocks.

Most of the redbed specimens from Group B were demagnetized thermally. Of these, some were demagnetized in alternating fields before thermal treatment. The remainder was chemically leached and/or demagnetized in alternating fields. The quartzitic site D showed erratic or inconsistent behaviour during thermal, alternating field and chemical treatment. Consequently, the site has been omitted from the group average, even though its mean direction is not very different from those of the other sites (Table 1). The two other redbed sites showed thermal behaviour similar to that of the Late Devonian from the Syncline of Montmartin in Normandy with the addition of a low-temperature component. As in Group A, a high-temperature component is seen in some of the samples.

Unlike Group A, the chemical demagnetizations of the Group B redbed samples were in apparent disagreement with the thermal and alternating field demagnetizations. Eight specimens of fine-grained red sandstone from site H were partially or wholly chemically demagnetized. In all but one case the inclination steepened as leaching proceeded. Slicing of one specimen showed that the red pigment was being removed throughout the core and therefore the steepening of inclination could not be caused by incomplete penetration of the acid which, in turn, would cause increasing predominance of the NRM from unleached portions of the core. Alternating field demagnetization of two of the chemically leached samples that had not yet been completely demagnetized showed removal of a 'soft', low-coercivity component of steep inclination (more than 50 per cent of the intensity remaining

Table 1. Site means and group means of the characteristic directions of magnetization.

Site	N/N_0	Decl./incl. before structural correction	k_1	α_{95}	Mean pole	Decl./incl. after structural correction	k_2	α_{95}	Mean pole	k_2/k_1
Group A, Late Devonian from the Syncline of Montmartin, Normandy										
A	13/13	215.0/+1.7	34.6	7.2°	31.8 N, 136.1 E	218.7/+23.7	34.3	7.2°	19.8 N, 138.1 E	
B	7/7	203.8/−1.7	121.3	5.5°	37.7 N, 148.1 E	208.6/+25.8	121.1	5.5°	22.5 N, 148.4 E	
C	9/9	211.3/+12.3	68.1	6.2°	28.4 N, 142.8 E	208.7/+43.5	70.7	6.2°	11.3 N, 152.5 E	
M	15/15	217.8/−3.9	32.9	6.8°	33.0 N, 131.6 E	220.7/+19.3	33.0	6.8°	21.1 N, 135.0 E	
N	7/7	203.9/+7.3	49.9	8.6°	33.4 N, 149.6 E	209.0/+25.6	49.9	8.6°	22.4 N, 147.9 E	
Mean	5/5	210.4/+3.2	77.8	8.7°	33.0 N, 141.5 E	213.4/+27.7	57.4	10.2°	19.8 N, 144.2 E	0.74
Mean (A, M, N)	3/5	(212.3/+1.7)	(77.3	14.1°	32.9 N, 139.1 E	216.2/+23.0)	(151.4	10.1°	21.2 N, 140.8 E)	1.96
Group B, Cambro-Ordovician from the Paimpol-Bréhec area, N. Brittany										
D	4/7	(198.3/−13.9)	(2.7	71.2°	45.6 N, 150.4 E	198.5/+13.3)	(2.7	71.2°	32.2 N, 155.0 E)	
E	9/9	210.5/+26.2	63.9	6.5°	21.8 N, 144.9 E	207.1/+4.3	63.9	6.5°	33.9 N, 143.7 E	
F	7/7	202.8/+5.3	59.1	7.9°	35.0 N, 148.9 E	204.7/+10.7	59.2	7.9°	31.8 N, 147.7 E	
G	10/11	197.7/+5.0	33.0	8.5°	36.5 N, 154.8 E	202.2/+19.0	32.5	8.6°	28.3 N, 152.0 E	
H	17/22	210.8/+16.6	88.2	3.8°	26.7 N, 142.5 E	209.2/−10.4	76.1	4.1°	39.9 N, 137.7 E	
I	12/13	228.4/+10.1	23.3	9.2°	21.7 N, 123.8 E	226.8/−5.2	24.5	9.0°	29.0 N, 120.7 E	
Y	6/6	218.5/+34.9	16.5	17.0°	13.9 N, 139.8 E	200.5/+28.1	16.9	16.9°	23.8 N, 155.4 E	
R	5/5	223.7/+19.7	49.2	11.0°	19.7 N, 130.8 E	221.7/−0.8	49.3	11.0°	29.9 N, 127.0 E	
Mean	7/8	213.0/+17.1	27.8	11.6°	25.6 N, 140.7 E	210.5/+6.6	23.3	12.8°	31.6 N, 140.5 E	0.84

Group C, Cambro-Ordovician (?) from the Erquy-Cap Fréhel area, N. Brittany										
J	9/10	197.5/−12.9	104.7	5.1°	45.3 N, 152.4 E	196.0/+24.9	104.3	5.1°	26.7 N, 160.1 E	
K	14/16	(245.0/+53.3)	(9.3	13.7°	18.8 N, 127.6 E	293.7/+59.7)	(9.3	13.7°	43.6 N, 283.6 E)	
S	5/5	190.2/+29.7	19.1	18.0°	24.8 N, 166.8 E	196.4/+37.4	19.1	18.0°	18.9 N, 161.5 E	
T	5/5	(194.0/+3.1)	(3.1	52.3°	38.3 N, 159.8 E	195.3/+22.2)	(3.1	52.3°	28.3 N, 160.6 E)	
Mean	14/36	195.1/+1.7	11.3	12.4°	38.8 N, 158.0 E	196.1/+29.2	36.1	6.7°	24.1 N, 160.6 E	3.20
(Sites J and S)										
Group D, Cambro-Ordovician from the Zone Bocaine, Normandy										
L	4/5	213.1/+26.2	24.2	19.1°	20.7 N, 144.7 E	214.5/+71.2	24.2	19.1°	18.7 S, 159.5 E	
P	9/9	199.3/−5.0	102.5	5.1°	40.7 N, 153.5 E	197.5/−13.7	102.3	5.1°	45.4 N, 154.2 E	
Q	6/6	200.8/+30.5	8.5	24.4°	22.1 N, 157.9 E	200.8/−27.5	8.5	24.3°	51.6 N, 145.9 E	
O	8/8	213.0/+0.7	147.9	4.6°	33.1 N, 138.4 E	244.7/−39.3	140.3	4.7°	33.0 N, 92.4 E	
U	7/7	185.8/+6.2	57.6	8.0°	37.7 N, 171.8 E	187.5/+7.8	57.4	8.0°	36.7 N, 169.7 E	
V	6/6	203.1/−7.6	48.9	9.7°	40.8 N, 148.1 E	192.8/−38.0	48.9	9.7°	60.6 N, 154.4 E	
W	15/15	205.4/+4.4	23.8	8.0°	34.3 N, 147.7 E	209.6/−14.7	23.8	8.0°	41.6 N, 138.1 E	
Mean	7/7	202.9/+7.9	21.8	13.2°	33.4 N, 151.5 E	204.7/−11.6	4.2	33.7°	(42.1 N, 145.1 E)	0.19

N/N_0 is the ratio of samples used to compute the mean to the total number of samples analysed; k_1 and k_2 are the Fisher precision parameters before and after correction for the tilt of the strata, respectively; α_{95} is the semi-angle of the cone of confidence at the 95 per cent probability level.

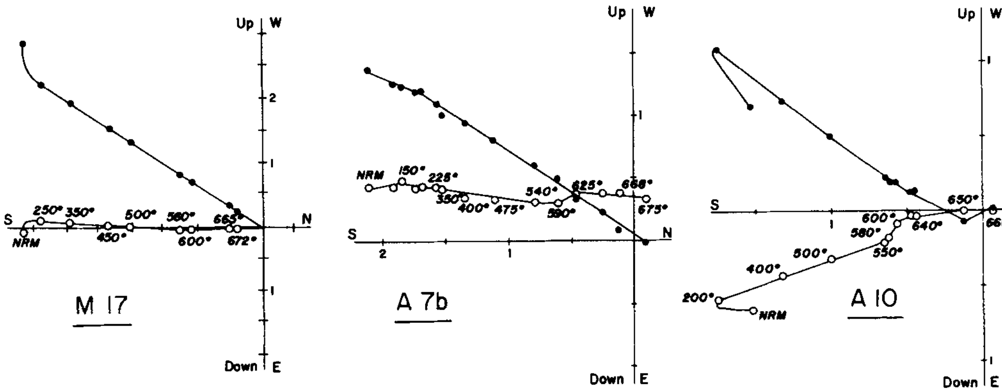

Figure 3. Orthogonal demagnetization projections (Zijderveld 1967) of the successive endpoints of the magnetization vector during progressive thermal demagnetization, before correction for the tilt of the strata (i.e. with respect to the present-day horizontal). Demagnetization temperatures are indicated in degrees Celsius. Solid circles represent projections on to the horizontal plane, and open symbols those on the north–south vertical plane. Units are indicated for the axes in 10^{-3} Am^{-1} (10^{-5}emu per sample of 10 cm^3). The samples are from the Devonian red siltstones of Group A (Syncline of Montmartin).

after leaching was removed by 50 mT). A similar, most likely secondary, steep, low-coercivity component was removed in samples that were demagnetized in alternating fields before any other demagnetization was performed. As illustrated in Fig. 6, it appears that the steep, 'soft' component was only partially removed during chemical demagnetization while the characteristic direction (as seen in thermal demagnetization) was almost completely removed. Since at no time during chemical leaching this characteristic direction could be isolated, the chemically demagnetized samples of site H have not been used in calculating the site mean.

The trachyandesites from Group B were demagnetized thermally and with alternating fields. Initial intensities were low, ranging from 10^{-1} A/m (10^{-4}emu cm^{-3}) to 10^{-3} A/m (10^{-6}emu cm^{-3}). All samples showed at least two components of magnetization, several showed three (see Fig. 7). One dike sampled (site Y) records the only normal polarity in Group B. Five of the six samples from this dike had characteristic magnetizations almost exactly antipodal to the rest of Group B (Fig. 8(a)).

In addition to demagnetization studies, polished thin sections of seven trachyandesite samples were examined. The thin sections showed a preponderance of a hematitic alteration product, a scarcity of original magnetite, as well as a very fine-grained ($\leqslant$ 1 μm in diameter), optically unidentifiable, opaque phase. The low initial intensities observed in the demagnetization studies are in agreement with the predominance of hematite. However, the low-temperature and characteristic components were removed below or by the Curie temperature of magnetite (*c*. 580°C). Thus, the hematite may be the result of two different alterations and be rich in titanium. The latter is also suggested optically by occasional intergrowths of hematite and rutile. The high-temperature component seen in Fig. 7 was removed near the magnetite Curie point. In other samples it was removed near or above 580°C. Thus, the carrier of this high-temperature component must be relatively pure iron oxide and may be associated with the unidentified fine-grained opaque phase, perhaps 'primary' in origin.

The directions of magnetization observed in the Cambro-Ordovician of Brittany based on

Table 2. High-temperature directions and their means.

Age and area	N	Decl./incl. before structural correction	Decl./incl. after structural correction	k_2	α_{95}	Mean pole	Polarity	k_2/k_1
Upper Dev.	3	283.6/+55.7	329.1/+57.5	2.1	>90°	65.4 N, 254.2 E	R + N	1.21
Montmartin	(19)	(273.2/+11.1)	(277.9/+12.7)	(2.0)	(33.9°	10.0 N, 266.9 E)	(R + N)	(1.04)
Cambro-Ord.	6	330.8/+23.3	325.0/+37.0	12.5	19.7°	50.4 N, 234.4 E	R + N	3.19
Paimpol-B.	(20)	(300.1/+28.5)	(294.4/+32.6)	(2.1)	(30.8°	29.3 N, 260.7 E)	(R + N)	(1.06)
Cambro-Ord. Erquy-C.F.	12	308.5/+15.2	312.0/−0.7	4.9	21.8°	25.9 N, 233.2 E	R + N	1.00
Cambro-Ord.	5	265.8/+48.9	235.6/−1.1	1.5	>90°	22.2 N, 116.2 E	R + N	0.86
Zone Bocaine	(38	230.3/+21.0)	(225.2/+9.9)	(1.9)	(24.8°	23.3 N, 128.8 E)	(R + N)	(0.94)

N is the number of samples used in calculating the mean; k_1 and k_2 and α_{95} are explained in the footnote to Table 1. R denotes reversed polarity and N denotes normal polarity. Entries without parentheses indicate a mean direction based on high-temperature components that meet the reliability criteria. Entries within parentheses indicate a mean direction that is based on all final high-temperature components whether they meet the reliability criteria or not.

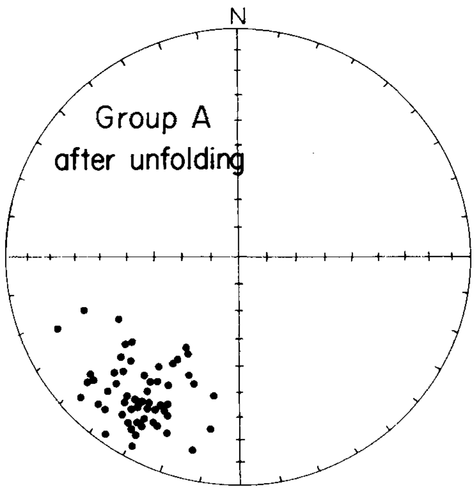

Figure 4. Equal-area projection of the directions obtained through demagnetization techniques from the samples of Group A (Syncline of Montmartin). Open (solid) symbols represent projections on to the upper (lower) hemisphere.

well-defined high-temperature components will be discussed in more detail in a later section. Let it suffice now to say that they show the greatest directional consistency of high-temperature directions of any of the areas sampled – they pass a fold test at the 95 per cent confidence level (McElhinny 1964) and yield a mean declination/inclination of 325.0°/+37.0° after structural correction.

The characteristic direction of magnetization seen in all Group B samples has a declination/inclination of 210.5°/+6.6° and yields a pole position of 31.6° N, 140.5° E. However, this characteristic magnetization is most likely a remagnetization. The presence of a small, although consistent, high-temperature direction and the oxidation of the trachy-andesites examined in polished thin section suggests that the characteristic direction is not primary. In view of the reset K/Ar ages (345 MA) and the proximity of this pole to the Late Devonian pole of Group A from Normandy we interpret the pole position to be Late Devonian(?).

GROUP C – CAMBRO-ORDOVICIAN(?) OF ERQUY-CAP FRÉHEL, BRITTANY

Various lithologies were sampled within the redbeds of Erquy-Cap Fréhel in Brittany. A corresponding variation in magnetic behaviour and results was observed. Two of the four Group C sites (site S and T) are located in relatively coarse, quartzitic pink sandstone. Samples taken from site J were of pink sandstone, of red siltstone lenses within the pink sandstone and of well-indurated arkosic sandstone. Samples at site K were of somewhat fissile, fine-grained, very red sandstone (see Fig. 5 for sampling localities).

The Erquy-Cap Fréhel redbeds are taken to be Late Cambrian–Early Ordovician in age. This age is based on: (1) a stratigraphic correlation of the Erquy-Cap Fréhel redbeds across the Bay of St Brieuc with the redbeds of la Roche-Jagu of Group B and an overlying sandstone, and on (2) a Rb/Sr isochron of 482 ± 10 MA for the Erquy spilites and supportive microfossil evidence below the conformable overlying redbeds of Erquy-cap Fréhel (Vidal

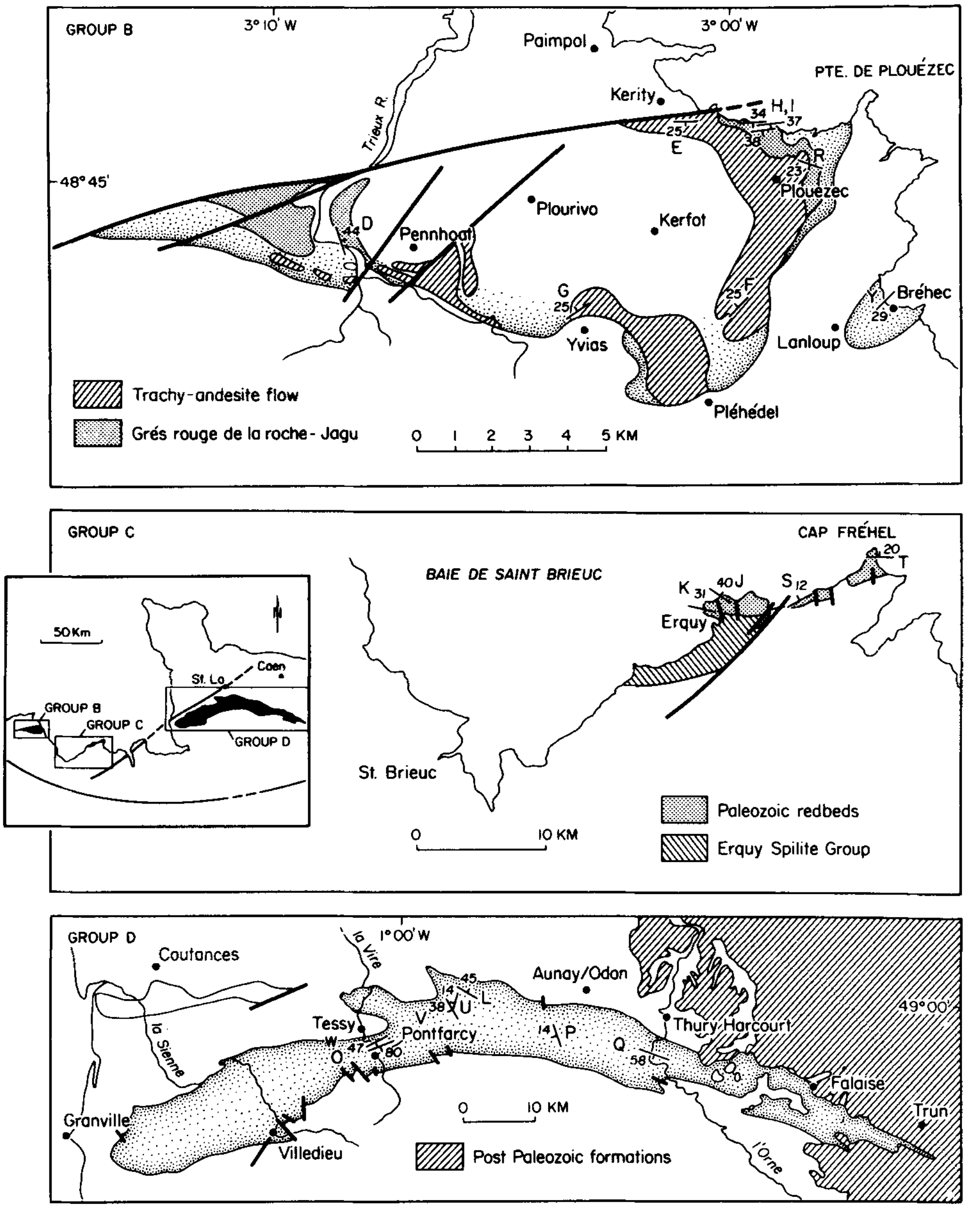

Figure 5. Schematic geologic maps of the sampling sites of Groups B, C and D from the Paimpol-Bréhec area, the Erquy-Cap Fréhel area and the Zone Bocaine in Normandy, respectively. The inset shows the locations of these areas. The sites are indicated as in Fig. 2.

1976). There is some controversy about Vidal's age determination of the spilites (Brown & Roach 1972a, b; Auvray *et al.* 1972). A whole rock K/Ar age determination and sedimentological arguments led Brown & Roach to include the Erquy spilite group in the Precambrian Brioverian sequence. However, the close agreement of two separate Rb/Sr isochron ages on either side of the Bay of St Brieuc and the stratigraphic correlation of redbeds lends support to the Late Cambrian–Early Ordovician age used in this study.

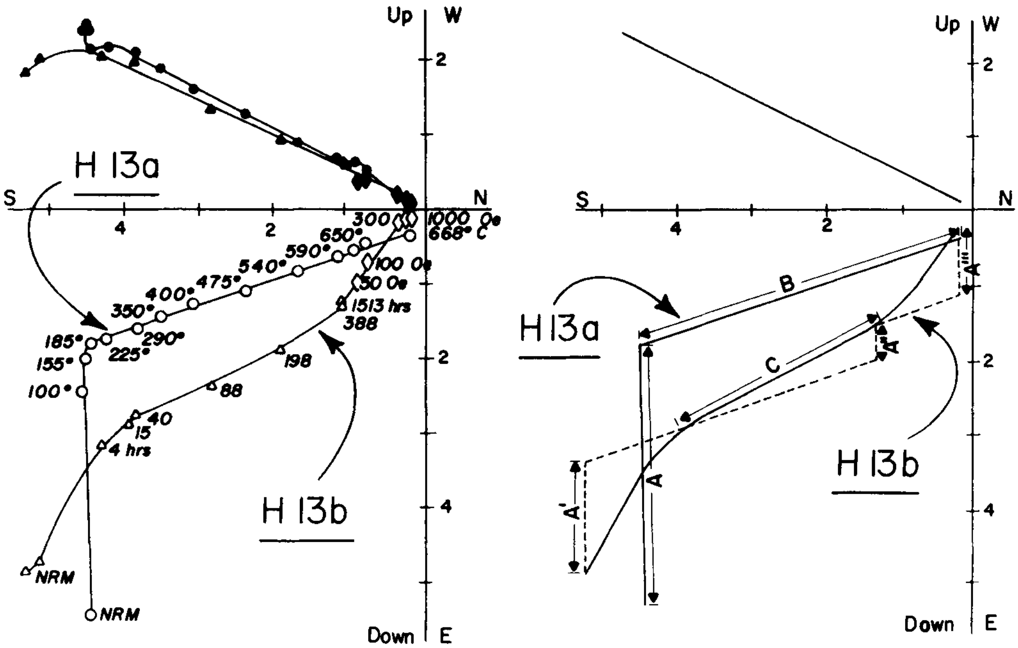

Figure 6. Orthogonal demagnetization projections (as in Fig. 3) of a combined chemical-alternating field treatment and a thermal demagnetization of samples from the same core (redbed site H from Group B, Paimpol-Bréhec area). Temperatures are indicated in degrees Celsius for thermal treatment (circles), alternating field peak values are in oersteds (diamonds) and chemical leaching times are in hours (triangles). Units for the axes are in 10^{-3} Am^{-1} (as in Fig. 3). On the right the demagnetization trajectories are schematically presented: they show the continuous and incomplete removal during chemical leaching of the 'soft' component of magnetization. This component has been labelled A in the thermal demagnetization where it is observed to have low blocking temperatures; it has been labelled A′, A″ and A‴ in the chemical and alternating field demagnetization, where it is observed to have a broad range of solubilities, but relatively low coercivities. At no time is the equivalent of the 'stable' B component (observed in thermal demagnetization) isolated in chemical leaching.

All but three of the redbed samples from Erquy-Cap Fréhel were thermally demagnetized. The three remaining samples were chemically leached. Site J generally shows good demagnetization curves, initial intensities from 2.9 to 0.3 × 10^{-3} A/m, good grouping of characteristic directions at the site mean level and little evidence of a high-temperature component. Site S, of quartzitic pink sandstone, showed a wide range of blocking temperatures and initial intensities from 2.0 to 8.0 × 10^{-3} A/m and at least two distinct components of magnetization. The lower, and larger, component is taken as the characteristic direction of magnetization since the higher-temperature component is very scattered. Site T, also of quartzitic pink sandstone, consisted of samples with generally low blocking temperatures (most below 450°C) and inconsistent directions of magnetization; the one high-temperature direction (600°C) is similar to those seen in sites S, J and the 'Devonian' directions. However, the site as a whole has been eliminated from the group mean, even though its mean direction is very close to those of the other sites (Table 1).

Site K is anomalous with respect to the other Erquy-Cap Fréhel results. The highest temperature components of magnetization are within the hematite blocking temperature range, in most cases being removed between 655°C and 660°C and often within a 2° or 3° interval (Fig. 9). Initial intensities were somewhat higher than those of the preceding three

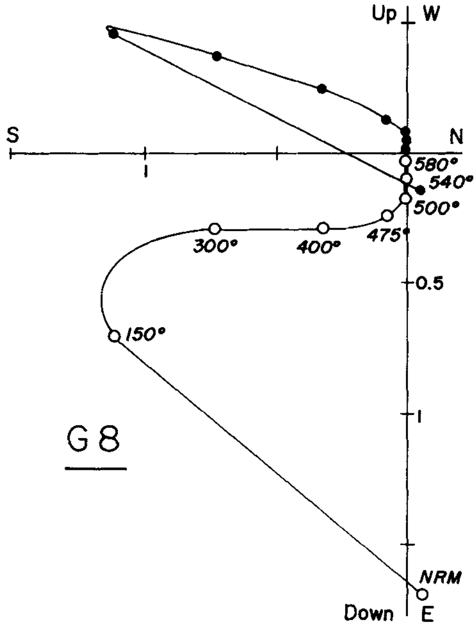

Figure 7. Orthogonal demagnetization projection (as in Fig. 3) of a sample from Group B, site G (trachy-andesite). Note the multivectorial nature of the magnetization and the presence of a significant high-temperature component eliminated above 500°C. Units for the axes are the same as in Fig. 3.

sites, being between 1.5 and 0.1 x 10^{-2} A/m. The high-temperature components show a somewhat scattered grouping and a mean direction of $D = 308.5°$, $I = +15.2°$ before structural correction and $D = 312.0°$, $I = -0.7°$ after structural correction (Table 2). Site K included one sample of reversed polarity with respect to the rest. The site also included two samples of possible transitional polarity (from the same approximate stratigraphic level as

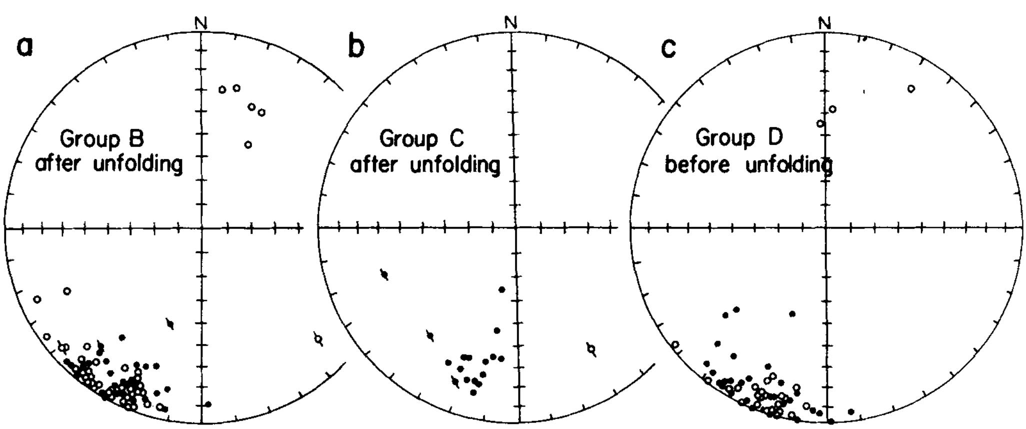

Figure 8. Equal-area projections of the characteristic directions of magnetization obtained from the samples of Groups B, C and D from the Paimpol-Bréhec area, the Erquy-Cap Fréhel area and the Zone Bocaine in Normandy, respectively. Full and open symbols are as explained in Fig. 4; the symbols with a slash through them are from sites not included in the calculation of the mean direction of magnetization.

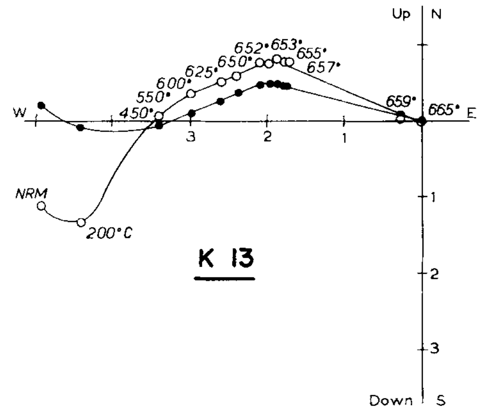

Figure 9. Orthogonal demagnetization projection of a thermal demagnetization of a sample from Group C (Erquy-Cap Fréhel redbeds), before correction for the tilt of the strata. Symbols and units for the axes are the same as those used in Fig. 3, except that the vertical projections are made here on to the east–west vertical plane. Note the presence of a high-temperature component of magnetization, which is removed in the narrow blocking-temperature interval of 657 to 659°C.

the reversed (?) polarity sample) that show poor demagnetization curves and have been eliminated from the site mean. The high-temperature direction is similar to that seen in the well-defined high-temperature directions of the Cambro-Ordovician of Paimpol-Bréhec and will be further discussed in a later section. The lower-temperature directions of site K, although less scattered, are also somewhat anomalous. The declination/inclination before unfolding is 245.0°/+53.3° and after unfolding is 293.7°/+59.7°. Thus, there appears to be no record in site K of the same 'Devonian' directions observed in Groups A and B and in sites S and J, unless the lower-temperature directions are interpreted as the simultaneous removal of a Devonian direction and the north-westerly high-temperature direction.

Table 1 gives the group mean for the characteristic direction of sites S and J alone. Site K is not included in the group mean since its lower-temperature component may contain

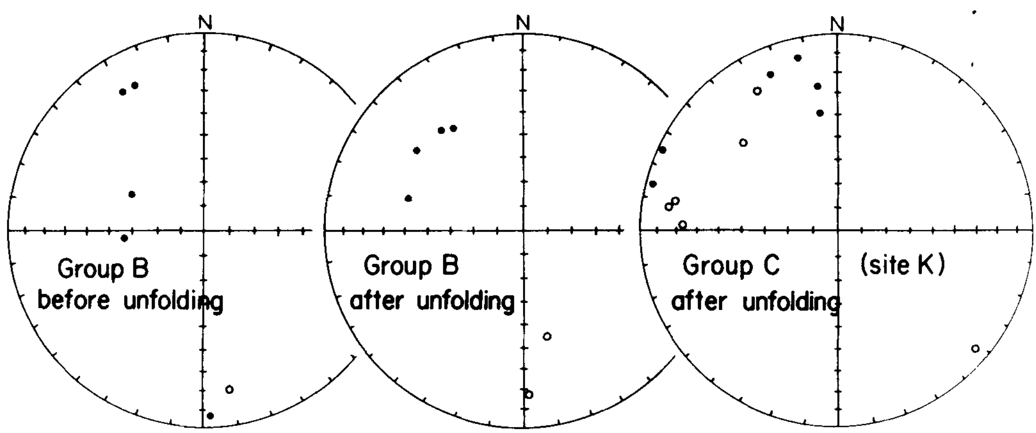

Figure 10. Equal-area projections of the high-temperature directions of magnetization obtained from the samples of Groups B and C, from the Paimpol-Bréhec area and the Erquy-Cap Fréhel area, respectively. Symbols as in Figs 4 and 8.

some of the high-temperature direction. The group mean ($D = 196.1°$, $I = +29.2°$ after unfolding) is in close agreement with the Devonian result of Group A. For this reason we interpret these directions (shown in Fig. 8) in a similar fashion as those from Paimpol-Bréhec – the directions are assumed to be of Late Devonian(?) age and are remagnetization directions. The high-temperature direction of site K (Fig. 10) is listed in Table 2. There is no evidence of this high-temperature component in either site J or S, although some directions of site T appear to support the high-temperature directions of site K. The high-temperature direction is discussed in a later section of this paper along with the high-temperature directions from the other groups.

GROUP D – LATE CAMBRIAN–EARLY ORDOVICIAN OF NORMANDY

The Cambro-Ordovician redbeds of the Syncline of the Zone Bocaine are definitely remagnetized. As seen in Table 1, they fail a fold test, even at the 99 per cent confidence level (McElhinny 1964), and hence prove to have been remagnetized during, or subsequent to, the time of folding of the Syncline.

Seven sites of red siltstones of the redbeds of St. Rémy were sampled within the Syncline of the Zone Bocaine (Fig. 5, bottom). In the eastern and western portions of the Zone Bocaine, the 'syncline' is, in fact, a synclinorium made up of two synclines separated by an anticline (Robardet 1973). Sites are located on both north and south limbs of the synclines. Consequently, the collection encompasses considerable structural variation with strike/dip ranging from 73°/80° to 302°/45°.

In the explanation of the Coutances geological map, Graindor (1966) calls the redbeds of St Rémy (which are included in the 'schistes et grès rouges') Tremadocian in analogy to other Armorican redbeds of that age. An age discrepancy arises in both the placement of the Tremadocian as a stage and in other authors' age assignments of the same beds. Doré (1969, 1972) and Robardet (1973) assign a Cambrian age to these redbeds since they underlie the Grès de Montabot of latest Cambrian age. The Tremadocian age, although of little significance in light of the complete remagnetization, has been used in this study and is taken to be latest Cambrian to earliest Ordovician.

Site Q was the only site of all the Cambro-Ordovician sites in Normandy that showed two distinct components of magnetization. The higher-temperature component was large enough and, although somewhat scattered, consistent enough to be taken as the characteristic direction ($D = 200.8°$, $I = +30.5°$ before unfolding; $D = 200.8°$, $I = -27.5°$ after unfolding). This component was of mixed polarity, containing the only normal polarities seen in Group D. The lower-temperature component showed a steep negative inclination ($D = 187.4°$, $I = -42.3°$) before structural correction, and an anomalous direction ($D = 67.6°$, $I = -74.2°$) after structural correction. The *in situ* lower-temperature direction could represent a Late Mesozoic–Early Cenozoic remagnetization since the resulting pole of 64.8° N, 163.5° E is in close agreement with poles of this time for Western Europe and the Russian Platform (McElhinny 1973, table 29, p. 244).

The mean of all *in situ* directions for the redbeds of St Rémy (Figure 8(c)) yields a 'remagnetized' pole at 33.4° N, 151.5° E. This pole is compared to those for stable Europe in the last section.

High-temperature directions – further discussion

All four groups within the collection of Devonian and Cambro-Ordovician rocks showed some evidence of high-temperature components of magnetization. Few of these high-temperature components were well defined for the following reasons: (1) low intensities remained in most of the samples after the characteristic component was removed, (2) some samples picked up spurious laboratory magnetizations as susceptibilities changed at high temperatures, and (3) there may have been an overlap of blocking temperature spectra of the characteristic direction and the high-temperature direction in some of the samples.

Laboratory methods were used that minimized the first two problems. The Cryogenic magnetometer with sensitivity to 10^{-5} A/m for a 10 cm^3 sample was used for all samples of low initial intensity, as well as for many of the rest of the samples. The spurious magnetization observed was most frequently the result of the sample being in the Earth's field during transfer from furnace to magnetometer and particularly while held stationary in an upright position during insertion in the sample holder of the Cryogenic magnetometer. Once placed in the field-free space of the magnetometer this magnetization decayed exponentially. Since the largest portion of the Earth's field is in the vertical component at the latitude of our laboratory, an averaging technique was used to cancel out the introduced magnetization. The sample was measured in the upright position, then inverted (which had to be done in the Earth's field again) and measured again; the two measurements were then averaged.

If the blocking temperature spectra of the characteristic direction and that of the high-temperature direction were discrete and it was possible to measure the sample up to the blocking temperature of the high-temperature component without interference of the spurious magnetization or noise-level intensities, then the high-temperature direction was seen as a univectorial decay to the origin. Criteria of reliability were set to correspond with this situation. If the high-temperature magnetization was defined by at least three roughly co-linear points, decayed to the origin, and was different from the characteristic direction, it was taken to be reliable. Group means of the reliable high-temperature directions are shown in Table 2 without parentheses. However, if the blocking temperature spectra of the two components overlapped, and either there was interference by the spurious magnetization or intensities were too low, then the high-temperature component was never seen without some contribution from the characteristic direction and univectorial decay would not be observed. These directions are averaged with the reliable directions, but the results are entered in Table 2 in parentheses.

Halls' (1976) least-squares method of determining convergence of remagnetization circles was used in an effort to isolate the high-temperature component. Best-fitting great circles were defined for those portions of the demagnetization that involved the high-temperature components. As Halls (1976) has noted the method only works when the recorded portions of the high-temperature directions approach a tighter cluster than that of the characteristic direction. This is not the case, as was seen in the Syncline of Montmartin and also the Cambro-Ordovician of Normandy, even after unfolding where characteristic directions show a large dispersion. Thus, it was not possible to define the high-temperature component by the converging great circle method.

Group means were calculated for the high-temperature components meeting the criteria of reliability set above. Only Group B (Cambro-Ordovician of Paimpol-Bréhec) yields a Fisher precision parameter value greater than 10. This group of high-temperature directions passes a fold-test (as seen in Fig. 10 and Table 2). Group means were also calculated for all final high-temperature components whether they passed the reliability criteria or not and are seen in Table 2 in parentheses. Most of the group means showed very poor grouping (see Fisher precision values in Table 2).

Despite the large scatter in the high-temperature directions, the group mean directions all lie between the Devonian characteristic direction and the reliable high-temperature direction of the Cambro-Ordovician of Paimpol-Bréhec. Although not much significance can be placed on this, it does support the reliable high-temperature direction of Paimpol-Bréhec. Other studies that are still in progress at the Universities of Rennes, Southampton and Michigan, involving Cambrian and Ordovician rocks, also show these directions.

Discussion

The present results from the Devonian and Cambro-Ordovician of Normandy and Brittany can be divided into three groups: (1) those from the Late Devonian redbeds (Group A) with a south–south-westerly declination and shallow positive inclination, (2) the remagnetized directions from the Cambro-Ordovician redbeds and volcanics (Groups B, C and D), and (3) the set of directions obtained from the high-temperature components of magnetization (Groups B and C).

The Late Devonian redbeds of the Syncline of Montmartin, Normandy, yield a group mean declination/inclination of 213.4°/+27.7° after unfolding and a pole position at 19.8° N, 144.2° E. This result from Group A is the only result for which there is no evidence for remagnetization. Although some high-temperature directions were observed, these were essentially random. Chemical, thermal and alternating field demagnetizations all agreed with each other and revealed only one characteristic direction of magnetization. Unfortunately, a fold test is not possible because of a lack of different structural corrections.

The second set of results is obtained from the Cambro-Ordovician redbeds and volcanics. The redbeds from Normandy (Group D) were remagnetized during or after the folding of the synclinorium as seen in the failure of the fold test. The pole position obtained from the *in situ* directions corresponds to the pole at the time of remagnetization and is located at 33.4° N, 151.5° E (see Fig. 11). The other two Cambro-Ordovician collections from Paimpol-Bréhec and Erquy-Cap Fréhel in Brittany are probably remagnetized as well. Because of the lack of different structural corrections, fold tests are inconclusive for Groups B and C, and we have, therefore, plotted two pole positions for these groups in Fig. 11 – one pole corresponding to the directions before unfolding, the other pole representing the directions after unfolding (see also Table 1). Even though there is no palaeomagnetic indication whether the directions of magnetization of Groups B and C are pre- or post-folding, there are some geologic arguments that point to a post-folding age. The folding phases in Brittany are the Bretonian (*c.* 360 MA) and Sudetian (*c.* 320 MA) phases (e.g. Rutten 1969). Post-tectonic dikes, however, cut the formations along the northern coast of Brittany, and have recently been dated at The University of Rennes as 325 MA old, which indicates that the Bretonian phase is probably responsible for the deformation of Groups B and C. If we assume that the secondary K/Ar age of 345 MA obtained from the Paimpol-Bréhec trachy-andesite corresponds to the age of the remagnetization, we can assume also that the magnetization is of post-folding age. Consequently, we have favoured the pole positions for Groups B and C calculated for the *in situ* directions.

A mean direction calculated from the site means of Group A (after tectonic correction) and the site means of Groups B, C and D (before tectonic correction) gives a declination/inclination of 207.8°/+15.9° ($N = 21$; $k = 19.9$; $\alpha_{95} = 7.3°$). This direction results in a combined pole position at 28.1° N, 146.4° E ($dp = 3.87°$; $dm = 7.50°$), which can be compared with poles from the part of Europe north of the Hercynian fold belt ('stable Europe'). A stable-European Late Devonian mean pole at 30.2° N, 161.4° E ($N = 14$, $A_{95} = 4.8°$) and a nearby Early Carboniferous mean pole at 28.5° N, 163.6° E ($N = 16$, $A_{95} = 6.5°$) are based on data from Norway, Great Britain and the Russian Platform (French 1976). The time of the polar wander shift between Early and Late Carboniferous is not well documented. Russian Platform data of Early and Middle Carboniferous age (the Russian

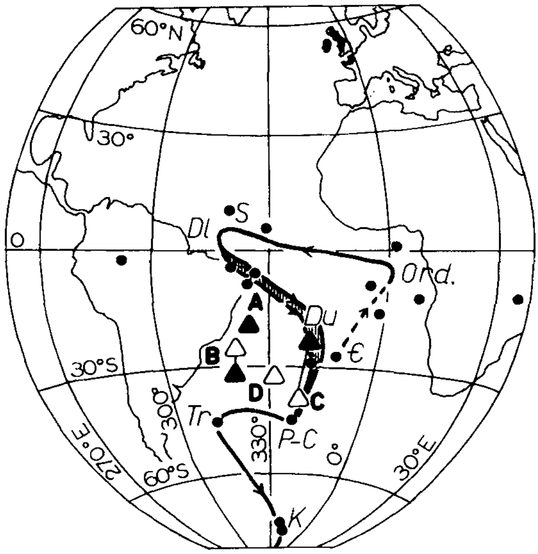

Figure 11. Poles from this study (triangles) superimposed on the Phanerozoic apparent polar wander path (south poles) for the British Isles from Briden *et al.* (1973). Capital letters refer to the Groups of this study – open triangles are for poles obtained from *in situ* characteristic directions, closed triangles are for poles obtained from directions after correction for the tilt of the strata. The dots represent the more reliable poles from Great Britain, after Briden *et al.* (1973, table 1). Letters in italics denote the following ages: Є is Cambrian, *Ord.* is Ordovician, *S* is Silurian, *Dl* is lower Devonian, *Du* is upper Devonian, *P–C* is combined Permian and Carboniferous, *Tr* is Triassic and *K* is Cretaceous. Note that a counterclockwise rotation of the Armorican Massif brings the poles from this study into agreement with the upper Devonian to Carboniferous poles from Great Britain.

middle Carboniferous being equivalent to the early Late Carboniferous of Europe (Harland, Smith & Wilcock 1964)) appear to record a continuous shift (Briden, Morris & Piper 1973). The Late Carboniferous mean pole for Europe (French 1976) based on British, Swedish, Russian Platform, French, Polish and Czech results is located at 41.3° N, 166.7° E ($N = 10$, $A_{95} = 9.9°$) and certainly is younger than our poles from the Armorican Massif, with their most likely ages being between 360 and 320 MA.

We will discuss the implications of these pole positions before turning our attention to the third set of results, obtained from the high-temperature directions of Groups B and C.

If correctly dated, the mean pole obtained from all characteristic site-mean directions as given above, implies little or no separation between Hercynian and stable Europe. A 14° counterclockwise rotation of our sampling areas places this mean pole at 31.8° N, 161.8° E and very near to the Late Devonian and Early Carboniferous poles for stable Europe (*c*. 30° N, 162° E). The 14° rotation is statistically significant and indicates that domains in the Armorican Massif may have acted as microplates. If a Late Devonian–Early Carboniferous ocean between the Armorican Massif and stable Europe is required to account for the crustal shortening near the Hercynian Front in Late Carboniferous times, it must have been small and could have existed only within the error limits of our data (*c*. 5° or 550 km). Taking the result of Group A alone, an 18° counterclockwise rotation is required to bring its pole close to the Late Devonian pole positions from the British Isles and from stable Europe as a whole. Again, any separation between Hercynian and stable Europe in the Late Devonian could only exist within the error limits of the data (*c*. 10°).

Fig. 12 illustrates this in a different manner. It shows palaeolatitude reconstructions of the European and Gondwana continents in the Late Devonian and the Early Carboniferous

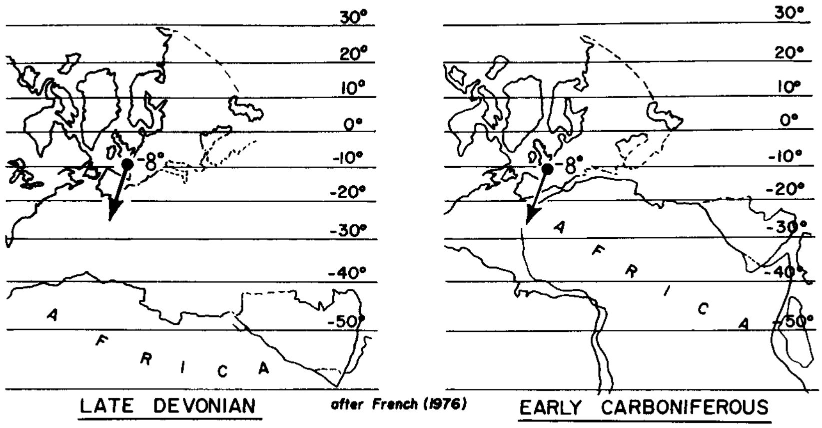

Figure 12. Palaeolatitude maps for the Late Devonian and Early Carboniferous (after French 1976); the uncertainties in the latitudinal positioning of Europe are 4.8° for the Late Devonian and 6.5° for the Early Carboniferous, respectively. The arrow at the sampling area (the declination) points to the average pole derived from Group A (after unfolding) and Groups B, C and D (before unfolding). Their average inclination yields an average palaeolatitude of 8° S ± 4°. (The error margin being based on the oval of confidence about the mean pole, with semi-axes dm = 7.50°, dp = 3.87°.) This indicates no significant north–south separation between the Armorican Massif and the North European Foreland (see Fig. 1). Group A alone yields a palaeolatitude value of 15° S, (Late Devonian), which again is not significantly different.

(from French 1976). Similar maps have recently been published by Irving (1977). The location of the Gondwana continents in the Late Devonian is based on the compilation from French (1976) of a mean pole at 10.5° N, 199.3° E in African coordinates, derived from the Late Devonian Msissi Norite of Africa and the Devonian Picos and Passagim Series in Brazil (both listed in Hailwood 1974). With little or no separation between Hercynian and stable Europe, a separation does exist between Hercynian Europe and the Gondwana continents of Africa and South America in the Devonian. The (late) Early Carboniferous mean pole from French (1976) for the Gondwana continents, based on the Dwyka varves of Africa and the Gilmore and Isismurra volcanics of Australia (both given in McElhinny 1973) is located at 37.3° N, 201.6° E in African coordinates. Thus, the Gondwana continents moved northward relative to stable Europe between the Late Devonian and the late Early Carboniferous. Consumption of intervening oceanic crust would have occurred during this time. The location of a subduction zone is not clear for three reasons: (1) ocean–ocean subduction is possible during most of the intervening time, (2) the Alpine orogeny has overprinted the southern portion of the Hercynian orogen, and (3) no detailed Palaeozoic palaeomagnetic data exist for portions of the Hercynian orogen that may have acted as microplates. We conclude in the light of our present data that subduction or collision tectonics could be the source of the Hercynian orogeny if microcontinents existed within Hercynian Europe or if subduction took place south of Hercynian Europe and the remnants of the zone were incorporated into the Alpine belt.

The third set of results yielded pole positions significantly different from the other data sets. These poles were obtained from the six reliable high-temperature directions from the Cambro-Ordovician of Paimpol-Bréhec and from site K from the Cambro-Ordovician(?) of Erquy-Cap Fréhel. A discussion of the implications of these poles has limitations that must be emphasized before proceeding. Both poles are based on a few samples, and in the case of Erquy-Cap Fréhel they are all from a single site. Consequently, the poles cannot be taken as representative of the entire collection.

The mean declination/inclination after unfolding of the six reliable high-temperature directions from Paimpol-Bréhec is 325°/+37°, is taken to be of normal polarity, and yields a pole position at 50.4° N, 234.4° E. High-temperature components of site K give a mean declination/inclination of 312°/−1° and a pole position at 25.9° N, 233.2° E. These mean directions and pole positions could, with the above-mentioned reservations, be taken as representative of the Late Cambrian–Early Ordovician palaeomagnetic field. A comparison with contemporaneous poles from Great Britain reveals that the areas may have had entirely different positions. This is particularly apparent in their palaeolatitudes as indicated by their inclinations. Whereas the Armorican Massif was at latitudes between the equator and 20°, Great Britain occupied Early Ordovician latitudes of at least 30°. Current interpretations of the British ('Caledonian') apparent polar wander path make this a southern hemisphere palaeolatitude, implying that the Armorican Massif was more northerly than Great Britain! It should be noted, however, that the Caledonian mobile belt may not be representative of the stable part of Europe (the Baltic Shield and the Russian Platform) at that time and that a comparison between the Armorican Massif and the Caledonides may not be very meaningful. The few Cambrian and Ordovician poles from the Russian Platform are rather unsubstantiated, but they do agree favourably in latitude with our results and would not indicate the need for a large ocean between stable Europe and the Armorican Massif. As these conclusions must be rather tentative, and since other studies on Cambrian and Ordovician rocks of the Armorican Massif are in progress at the Universities of Rennes, Leeds and Michigan, we will not elaborate at this point.

Based on the bulk of data from this study of redbeds and trachy-andesites of Normandy and Brittany, there appears to be no significant separation of Hercynian Europe from stable Europe in the Late Devonian and Early Carboniferous. A plate tectonic model calling on Late Palaeozoic subduction of a large ocean separating the two areas and ending in a continent–continent collision is not supported. A separation of Hercynian Europe (i.e. the Armorican Massif) and the African and South American continents in the Devonian and the subsequent collision of the two land masses would suggest the possibility of a subduction zone to the south of Hercynian Europe. An ensialic cause of the Hercynian orogeny in southern England, northern France and Belgium remains a possibility, although our data do not present the resolution needed to decide whether a small ocean could have existed there.

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