Palaeomagnetic estimates of total rotation in basement thrust sheets, Axial Zone, Southern Pyrenees

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ABSTRACT

Palaeomagnetism is a powerful tool for identifying rotations about any axis. A palaeomagnetic study in basement thrust sheets in the southern Axial Zone, Pyrenees, has demonstrated that 3-D rotations can be identified in basement terrain where no other palaeohorizontal markers exist. Three different movement histories are described within a stack of six thrust sheets. The lowermost unit has experienced doming and tilting about a horizontal axis at a different time to clockwise rotation about a vertical axis of 25°. The middle four sheets have rotated clockwise by 35 to 60° and have been tilted by 40 to 65° to the north. The uppermost sheet has experienced no rotation and tilting, indicating that the thrust (or reverse fault) had an original attitude similar to its present steep northward dip. This study illustrates the potential of the palaeomagnetic method for discriminating between models of the evolution of the Pyrenees which invoke steep structures in the central region to have had an originally steep attitude, either rooted into a zone of inhomogeneous shortening in the lower crust or decolled on a shallow fault, and those which invoke originally shallow structures which have been subsequently back-steepened.

INTRODUCTION

The geometry of structures in the internal parts of orogenic belts can be difficult to determine since the palaeohorizontal orientation of igneous or polydeformed basament rocks is not known. This problem is of great significance in the Pyrenees where conflicting and fundamentally different models of the deep structure have been proposed. The surface expression of Tertiary thrust faults in the Pyrenees shows a fanning geometry which has been described by many authors. Seguret and Daignieres (1986), Seguret (1972), and Choukroune and Seguret (1973) favour a vertical tectonic interpretation in which the thrusts steepen downwards into a zone of inhomogeneous shortening in the lower crust. Williams and Fischer (1984), and Parish (1984) prefer a thin skinned model in which all thrusts are assumed to have originated at shallow angles and to have been subsequently steepened by backthrusting or by piling of lower imbricates into antiformal stacks. Deramond et al (1985) propose a thick-skinned model in which thrusts root down to join a basal detachment at the Moho. McCaig (1986) has discussed the relative merits of these models.

In this paper we will demonstrate that palaeomagnetic estimates can be made of total three-dimensional (3-D) rotations in basement thrust sheets, palaeomagnetic methods therefore may enable us in future to resolve the conflict between vertical, thin and thick-skinned models. Here we present a preliminary palaeomagnetic study of a suite of late Carboniferous dykes which cut Silurian to Carboniferous rocks on the southern margin of the Pyrenean Axial zone, south of the Maladeta granodiorite. In this area post-Hercynian Triassic redbeds have been imbricated and folded into an antiformal stack during Alpine southwards directed thrusting. Where Triassic rocks are preserved overlying the basement the palaeomagnetic estimates of tilt about a horizontal axis agree well with the amount of tilting of the Triassic bedding.

GEOLOGICAL BACKGROUND

The geology of the southern Axial zone, south of the Maladeta granodiorite in the area of Pont de Suert, has been described by Mey, (1969). Fig. 1 shows a much simplified sketch map of the area with sampling localities. Hercynian deformation has affected sediments from Cambro-Ordovician to lower Carboniferous in age. These are cut by intrusives of the late Carboniferous Bono complex, which is probably asssociated with the Stephanian volcanics found at Erill Castell. Unconformably overlying the Hercynian deformed basement are upper Carboniferous, Permian and Triassic conglomerates and red sandstones. The southward directed Alpine thrusting has imbricated sheets of basement and ocassional Triassic redbeds into an antiformal stack. Six separate thrust can be identified. The lowermost sheet (sheet 1) extends southwards to the northern edge of the Nogueras zone (Figs. 6 and 7). Triassic redbeds are preserved overlying the basement at the northern and southern ends of the exposure of sheet 1. The unconformity is steeply southward dipping at the southern edge and is shallowly northward dipping at the northern edge indicating that the

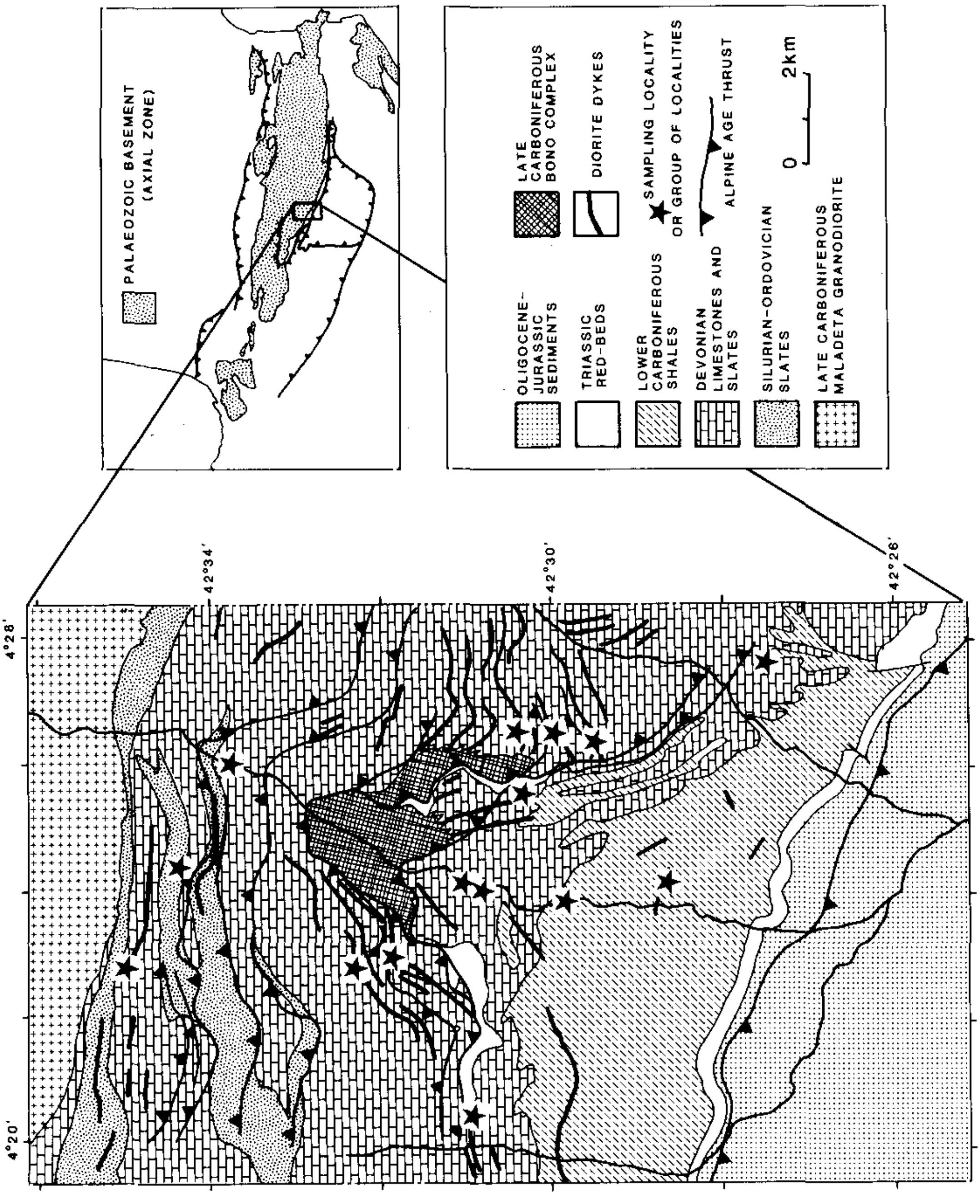

Fig. 1. Simplified geological sketch map of southern Axial zone, south of the Maladeta granodiorite. Thrust sheets are numbered in Fig. 6.

thrust sheeet has a domal structure, probably due to movement on lower thrusts. Thrust sheets 2 to 6 have northward-dipping thrust contacts. These thrusts die out westwards into fold structures.

The Bono complex consists of a central intrusion of diorite to granodiorite composition from which a suite of quartz and feldspar phyric intermediate to felsic dykes radiate. These dykes outcrop in all thrust sheets in the study area. This paper concentrates on a palaeomagnetic investigation of the remanence carried by these dykes.

PALAEOMAGNETIC RESULTS

Palaeomagnetic samples have been collected from 30 dykes in 5 different thrust sheets. An average of eight cores were drilled from each dyke and where the host rock was sampleable, a series of cores were drilled across the contact aureole. At this stage in our study we have thermally demagnetized 108 samples from dykes and contact aureoles. The remanence structure has been analysed by using the Linefind algorithm (Kent, Briden and Mardia, 1983) to rigorously determine the direction of magnetization components. Two dimensional representations of the three dimensional vector structure can be made using vector plots of thermal demagnetization data (see Fig. 2 for example), in which the measured direction of magnetization after each thermal treatment step is projected onto both a horizontal and a vertical plane. A single component remanence changes during thermal demagnetization only by the intensity decreasing. This is represented on a vector plot by two lines trending towards the origin, one in the vertical, the other in the horizontal projection. On thermal demagnetization of multicomponent remanences, lines in the direction of the various magnetization components are traced out in each projection of the vector plot.

A total of 80 samples from 23 of the dykes and contact aureoles, have a well defined characteristic remanence determined by detailed thermal demagnetization. In some dykes the remanence is carried exclusively by magnetic and hematite. Figure 2 shows typical vector plots of three samples (87p53-7, 87p54-6 and 87p21-4) which display these features. 87p53-7 has a single component remanence carried by magnetite with a distributed blocking temperature spectrum. 87p54-6 has a single component remanence carried by magnetite, with a blocking temperature range of 427-580°C and by hematite, with a blocking temperature range of 655-685°C. 87p21-4 has a present earth's field overprint with low blocking temperatures (up to 250°C) and a characteristic remanence with blocking temperatures between 328°C and 685°C.

The primary nature of the characteristic dyke remanence directions has been demonstrated by four full and two partial positive contact tests.

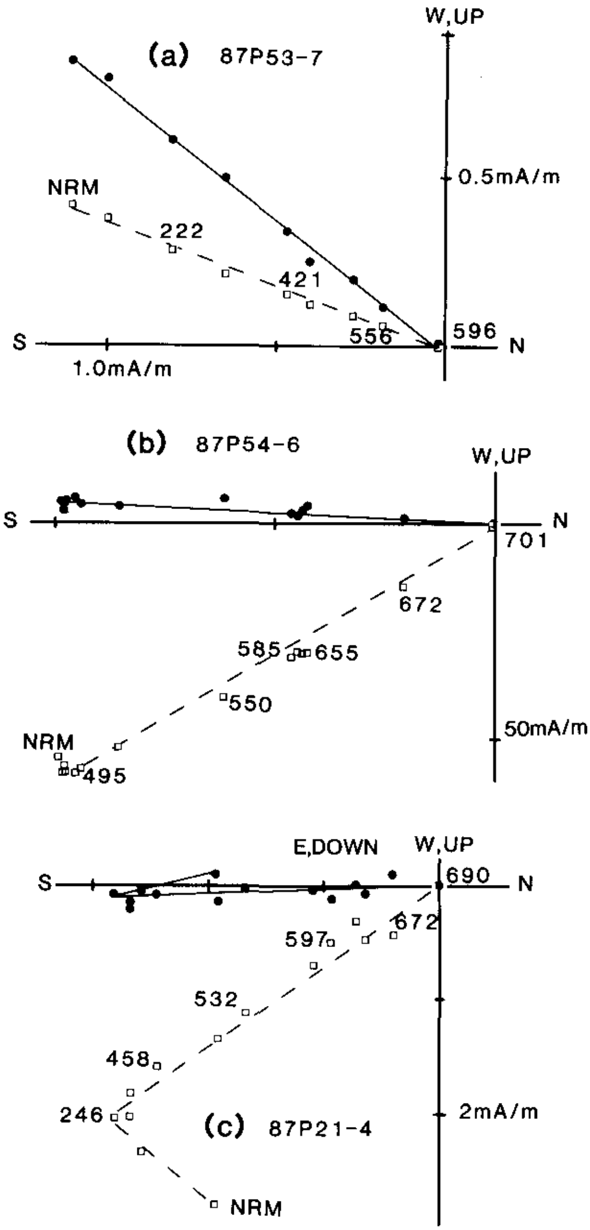

Fig. 2. Typical vector plots of thermal demagnetization of remanence from dykes. Filled circles represent projection of vector in horizontal (N, S, E, and W) plane, open squares represent projectionof vector in vertical (Up, N, Down and S) plane. Numbers next to points indicate temperature of thermal treatment. (a) 87 pp. 53-7. Dyke in thrust sheet 3a. (b) 87p21-4. Dyke in thrust sheet 1.

In a full contact test, the host rock close to the dyke margin has a single component remanence statistically identical to that of the dyke, indicating that the host rock was heated above the Curie point of its remanence carriers during the intrusion of the dyke. Further from the dyke, where the host rock was heated to a temperature less than the Curie point, the remanence is two component, the lower blocking temperature component having been acquired during the contact heating, and the higher blocking temperature component predating the heating. This indicates that no remagnetization event has occurred since the intrusion. In a partial contact test, the host rock close to the dyke margin has the same remanence direction as the dyke. Figure 3 shows a full contact test from site 16, where the dyke (Fig. 3 (a)) and close contact rock (Fig. 3 (b)) have the same single component remanence, and the host rock 10m from the 5m wide dyke (Fig. 3 (c)) has this same component with blocking temperatures below 580°C. The direction of the high temperature component is not properly isolated because above 580°C thermal alteration begins, and the magnetization direction beomes erratic. However, the high temperature direction is significantly different from that of the dyke overprint.

Mean characteristic dyke directions from groups of dykes close to each other have been calculated. Figure 4 shows the distribution of mean directions from locations within sheet 1. The directions are distributed along a north/south axis, (i.e. their declinations are close to 180°) and the inclination of remanence is related to the geographical position of the site. The most southerly site has the steepest inclination and the most northerly site has the shallowest inclination. The circles indicate the cone of 95 % confidence that the direction lies within this circle (alpha 95). Figure 5 shows the distribution of mean directions from thrust sheets 3 to 6. All directions from sheets 3 to 5 are upward directed to the south-west, whereas the directions from sheet 6 are downwards directed to the south-east. Figure 6 shows the remanence directions in their geographical locations, represented as an arrow in the direction of declination and a number indicating the inclination, plotted on a map of the thrust sheets.

INTERPRETATION

The remanence in the dykes has been shown to date from their intrusion in late Carboniferous times. The palaeomagnetic field direction which would be expected in rocks of this age from stable Iberia, has been proposed by Vandenberg and Zijderveld (1982), to have Dec=150°, Inc=+15°; this direction takes the rotation of Iberia into account. The original orientation of the magnetization in the dykes has therefore been rotated into this direction by the rotation of Iberia. Any significant directional difference between the present direction of dyke magnetization and this refe-

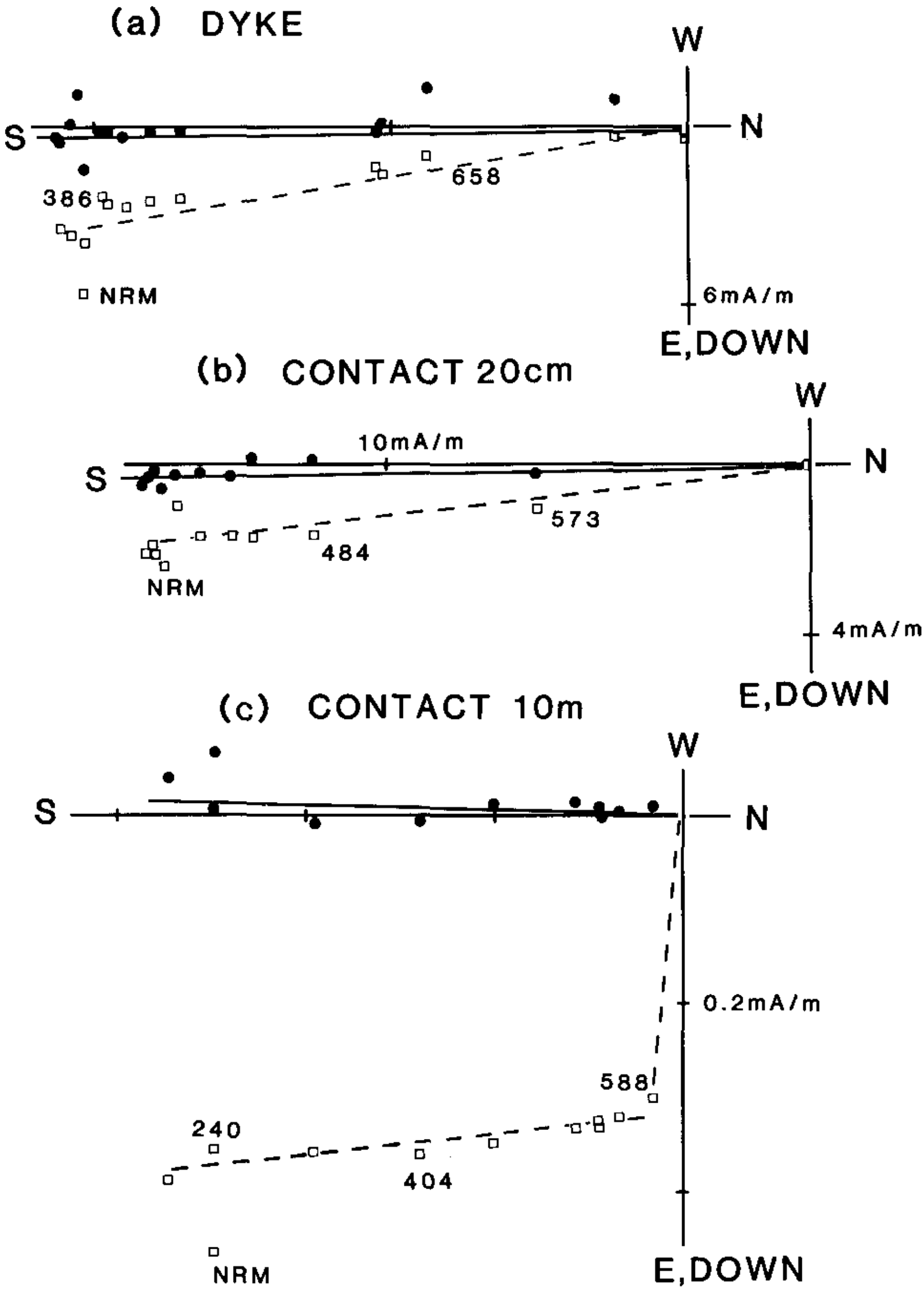

Fig. 3. Contact test from dyke 87p16 in thrust sheet 1. Projection and symbols as in Fig. 2.

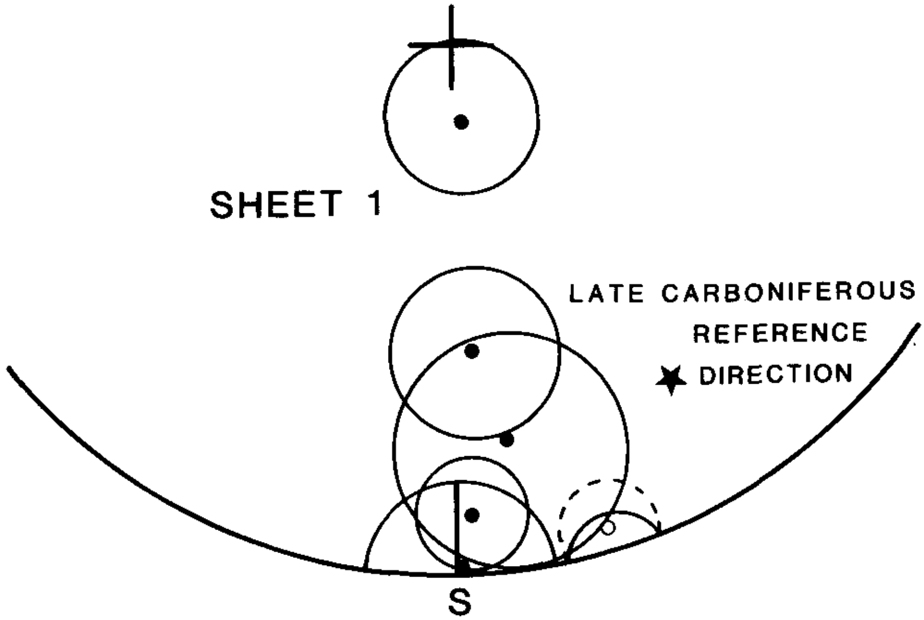

Fig. 4. Segment of equal angle projection of mean remanence directions from thrust sheet 1. Filled symbols indicate a downward pointing, lower hemisphere vector, open symbols indicate upward pointing, upper hemisphere vectors.

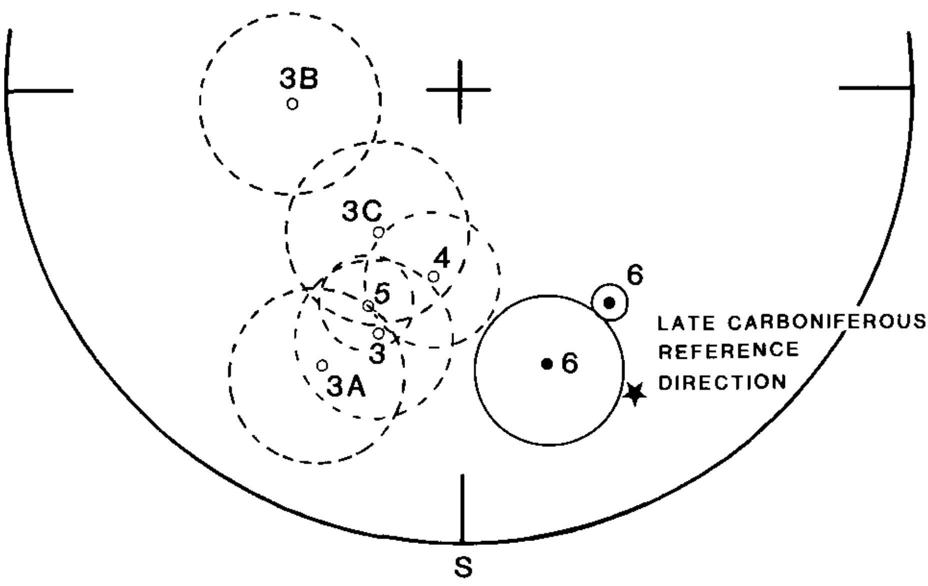

Fig. 5. Equal angle projection of mean remanence directions from thrust sheets 3 to 6. Dotted circles indicate error circles projected onto the upper hemisphere. Symbols as in Fig. 4.

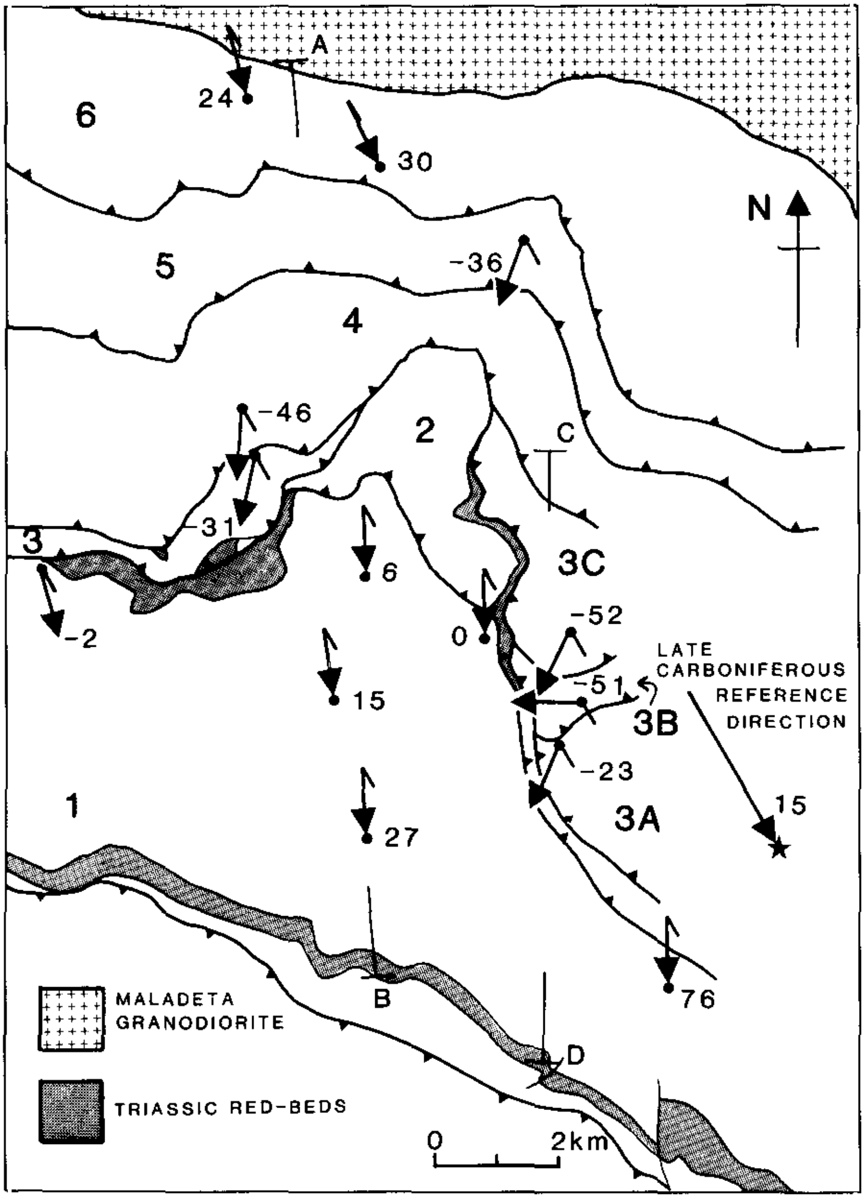

Fig. 6. Mean remanence directions plotted at geographic location. Direction of arrow indicates actual declination of magnetization vector, number by arrow indicates inclination. Filled circle indicates sampling site or group of sites, arrow points away from site for negative inclinations, towards site for positive inclinations. Small line at end of arrow indicates late Carboniferous reference direction, the angle between this line and the arrow is the estimate of clockwise rotation about a vertical axis. Thrust sheets are numbered 1 to 6. Cross-sections are shown in Fig. 7.

rence field direction indicates a block rotation of the dykes during the evolution of Alpine age thrust sheeets. Here we neglect any rotations which may have occurred during the formation of early extensional faults. The amount of 3-D rotation of the thrust sheets can be estimated in this way. However, any rotation (or component of rotation) about an axis parallel to the magnetization direction is missed by this method. It is fortuitous that the reference field direction is perpecdicular to the main axis of folding in the Pyrenees so the effect of this limitations is minimized.

Poles to bedding in Triassic redbeds from thrust sheet 1 are distributed on a north-south girdle giving an easterly, sub-horizontal mean fold axis. The distribution of remanence directions from dykes in this thrust sheet (Fig. 3 and 5) is consistent with the dykes and their remanent magnetism having undergone two components of rotation since their intrusion. All declinations are about 25° west of the expected late Carboniferous declination of 150°, i.e. they have been rotated 25° clockwise about a vertical axis. The remanence directions also appear to have been rotated about the sub-horizontal fold axis defined by poles to Triassic bedding, as passive markers during folding of the thrust sheet. For example, the southernmost group of dykes has a remanence which has been tilted downwards to the south by 60°. This locality is the closest to the southern unconformity with overlying Trias where the Triassic bedding dips south at about 60°. Similarly, the two northernmost groups of dykes which lie just under the northern unconformity where the Triassic bedding dips 10 to 20° north, have remanences which have been tilted downwards to the north (or upwards to the south) by 10 to 15°, away from the reference direction. Hence the palaeomagnetic estimates of tilt about a horizontal axis agree well with the amount of tilting of the Triassic bedding, and therefore can be used as an independent tilt estimate in higher thrust sheets, where Triassic sediments are not preserved. The errors on palaeomagnetic estimates in this preliminary study are approximately ±15°.

Remanence directions from thrust sheets 3 to 5 indicate that more rotation about both horizontal and vertical axes has ocurred than in sheet 1. All remanences are upward directed in the southwest quadrant, indicating tilting upwards to the south and clockwise rotation of 35 to 60°. With the present data set, it is not possible to distinguish between remanence directions from sheets 3 to 5. Remanence directions from thrust sheet 6, which is in contact with the Maladeta granodiorite, are, however, significantly different from those in underlying sheets. They lie within the experimental error of 15° of the expected late Carboniferous field direction, implying no significant rotation or tilt has occurred. Rotations about a vertical axis are illustrated in Fig. 6.

Fig. 7 shows two schematic N-S cross-sections through the area, with the palaeomagnetic estimates of tilt about a horizontal axis. The arrows are oriented at the angle of tilt estimated from the mean remanence di-

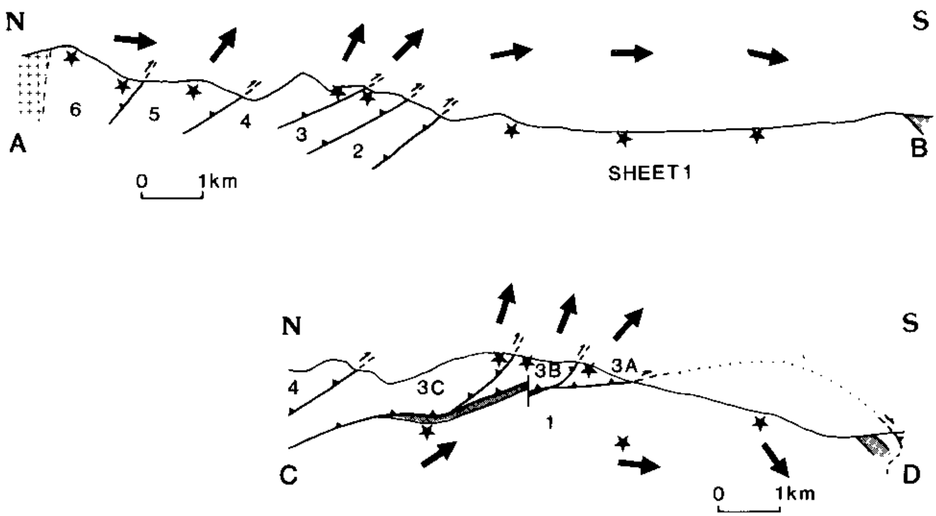

Fig. 7. Schematic N-S cross-sections showing palaeomagnetic estimates of tilt about a horizontal axis. The arrows are oriented at the estimated angle of tilt obtained from the group of dykes below the arrow.

rection from the group of dykes at that locality. The doming of the rocks within thrust sheet 1 is clearly shown in this diagram.

These palaeomagnetic estimates enable us to interpret the sequence of Alpine-age thrusting in this area. Thrust sheets 3 to 5 moved first and, being pinned to the west of the area, this movement caused clockwise rotation and some back-tilting. Movement must then have occurred on a deeper thrust coming up under sheet 1, which caused the doming and clockwise rotation of sheet 1 and the further back-steepening and rotation of sheets 3 to 5. Lastly, thrust sheet 6 moved on a breaching thrust which had an originally steep attitude similar to its present attitude causing no rotation or tilting, and which postdates the underlying antiformal stack.

CONCLUSIONS

The dykes preserve a remanence component dating from their intrusion, and so record the late Carboniferous palaeohorizontal. The primary nature of their remanence has been demonstrated by contact tests. Subsequent tectonic rotations of the dykes has been established by comparison with the known late-Carboniferous reference direction for Iberia (150°-15°). Where Triassic rocks are preserved overlying the basement, the present-day inclinations of dyke remanences agree well with those predicted from the amount of tilting of the Triassic bedding. However, declinations are rotated clockwise by 20-60°, and data from four separate thrust sheets show an increase of rotation upwards in the thrust pile. Our data suggets that clockwise rotations are the result of cumulative rotation in a piggy-back thrusting sequence. Field evidence suggests that many of the thrusts die out westwards in fold structures so that the rotations reflect pinning of thrust sheets west of the area. In the northern part of our study area where Triassic rocks are not preserved, inclination data indicate northward tilting of basement thrust sheet by up to 60° in sheets 3 to 5, but no significant tilting in thrust sheet 6 adjacent to the Maladeta granodiorite. These palaeomagnetic results have enabled us to identify thrust 6 as a breaching thrust which had an originally steep attitude similar to its present attitude, and which postdates the underlying antiformal stack.

Section balancing techniques are difficult to apply directly to igneous or polydeformed basement rocks since no palaeohorizontal orientation is known. Palaeomagnetism offers an independent method of establishing the palaeohorizontal in such rocks and so constraining the geometry of structures which affect them.

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