Patterns of Strain Variation in Arcuate Fold Belts

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Patterns of strain variation in arcuate fold belts

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Many mountain ranges (Alps, Carpathians, Himalayas) and volcanic island ridges (Aleutians, Banda, Mariana) are curved or sinuous, often so regularly as to be described as arcs. Their curvature may be primary or secondary. Among numerous models proposed to account for the curvature are the orocline or secondary bending hypothesis of Carey (1958), the inextensional bending model of Frank (1968) and the spreading of marginal seas and lateral compression (Matsuda & Uyeda 1971). Different models imply different patterns of finite strain. Palaeomagnetic measurements can also be used to discriminate between them. Criteria for discriminating are examined, with particular reference to the Variscan arc in the Iberian Peninsula.

Introduction

Arcs are characteristic elements of active and geologically recent consuming plate margins. The Benioff zones along which oceanic crust is subducted outcrop as a series of linked arcs, usually convex towards the plate being consumed. Arcuate chains of islands and arcuate mountain ranges occur parallel to the arcuate outcrops of the subduction zones. These arcuate structures may be interpreted either as primary or as secondary features. Other arcs, formed in geologically earlier periods, may be unrelated to consuming plate margins. The patterns of finite strains within the arcs will differ according to their origins. Our purpose here is to examine the strain patterns in arcs formed by different mechanisms in order to determine the origin of the Iberian arc, which is an important element of the Variscan fold belt of Western Europe (figure 1).

Various hypotheses have been proposed to explain how arcs may develop as primary features. Lake (1931) suggested that they represent the outcrop of plane thrust surfaces on the spherical surface of the earth, but the seismically defined zones of movement dip much too steeply to fit this hypothesis and are conical rather than planar. Argand (1924) attributed the arc of the Jura mountains to the forward motion of superficial sedimentary layers resting on a layer of evaporites between two obstacles, the Vosges and Schwarzwald Massifs, which lie at either end of the arc. This interpretaton can only apply to arcs that are essentially superficial and not to those which are underlain by Benioff zones. Bucher (1933) compared the pattern of linked arcs along the western side of the Pacific to linked cracks in spreading asphalt and from this he argued that the pattern was initiated by tensional stresses. This seems unlikely since no such linked arcuate fractures are seen along the mid-oceanic ridge systems which are produced by tensional stresses. Wilson (1954) at one time regarded these linked arcs as outcrops of a series of conical fractures produced by crustal compression above a level of no strain as the Earth's interior contracted. This interpretation was abandoned when the contraction theory was superseded by the plate tectonic theory. Tuzo Wilson also showed that the centres of the geologically recent arcs plot close to two mutually perpendicular great circles, a fact which remains unexplained. Scheidegger (1963) pointed out that many arcs are spiral rather than circular curves, suggesting lateral propagation.

The theory of plate tectonics led to new interpretations. Frank (1968) showed that if a flexible inextensible shell is bent inwards so that it makes an angle θ with the unbent portion of the shell, the bent portion is part of a spherical surface having the same radius as the shell. The intersection of the bent shell with the spherical earth is a portion of a small circle whose radius of curvature ϕ (expressed as an angular measure on the sphere) is $\frac{1}{2}\theta$. Le Pichon *et al.* (1973) pointed out that in many arcs this relation between dip and curvature does not hold; the radius of curvature is much less than the predicted value, implying large extensions parallel to the strike of the arc, for which there is some seismic evidence. Some steeply inclined, nearly straight subduction zones may fit an alternative solution, $\phi = \frac{1}{2}(\pi - \theta)$ suggested by le Pichon *et al.* (1973). It has been shown (Luyendyk 1970) that the dip of the Benioff zones is correlated with the rate of plate consumption, steeper dips being found where the rate is lower. This suggests that the dip of the descending slab depends on the relative values of the tangential force by which it is moved away from a spreading ridge and the vertically acting body force due to the weight of the dense slab. It therefore seems likely that primary arcs develop initially with a curvature

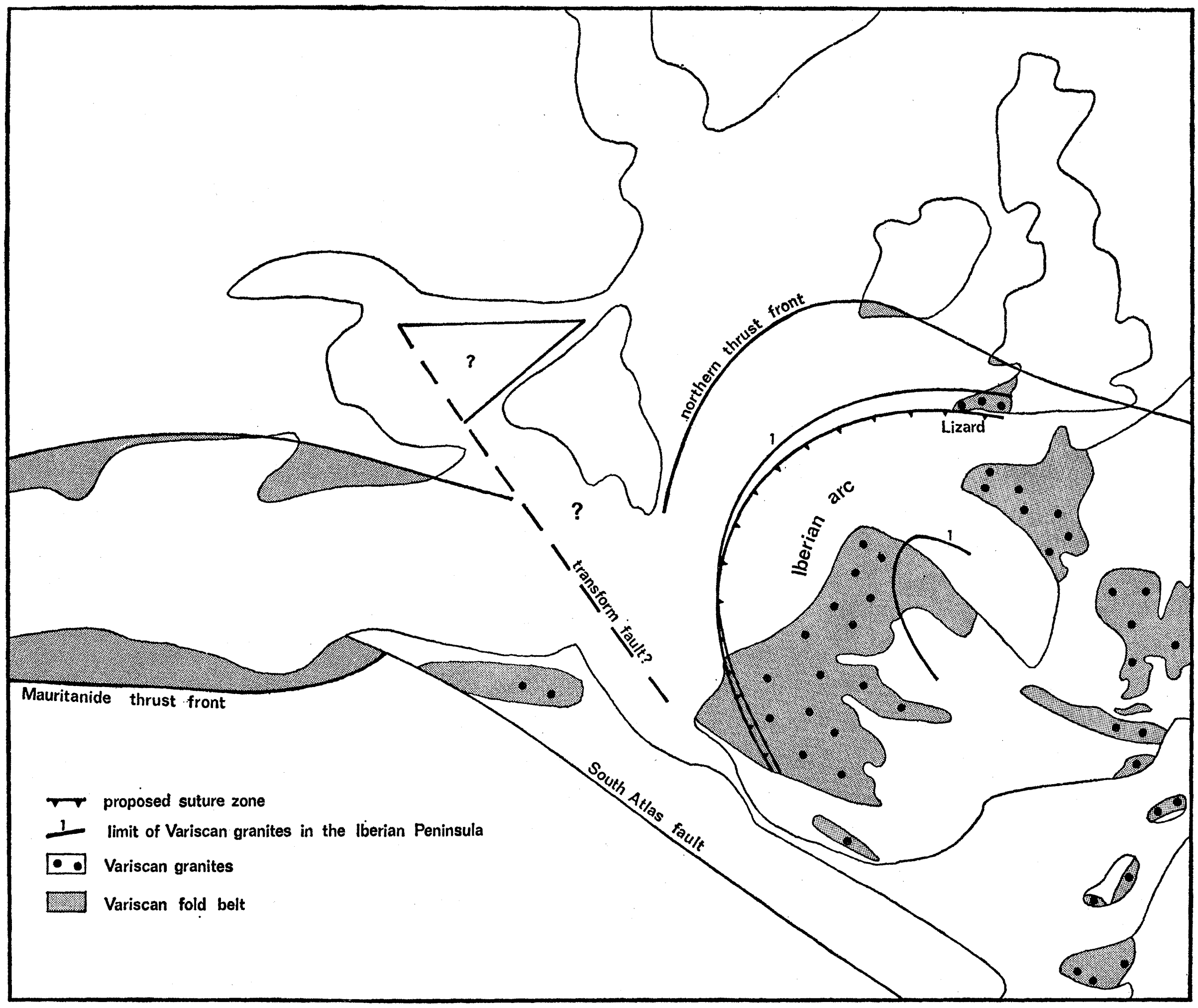

FIGURE 1. A possible pre-Mesozoic configuration of the Variscan fold belt in Western Europe, North America and North West Africa.

which is dictated by the condition for inextensional deformation, but that the dip is usually increased, with consequent subsurface extension parallel to the length of the arc, owing to the weight of the sinking slab.

Proposals to explain the formation of secondary arcs have not been so clearly stated. Wegener (1929) regarded the Caribbean arcs as a 'festoon' lagging behind as the American continents on either side moved westwards. Brouwer (1951) envisaged large horizontal movements of island arcs, usually towards the oceans but sometimes away from them. He recognized that in the process the curvature might be increased or in some cases diminished. Carey (1955, 1958) proposed the term orocline for 'an orogenic belt with a change in trend which is interpreted as an impressed strain'. The evidence used by Carey to identify an arc as an orocline was the presence of structures indicating tension on the convex side of the oroclinal bend, compressional structures on the concave side and in a few cases, palaeomagnetic evidence of rotation. The examples cited by Carey (1958) were the Riff, Sicilian, Ligurian, Baluchistan, Alaskan and Novaya Zemlya oroclines. After development of the plate tectonic hypothesis, interpretations involving deformation of plates were at first ignored but as complications such as the existence

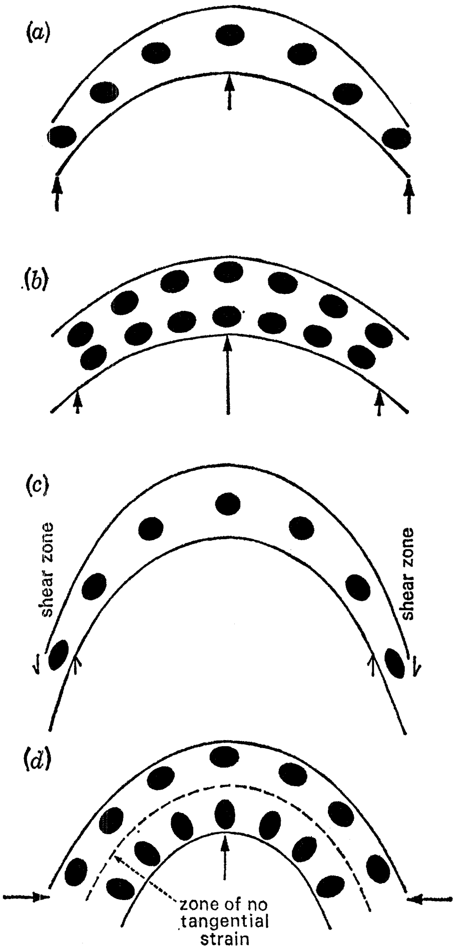

FIGURE 2. Patterns of strain ellipses in different types of arc. Arrows show motions of plates. (*a*) Primary arc, (*b*, *c*, *d*) secondary arcs; (*b*) maximum forward motion in centre of arc; (*c*) dextral and sinistral shear zones at flanks of arc; (*d*) flanks moving towards one another.

of microplates and soft-margin deformation were recognized, secondary bending of arcs again became acceptable. Carey's Ligurian and Sicilian oroclines are consistent with recent interpretations of microplate motions in the Mediterranean region (Dewey *et al.* 1973); horizontal motion, probably involving increase in curvature of the arcs, has been attributed to back-arc spreading behind the Scotia and Japanese arcs (Dalziel & Elliott 1971; Karig 1970).

The strain variations within the arcs must differ according to their origin, as strain patterns differ in folds formed by buckling, bending or simple shear. In a primary arc it may be assumed that an annular segment of the crust is compressed between the curved margins of two rigid plates (figure 2*a*). Since the length of the arc remains constant there will be no finite strain parallel to the arc and the shortening between the two plates will be compensated by extension upwards. Lines are not rotated. Thus an undistorted primary arc will show constant orientation of remanent magnetism.

Three types of secondary arc may be considered (figures 2*b*, *c*, *d*). In the first the strains are comparable to those resulting from the bending of a beam (Tromp 1937). There is tangential extension throughout the arc and the magnitude of the extension increases radially outwards. A second type (figure 2*c*) would be produced by simple shear, for example between a pair of transform shear zones. In this case the strain would increase from a minimum at the centre of the arc to a maximum on the flanks. The strain patterns would be those described by Ramsay & Graham (1970). In the third type (figure 2*d*) the strains are analogous to those in a buckling fold. Since, however, the strains being discussed are those seen on the surface of a lithospheric plate, which would buckle, if at all, in a vertical direction, the strain pattern shown in figure 2*d* cannot be attributed to buckling of a lithospheric plate but must be the result of rotational stresses. In this case, there is tangential extension increasing outwards in the external parts, and the tangential contraction in the internal parts. Between the two is a zone of no tangential strain. While it is likely that in the crust we shall find complex combinations of these simple models, it is also clear that study of the patterns of finite strains should provide evidence of the way in which arcs have been produced.

IBERIAN ARC

It is proposed that the Iberian arc is a secondary arc or orocline produced by the tectonic bending, during the Variscan orogeny, of an originally straight or much less curved fold belt. For reasons summarized elsewhere (Ries 1974), the reconstruction proposed by Carey (1958) and Williams (1973) which implies a simple rotation of the Iberian Peninsula relative to Brittany with little or no lateral displacement in the Pyrenean zone, is assumed. By using this model, figure 3 shows the arcuate nature of the Variscan fold belt in the Iberian Peninsula and south Brittany in pre-Mesozoic times. The main structural trend curves west in south Brittany through southwest and south in northwest Spain to southeast in central and south Spain. In north Spain the structures tighten eastwards so that in Cantabria they curve through 180°. An unusual feature of the Iberian arc is that the principal Variscan folds, which vary from steep to recumbent, face inwards; the apparent direction of movement is towards Cantabria, in the centre of the arc.

By evaluating the finite strains in the Lower Palaeozoic and late Precambrian rocks in south Brittany and the Iberian Peninsula and comparing these strains with those deduced for the different models above, it should be possible to determine the primary or secondary nature of the Iberian arc. It must, however, be emphasized that it is the finite longitudinal strain, parallel to the arcuate folds, that is relevant to this discussion. The orientation of the stretching lineation, especially in the domains of polyphase folding, will vary in orientation even from the limbs to the hinge of a single fold; where there is extensive horizontal movement, as in zones of recumbent folding, the stretching lineation will usually be parallel to the movement direction. To discriminate between different types of arcuation it is necessary to find out whether the strain axis parallel to the arc has been extended or contracted.

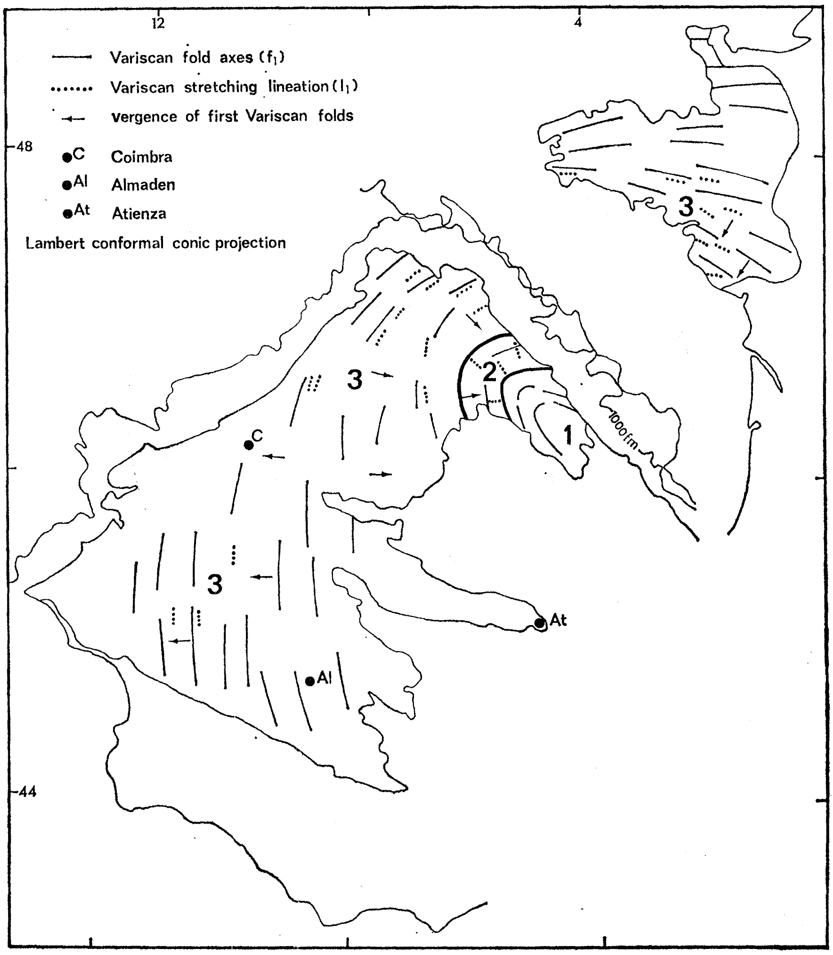

Figure 3. Structural zones in Brittany and the Iberian Peninsula and palaeomagnetic sites of Van der Voo (1969). Pre-Mesozoic reconstruction after Carey (1958).

In zone 3 (figure 3) the stretching lineation (X direction of the strain ellipsoid) plunges at low angles parallel to the main fold axes in south Brittany and in the external† parts of the Variscan fold belt in the Iberian Peninsula. The shapes of deformed objects in this zone indicate that the finite extension increases outwards and that it is commonly greater than 100 % in the outer part of the Iberian arc. In the inner part of the arc (zone 2) the finite stretching lineation plunges down-dip and appears to fan round the arc, so that as the fold axes change direction the perpendicular relation of stretching lineations to fold axes is maintained. The change from the domain of horizontal stretching to that of down-dip stretching is marked approximately by the

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† External is used to refer to the convex side of the arc, and not the side nearest to an undeformed foreland, which is not seen in the Iberian Peninsula.

line separating zone 3 from zone 2 on figure 3. This line represents a zone less than 10 km wide. The steep orientation of boudin axes and the growth of fibres sub-parallel to the main fold axes shows that in zone 3 the longitudinal extension is real and is not merely an apparent extension produced by superimposed strains or by volume reduction or by rolling. It is more difficult to exclude the possibility that the extension is due to plunge variations of the extension axes X, associated with heterogeneous strain (cf. Wood 1971), but finite longitudinal strains of 100 % appear to be too large and the plunge variations too small to be explained in this way. In zone 1 where the curvature of the arc is greatest the arcuate folds are buckled by a fan-shaped bundle of later E–W trending folds (Julivert 1971) which has the effect of increasing the curvature of the arc.

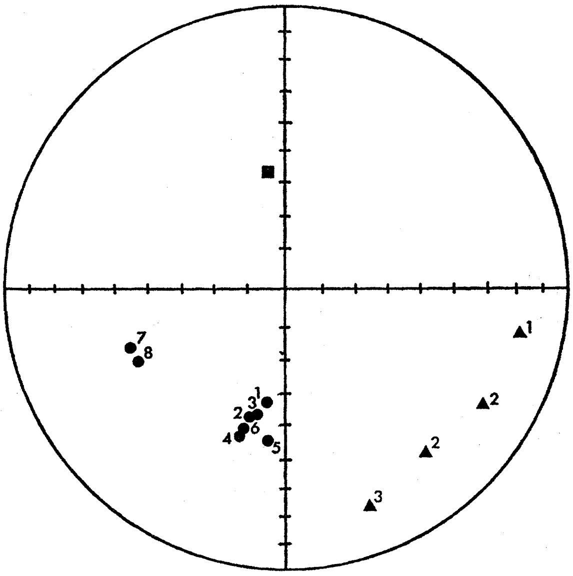

FIGURE 4. Equal area projection of the mean directions of characteristic magnetizations obtained from Ordovician and Silurian rocks of the Iberian Peninsula (▲) and from Ordovician-Devonian rocks of Norway, Scotland and England (●). Reproduced with permission from Van der Voo (1969). ▲[1], Coimbra volcanics (Upper Ordovician); ▲[2], Almaden volcanics (Upper Silurian); ▲[3], Atienza volcanics (Upper Silurian); ■, present day local geomagnetic field of Madrid. (Symbols represent north-seeking poles pointing downwards with a positive inclination.)

Van der Voo (1969) published palaeomagnetic data which also appears to support a secondary origin for the Iberian arc. The Iberian sites sampled by Van der Voo are plotted on figure 3. Comparison of a plot of the mean directions of magnetizations obtained from Ordovician and Silurian rocks of Northern Europe with those from the Spanish Meseta (figure 4) shows that the two groups differ both in inclination and declination; the data from the Iberian Peninsula show a large scatter in declination. There appears to be an angular difference in declination of approximately 65° between the data for Northern Europe and the mean of the data calculated from the Almaden site (Spain). If 35° (the angle through which the Iberian Peninsula rotated to form the Bay of Biscay between the Late Triassic and Late Cretaceous (Van der Voo 1969)) is subtracted from the total angular difference in declination, this data shows that that part of the Variscan fold belt rotated at least 30° before the Late Triassic.

CONCLUSIONS

Comparing the strain patterns observed with those implied by the several models which are put forward, we find that the observations fit the third type (figure 2*d*). It is only in this model that we find tangential extension on the outer side of the arc and radial extension, tangential shortening on the inner side.

A different interpretation has been proposed by Matte & Ribeiro (1975). They suggest that the arc is partly secondary and was produced by a relative movement towards the west of the Cantabrian block. The structures on either side of the block are envisaged as steep shears, dextral on the north side (Brittany) and sinistral on the south (Portugal). West of the block, eastward-facing recumbent folds (Mondeñedo nappe) developed, with the extension axes X parallel to the movement direction. This model is similar to our second type (figure 2*c*), with some features of the first (figure 2*b*). Features which are unexplained by this interpretation are the northward-facing recumbent folds in southern Cantabria (de Sitter 1962) and the northward movement of the Esla nappe, the east–west fan of secondary folds (Julivert 1971) which indicates substantial north–south compression of the Cantabrian arc, and the tangential orientation of the extension axes in Galicia, west of the postulated block. Our observations show tangential extension throughout the external (western) part of the arc and radial extension in the interior parts (figure 3). This model implies clockwise rotation on the north side of the Cantabrian arc and counter-clockwise rotation on the south side while our interpretation implies counter-clockwise rotation throughout. Palaeomagnetic measurement should discriminate between the two hypotheses.

We conclude that the Iberian arc is a secondary arc produced by a counter-clockwise rotation of the Iberian Peninsula relative to Brittany, the amount of rotation increasing southeastwards round the arc.

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