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Evolution of folds during progressive shear in the South Armorican Shear Zone, France

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Abstract—The South Armorican Shear Zone (S.A.S.Z.), itself composed of several ductile shear zones, may be followed for more than 300 km in southern Brittany (France). Developed during late Hercynian times, the S.A.S.Z. deforms (a) leucogranites emplaced at 320 Ma, and (b) late Precambrian and Lower Palaeozoic sediments.

In Palaeozoic rocks of the studied area, folds are highly non-cylindrical and sheath-like, especially on the limbs of a major syncline. In the Precambrian rocks, folds are non-cylindrical and some are conjugate. A detailed geometric study of the conjugate folds is presented, and a model is proposed to account for the simultaneous development of the two types of folds during progressive shear. According to this model, the type of fold that develops depends on the initial orientation of the surface to be folded. In Palaeozoic rocks, the surface to be folded is initially subparallel to the shear direction and the rotation axis. In Precambrian rocks, the surface is highly oblique to both directions. The initiation of non-cylindrical and conjugate folds involves a mechanical instability, either localised at heterogeneities, or periodic. The amplification is at first partly mechanical but becomes largely kinematic at later stages of shearing.

INTRODUCTION

The study of fold mechanisms in non-coaxial deformation regimes has been the object of increasing interest in recent years. Fold axes are frequently rotated towards the stretching lineation (Bryant & Reed 1969, Escher & Watterson 1973). Reorientation by progressive curvature of fold axes (Hansen 1971) may be so extreme that folds take on highly elongated sheath forms (Carreras *et al.* 1977, Quinquis *et al.* 1978, Cobbold & Quinquis 1980). Natural non-cylindrical folds have been tentatively correlated in the past with various types of finite strain ellipsoid (flattening type of Dearman 1969, constriction type of Borradaile 1972, Sanderson 1973) but many recent correlations are with non-coaxial plane strain (simple shear) (Rhodes & Gayer 1977, Quinquis *et al.* 1978, Cobbold & Quinquis 1980).

We have studied folds in the South Armorican Shear Zone because this structure has a relatively simple geometry (Jegouzo 1980) and deformation history (Berthé *et al.* 1979a). Sheath folds, mildly non-cylindrical folds and conjugate folds have been observed in one particular area of sedimentary rocks (Fig. 1a). The three-dimensional geometrical features of these folds provide important constraints on the history of their development, for which we propose a model.

Tectonic setting

The South Armorican Shear Zone is composed of several ductile branches and may be followed for more than 300 km in southern Brittany (Cogné 1960, Jegouzo 1980) (Fig. 1a). In the area studied (eastern part of the northern branch, Fig. 1b), tectonic structures are controlled by; (a) a N–S crustal shortening associated with the diapiric ascent of Hercynian leucogranites dated at 320 Ma (Vidal 1973, Le Corre 1978), and (b) by a subhorizontal component of dextral shear.

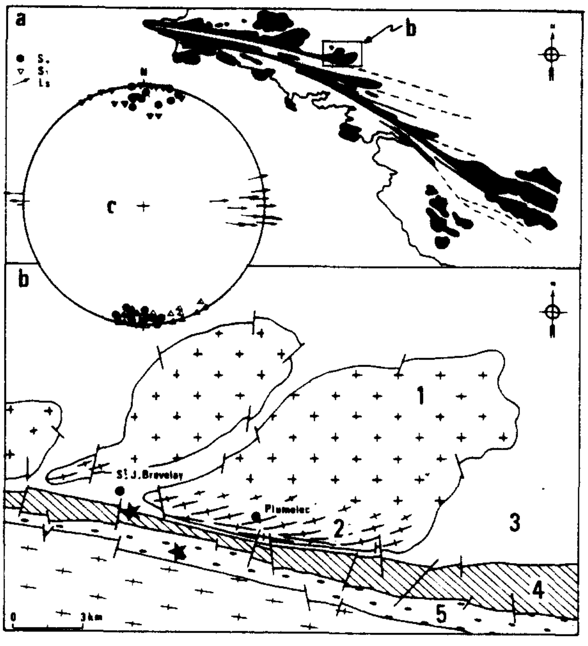

Fig. 1. (a) Map of Brittany showing South Armorican Shear Zone, Hercynian leucogranites (black) and area studied. (b) Main rock types and sample localities (black stars). (1) Undeformed isotropic granite. (2) Mylonitic leucogranite. (3) Brioverian sedimentary rocks. (4) Palaeozoic sedimentary rocks. (5) 'Schistes et arkoses de Bains', Brioverian in part. (c) Stereographic projection (lower hemisphere) showing poles to bedding (black circles), poles to cleavage (triangles) and stretching lineation (arrows).

Outside the shear zone, the leucogranites are undeformed and have an isotropic fabric. Within the shear zone, there is a subvertical foliation (striking N100°E in the ultramylonites) which bears a strong subhorizontal stretching lineation marked by syntectonic crystallisation (Fig. 1c). A study of deformation in the mylonites has demonstrated that; (a) strain increases in intensity from the boundaries to the centre of the zone,

(b) deformation is dominantly by simple shear, (c) the shear direction is subhorizontal, striking N100°E, and (d) the sense of shear is dextral (Berthé *et al.* 1979 a, b).

Precambrian and Palaeozoic sedimentary rocks are exposed to the south of the granites in a major syncline striking N100°E (Fig. 1b). Bedding is steeply dipping and an axial plane schistosity is generally parallel to it; the stretching lineation is subhorizontal (Fig. 1c). We will describe folds developed, firstly in mylonitic pegmatites and Palaeozoic sedimentary rocks and secondly in Precambrian rocks.

FOLDS IN THE PALAEOZOIC ROCKS AND THE MYLONITIC PEGMATITES

In both Palaeozoic sedimentary rocks and mylonitic pegmatites, non-cylindrical folds are relatively common. Their amplitudes range from 1 to 100 cm. Generally, fold axes are subparallel to the stretching lineation, and axial planes are vertical and subparallel to the cleavage. Less amplified folds have a clear dextral asymmetry. In the sedimentary rocks the folded surfaces may be bedding, bedding plus cleavage, or quartz veins. In the pegmatites, the folded surface is mylonitic banding. The fold shape varies greatly with rock type and structural position within the major synform. Most of the observed folds are strongly non-cylindrical (sheath-like folds, Carreras *et al.* 1977, Quinquis *et al.* 1978) and present, in sections normal to the stretching lineation, characteristic eye-like structures, which have been experimentally reproduced (Cobbold & Quinquis 1980).

FOLDS IN THE PRECAMBRIAN ROCKS

Minor folds are relatively frequent in the finely-laminated pelites and greywackes of the 'schistes et arkoses de Bains' formation, partly attributed to the late Precambrian (Le Corre 1978). These folds are everywhere non-cylindrical and some are conjugate (Fig. 2). Their complex three-dimensional geometry has been reconstructed from serial sections.

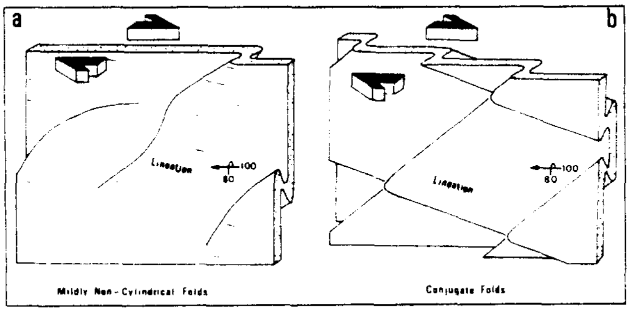

Fig. 2. Relative position of mildly non-cylindrical folds and conjugate folds in the Precambrian rocks.

Mildly non-cylindrical folds

These are the only well developed folds observed at outcrop. They appear as asymmetrical folds whose axes are curved and oblique to the stretching lineation (Fig. 3a), and which die out along the length of the axes (Fig. 2a). Short limbs may be up to 30 cm long. Asymmetric fold traces on horizontal sections are everywhere dextral and compatible with the sense of shearing deduced from the study of deformed granites. Some examples of folds are localized around heterogeneities such as quartz pebbles (Fig. 4).

A study of fold shape as a function of axial curvature has been undertaken using sections cut normal to hinge lines of folds (Fig. 3a). Variations of (a) amplitude A, and (b) fold hinge thickness T, have been plotted as functions of the angle α between the fold axes and the stretching lineation (Fig. 3c).

For the example shown in Fig. 3(a) we have studied three successive competent layers of which the most competent is the outermost quartzitic one. We define the fold amplitude A as half the value H taken by Hansen (1969, p. 11). For each layer, the plot of A vs angle α is an asymmetric bell-shaped curve with a peak in the region $40° < \alpha < 80°$. Superposition of the curves for the three layers shows that the folds are arranged in an en échelon pattern.

A graph of T vs α shows maxima in the region between 60° and 90°. Each maximum is bounded by two minima when the curve is complete. For a given layer, the difference between the maximum and minimum may be used as a qualitative index of strain intensity. Thus, in Fig. 3(c) the layer K is the least deformed.

It is useful to compare the graphs of A vs α and T vs α. For each layer, the thickness maximum is displaced with respect to the amplitude maximum by an angle $12° < \alpha < 20°$. The least deformed layer K shows the lowest amplitude maximum for the greatest value of α. In contrast, layer M shows the greatest amplitude maximum for the lowest value of α. These facts indicate that A and T are functions of strain intensity. They also suggest that fold axis curvature is a consequence of reorientation during progressive deformation. Folds appear with their axes highly oblique (90°) to the stretching lineation and as they amplify, their axes rotate towards it.

Conjugate folds

These are rarely observed directly at outcrop. They have been reconstructed from photographs of serial sections cut in blocks in which they are more easily observable (Fig. 5c). The stretching lineation is everywhere slightly oblique on one family of fold axes. At outcrop, only the folds with strongly oblique axes are markedly apparent. Although each family of folds has its own characteristic asymmetry, all the fold profiles in the horizontal plane have the same dextral-asymmetry compatible with a dextral sense of shearing (Fig. 2b).

Where two families intersect, they produce interference structures (Figs. 5b & c) whose size varies with the dimensional parameters of the multilayers (competent-layer spacing and thickness, total thickness of the multilayer). When the interference structures are small, the

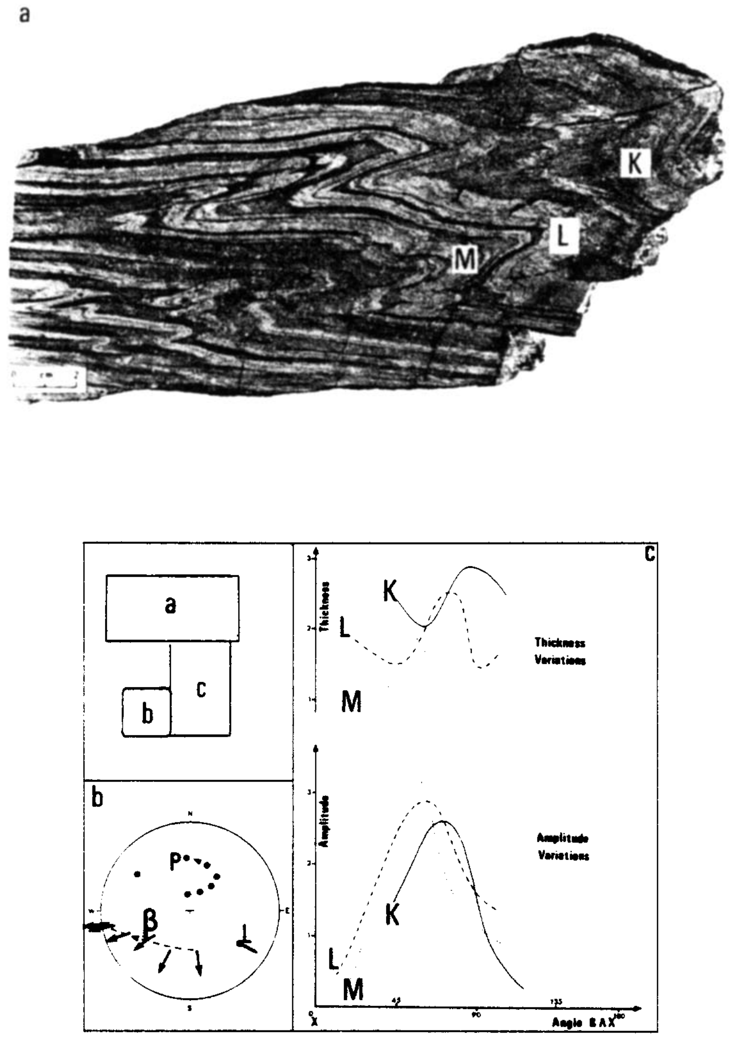

Fig. 3. Geometry of mildly non-cylindrical folds. (a) Section showing three successive competent layers (*K*), (*L*) and (*M*). Fold axis for layer (*K*) is exactly normal to section. Axes for (*L*) and (*M*) deviate slightly from the normal. True profiles for (*L*) and (*M*) have been reconstructed by projection. (b) Stereographic projection (lower hemisphere) showing locus of reorientated fold axes (β), locus of poles to axial planes (p) and stretching lineation (*L*). (c) Upper part: hinge thickness (*T*) vs angle (α) between fold axis and stretching lineation. Lower part: amplitude(*A*) verses (α).

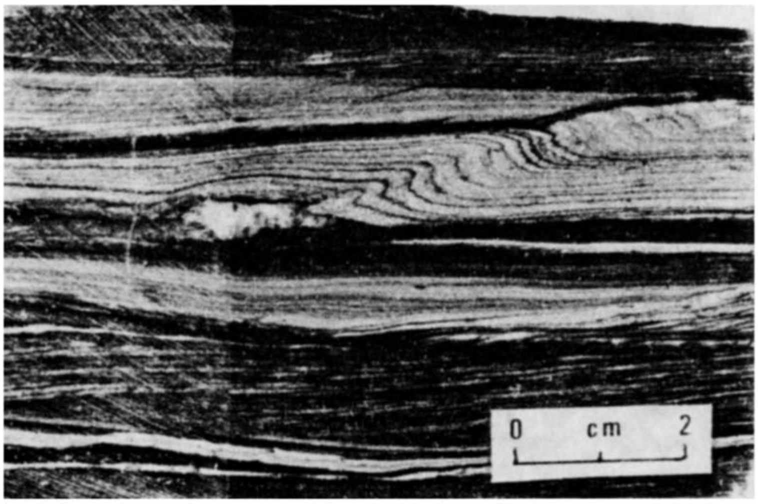

Fig. 4. Nucleation of an asymmetric fold around a quartz pebble. Note that the fold amplitude dies out along the axial plane.

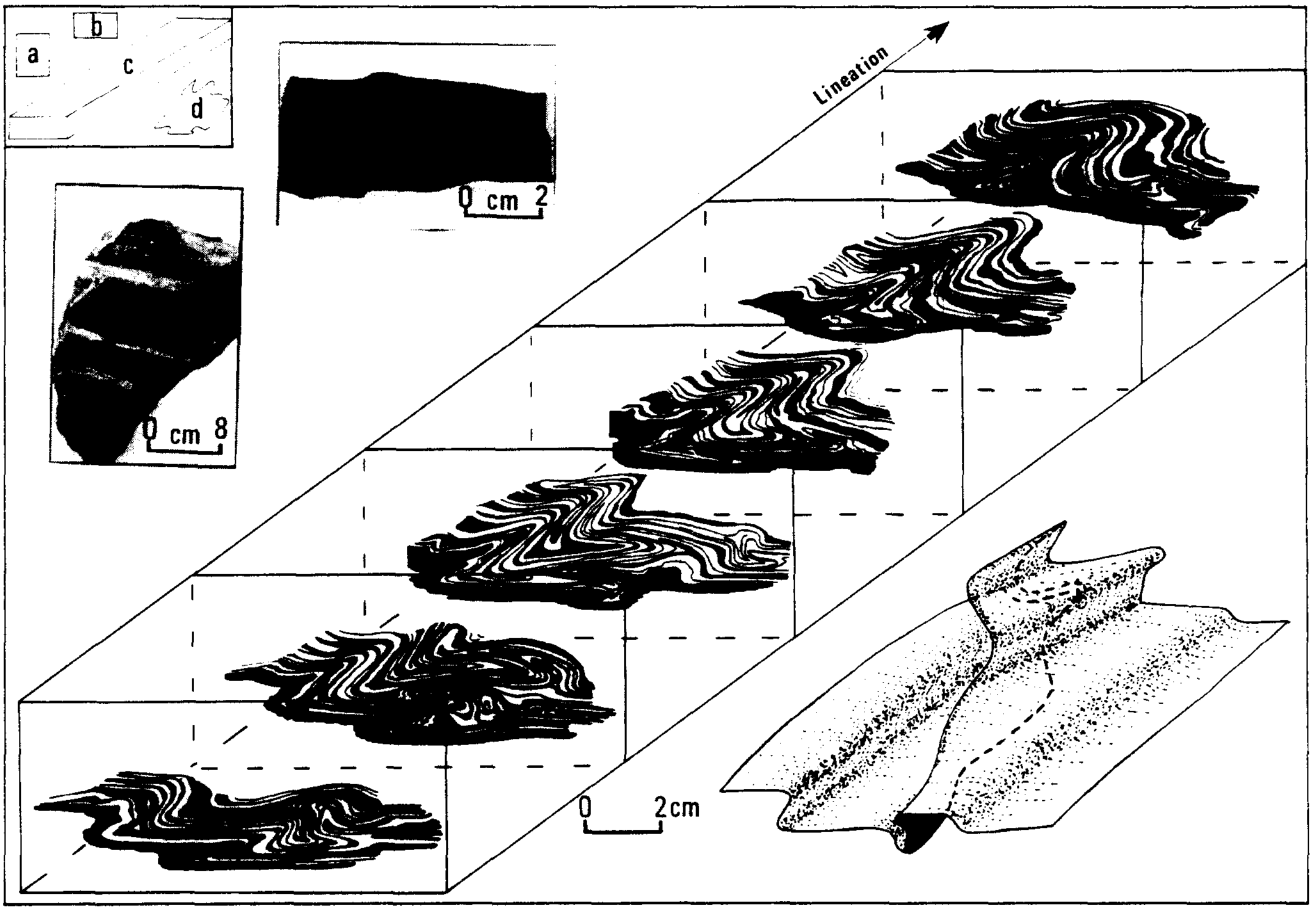

Fig. 5. Geometry of conjugate folds. (a) Photograph showing characteristic parallelograms bounded by axes of conjugate fold sets. (b) Section normal to stretching lineation at point of intersection of two fold sets, showing interference geometry. (c) Block diagram showing serial sections through another example with greater reorientation of axes. (d) Three-dimensional reconstruction of the shape of one layer from block diagram (c).

two fold sets deflect the bedding into characteristic parallelogram shapes (Figs. 2b and 5a) (cf. Ramsay 1962, p. 519, Ramsay & Sturt 1963, p. 418). When the interference structures are large, only one of the fold sets appears on the bedding planes. In this case, the interference structures may be reconstructed from serial sections in three dimensions (Figs. 5c & d). These are similar to the type 3 interferences described by Ramsay (1967) and could be easily confused with superposed folds of two distinct phases.

A MODEL FOR DEVELOPMENT OF FOLDS DURING PROGRESSIVE SHEAR

The salient features of the folds described above, that is; (a) the dextral asymmetry of folds oblique to the subhorizontal stretching lineation, (b) the existence of highly elongated sheath folds, and (c) the progressive reorientation of fold axes towards the lineation, are compatible with the existence of a dominant, transcurrant, dextral shear regime, as deduced from the study of deformed granites (Berthé *et al.* 1979 a, b).

Consider a simple shearing with shear direction *a*, and axis of rotation *b*, where *b* is normal to *a* in the shear plane. When the surface to be folded contains *b*, folds initiate at high angles (90°) to the lineation and then reorientate symmetrically about it (see Cobbold & Quinquis 1980). This occurs in the Palaeozoic rocks and mylonitic pegmatites. If the initial position of the surface to be folded in the Precambrian rocks had been close to that observed now at outcrop, the conjugate fold axes would have been normal to the shear direction (Johnson 1971, 1977), the *b* axis also being subparallel to the surface. Therefore, the bedding in Precambrian rocks must have been highly oblique to the *a* and *b* axes. Because the South Armorican Shear Zone strikes N100°E and is dextral, bedding in Precambrian sedimentary rocks must have had an initial strike between N100°E and N–S. The following model describes fold development during progressive dextral shear for an oblique layer and takes into account the possible coexistence of mildly non-cylindrical folds, conjugate or otherwise.

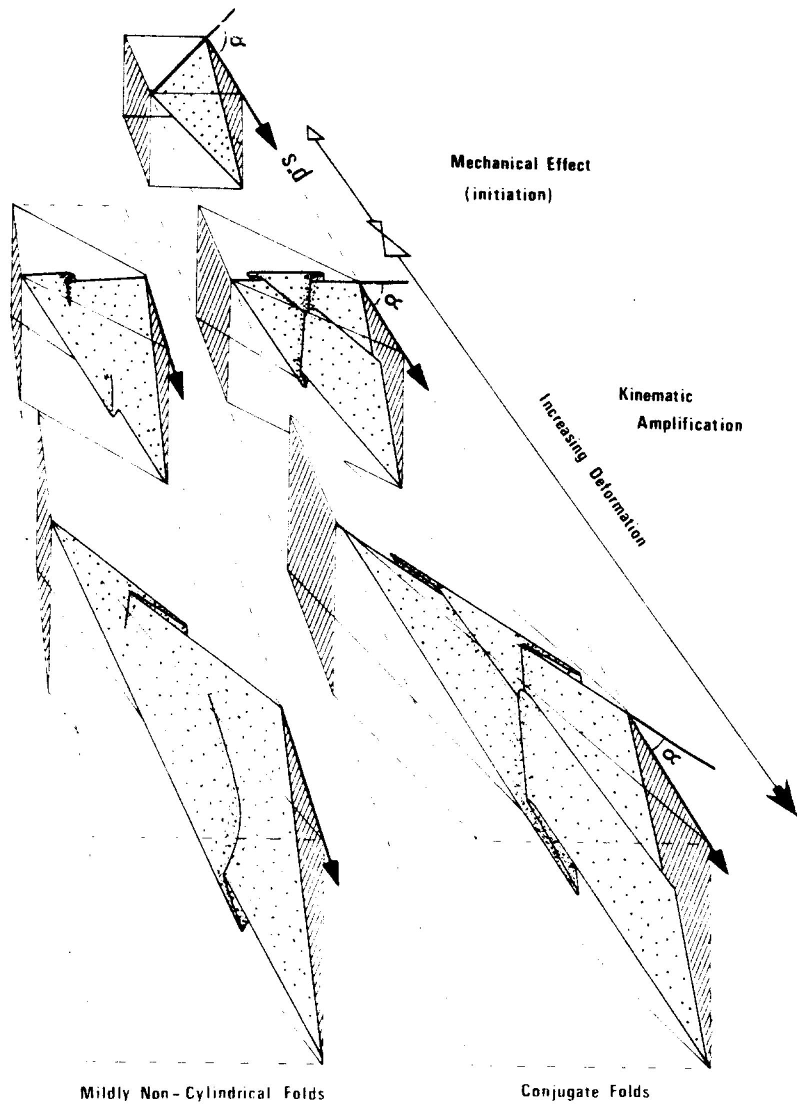

Fig. 6. Purely geometrical model for the development of the two types of fold during progressive simple shear (plane with diagonal shading is the shear plane). If the surface to be folded makes an initial angle (α) of more than 90° with the shear direction (s.d), conjugate fold sets develop (right). If the initial angle (α) is less than 90°, only one set develops (left).

Role of mechanical effects

For conjugate folds to develop, the deforming medium must be layered or mechanically anisotropic (Paterson & Weiss 1960, Cobbold *et al.* 1971, Johnson 1977). The periodicity of the characteristic parallelogram shapes (Fig. 5a) is an argument in favour of mechanical effects. On several samples, folds are localized around heterogeneities (Fig. 4). Therefore, some localized mechanical effects may also have played a significant role in the initial development of folds.

For many of the well reorientated and highly amplified folds observed in the field, there is little evidence of mechanical effects such as cleavage refraction or localized strain gradients. We propose a model of progressive folding in which, during the first stages, mechanical effects (anistropy or local heterogeneities) play an important role in fold initiation whereas, during later stages, reorientation of axes and amplification is almost purely passive (Fig. 6).

Reorientation of fold axes

The problem of fold axis reorientation is perhaps more easily understood by means of a simple geometrical model (Fig. 6). Suppose that early mechanical effects have produced two conjugate fold sets symmetrically disposed about the direction of principal extension in the plane to be folded. Let the subsequent stages of deformation be by homogeneous simple shear. As a result, one of the sets rotates faster than the other towards the stretching direction (Fig. 7). The angle between the two sets decreases as the bulk shear strain increases. For a shear value $\gamma = 5$, the two sets of fold axes become slightly oblique to the stretching direction. The most oblique axes are the most reorientated. The illustration given here (Fig. 7) for the reorientation of conjugate fold axes may be immediately transposed to the instance of non-cylindrical folds. Fold axis dispersion observed in the field (Fig. 3b) is compatible with the theoretical paths predicted by the geometrical model.

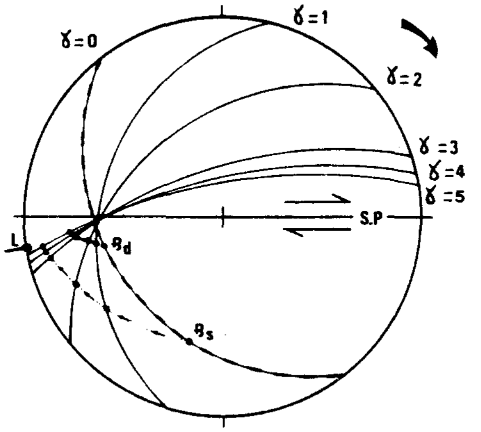

Fig. 7. Stereographic projection showing loci of reorientated fold axes during progressive simple shear (S.P. = shear plane). Dashed line is initial position of surface to be folded; solid great circles indicate reorientated surface for successive values of α; L is stretching lineation for $\gamma = 5$; B_d is locus of dextral fold axes; B_s is locus of sinistral fold axes.

When the angle (α) between the rotating surface and the shear direction is less than 90°, only one fold set can initiate (Fig. 6). The simultaneous occurrence of conjugate and non-conjugate non-cylindrical folds is therefore a direct result of reorientation of the surface during progressive shear.

CONCLUSIONS

For the South Armorican Shear Zone, we conclude that:

(a) Folds develop during a dominant dextral simple shear;

(b) Minor folds are commonly highly non-cylindrical;

(c) Variations in fold geometry may be attributed to variations in the rheological properties of sediments, and the initial position of the surface to be folded;

(d) Mechanical effects play a dominant role during the first stages of fold development whereas later amplification of folds is mainly kinematic;

(e) Reorientation of fold axes is controlled by the initial position of the surface to be folded. If the surface is subparallel to the shear rotation axis, the reorientation is symmetric around the stretching lineation. If the surface is oblique to the shear rotation axis, reorientation is asymmetric;

(f) If the surface to be folded subtends an angle with the shear direction greater than 90°, conjugate fold sets can initiate.

Many of these conclusions are probably valid for other shear zones. Further work, including theoretical, experimental and field aspects, would be useful.

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