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Vein arrays as kinematic indicators in kinked anisotropic materials

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Abstract—Vein arrays associated with natural kink bands have been, even recently, used by some workers as kinematic markers to distinguish between the migration and the rotation models of kink band mechanics.

In an outcrop of schistose meta-agglomerate, conjugate kinks and synthetic sinistral shears are associated with a component of sinistral slip along the foliation. Discordant scalariform vein arrays form in association with the shears, but not the kinks. Tension gash elements of the arrays form by combined layer-parallel slip and layer-parallel extension along the rotated schistosity. They are only kinematically significant at the scale of the length of the rotated segment anisotropy.

Applying this analysis to kink bands elsewhere, it is concluded that discordant vein arrays are not diagnostic of the rotational kink band model, or of high resolved shear stress on kink boundaries.

INTRODUCTION

KINK BANDS are monoclinal flexures developed in anisotropic materials, where the layering between the two kink band boundaries (KBB) is rotated with respect to the external layering (Anderson 1964). The rotation is effected by predominant layer-parallel slip within the kink band (Paterson & Weiss 1966, Donath 1968). From experimental work, there are two principal models of kink band mechanics: the migration model (Paterson & Weiss 1966) and the rotation model (Donath 1968). In the former, kink bands develop by progressive separation of the KBB's while the orientation of the layering in the rotated segment remains constant. In the latter, the misorientation of the rotated segment increases with increasing strain.

Veins of quartz or calcite commonly occur in association with natural kink bands. A complete vein array is a scalariform structure composed of three types of element: (1) triangular or irregular nodes formed at the intersection of the KBB's with the layering; (2) concordent veins formed within or between the layers of the rotated segment of the kink band and (3) discordant veins cross-cutting the layering and lying within or outside of the rotated segment (Anderson 1964, 1968, Marshall 1964, 1966, Dewey 1965, 1969, Ramsay 1967, pp. 447–456, Clifford 1968).

Some workers, even recently, have attempted to use vein arrays as kinematic indicators in order to distinguish between the migration and rotation models of kink band formation (e.g. Marshall 1964, 1966, Dewey 1965, 1969, Garnett 1974, Verbeek 1978, Roussel 1980). Roussel (1980) in particular relates vein formation to the rotation of rigid plates (rock fragments) which in turn control the kinking mechanism in a foliated breccia. However, the use of vein arrays as kinematic indicators necessitates establishing the correct scale at which to apply the strain analysis. In other words, to domains the size of the kink band width, kink band length, or encompassing many kink bands.

The present contribution examines arrays of veins and 90 kink bands and shears from an outcrop of schistose

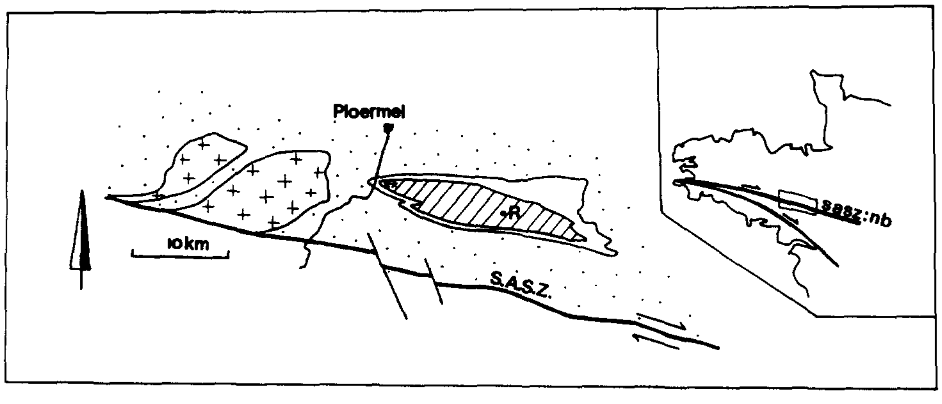

Fig. 1. Location of outcrop studied (asterisks) at western end of elliptical Reminiac (R) syncline. Late-Proterozoic sediments (dots); Schistes Pourprés de Montfort (blank); Ordovician sediments (cross-hatched); Carboniferous granite (crosses); S.A.S.Z., South Armorican Shear Zone; n.b., northern branch. (after Queté 1975 and Berthé *et al.* 1979).

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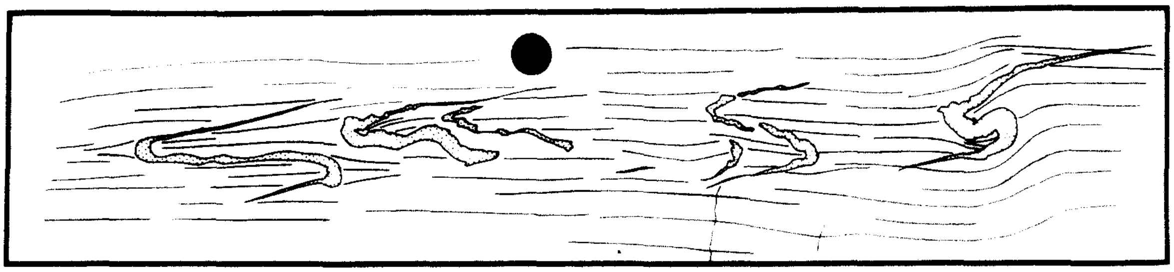


Fig. 2. En-echelon sigmoid veins indicate sinistral slip along the schistosity. Slip attenuating towards right. Note isolated thin veins perpendicular to schistosity. Circular scale 2.5 cm.

meta-agglomerate adjacent to the South Armorican Shear Zone (S.A.S.Z. Berthé *et al.* 1979) in Brittany, France. Three questions are addressed.

(1) What are the mechanics and kinematics of kink band and shear formation?

(2) What is the kinematic framework indicated by the vein arrays?

(3) What light does the relationship between (1) and (2) shed upon other kink band/vein array associations?

GEOLOGICAL SETTING

The kink bands and vein arrays occur in a single outcrop of Ordovician meta-agglomerate at the western end of the Reminiac Syncline (Queté 1975), south of Ploermel (Fig. 1). The major structure is a elongate, WNW–ESE trending, doubly plunging, upright syncline whose axial trace is parallel to the northern branch of the transcurrent S.A.S.Z. A well developed penetrative vertical schistosity is axial planar to the syncline and both the folding and schistosity are of Hercynian age (Hanmer *et al.* 1982).

Major dextral movement occurred along the S.A.S.Z. during the Carboniferous (Cogné 1957, Berthé *et al.* 1979). Carboniferous granites, syntectonic with respect to the folding and schistosity of the sedimentary country rocks (Hanmer & Vigneresse 1980), were mylonitized along the S.A.S.Z. and a component of simple shear, along the country rock schistosity planes, increases in intensity towards the S.A.S.Z. (Gapais 1979).

The outcrop

The outcrop (Fig. 1) examined was selected for its size and relief, both uncommon in this poorly exposed region, and for the exceptional development of kink band and vein arrays, neither of which are present in neighbouring exposures. No regional extrapolation from this single outcrop is intended.

The outcrop, 150 × 30 × 10 m comprises a fine grained, homogeneous quartz-chlorite schist with a vertical, 100–110° striking, planar schistosity. No mineral elongation lineation is developed. On horizontal surfaces, discrete, elongate, elliptical sections through rock fragments of matrix composition are visibly flattened in the schistosity.

Kink bands are locally developed. Where they are

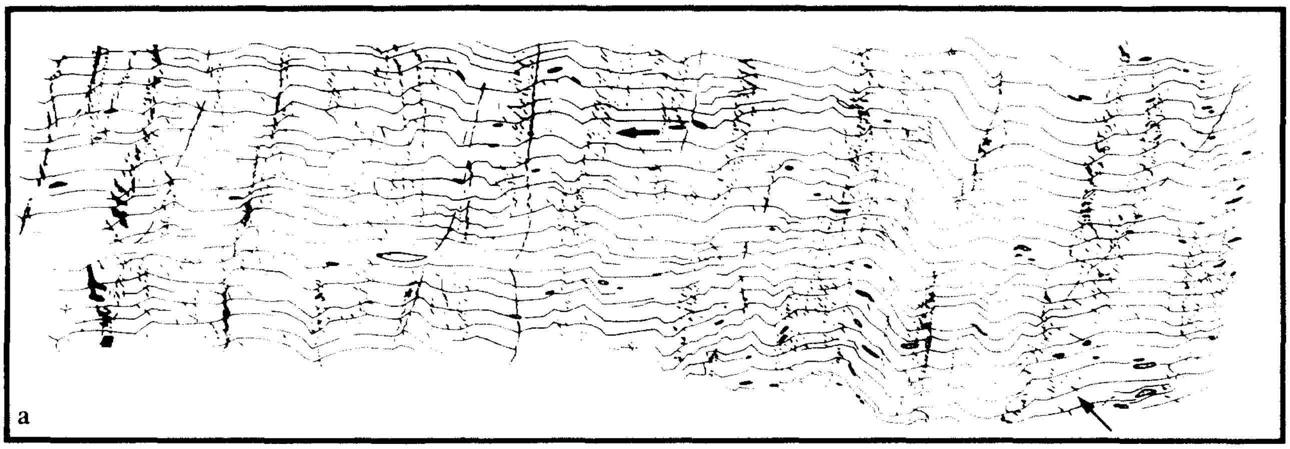
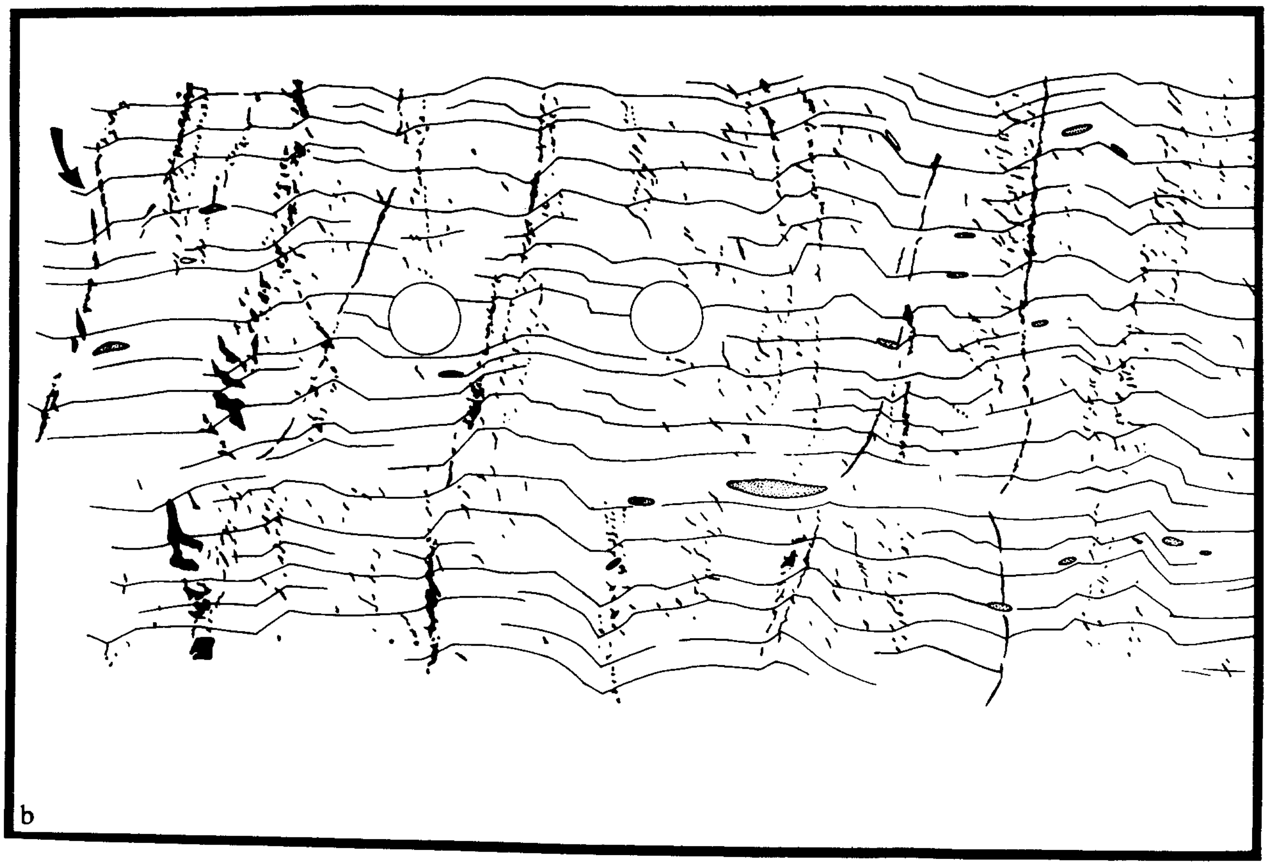


Fig. 5. Conjugate kink bands, sinistral shears, scalariform vein arrays (black), and rock fragments (stippled few only for clarity) in schistose meta-agglomerate (plan view whole outcrop plus detailed enlargements). Note the long isolated thin veins cross-cutting kinks and shears (right), the type 3' elements in non-kinked, non-sheared domains (e.g. thin arrow) and rare association of type 1 elements with sinistral kink band (curved arrow). Scalariform vein arrays generally associated with shears, but also present in non-kinked intervening domains (bold arrows). Circular scales 2.5 cm. See text. Figs. 5(b) & (c) are enlargements of (a).



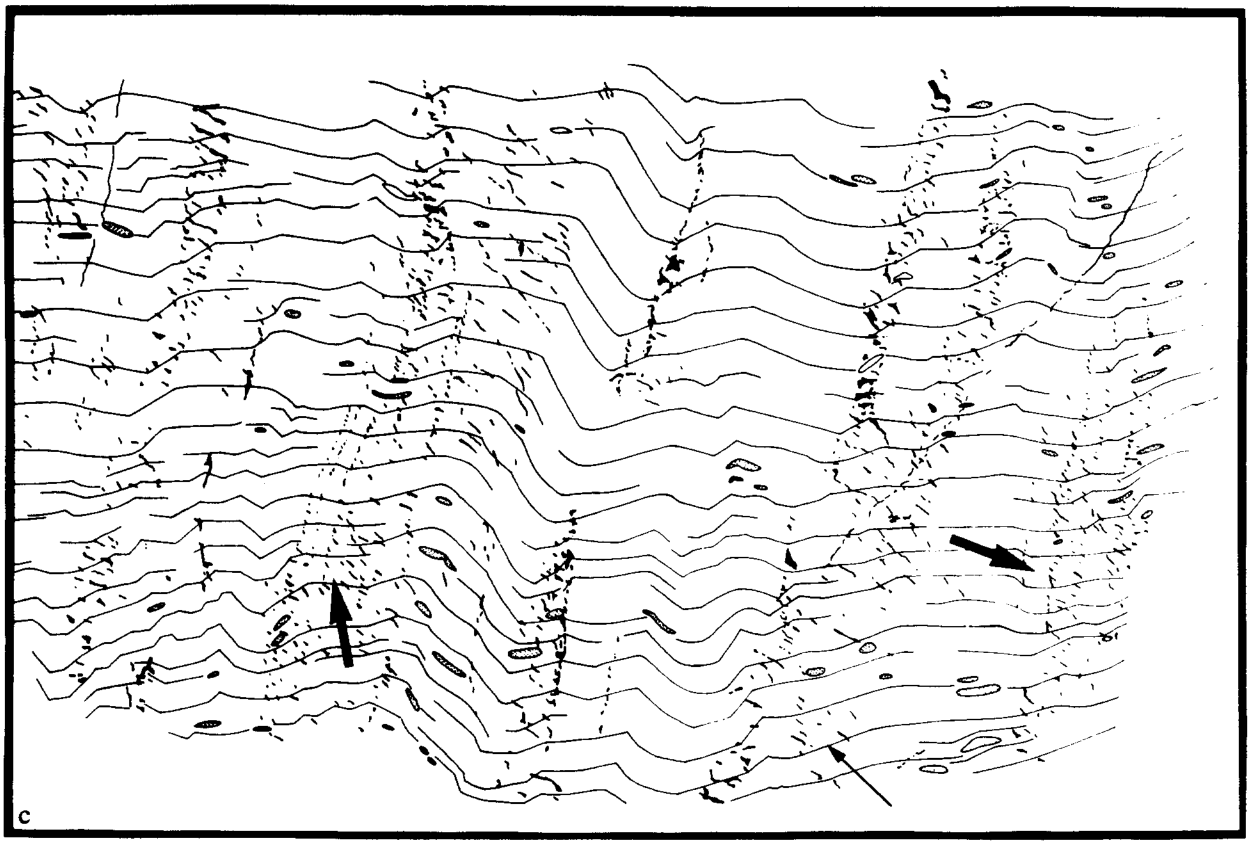


Fig. 5. (b) & (c). Caption opposite.

absent, thin, vertical folded quartz veins contain the schistosity in their axial planes. They indicate pre- or syn-schistosity vein formation. Other vertical veins lie at a high angle to the schistosity. Their orientation varies from perpendicular to 30–60° (anticlockwise) to the schistosity and indicates no-slip (flattening) and sinistral slip along the foliation respectively (Ramsay & Graham 1970). A single example was observed of a foliation-parallel zone, 3 m long, of en-echelon, sinistrally rotated sigmoid veins (Fig. 2). Irrespective of their orientation, all vein types are frequently divided into 5–10 mm segments by sinistral slip along the schistosity of the order of several millimetres.

The part of the outcrop where the kink bands are best developed is the subject of the rest of this contribution.

KINK BANDS AND SHEARS

The kink bands form a dense array and are generally oriented at high angles to the ESE-trending schistosity. They display a near orthorhombic symmetry with respect to the foliation (Ramsay 1962). They fall into three classes: sinistral (N–S), dextral (NNE) (Fig. 3) and sinistral (NNE) (Fig. 4). The use of the term 'kink' for the latter sinistral structures has been rightly challenged by Weiss (1968a), so the term shear will be used here to designate this class of structure.

Both kink bands and shears have an angular to rounded morphology. Their geometry and distribution is illustrated in Fig. 5. The schistosity is generally continuous across the KBB's and shear boundaries, although in some cases the KBB's are marked by joints.

A detailed geometrical analysis of these structures is presented in Fig. 6. The following distinctions are made between the dextral and sinistral kink bands, although the small sample size does not allow the assumption of statistical significance for (b) and (c): (a) Within the area analysed, 73.5% of the kink bands are dextral (Figs. 6a–h). (b) Although conjugate, the distribution of the kink band orientations is mildly asymmetrical about the schistosity. The mean angle between the KBB and the external schistosity (α) is 6° greater for the dextral kink bands (Figs. 6a & e). (c) Whereas the sinistral class corresponds geometrically to the ideal kink band of Paterson & Weiss (1966), i.e. $\alpha = \beta$ (Figs. 6e, f & h), the dextral kink bands are generally mildly over-rotated ($\alpha > \beta$) by up to 9° (Figs. 6a, b & d).

The geometrical analysis of the shears is given in the same form as that of the kink bands for convenience only (Figs. 6i–l). The shear boundaries are sub-parallel to the dextral KBB's (Fig. 6i), but the shears show a sinistral relative displacement (Fig. 6m). In number, and therefore density, they are similar to the dextral kink bands (Fig. 6). In other words, shears, dextral and sinistral kink bands occur in the ratio of 3:2.7:1 respectively.

Differences in the morphology, colour and degree of weathering of the schistosity are not detectable across the shear boundaries and KBB's. The structure of the schistosity has not, therefore, been markedly modified in the kinks and shears (Clifford 1968). The elliptical rock fragments aligned in the schistosity are locally sited within the kink bands and shears. However, they are also deflected with the schistosity at KBB's (Fig. 4) and their spatial distribution does not influence the orientation of the kink bands and shears (Fig. 5). The rock fragments therefore, are not more competent than the matrix (Hanmer 1979) and do not play a specific role in the generation of the kinks and shears (cf. Roussel 1980).

VEINS

These quartz veins differ from those isolated examples developed in the absence of kinks and shears, in that the outcrop is dominated by discordant, scalariform arrays of short, vertical veins (Fig. 5). These arrays lie both within the shears (Fig. 4) and in the intervening domains separating the kink bands and shears (Figs. 3 and 5). The scalariform arrays are never complete and are generally composed of type 1 and type 3 elements (Fig. 4), i.e. triangular nodes and discordant veins. While a few partial arrays of type 1 elements may be associated with either class of kink band, it is emphasised that scalariform arrays only occur within the shears and in non-kinked intervening domains.

The geometrical analysis of the scalariform vein arrays is given in Fig. 6 (n and o). The distribution of orientations of array elements spans the range 0–95° with respect to the external schistosity. The histogram peaks correspond to bimodal distributions of the type 1 (θ = 67.5° and 82.5°) and type 3 (θ = 27.5° and 50°) elements. From the data, an idealized segmented, composite 'rung' of the scalariform arrays can be constructed (Fig. 6o), whose orientation is consistently clockwise to the external schistosity. Type 3 elements occur more frequently than type 1 elements (Fig. 6n). From Figs. 6(k) and (n), the type 3 elements make an angle of 67–90° with the rotated schistosity within the shears indicating that dextral (clockwise) slip occurred along the rotated foliation. Note that the form of the scalariform arrays in the shears is indistinguishable from that of scalariform arrays occurring in the non-kinked intervening domains.

Two other types of veins occur, individually or in irregular swarms, in the non-kinked intervening domains (Fig. 5). The first show the same sense of obliquity to the schistosity as the type 3 elements of the scalariform arrays, although they are longer than the scalariform elements. They are designated here as 3'. They lie at 30–60° (clockwise) to the schistosity and indicate dextral slip along the foliation. The second type are long, isolated veins, oriented either perpendicular or at 30–45° (anticlockwise) to the schistosity. They cross-cut both the shears and the kink bands without detectable deflection and, therefore, indicate post-shear and post-kink sinistral slip along the foliation. This is supported by the division of the type 3 and 3' elements into short segments, delimited by sinistral off-sets of the order of several millimetres, indicative of the slip along the schistosity.

The spatial distribution and sequence of the opposed senses of slip along the schistosity as deduced from the veins is summarized in Fig. 7.

Fig. 3. Conjugate kink bands, sinistral (s) and dextral (d). Note asymmetry with respect to foliation. Partial array of type 1 elements along shear boundaries (top) pass into non-kinked, non-sheared domain (arrows). Dextral kink 1 cm wide.

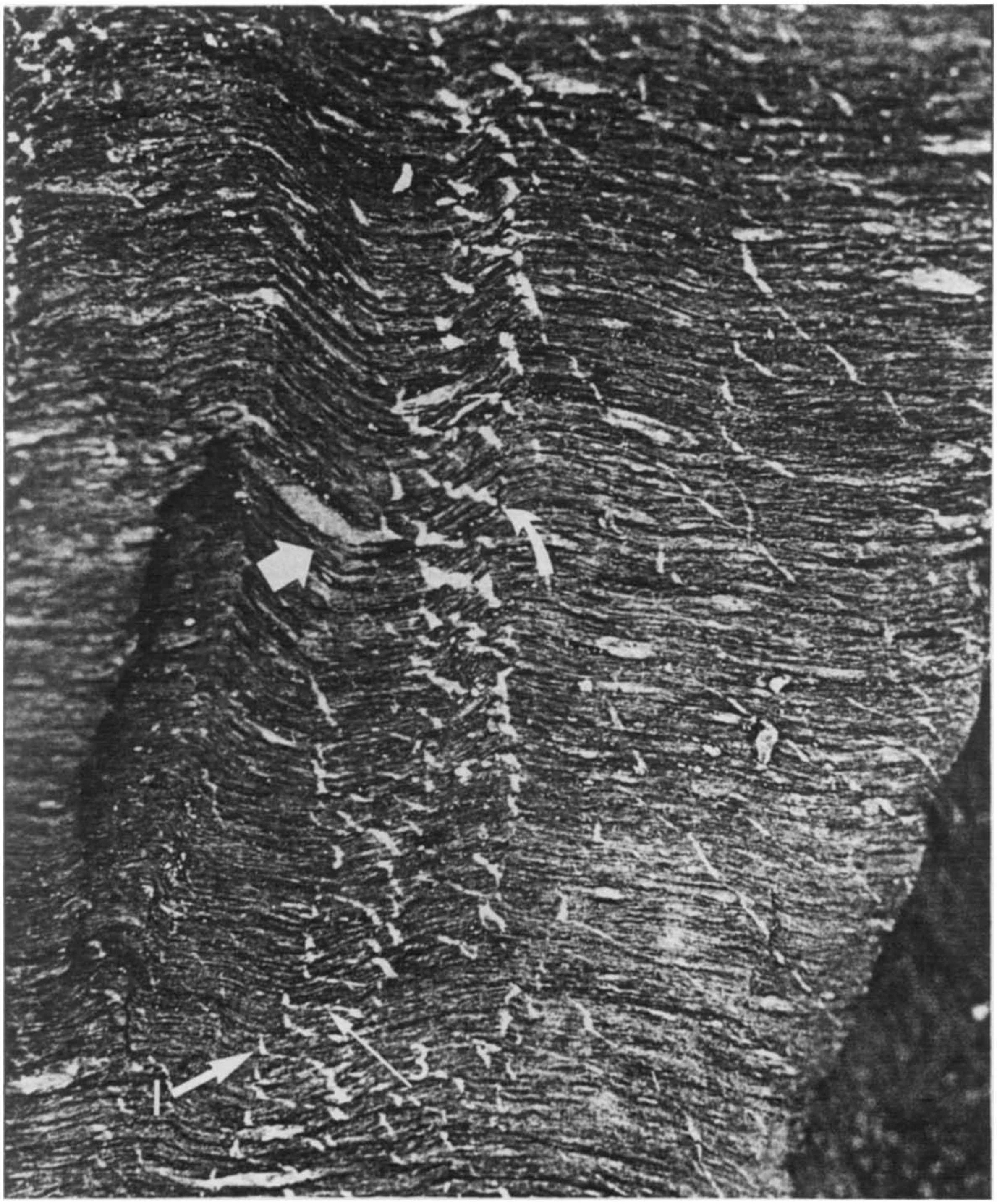


Fig. 4. Sinistral shears and associated scalariform arrays of veins composed of type 1 and type 3 elements (arrows and numbers). Type 3 elements segmented by sinistral slip along the schistosity (curved arrow). Irregular distribution of type 3′ elements outside of shear (right). Note elliptical rock fragments aligned in schistosity and bent at shear boundaries (bold arrow). Arrowed rock fragment 1.5 cm long.

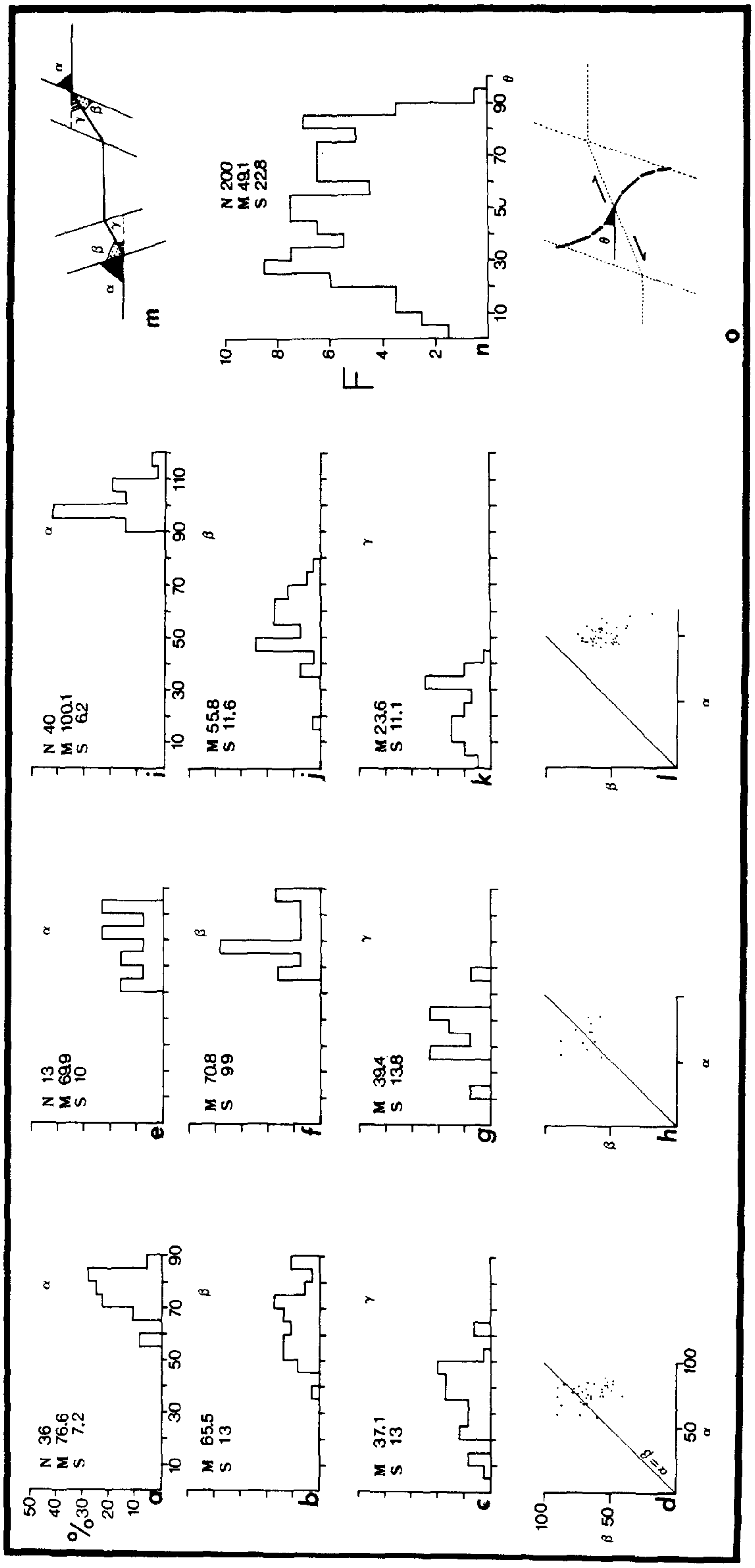


Fig. 6. Geometrical analysis of dextral kink bands (a–d), sinistral kink bands (e–h), sinistral shears (i–l) and scalariform vein arrays (n). Kink band and shear angles shown in (m). Constructed ideal "rung" of scalariform array and angle θ measured with respect to external schistosity shown in (o). All horizontal scales in degrees. Vertical axes in d, h and l in degrees. F = frequency, N = sample size, M = mean, S = standard deviation. Discussed in text.

SLIP POST VEIN FORMATION	SLIP DURING VEIN FORMATION			
sinistral	none + sinistral + dextral			KINKS & SHEARS ABSENT
sinistral	dextral	IN-SHEAR		KINKS & SHEARS PRESENT
sinistral	dextral	SCALARIFORM	INTERVENING DOMAINS	
sinistral	dextral	3°		
——	none + sinistral	LONG		

Fig. 7. Tabulation of distribution and sequence (with respect to formation of particular vein indicator) of layer-parallel slip. Discussed in text.

DISCUSSION

Veins arrays have been interpreted as kinematic indicators and used by some workers as criteria for distinguishing between possible models of kink band mechanics. In this study, the geometry of the kink bands and shears is indicative of the kinematics and mechanics of the deformation and offers a control over the interpretation of the associated veins.

Kink bands and shears

The mechanics of kink band formation have been studied under controlled experimental conditions (Paterson & Weiss 1962, 1966, Donath 1968, Weiss 1968b, Johnson 1970, Cobbold *et al.* 1971, Gray & Weiss 1974, Anderson 1974, Honea & Johnson 1976, Reches & Johnson 1976) and by theoretical analysis (e.g. Weiss 1980). Attempts have been made to apply some of the resulting models to natural examples (e.g. Ramsay 1962, Anderson 1964, 1968, Dewey 1965, 1969, Clifford 1968, Roberts 1971, Garnett 1974, Verbeek 1978, Roussel 1980). Two principal models and their variants have been proposed.

(a) *Migration model* (*Paterson & Weiss* 1966). Kink bands grow from a point or line source by lateral migration of the KBB's such that the geometrical condition $\alpha = \beta$ obtains throughout the growth of the kink. This model is dependent upon the concept of an ideal foliated body in which "the only fundamental mechanism of plastic deformation is glide on closely spaced surfaces parallel to the foliation. During glide, the spacing of these surfaces and the lengths of all lines lying in them remains constant and volume is conserved" (Paterson & Weiss 1966, p. 359). Furthermore, in layer-parallel shortening, slip is confined to the rotated foliation segment between the KBB's. This model of ideal kinking is supported both by further experimental work (Weiss 1968b, Cobbold *et al.* 1971, Gay & Weiss 1974) and the study of natural examples (e.g. Anderson 1968, Cobbold 1976, fig. 7).

(b) *Rotation model* (*Anderson* 1964, *Donath* 1968). Kink bands form as segments of fixed length which rotate between invariant KBB's fixed in material space. The rotation is partly accomplished by layer-parallel slip in the rotating segment and partly by initial increase and subsequent decrease in the orthogonal distance between the KBB's. Slip continues until the orientation of the rotated layering is such that slip is no longer possible. Further strain within the kink band is then accomplished by slip along the KBB's and by volume loss within the kink. In this model the KBB's are planes of high resolved shear stress. Field examples have been used to support the rotation model (Dewey 1965, 1969, Clifford 1968, Garnett 1974, Verbeek 1978, Roussel 1980).

In the Reminiac example, the sinistral kink bands correspond geometrically to the ideal constant volume, migration model. The slight general over-rotation of the dextral kinks only deviates mildly from ideal kink geometry. Although the slight orientation asymmetry of the conjugate kinks cannot be taken as significant, it does accord with the much greater frequency of dextral kink bands when compared with the experiments of Reches & Johnson (1976). Such experiments involve a major component of layer-parallel slip. Similar configurations are observed in other experiments (Paterson & Weiss 1966, Donath 1968, Weiss 1968b, Cobbold *et al.* 1971, Gay & Weiss 1974) and in natural examples (Dewey 1965, figs. 22–24, Faill 1973). By analogy, sinistral layer-parallel slip has occurred during kinking in the Reminiac example and the direction of the principal kinematic axis of extension was clockwise, oblique to the general schistosity plane. The synthetic sinistral shears are therefore kinematically analogous to high angle coarse shear band foliation structures, (White *et al.* 1980). This interpretation of the kink band shear geometry is supported by the observed zone of sigmoidal en-echelon tension gashes.

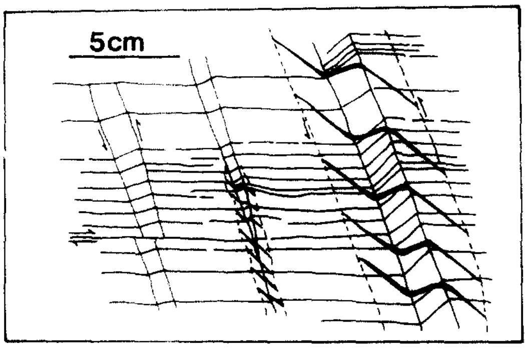


Fig. 8. Sinistral kink bands and associated vein arrays from Telgruc Bay, Brittany. Traced from fig. 22 of Dewey (1965, p. 482). Discussed in text.

Vein arrays

Element types 1, 2 and 3 of scalariform arrays are well known from kink band associations. Type 1 elements are a necessary consequence of layer-parallel slip, continuity of layering across KBB's, and internal buckling of layers at KBB's in kink bands (Ramsay 1967, fig. 7–121, Johnson & Honea 1975). They are, therefore, not diagnostic of "joint drag" (Flinn 1952, Knill 1961, Dewey 1965) variants of the rotation model. Indeed, migration of kink band boundaries and of type 1 element sites may leave fine veins, either concordant or mildly discordant to the layering between the KBB's (Cobbold 1976, fig. 7). Such veins are low angle type 3 elements. Some of the lower angle type 3 elements of the Reminiac shears resemble such veins and may suggest a component of shear boundary migration during deformation.

Concordant veins (type 3) would not form in ideal kink bands, nor in shears, since they are associated with volume increase (Clifford 1968).

Discordant type 3 elements have been used as kinematic indicators, providing critical evidence in favour of the rotation model in examples of natural kink bands (e.g. Dewey 1965, 1969). Arrays of type 3 elements (see Fig. 8) are interpreted by Dewey as en-echelon tension gashes indicating high shear stresses resolved onto the KBB's (see also Marshall 1964, 1966, Dewey 1969, pp. 206–207, Garnet 1974).

In the Reminiac example, identical arrays of type 3 elements occur within the sinistral shears. Sinistral shear across an anisotropy, combined with layer-parallel slip necessarily implies dextral slip along, and compresssion across, the rotating anisotropy. In the absence of significant volume loss within the rotating segment, the rotating anisotropy must extend. For a dextral layer parallel slip component of strain, combined with a component of layer-parallel extension, the resultant kinematic extension direction lies at less than 45° (anticlockwise) to the rotated anisotropy. Hence the type 3 elements are tension gashes oriented at 67–90° to the schistosity within the shears. This interpretation may also be extended to kink bands, where it suggests that tension gash arrays are compatible with both the rotational and non-ideal migration ($\alpha > \beta$, Fig. 6 m) models of kink band formation. Tension gashes in over-rotated kink bands are therefore, not *a priori* evidence of high resolved shear stress along the KBB's.

Offset of type 3 and 3′ elements, both inside and outside the shears, indicates post-vein sinistral slip along the internal and external layering. The long, cross-cutting veins (Fig. 5) indicate a post-kink and shear component of sinistral slip. This late component of slip may account for scalariform arrays occurring in domains of no visible finite rotation of the schistosity. Sinistral slip along the internal schistosity of sinistral shears with fixed boundaries must produce a back-rotation of the internal schistosity towards the maximum compressive stress (Rondeel 1968, Donath 1968, Weiss 1968b, Gay & Weiss 1974). From experiment, the maximum compression must lie close ($\approx 5°$; e.g. Gay & Weiss 1974) to the general schistosity direction in order to account for the associated kink band geometry. Back-rotation could thereby efface the less well developed shears, leaving the relic vein arrays with type 3 elements at a clockwise angle ($< 45°$) to the schistosity. Without due attention, interpretation of such arrays could erroneously suggest dextral slip along the general (ESE) schistosity plane.

The local isolated type 3′ veins, lying clockwise oblique to the general schistosity plane outside of the kink bands and shears, are anomalous. One tentative suggestion is that they are an elastic rebound structure associated with episodic sinistral layer-parallel slip, thereby accounting for their later deformation and segmentation.

Regional context

The Carboniferous deformation described here has occurred in close spatial association with the contemporaneous dextral motion along the S.A.S.Z. In view of the parallelism between the Reminiac schistosity and the S.A.S.Z, it is surprising to find evidence of sinistral slip along the schistosity. This apparent contradiction is resolved here by assuming that in the area studied the regional schistosity has rotated clockwise into its present position, as expected in a dextral non-coaxial strain regime. A component passive slip along already formed schistosity planes during such a rotation would be of sinistral sense.

CONCLUSIONS

In an outcrop of schistose meta-agglomerate, sinistral layer-parallel slip has resulted in the formation of conjugate kinks and a single set of sinistral shears.

(1) Scalariform quartz vein arrays are associated with the shears and the non-kinked intervening domains. The arrays include discordant tension gashes formed within shears in response to combined dextral layer-parallel slip and layer-parallel extension of the rotated segment anisotropy. The tension gashes are, therefore, only kinematically significant to strain analysis at the scale of the rotated segment length.

(2) Tension gash arrays in kink bands are not *a priori* evidence for high resolved shear stresses on KBB's. Void formation and fill is not diagnostic of rupture along the KBB, and hence is not a criterion for models of kink formation.

(3) Scalariform arrays, and arrays of tension gashes, oriented at high angles to the anisotropy must be interpreted with care in non-kinked and non-shear domains. They may represent back-rotated effaced shears and be kinematically significant only at the centimetre scale.

(4) The agglomerate deformed as a statistically homogeneous anisotropic medium. Rock fragments have exerted no detectable mechanical influence over kink-band, shear or vein formation.

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