

The geometry and kinematics of a suite of conjugate kink bands, southeastern Australia

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Abstract—A conjugate set of subvertical kink bands is exposed in coastal outcrops of well-foliated Ordovician turbidites near Mystery Bay, Australia. All kink bands with widths exceeding 3 cm have complex internal structures including compound and parasitic kinks, stepped kink boundaries, internal crenulations, variable kink angles and prismatic voids. The kink bands are interpreted to result from rotation of short foliation segments between fixed kink planes with subsequent widening and modification by layer-parallel shear external to the kink band. Layer-parallel shear of both sinistral and dextral sense accompanied kinking and indicates a variable stress system during kink band development.

Conjugate kink bands are abundant and are used to estimate bulk strain orientations. In general, the dominant kink set of a conjugate pair is inclined at a lower angle to the external foliation than the weaker set and this angular disparity increases with increasing dominance of one set. These observations are at variance with relationships described from experimental bulk pure shear deformation of anisotropic materials. It is suggested that orthogonal constraints in these experiments restrict layer-parallel shear to within a developing kink band and are, therefore, unlike many natural kink systems. Simple shear experiments can produce structures geometrically similar to natural kink bands.

INTRODUCTION

A KINK band can be defined as a "thin band or plate, transverse to the foliation, bounded by the parallel or subparallel axial surfaces of a pair of angular folds of opposite sense" (Anderson 1968). Kink bands are common late-stage structures in many orogenic terrains and have been the subject of numerous studies. Experimental deformation of various anisotropic materials has produced structures similar in form to natural kink bands and has yielded valuable insights into kinking mechanisms (e.g. Paterson & Weiss 1966, Donath 1968, Cobbold *et al.* 1971, Anderson 1974, Gay & Weiss 1974). Although these experiments have produced a large data base for the geometric properties of kink bands, no single model can explain all the observed geometries. From geometric studies of conjugate kink bands, several authors have noted discrepancies between the stress-strain relationships derived from experimental studies and those inferred from the natural examples (e.g. Anderson 1968, Cudahy 1986, Paterson 1989). This paper investigates the geometry of one suite of natural conjugate kink bands exposed near Mystery Bay in southeastern Australia and evaluates existing models for their development.

deformation, the oldest and most prominent folds (F_1) are upright and tight with subhorizontal and meridionally-trending axes. A well-developed differentiated crenulation cleavage (S_1) parallels the F_1 axial surfaces (Williams 1972, Powell 1983) and imparts a strong mechanical anisotropy to the turbidite succession. At regional map scale, sharply bounded domains with internally consistent F_1 axial trends have been rotated about steep axes from regional trends (Powell 1983, Powell *et al.* 1985a). Outcrop-scale kink bands and crenulations are commonly associated with, and localized within, the most highly-rotated zones.

South of Mystery Bay, a regional-rotation hinge is exposed in coastal rock platforms. Within a distance of less than 1 km, F_1 trends exhibit a segmented counter-clockwise rotation of approximately 75° about a near-vertical axis from the regional 015° trend preserved in southern outcrops (Fig. 2). A detailed structural analysis of this area is presented by Stublely (1989b). South of the 'boundary fault', the turbidite succession has been divided, for analytical purposes, into nine domains with internally consistent F_1 trends (Fig. 2). Prolific kink band development occurs in Domains 4–9 and along the northern margin of Domain 3; an area of approximately $26,000 \text{ m}^2$ exposed at low tide.

GEOLOGICAL SETTING

The exposed sedimentary rocks of the Lachlan Fold Belt, southeastern Australia, consist predominantly of an Ordovician turbidite succession overlain unconformably by late Devonian quartzose clastics (Fig. 1). Three regional folding episodes are recognized in the turbidites (Powell *et al.* 1985b). Where unaffected by subsequent

THE MYSTERY BAY KINK BANDS

General features

All kink bands at Mystery Bay have reverse-kink geometry (Dewey 1965) and record local layer-parallel shortening (Fig. 3). The anisotropy exploited during kinking is generally the subvertical S_1 , although S_0 and

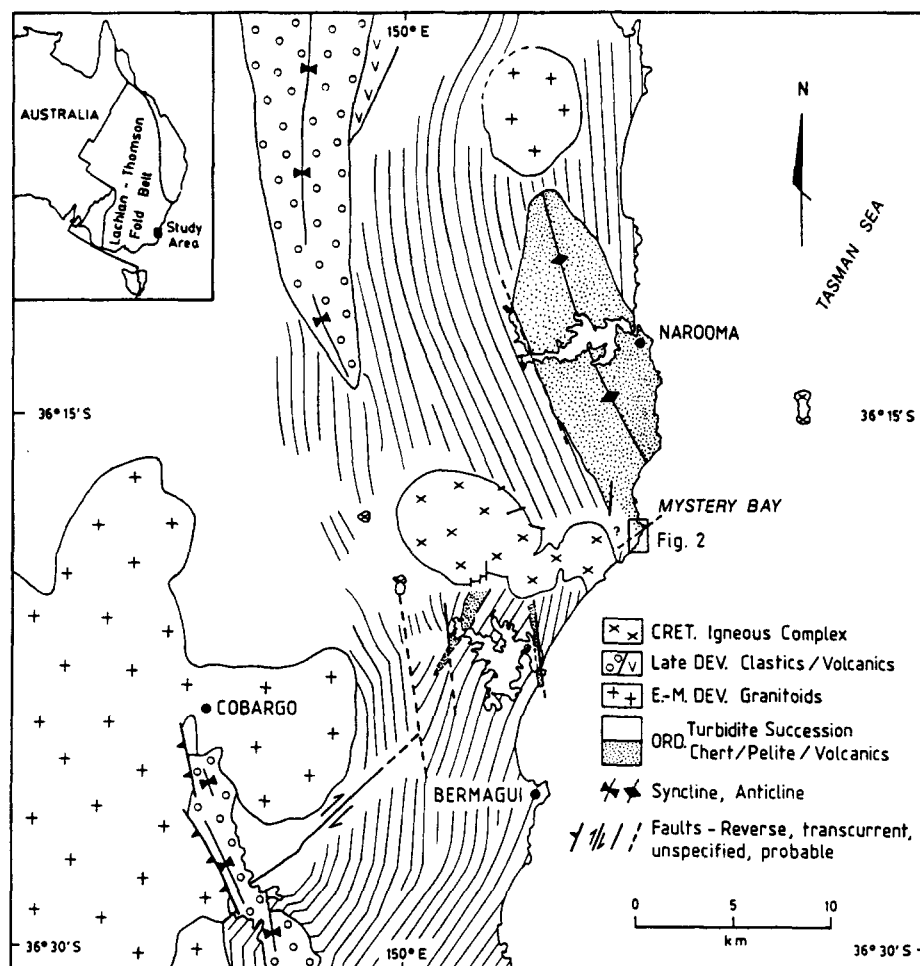


Fig. 1. Location map with generalized geology for the Mystery Bay area. Fine lines in Ordovician turbidite succession represent mean F_1 trends with interpretation north of latitude of Narooma from data of Cole (1982) and south of latitude of Bermagui from Powell *et al.* (1985a). Cretaceous outline from Eggleton (1987).

S_2 can be locally important. Kink planes are everywhere steeply dipping, generally greater than 75° (Fig. 4).

Conjugate kink bands exhibiting mutual interference are common (Figs. 5 and 6f-h), although, in general, sinistral greatly outnumber dextral kink bands. Sinistral kink bands have a greater size range than dextral ones, with widths up to 3 m and lengths up to 80+ m. In contrast, the maximum recorded width of a dextral kink

band is 25 cm and lengths are generally less than 5 m. The minimum size of kink bands is microscopic and a transition to angular crenulations and crenulation cleavage is apparent (Stubley 1989b). The disparity between the frequency and size of sinistral and dextral kink bands shows a general decrease in more northerly and more highly-rotated domains such that sinistral kink bands account for more than 95% of the kinked area in

Table 1. Conjugate kink band parameters by domains

Domain	Mean F_1 trend ($^\circ$)	Proportional area* 100(Sin/(Sin + Dex))	Measured conjugate pairs	Mean dihedral angle ($^\circ$)	Mean θ^\dagger ($^\circ$)
1 + 2 + 3	005	60-95	16	98.2 (16.3)	2.8 (8.6)
4	343	90-100	44	117.2 (12.4)	5.4 (5.4)
5	337	95-100	11	119.6 (6.6)	3.2 (6.9)
6-south	328	70-90	49	118.6 (11.4)	2.6 (5.7)
6-middle	324	60-85	41	119.6 (10.3)	1.7 (4.1)
6-north	321	60-80	40	121.2 (11.8)	2.1 (4.1)
7	305	60-80	23	116.1 (12.8)	-1.6 (4.9)
8	319	60-80	25	124.8 (7.6)	2.0 (4.6)
9	305	60-80	18	127.0 (14.0)	-1.5 (4.2)
Total	—	70-90	267	118.7 (13.0)	2.2 (5.5)

*Domains 4, 5 and 6 ratios based on 3-6 m² checks of representative areas, excluding kinks with widths exceeding 15 cm. Other domains are qualitative estimates.

†Measured from foliation to Z' , anticlockwise positive convention.

() Sample standard deviation.

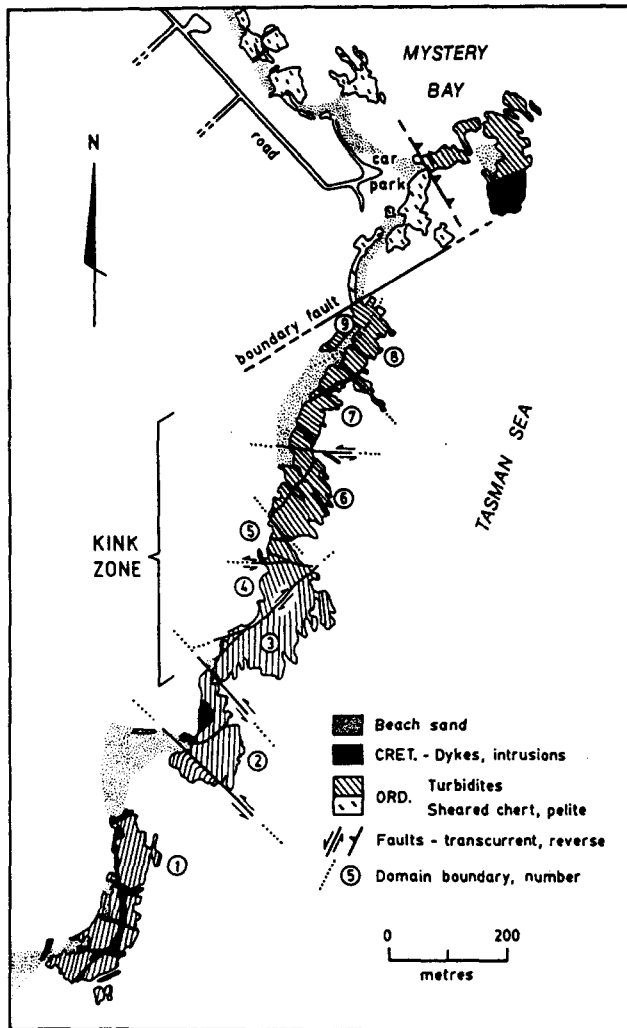


Fig. 2. Local geology south of Mystery Bay showing zone of kink band development. F_1 trends represented by fine lines in turbidite succession. 'Domains' selected for analytical purposes on basis of F_1 trend.

Domains 4 and 5 and approximately 60–80% in Domains 7–9 (Table 1).

Conjugate kink bands can show either right-handed or left-handed intersections as defined by Paterson & Weiss (1966) with the latter being slightly more prevalent. Commonly however, neither of the crossing kink bands is visibly offset and I term these 'neutral' intersections. In many instances, a kink band terminates or changes width at its intersection with a conjugate band (Fig. 5).

Kink bands most commonly terminate by a gradual decrease in angularity to gentle flexures (Fig. 5). Other

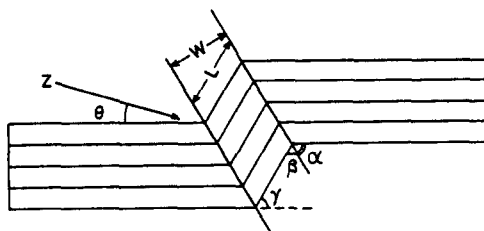


Fig. 3. Sinistral reverse kink band with descriptive parameters used in this paper. Z is the principal axis of shortening strain.

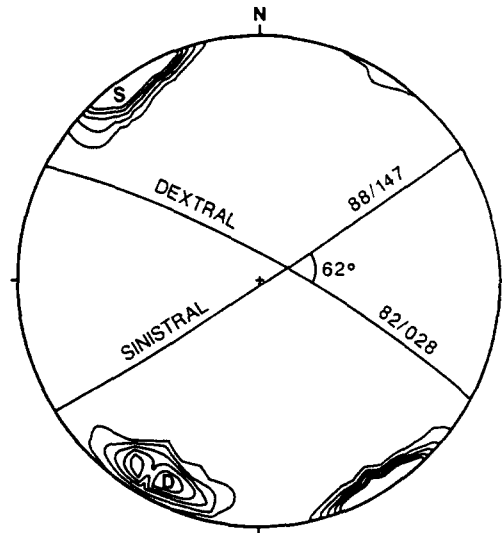


Fig. 4. Contoured stereoplots of poles to sinistral ($n = 591$) and dextral ($n = 324$) kink planes with mean planes indicated. To ease comparison and to eliminate the effect of the regional rotation of structural elements, all data have been individually rotated about a near-vertical axis ($83^\circ/069^\circ$) such that the local S_1 attains an arbitrary and consistent N–S strike (see Stubley 1989b). Contouring by method of Diggle & Fisher (1985) with equal-spaced contours and smoothing constant of 222. Lower-hemisphere, equal-area projection.

terminations are abrupt against surfaces of décollement or bedding, or at intersections with conjugate bands. Fractures along kink planes are weakly developed and, where observed, offsets along these fractures are rarely apparent. In some instances, fractures parallel to the kink planes occur wholly within the kink band (Fig. 6a). The fractures are generally short and irregular and show no apparent correlation with lithology or angularity of the kink band. A strong spatial, and possibly genetic, relationship between the kink bands and strike-slip faults is discussed by Stubley (1989a).

Shortening parallel to layering due to kinking has been determined at several locations by measuring along single layers and assuming only a flexural-slip folding mechanism. Maximum shortening strains approach 8% over distances of 50–60 m; this upper limit corresponds to an average long-limb to short-limb ratio of approximately 5.5 for 'ideal' 60° kink bands. Typically however, local shortening strains are of the order of 3–5% within the zone of kink bands.

Internal structures

A striking feature of the Mystery Bay kink bands is the non-planarity of the internal foliation. Although the foliation within narrow kink bands can be approximately planar, all kink bands with widths in excess of 3 cm have complex internal structures. Commonly, small-scale crenulations or kink bands are developed wholly within a larger band (Fig. 7). Generally, the internal folds have the same sense of asymmetry as the host kink band and orientations ranging from parallel to approximately 25° oblique to the host. Where oblique, the internal crenulations are orientated at lower angles to the external

foliation than the host kink planes (Fig. 6c) (Stubley 1989a, figs. 4 and 10). The only exceptions to this observation are for rare internal crenulations or kink bands with opposite asymmetry to the host structure. The foliation between the internal folds can range in orientation from parallel to the external foliation, in which case the kink band has a compound nature (Donath 1968), to subparallel to the foliation within the internal folds where the crenulations appear indistinct (Fig. 6d). As many as three orders of subparallel kink bands can be observed in the largest structures.

In many kink bands, the internal folds have the form of parasitic kinks (Dewey 1969, Anderson 1974). The parasitic structures are generally single angular kink bands contained wholly within a host band and which either lens out within, or terminate abruptly at the boundaries of, the host structure. As with the general case for oblique internal folds described above, the observed parasitic kinks everywhere have the same sense of asymmetry as the host structure and are orientated at lower angles to the external foliation than are the host's bounding surfaces (Figs. 6a & h and 7b).

In other kink bands, the internal folds can be more irregular and complex (e.g. Fig. 6e). In all kink bands with internal folds, a simple geometric relationship between the kink width parameters, W and L (Fig. 3), cannot be realized. Whereas commonly the perpendicular width (W) is approximately constant along a single kink band, the length of the rotated foliation (L) can be extremely variable. The space problem created by adjacent foliation segments of different lengths commonly results in the formation of prismatic voids elongate parallel to the kink axis or of stepped kink band boundaries (Figs. 6b & h) (Powell *et al.* 1985a, fig. 8c).

Unlike classical interpretations of kinking mechanisms, layer-parallel slip at Mystery Bay is not entirely confined between kink planes. Commonly, offset quartz veinlets or fractures oblique to the foliation record discrete slip along external foliation surfaces (Fig. 6b) (Powell *et al.* 1985a, fig. 8c). Sinistral offsets are more commonly observed than dextral ones; in some instances, both senses of slip can be observed in a single sample (e.g. Fig. 6b). In every instance where a discrete slip surface can be traced to an adjacent kink band with the same sense of external rotation, it marks the position of a discrete change in the internal geometry of the kink band. The changes include prismatic voids, stepped kink band boundaries, nucleation of parasitic kinks and internal folds, and sharp variations in the kink angles β and γ . It is probable that much of the internal complexity of the Mystery Bay kink bands can be attributed to variable and discrete slip along the external foliation.

Kink angles

The most consistent feature of individual kink bands at Mystery Bay is the angle between the kink plane and the external foliation, α (Fig. 8). As kink planes can be gently curved along their length, measurements were always recorded at representative planar sections. Due

to their high density, only a small proportion of the outcropping sinistral kink bands were measured and these were selected, as far as possible, to best represent the entire suite. The data in Fig. 8 show that the mean value of α is generally lower for the dominant sinistral kink bands than for the dextral ones. Only in Domains 7 and 9, the two most highly rotated domains, do dextral kink bands have the lower mean α value. Values of α are non-normally distributed in Domains 3, 4, 6-south and 9, and these distributions are best interpreted as bimodal samples (Stubley 1989a).

Where possible, the angular deflection of the foliation across the kink plane (γ) and the internal kink angle (β) were also recorded. However, due to the internal complexity of the kink bands, these measurements are highly selective; every attempt was made to record a maximum γ , and hence minimum β , for the kink band at a representative position with relatively planar internal foliation. Measurements were not recorded for many complex kink bands although in some cases, more than one measurement was made for long relatively simple ones. Recorded values of α , β and γ are presented in Fig. 9. Values of β exceed α in 77% of the measurements which indicates a general tendency for dilation within individual kink bands. Comparison of fixed-sum variables produces a forced negative correlation between any two of the variables. However, the variance of α is only weakly dependent on either β or γ . As a result, a strong negative correlation ($r = -0.76$) exists between β and γ as their sums are approximately equal. No consistent relationship between any of the kink angles and the kink band width are realized.

Conjugate structures and principal strains

Ramsay (1962) outlined a method for determining the principal stress orientations from a pair of conjugate folds. However, since folds record heterogeneous strain and not the stress which could have been variable during fold development, the method should only be used to estimate the orientation of the bulk strain axes (e.g. Ramsay 1967 p. 455, Paterson 1989). It is emphasized that, in general, stress and strain axes do not maintain parallelism in anisotropic rocks. By reinterpretation of Ramsay's (1962) 'conjugate bisector' method, the intermediate strain axis (Y) is approximately parallel to the intersection of conjugate kink planes and the maximum and minimum strains bisect the kink planes ($\pm 20^\circ$, discussed later). The shortening direction (Z) is contained within the same dihedral angle between the kink planes as the external foliation.

Orientations calculated by the conjugate bisector method are plotted in Fig. 10. The conjugate intersection direction (Y') is relatively constant and insensitive to variations in dip of the external foliation which can be up to 25° either side of the mean. The shortening bisector (Z') is orientated, in general, slightly anticlockwise to the foliation (mean $\theta = 2.2^\circ$) as is expected in a region where sinistral kink bands have lower α -values than do dextral ones. Although dihedral angles between

Conjugate kink bands, southeastern Australia



Fig. 5. Profile view of conjugate kink bands in greywacke. Shortening parallel to layering due to kinking is approximately 6–7% for width of photograph. Location: central Domain 6. Pocketknife is 9 cm.

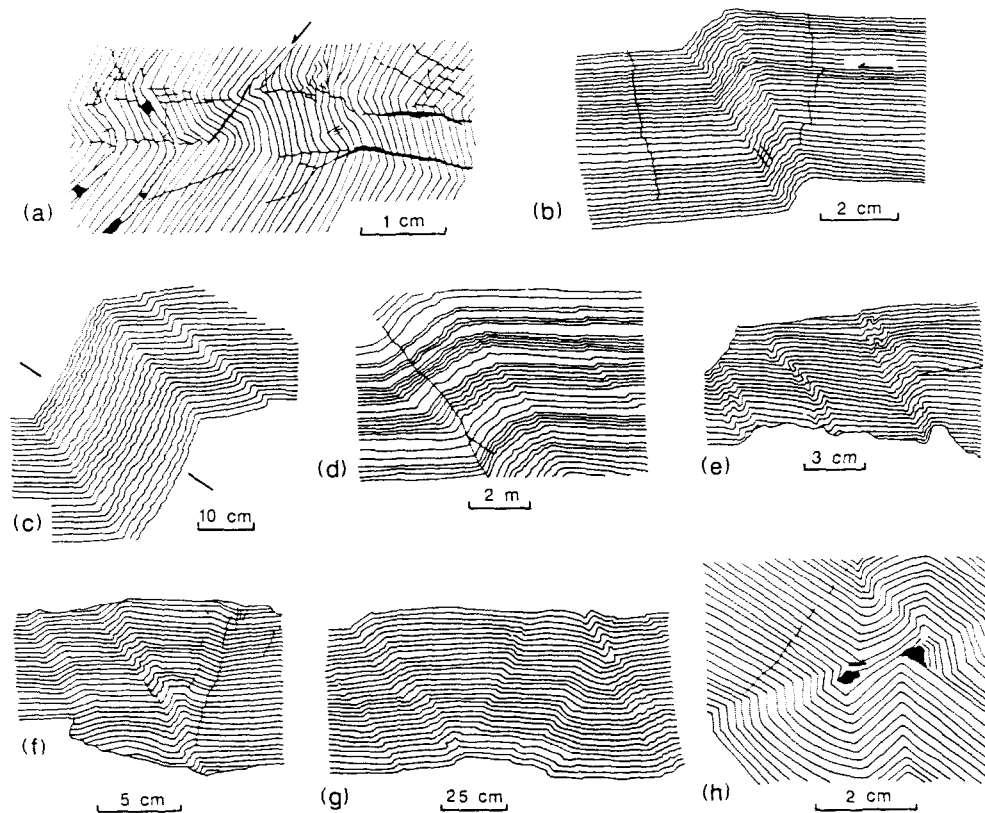


Fig. 6. Representative geometries of sinistral (a–e) and conjugate (f–h) kink bands as discussed in text. In (c), trace of internal crenulations indicated by dashes. Fractures and voids = solid; quartz veins = stipple. All illustrations traced from photographs. Note variable scales.

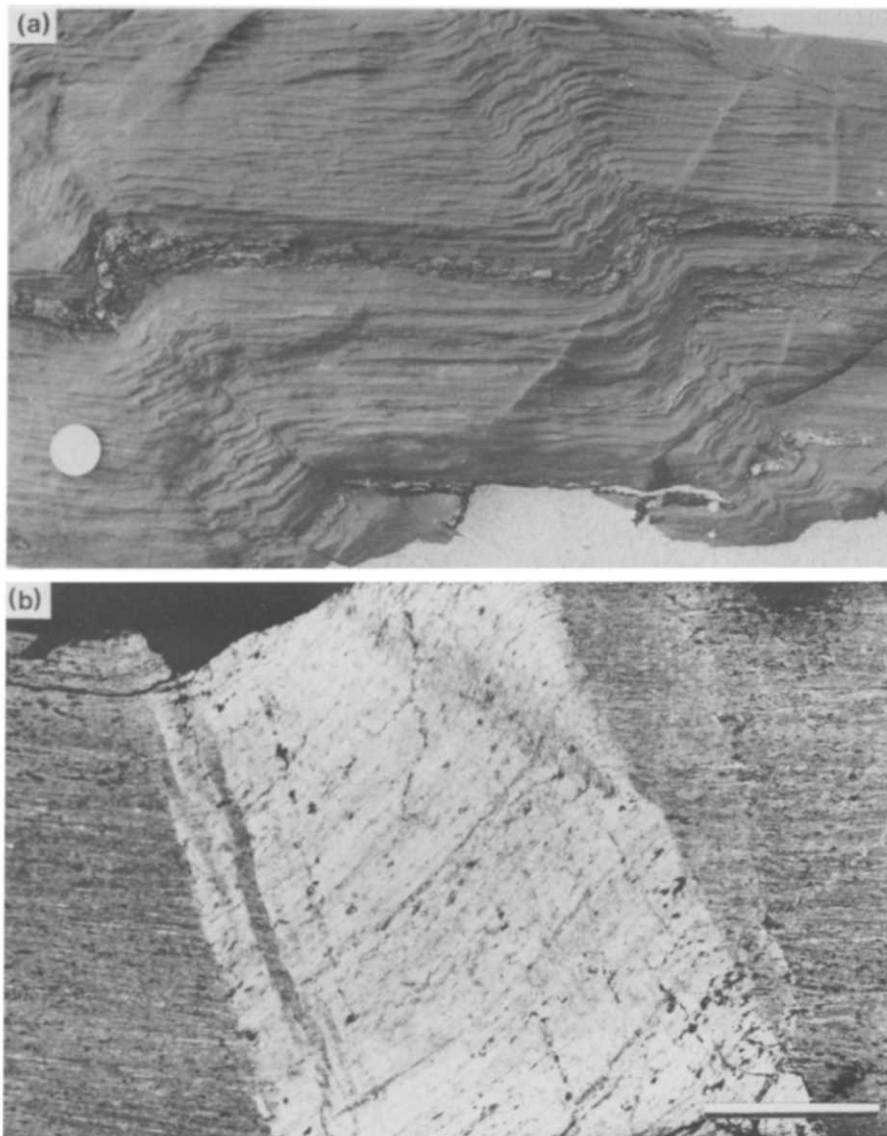


Fig. 7. (a) Subparallel sinistral kink bands in greywacke showing internal folds. Location: Domain 4. Coin is 28 mm diameter. (b) Thin section of sinistral kink band in metapelite showing complex internal structures. Small-scale kink bands and crenulations developed parallel to master kink band boundaries and adjacent to central zone of relatively planar foliation. Parasitic kink nucleated on stepped kink band boundary in upper right. Scale bar = 1 cm.

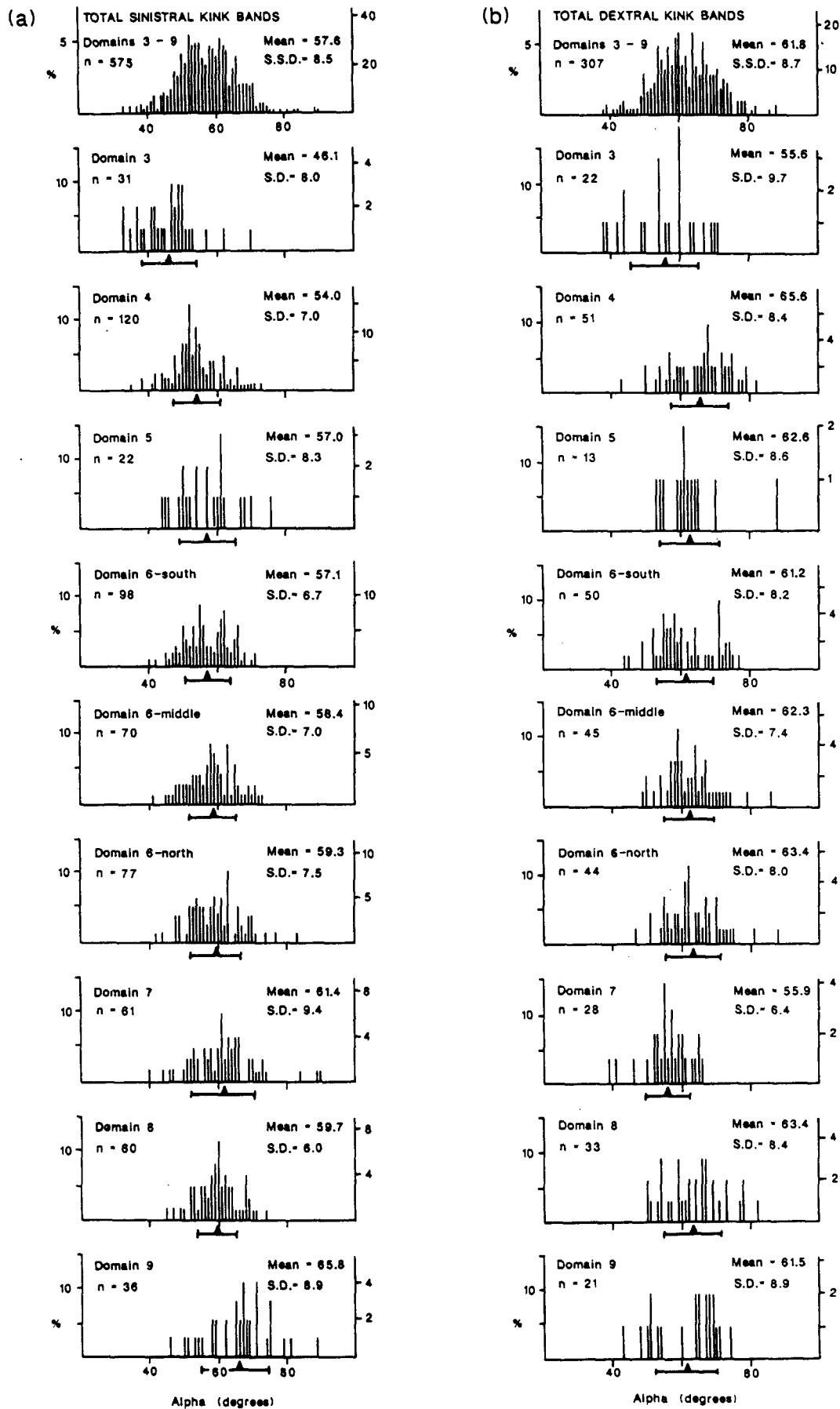


Fig. 8. Domainal distributions of the angle, α , between the kink plane and external foliation of (a) 575 sinistral and (b) 307 dextral kink bands from Domains 3-9. Vertical axes give frequency as percent (left-hand side) and absolute (right-hand side). Means and standard deviations given numerically and by bar scales assuming normal distributions; an assumption not valid for some domains (see text and Stubley 1989a).

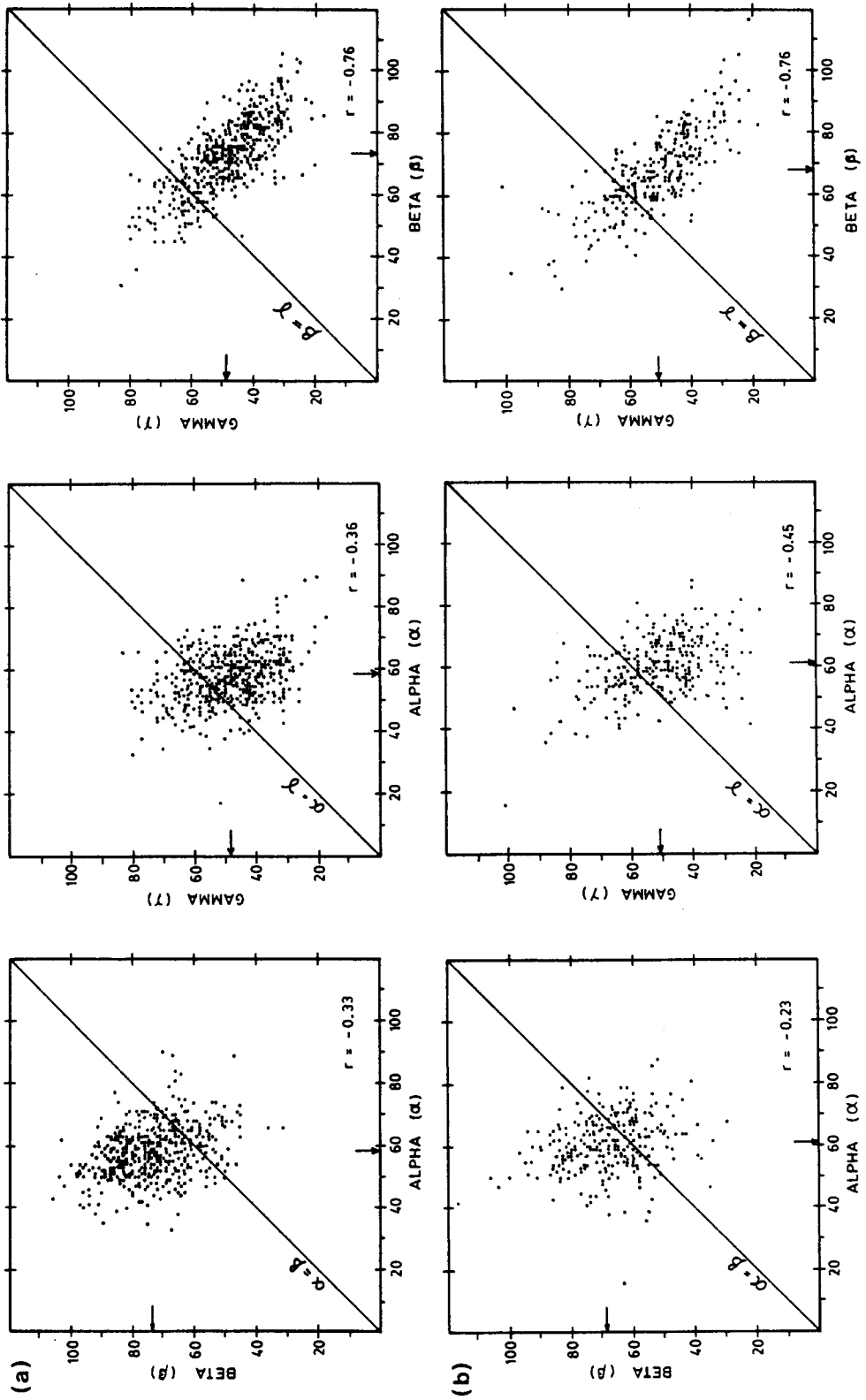


Fig. 9. Plots of angular parameters of (a) 503 sinistral and (b) 284 dextral kink bands. Mean values indicated by arrows. r is the correlation coefficient.

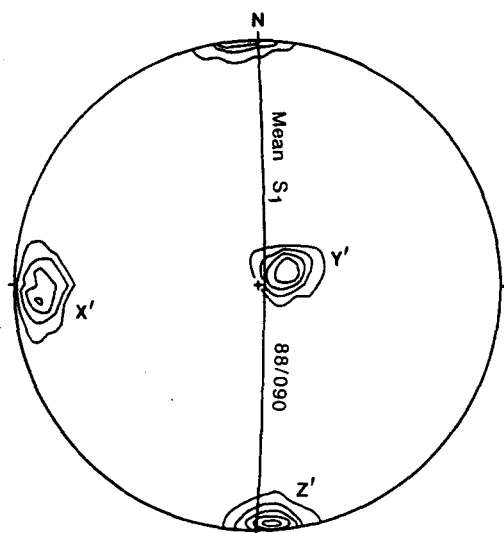


Fig. 10. Stereoplot of bisector orientations relative to the external foliation determined from 267 conjugate kink band sets, Domains 1–9. X' and Z' are kink plane bisectors and Y' is the intersection direction; these may approximate principal strain orientation ($X > Y > Z$). For comparative purposes, all data rotated as per Fig. 4. Contouring by method of Diggle & Fisher (1985) with five equally-spaced contours and smoothing constant of 315. Lower-hemisphere, equal-area projection.

conjugate pairs show a considerable range, the external foliation is contained within the obtuse angle in greater than 97% of cases (Fig. 11).

Domainal variations of the conjugate kink band dihedral angles and of angles between Z' and the foliation (θ) are presented in Table 1. Of significance are the generally greater anticlockwise values of θ in domains with greater sinistral kink band dominance. Variations in dihedral angles show no consistent relationship to position within the kink zone.

DISCUSSION

Existing models for kink genesis

Field studies and experimental deformation of anisotropic materials by bulk pure shear processes have yielded two contrasting models of kinking mechanisms; the hinge-migration model (Paterson & Weiss 1966) and the constant-segment-length model (Anderson 1964, Dewey 1965, Donath 1968). Although variations to both models have been proposed, the basic concepts of each are as outlined below.

The hinge-migration model assumes that a kink band initiates as a small lensoid structure that propagates longitudinally and then widens by lateral migration of the kink planes during progressive strain. At all times, the kink planes bisect the internal and external foliation directions (i.e. $\alpha = \beta$) such that volume and foliation spacing are conserved. Implicit in this model is the folding and unfolding of the internal foliation as the kink planes change their material positions.

In the constant-segment-length model, the material

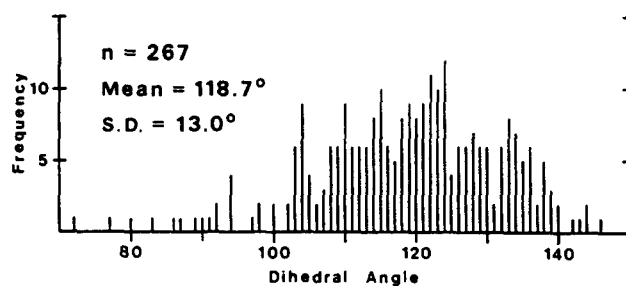


Fig. 11. Frequency distribution of the dihedral angle between conjugate kink bands which encloses the external foliation.

positions of the kink planes, and hence α , are determined at infinitesimal strain. With progressive strain the internal foliation rotates between these planes such that an inverse relationship exists between β and γ . Volume and foliation spacing vary during rotation although can attain their original values if the rotation progresses to bisection where $\alpha = \beta$.

Neither the hinge-migration nor the constant-segment-length model can solely explain the geometry of the Mystery Bay kink bands. However, characteristic features of both models are observed in the natural examples. The general independence of α on values of either β or γ , and hence the strong anticorrelation between β and γ (Fig. 9), favours the constant-segment-length model. Yet, crenulations or fine kink bands developed parallel to, and wholly within larger kink bands (e.g. Fig. 7b) are most easily explained by a hinge-migration mechanism. Neutral intersections of conjugate kink bands and changes in band widths (W) at conjugate intersections can be interpreted as resulting from selective lateral kink-growth. In their ideal form, neither model can explain some of the complex internal structures observed at Mystery Bay. Perhaps it is significant that both models assume deformation is wholly confined within the developing kink band.

Stress-strain relationships and natural kink band geometries

Consistent stress-strain relationships are reported from all bulk pure shear experiments, regardless of the kinking mechanism, and are best summarized by the study of Gay & Weiss (1974). During these coaxial experiments, the maximum compression (σ_1) remains approximately parallel to the shortening direction (Z) such that relationships between kink plane orientations and either σ_1 or Z are interchangeable. In the following discussion all relationships derived by other authors are converted to the angular parameters defined in Fig. 3. Gay & Weiss (1974) report that conjugate kink bands develop where shortening occurs subparallel to the external foliation ($\theta \leq 5^\circ$). With increasing obliquity of the shortening to the foliation, there is a corresponding increase in the tendency for single sets of kink bands to develop. The shortening direction is always contained within the acute angle between the foliation and the dominant or sole set of kink planes. In addition there is a

positive correlation between θ and α of the dominant or sole kink set. Theoretical studies predict similar relationships (e.g. Reches & Johnson 1976). These relationships are summarized in Fig. 12 and form the basis of the 'kink-proportion' method of inferring stress systems associated with natural kink bands as employed by numerous authors (e.g. Kleist 1972, Aparicio & Lelubre 1976, Powell *et al.* 1985a). The conjugate bisector method described previously for estimating shortening directions relative to the foliation is demonstrated to be valid in pure shear experiments (e.g. Gay & Weiss 1974, fig. 5c).

The experimentally-derived relationships are not consistent with the geometry of the Mystery Bay kink bands. Due to the high proportion of sinistral to dextral kink bands, the kink-proportion method suggests that Z should be orientated clockwise to the external foliation; that is, within the acute angle between the foliation and the sinistral kink planes. Using the bisector of conjugate kink bands suggests, in general, the opposite relationship (Fig. 10, Table 1). Whereas Gay & Weiss' (1974) coaxial experiments predict that values of α will be greater where only one set of kink bands is developed (i.e. high θ areas), the opposite is observed at Mystery Bay and is exemplified by the low α -angles of the highly dominant sinistral kink bands of Domain 4 (Table 1).

The discrepancies between the experimentally-derived relationships and natural kink band geometries are not unique to the Mystery Bay outcrops. A review of the literature indicates that in many, if not most cases, the dominant kink set of a conjugate system has the lower α value (e.g. Dewey 1965, Anderson 1968, Roberts 1971, Kulakovskii 1982, Wallace & Clifford 1983). In addition, Cudahy (1986) reports that, in his study area, the lowest α values for the dominant kink set occur in a zone where the weaker set is the most poorly represented, as at Mystery Bay. The independent analyses of strain associated with kinking by Anderson (1971) and Paterson (1989) suggest shortening directed within the obtuse angle between the foliation and the dominant kink set, and possibly at significant obliquity to the foliation, which is also at variance to all pure shear or coaxial experiments.

Although coaxial experiments can produce kink bands of broadly similar form to many natural examples,

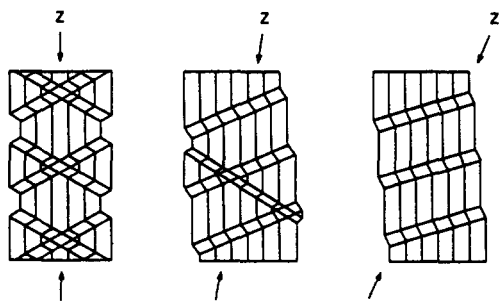


Fig. 12. Transition from conjugate kink bands to single sets with increasing obliquity of shortening (Z) to external foliation as determined from bulk pure shear experiments. Kink angles from Gay & Weiss (1974, figs. 5 and 6). [Experimental configurations not implied.]

the preceding discrepancies suggest to me that the two systems are not as directly comparable as is generally assumed. Orthogonal constraints imposed by the loading platens in these experiments restrict layer-parallel slip, except within developing kink bands, and therefore inhibit an important and common mechanism accompanying natural kink band development. The development of kink bands by simple shear of a salt-mica mixture by Williams & Price (1990) provides a mechanism more analogous to some natural conditions. Similar to the bulk pure shear experiments, Williams & Price (1990) report a general transition from conjugate kink bands to single sets with increasing initial obliquity of the foliation to the instantaneous shortening direction. The kink band angles, proportions and internal structures in some of their experiments closely resemble the Mystery Bay examples. The final kink angle α is reasonably constant (mostly 50–70°) for a variety of initial orientations and angular shear strains (Williams & Price 1990, fig. 4). This can explain the directional consistency in conjugate kink band bisectors (Fig. 10) from an area where stress variability is suspected. The conjugate bisector method gives reasonable estimates ($\pm 20^\circ$) for bulk strain orientations for most simple shear experiments (Williams & Price 1990, fig. 4). With progressive rotational strain, however, kink bands of one sense can be unfolded or reversed. The kink-proportion method can give grossly inaccurate inferences regarding principal strain orientations where only one set of kink bands is developed (e.g. Williams & Price 1990, fig. 5, experiment No. 232).

Model for kinking at Mystery Bay

I propose that the Mystery Bay kink bands initiated as thin bands ($L \leq 2$ cm) by rotation of the internal foliation between fixed kink planes (i.e. the constant-segment-length model), and were subsequently modified by layer-parallel shear external to the kink band during progressive strain (Fig. 13, discussed below). The initiation phase by rotation of fixed segments is supported by the general independence of α on either β or γ . Some kink bands (e.g. Fig 7b) have a central zone of relatively planar foliation that can be interpreted as recording the initial width of the rotated segments. The relative orientation of instantaneous shortening, and hence compression (σ_1) during kink band initiation cannot be determined with certainty as outlined above. However, the relative orientation during the modification and widening phase can be inferred by the sense of layer-parallel slip associated with this phase. It is emphasized at this point, however, that a local stress field of constant orientation or magnitude during progressive kink band development is highly unlikely and this is exemplified in locations where penecontemporaneous layer-parallel slip of both senses can be detected. The non-normal distributions of kink angles also suggest variations of the stress system during progressive kinking (cf. Norris 1968). Mechanisms for inducing variable

or oscillatory stress systems responsible for kinking are discussed by Stubble (1989a).

The sense of obliquity of σ_1 to the external foliation controls the possible modifications to an existing kink band. Where the instantaneous and local σ_1 is contained within the acute angle between an existing kink plane and the external foliation, a shear stress exists along the foliation of an opposite sense to the bulk rotation of the kink band (Fig. 13a). Shear failure along the external foliation is resisted due to the concave bend at the kink plane. In some instances however, shear offsets of the kink band can occur (e.g. Dewey 1965, fig. 24). Experimental studies suggest that development of new, or lateral expansion of existing kink bands is favoured under this assumed stress field (Paterson & Weiss 1966). Although a new kink band can nucleate at any position, a site of stress or structural irregularity is preferred (Weiss 1980, p. 19) such as exists adjacent to an existing kink band. Compound kink bands can develop which, with progressive strain, can tend to 'unfold' and result in a single band with wavy internal foliation (Fig. 13a). Within the widened kink band, a zone of relatively planar foliation bounded on one or both sides by a crenulated zone recording the unfolded former kink planes could be preserved (cf. Fig. 7b).

In situations where the local σ_1 is orientated within the obtuse angle between an existing kink plane and the external foliation (Fig. 13b), the kink band can widen by the compound-kink method described above. In addition, layer-parallel slip external to the kink band is less resisted than in the previous case and can result in several other modifications. Prismatic voids associated with changes in β and W (2) can develop where the

internal foliation separates in response to a single shear movement along the external foliation (e.g. Powell *et al.* 1985a, fig. 8c). If separation of the internal foliation does not occur, lensoid parasitic kinks (3) can nucleate on the external slip-surface (e.g. Figs. 6a & b and 7b). Where the external slip is more closely and evenly spaced (4), numerous small-scale parasitic kinks or crenulations can develop within, and oblique to, the host kink band (e.g. Figs. 6c and 7a) (Stubble 1989a, fig. 4). Other explanations for the internal crenulations exist and are discussed below. Combinations of two or more of the preceding modifications are commonly seen within single kink bands (e.g. Fig. 7b).

In each of the modifications illustrated in Fig. 13(b), discrete slip along the external foliation results in a staggered or stepped kink plane and hence, a variable perpendicular width (W) and constant internal-foliation length (L). Observations at Mystery Bay suggest that kink planes tend to smooth out by longitudinal propagation of the kink plane into the previously unknicked foliation and this results in modified kink bands with significantly greater variation in L than in W . In addition to modifications wholly within existing kink bands, external slip can be accommodated by buckling at the kink plane and result in an outward lateral migration of the kink band boundary (e.g. Fig. 6b).

Oblique crenulations in kink bands at Mystery Bay

Some of the internal structures of the Mystery Bay kink bands, in particular the oblique crenulations, could develop in response to mechanisms other than external

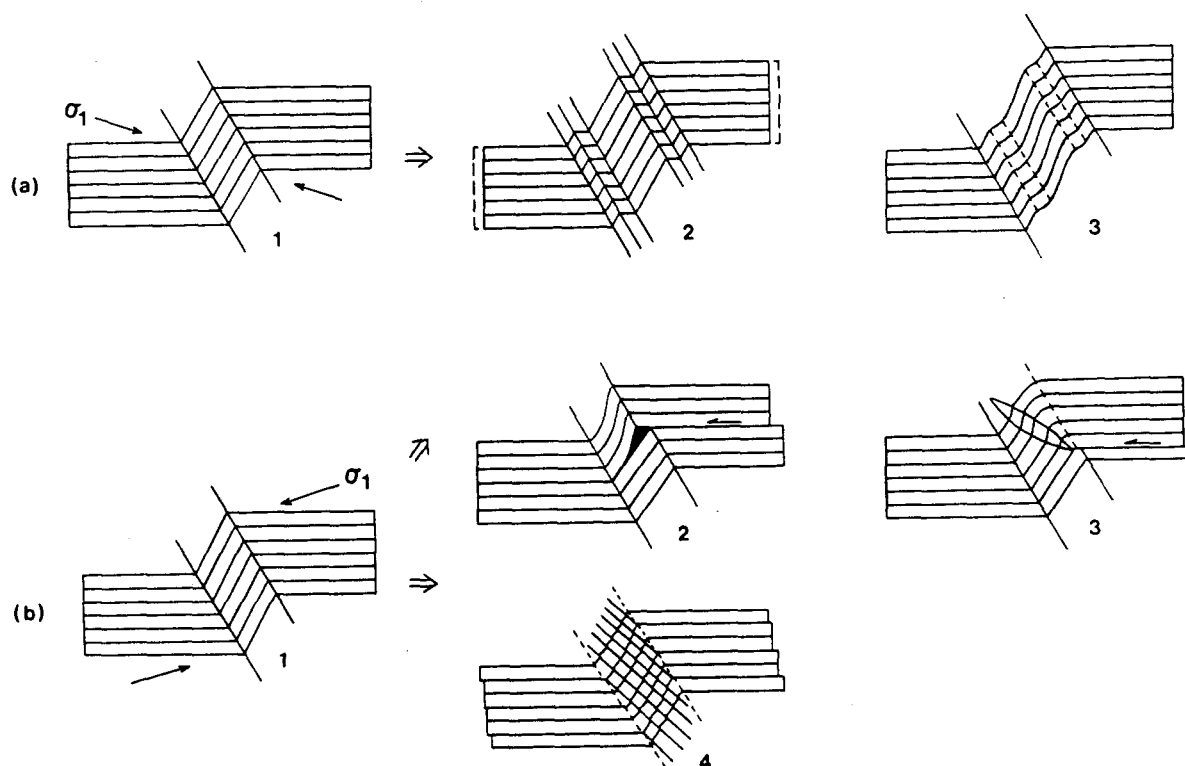


Fig. 13. Possible modifications to a pre-existing kink band by a local compression orientated within (a) the acute and (b) the obtuse angle between the kink plane and the external foliation. See text for discussion.

layer-parallel shear. Matte (1969) describes spectacular examples of internal crenulations which he interpreted as small shears analogous to 'strain-slip' cleavage. A feasible explanation for these structures could be the non-equality of α and β (Paterson & Weiss 1966, p. 353). If $\alpha < \beta$, shortening parallel to, or dilation normal to, the internal foliation is geometrically required where the foliation is continuous through the kink band. The internal crenulations could record this shortening strain. This effect would be most pronounced in kink bands developed by the constant-segment-length model where β exceeds α for most of the strain history. Another explanation for the crenulations could be a relative reorientation of the stress system such that the sense of shear stress on an existing kink plane is reversed. This situation could tend to 'unfold' the kink band with concomitant shortening of the internal foliation. Rotation of kink bands through semi-constant stress fields as described by Williams & Price (1990) or rotation of stress systems with respect to 'fixed' kink bands could induce this process. Either or both mechanisms could have operated at Mystery Bay (Stubley 1989a). To produce internal crenulations in both dextral and sinistral kink bands, as at Mystery Bay, would require relative rotations of approximately 90° or greater.

The relative importance of the above concepts at Mystery Bay is, however, unclear. None should show any preference for the width of the kink band, although at Mystery Bay the internal crenulations are most prevalent in wider kink bands. No correlation is apparent between kink angles and the presence of internal crenulations. These observations suggest to me that the crenulations are primarily modification structures developed during widening of pre-existing kink bands.

Comparison with other kink band systems

A review of the kink band literature reveals that the Mystery Bay examples are not unique (Stubley 1989a). The angular relationships are similar to many natural kink-systems. Although commonly less well developed, all the internal features described in this paper are reported from other studies. Episodic lateral growth of kink bands by the development of compound kinks is supported by the experimental study of Donath (1968). Evidence of external layer-parallel shear associated with kinking is abundant in many, if not most natural kink-systems; kink bands are common in fault and shear zones (e.g. Kleist 1972, Kulakovskii 1982, Wallace & Clifford 1983, Kimura *et al.* 1989). Shear along external layering is a fundamental mechanism in simple shear experiments where natural kink band geometries are developed (Williams & Price 1990) although is less commonly observed in bulk pure shear experiments. The common observation of natural kink bands terminating abruptly at décollement or bedding surfaces is most easily interpreted as due to variable slip along these surfaces. Clearly, a concept of kinking which involves deformation wholly between the kink planes is not applicable to many natural occurrences.

CONCLUSIONS

The geometric analysis of a suite of natural conjugate kink bands in southeastern Australia reveals strong similarities to studies from other localities. However, subtle but distinct differences occur between the natural examples and those produced experimentally by bulk pure shear. Theories based on results of the coaxial experiments are also at variance with relationships observed in nature. The major differences include the variation in kink angles and proportions with respect to the obliquity of shortening of a pre-existing foliation. In addition, the complex internal structures of many kink bands are not adequately accommodated by coaxial strain models of kink band development. The orthogonal constraints imposed during coaxial experiments restrict layer-parallel shear to within the developing kink band and are, therefore, unlike many natural examples.

At Mystery Bay, layer-parallel shear external to the kink band is an important mechanism for kink band modification and presumably also for initiation. Indicators of shear modification include offset kink band boundaries, variable internal foliation lengths, prismatic voids, parasitic kinks and, possibly, internal oblique crenulations. Simple shear experiments have produced kink bands similar to the natural examples with respect to kink angles, proportions and some internal structures; this mechanism is suspected to have been operative at Mystery Bay.

Although axes of principal stress and strain remain approximately parallel in irrotational experimental conditions, this relationship cannot be presumed in nature. Natural kink bands record only bulk inhomogeneous strain. Experimental studies illustrate the limitations of using kink bands for strain orientation determinations. For coaxial strain histories, principal orientations can be inferred, and should be consistent, by both the kink-proportion and conjugate bisector methods. For the more general case of non-coaxial strain histories, approximate ($\pm 20^\circ$) orientations can be calculated by the conjugate bisector method. Where only one asymmetry of the kink band is developed, the kink-proportion method should be used with caution.

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