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Three-dimensional geometry of kink bands in slates and its relationship with finite strain

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Abstract

Contractional, monoclinal kink bands that dip to the south and southwest deform northdipping slaty cleavage in Permian rocks of the Somport area (central Pyrenees). These bands are strongly curved such that the poles (normals) to individual kink bands define E–W-striking great-circle girdles in stereographic nets. The kink bands form an anastomosing network that isolates lozenge-shaped, undeformed domains. Cross-cutting relations between intersecting kink bands indicate that all the kink bands in the Somport slate formed penecontemporaneously during a single deformation event.

Total strain accommodated by the kink bands at Somport is small. Bulk shortening has been calculated assuming that slip during kinking was perpendicular to local kink fold axes. Bulk shortening of 3% and less than 1% have been calculated in the subvertical and E–W-striking subhorizontal directions respectively, indicative of constrictonal strain.

We propose the unusual geometry of the strongly curved kink bands at Somport is partly the product of non-plane-strain deformation. A model is developed that predicts the formation of up to four sets of kink bands during coaxial, non-plane-strain deformation, while two non-conjugate sets form during non-coaxial, non-plane-strain deformation such as occurred at Somport. This model is a natural extension of models proposed for the geometry and kinematics of brittle faults formed during non-plane-strain deformation. The kink bands at Somport probably formed before the cessation of Pyrenean convergence and were related to a modest gravity-induced spreading in the hinterland of the orogenic belt.

1. Introduction

Kink bands are a common feature in foliated rocks. Their internal geometry and the mechanisms and mechanics of their formation have been the focus of much research (e.g., Weiss, 1980; Stewart and Alvarez, 1991; Peacock, 1993; and references therein). There has been much less work devoted to describing the overall geometry of a system of kink bands within foliated rocks. Commonly, kink bands are described (or assumed) as forming monoclinal or conjugate sets, and numerous field studies have clearly documented such geometries (for example, single, monoclinal sets described by Hobson, 1973; Roussel, 1980; conjugate sets described by Johnson, 1956; Anderson, 1968; Stubley, 1990). Not all kink band systems, however, can be adequately described in terms of the two-dimensional geometry and kinematics displayed by well-developed monoclinal and conjugate kink bands.

It is the purpose of this paper to provide a detailed description of one kink band system located in the central Pyrenees that does not display the geometries commonly ascribed to monoclinal or conjugate kink

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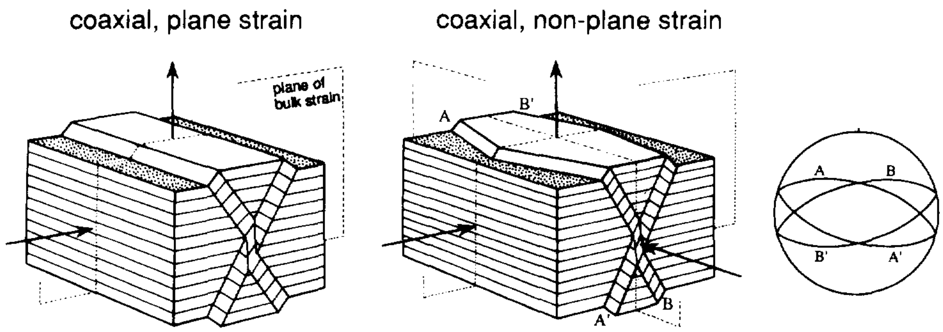


Fig. 1. Conjugate, contractional kink bands develop during coaxial plane-strain deformation when the principal stress and principal incremental strain axes are symmetrically disposed about the slaty cleavage plane. Also shown is a proposed orthorhombic arrangement of four (*A*, *A'*, *B*, *B'*) contractional kink bands that develop during coaxial, non-plane-strain deformation. Only two sets of kink bands, for example *A* and *B*, will develop during non-coaxial, non-plane-strain deformation.

bands. Unlike most kink bands described in the literature, these centimeter-wide, contractional kink bands are strongly curved and form an anastomosing network that isolates lozenge-shaped, unkinked domains. Cross-cutting relations between intersecting kink bands indicate that all the kink bands formed penecontemporaneously during a single deformation event. Total strain accommodated by kink band formation was small and resulted in constrictional bulk strain rather than plane strain.

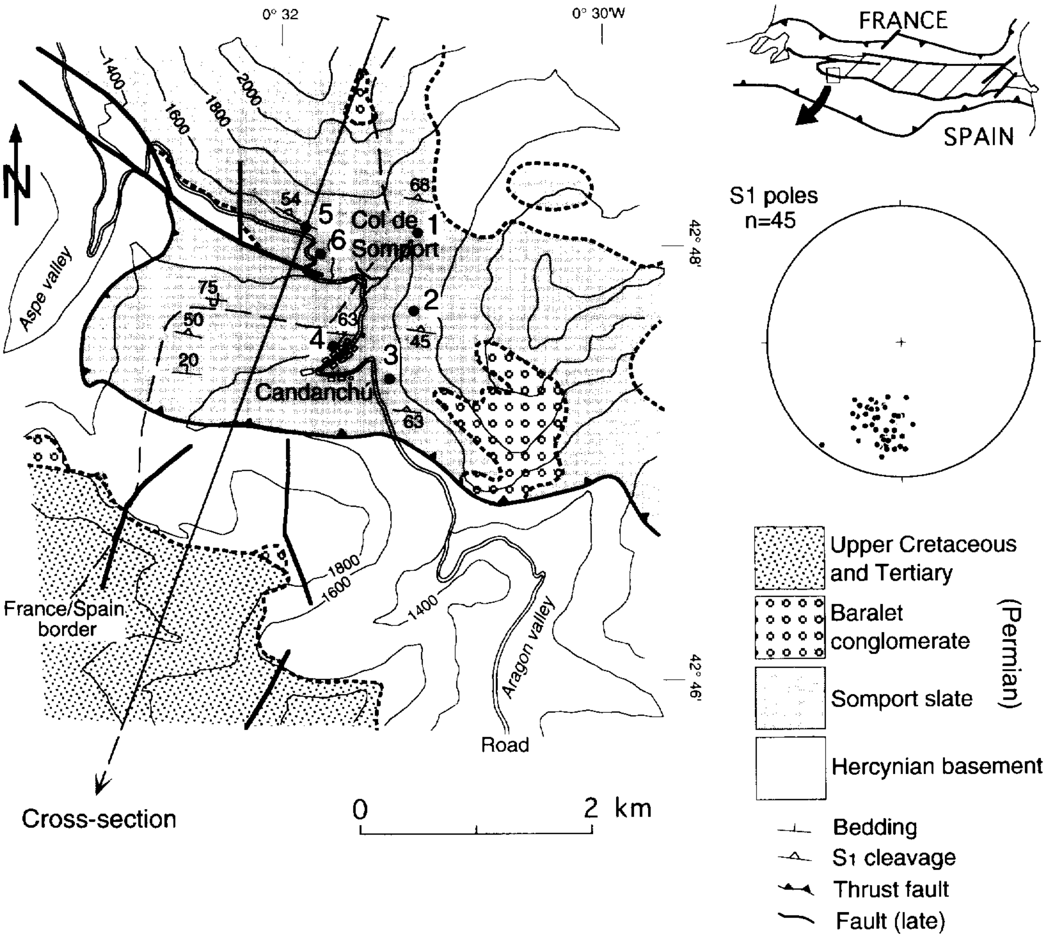
We propose the unusual geometry of the strongly curved kink bands is partly the product of a non-plane-strain deformation imposed on the rock mass and partly the result of local stress field modification along the lateral margins of propagating, overlapping kink bands. We present a model that correlates kink band geometry and kinematics with imposed bulk displacement (Fig. 1). This model is a natural extension of models that have been proposed for brittle faulting (Oertel, 1965; Aydin, 1977; Reches, 1978, 1983; Krantz, 1988, 1989), brittle–ductile en echelon vein arrays (Kirschner and Teyssier, 1994) and ductile shear zones (Gapais et al., 1987).

2. Kink bands at Somport

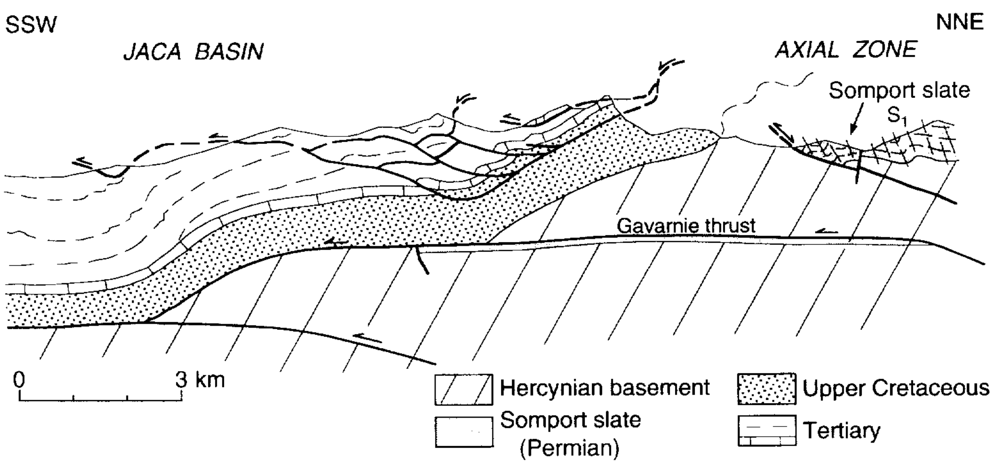
2.1. Geologic setting

The kink bands of this study are located in slates of the Somport formation, west-central Pyrenees (Fig. 2). The Somport formation is characterized by slates with minor sandstone and conglomerate beds, and is included in a series of terrigenous Permian red beds (Mirouse, 1966). The Somport slate is closely associated with the Axial Zone basement massif, a thrust-related Alpine culmination that occupies the central part of the Pyrenean range. The outcrops described in this study are located on the southern culmination of the Axial Zone, in close proximity to the hanging-wall ramp of the Gavarnie thrust (Fig. 2; Teixell, 1990, 1992). Deformation associated with motion on the Gavarnie thrust during Eocene to early Oligocene produced meter- to kilometer-scale south-verging overturned folds, with an average interlimb angle of 50° (Verbeek, 1975). A slaty cleavage (S1), which dips 50 to 70° to the NNE, is associated with these folds (Fig. 2).

Fig. 2. Geologic sketch map and cross-section of the Somport region at the southern culmination of the central Pyrenees Axial Zone (hatched region in upper-right figure). South-verging folds and associated north-dipping slaty cleavage (S1) in the Permian Somport slate are located in the hanging wall of the Gavarnie thrust (poles to S1 cleavage shown in equal-area, lower-hemisphere net). South-dipping kink bands, which represent the last folding event to affect the slate, were studied at six localities in the Somport slate.



0° 32
0° 30'W
42° 48'
42° 46'
1400
1600
1800
2000
Aspe valley
Col de Somport
Candanchú
France/Spain border
Aragon valley
Road
Cross-section
0 2 km
FRANCE
SPAIN
S1 poles
n=45
Upper Cretaceous and Tertiary
Baralet conglomerate
Somport slate
(Permian)
Hercynian basement
Bedding
S1 cleavage
Thrust fault
Fault (late)



SSW
NNE
JACA BASIN
AXIAL ZONE
Somport slate
S1
Gavarnie thrust
0 3 km
Hercynian basement
Somport slate (Permian)
Upper Cretaceous
Tertiary

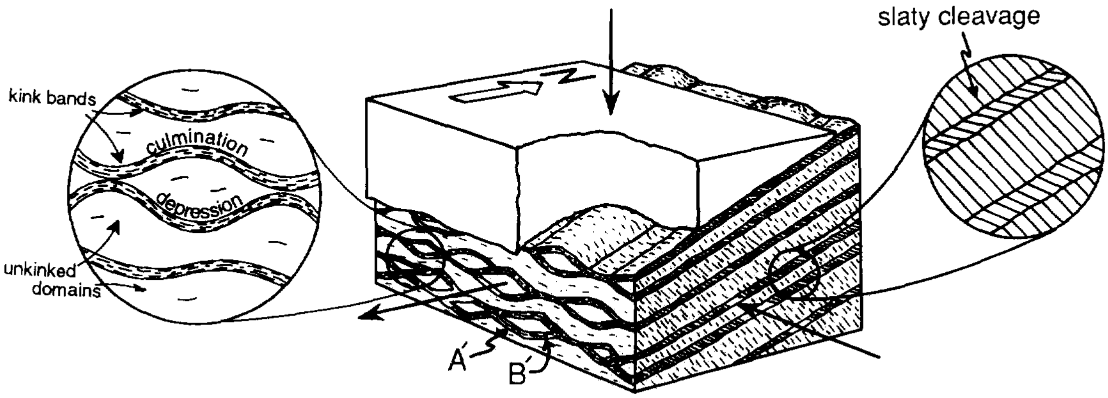


Fig. 3. Geometry of kink bands exposed in the Somport region. North-dipping slaty cleavage is crosscut by south-dipping kink bands that accommodated top-to-south sense of displacement. The kink bands are highly curved and form an anastomosing network that bounds unkinked domains (as observed in E–W striking subvertical outcrops). (Figure modified from Verbeek, 1978).

The kink bands are the last folding event that affected the slate. The kink bands are not homogeneously distributed throughout the formation, but are restricted to pure pelitic horizons and are rare or absent in the siltstones and sandstones. The kink bands are not pervasively developed even within pelites, but rather are localized in decimeter-scale regions. No structural control on their occurrence has been recognized, for they occur both in backlimb and forelimb positions with respect to the earlier ESE–WNW folds, which produced the slaty foliation. Nor is there an apparent association between kink bands and faults or shear zones in this area.

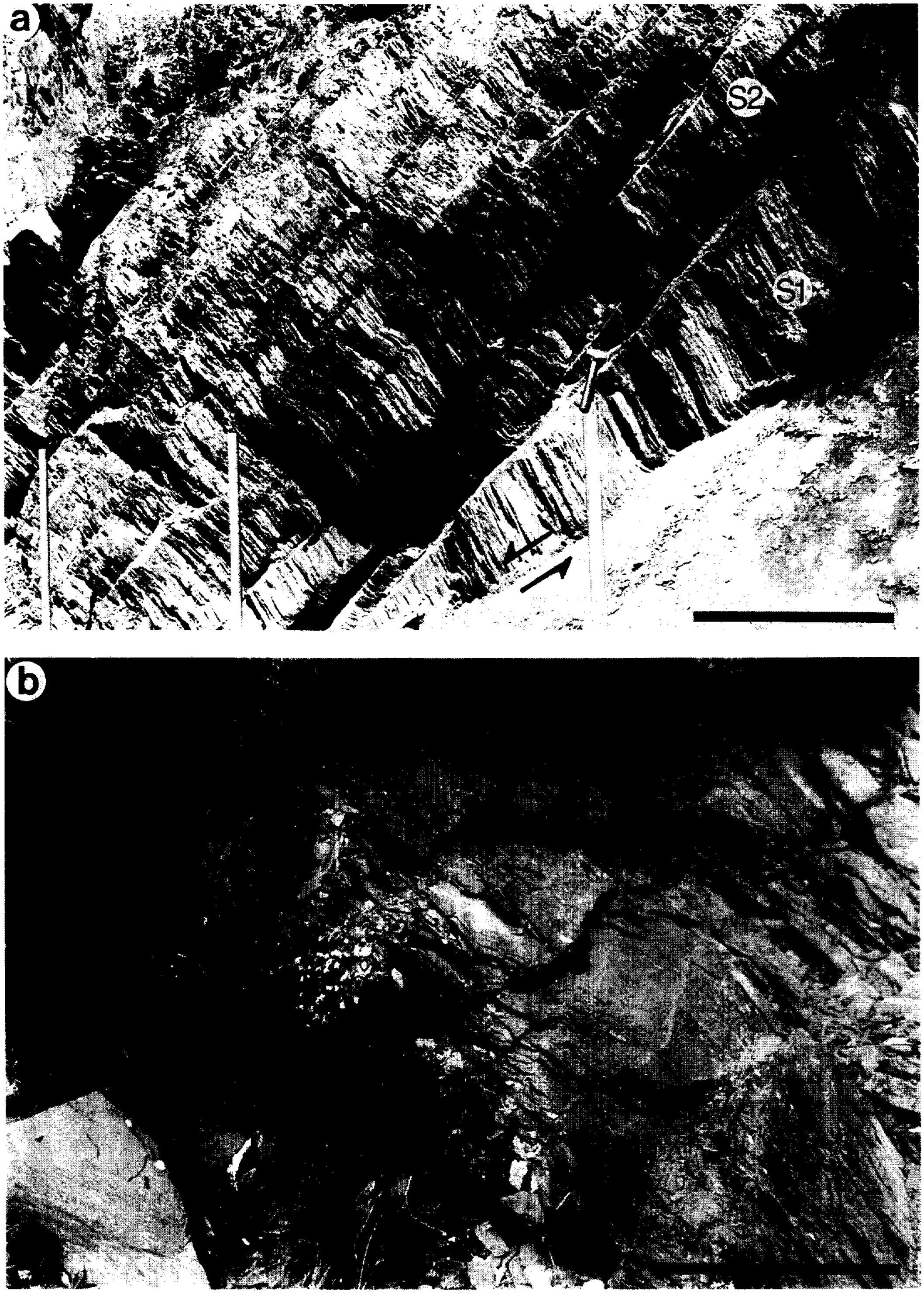
Six localities were studied in the Col de Somport area, between the town of Candanchú in Spain and the Aspe valley in France (Fig. 2). We restrict our observations of the kink bands to well-exposed road-cuts and man-made outcrops where weathering has not obscured the finer details of the structures. Three additional localities reported in Verbeek, 1975, 1978) are incorporated in the discussion of this paper.

2.2. *Geometry and orientation analysis*

The occurrence and geometry of these kink bands were originally reported by Verbeek, 1975, 1978), who limited his discussion predominantly to the 2-D geometry of individual kink bands in order to constrain the mechanism of kink band formation. In the following discussion we focus on the 3-D geometry and kinematics of the kink band arrays (Fig. 3).

In cross-section, individual kink bands near Somport are defined by planar limbs bounding angular to subangular fold hinges. The width of individual kink bands, which vary along individual bands and between different bands of the same outcrop, are on average less than 3 cm with few exceeding 5 cm. The angle between foliation, outside and inside kink domains, and the intervening kink band boundary (interlimb angles, α and β, respectively) range between 60 and 90° but are seldom equal across individual kink bands (cf. fig. 11 in Verbeek, 1978, and our own observations). Verbeek (1978) in a 2-D

Fig. 4. South-dipping kink bands offsetting north-dipping slaty cleavage (S1). Displacement of all kink bands is top-to-the-south. (a) North–south cross-section of kink bands at sample locality 4, as viewed towards the west (scale bar = 1 m). (b) Oblique view of kink bands at sample locality 5, as viewed towards the west (s.b. = 40 cm). (c). Anastomosing network of kink bands as seen in the plane of slaty cleavage at locality 4 (viewed towards the north; s.b. = 1 m). (d) Anastomosing network of kink bands as seen in the plane of slaty cleavage at locality 5 (viewed towards the south; s.b. = 40 cm). Arrows in (c) and (d) denote traverses used to calculate the magnitude of contraction due to kink band formation (cf. Table 1).


a
S2
S1
b

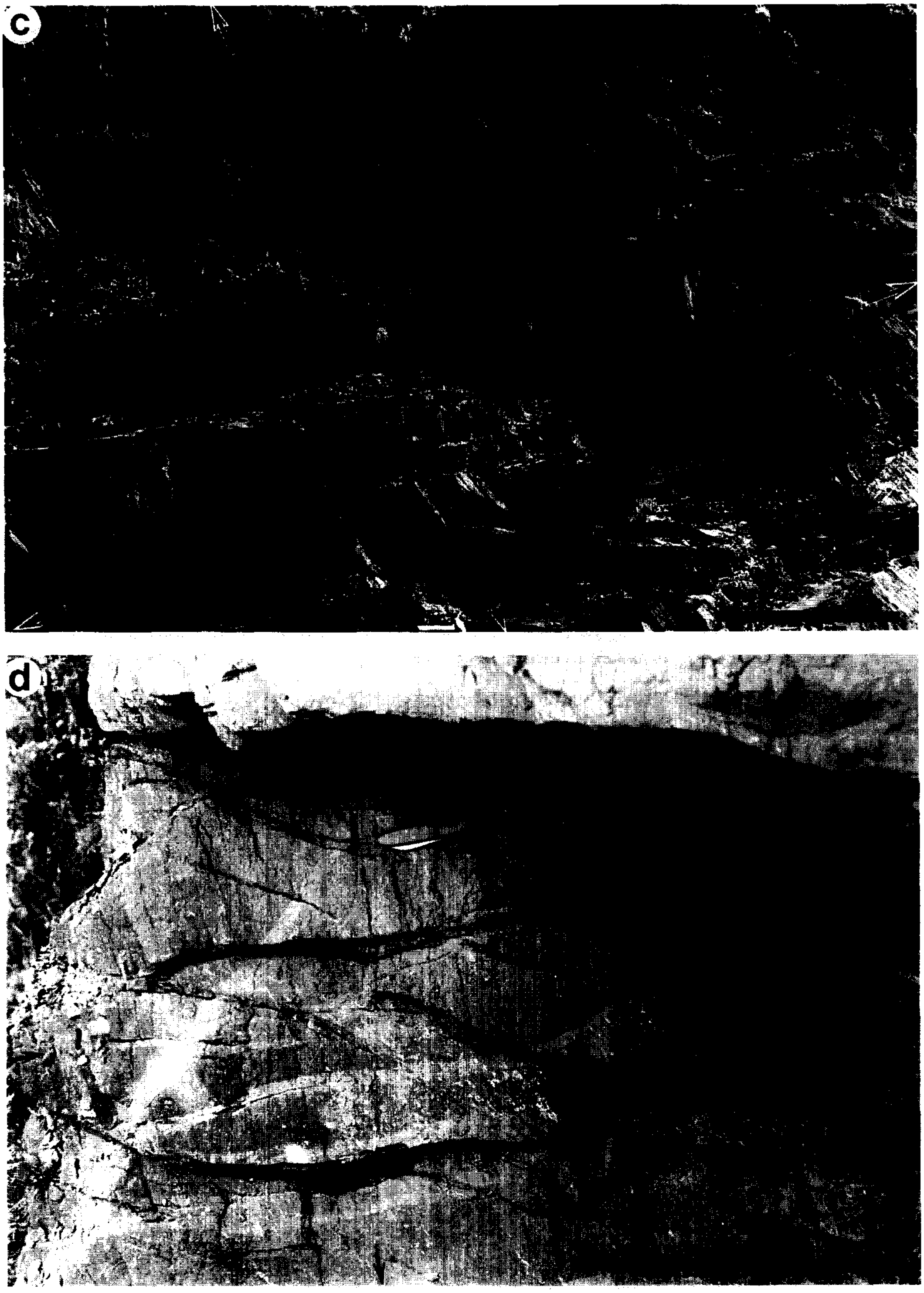


Fig. 4 (continued).

structural analysis of these kink bands suggested that the kink bands formed by a mechanism of rotation (Donath, 1968a,b; Clifford, 1968), in which the slaty cleavage of constant length rotated between the kink-band boundaries.

All the kink bands dip moderately to the south and exhibit the same sense of movement such that the top was displaced towards the south, resulting primarily in vertical shortening (Fig. 4). Less than 1% of the kink bands in the six localities studied are arranged conjugately in the classic sense. Individual kink band surfaces extend laterally up to 150 m^2 (Verbeek, 1978). The average spacing between adjacent bands is from 4 cm (at locality 5) to 15 cm (at locality 4). At the termination of many kink bands, their top-to-south displacement was transferred laterally to adjacent, en echelon-arranged kink bands (Fig. 5a, b). On a larger scale, the kink bands exhibit geometries commonly found in brittle fault systems, for example, as a system of listric kink bands (similar to listric normal faults) that merge and transfer slip into an underlying kink band.

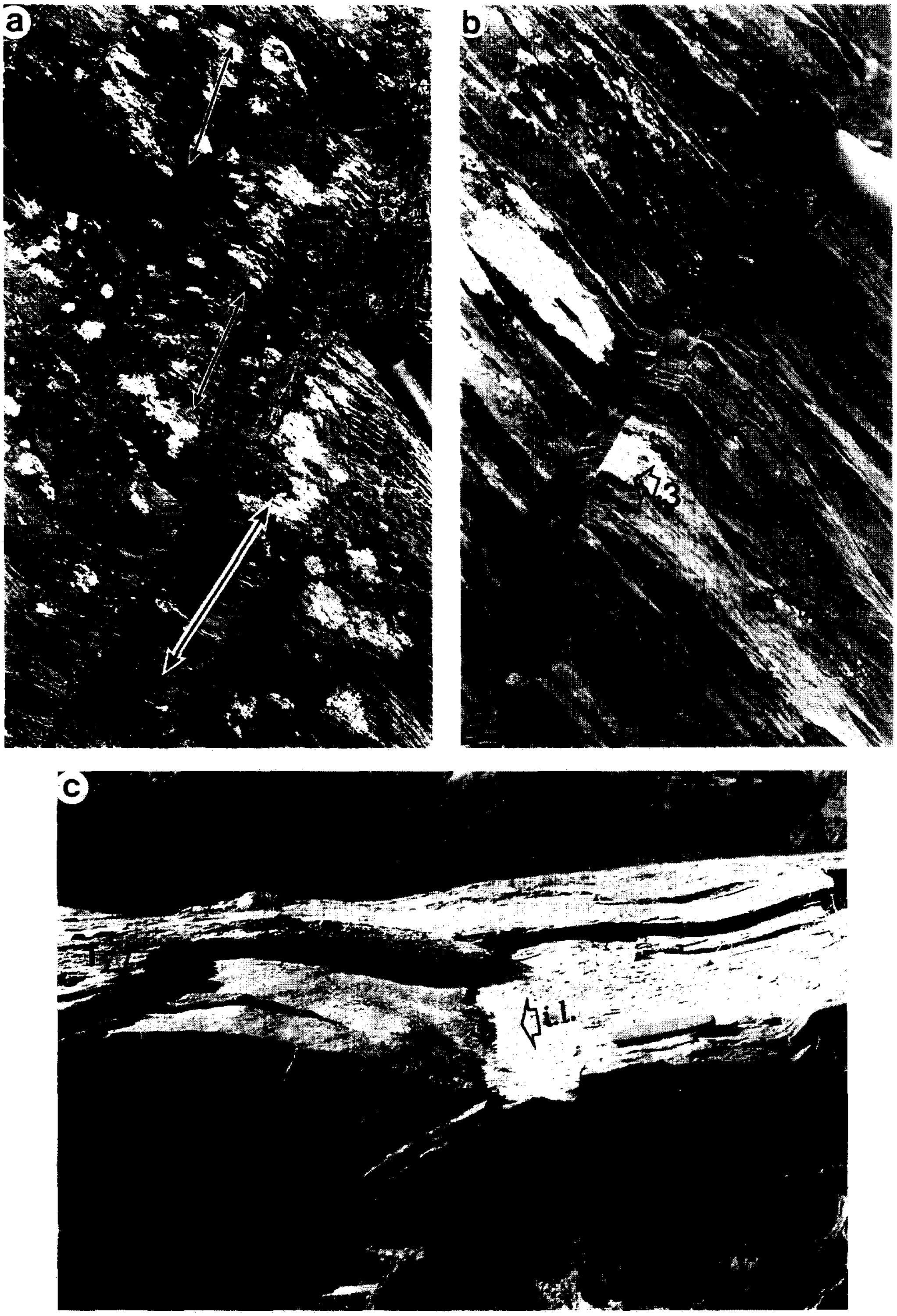
Most kink bands are not planar but curved as observed in steeply dipping, E–W-striking exposures (i.e., parallel to the S1 slaty cleavage, Figs. 4c, d, 5c). Concave- and convex-upward (depressions and culminations) kink bands form an anastomosing network that isolates lozenge-shaped unkinked domains (Fig. 3). Thus, the kink bands form an anastomosing network of cozonal kink bands. Rarely, individual kink bands form basin and dome structures that are less than one meter in wavelength.

The south-dipping kink bands crosscut the north-dipping slaty cleavage at ~65–70° angle at all sample localities (Fig. 6). The kink band orientations vary slightly between the six localities and are related to regional variations in slaty cleavage orientation. Shallower dipping kink bands occur at localities with steeper dipping cleavage (e.g. locality 4) and vice versa (e.g. locality 2). In addition, the slaty cleavage at locality 5 strikes on average 25–30° towards the south relative to that of locality 4, comparable to the difference in kink band orientations between these localities. Therefore, late variable rotations of fault-bounded blocks, which are common in the Somport area, are probably responsible for the variations in both cleavage and kink band orientations between the six localities.

There is significant dispersion of kink band orientations in individual localities with homogeneous cleavage orientation. The poles to kink bands lie approximately on great-circle girdles in the equal-area nets such that the normal to the girdles (the "zone axes") plunge ~40–65° to the south. Similar great-circle girdles are also defined by individual curved kink bands (Fig. 7). The slaty cleavage at the same localities define point maxima, not great-circle girdles. The curvatures of the kink bands, as exhibited by the great-circle girdles in the stereonets, are therefore unique to the anastomosing kink band array and are not the result of subsequent E–W folding. The departure of the data away from well-defined great-circle girdles reflect the minor anastomosing geometry observed in the north–south plane.

2.3. *Geometry of intersections and criteria of relative chronology*

The intersections between individual kink bands as observed on the slaty cleavage plane exhibit three geometries (Fig. 8). The simplest geometry involves the oblique truncation of one kink band on another kink band, resulting in a "*T*" shape intersection. Displacement accommodated by the abutting kink band decreases towards the intersection (as expressed by increasing interlimb angle) with no observable continuation of the kink band or deformation across the truncating kink band. In this situation, the abutting kink band is inferred to be younger than the truncating kink band. The second geometry involves the crossing of two kink bands to form an "X" shape intersection. This geometry was only observed for kink bands that crossed at moderate to steep angles. At the junction, the slaty cleavage in the older kink band has been unfolded and reoriented by the younger kink band. There is no observable expression of the mechanism of unfolding on the outcrop (e.g., microfracturing, microbrecciation, veining). The third geometry involves the asymptotic merging of two kink bands thus forming a "Y" shape intersection. This is the dominant type of junction for kink bands oriented at low to moderate angles to each other. The total displacement of the two individual kink bands approximates the total displacement accommodated by the merged segment. The relative chronology of kink band formation was


a
b
3
c
i.l.

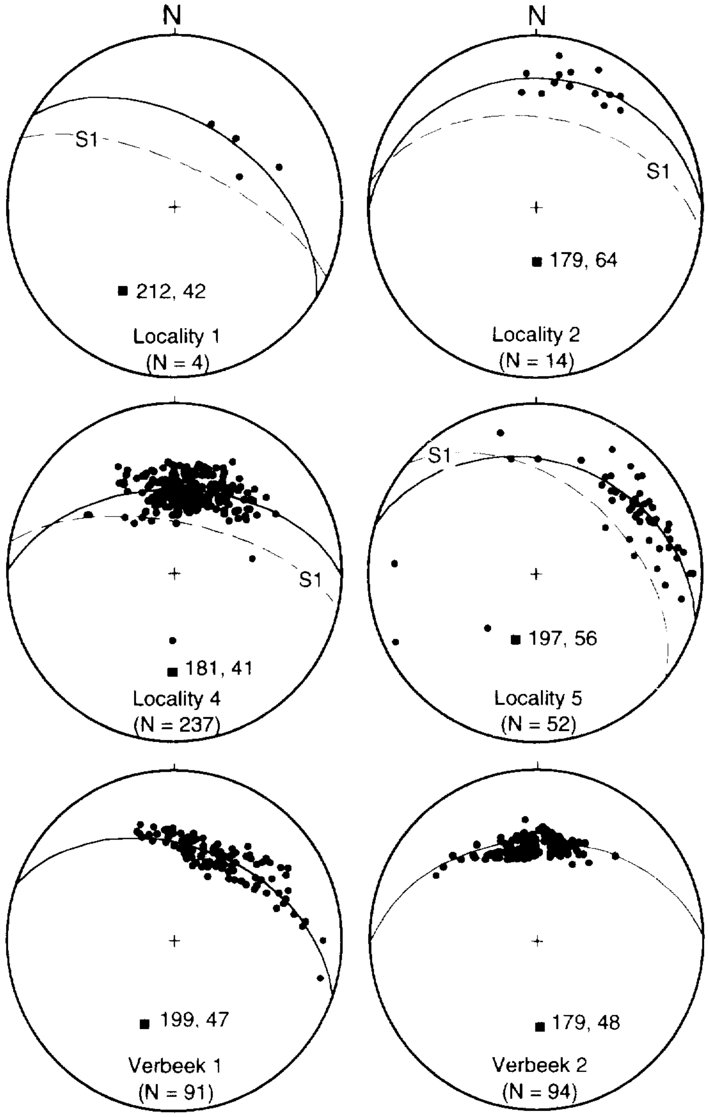


Fig. 6. Poles to kink bands (dots) from nine sample localities (three localities reproduced from Verbeek, 1978) lie along great-circle girdles in equal-area, lower-hemisphere nets. Average orientation of the slaty S1 cleavage at each locality is depicted by the dashed great-circle girdles. The dispersion of kink bands along east–west striking great-circle girdles is not due to east–west shortening (folding) post-dating kink band formation, but rather is a primary feature that developed concurrently with the kink bands in the Somport slate. (Best-fit great-circle girdles calculated with StereoPlot program of N. Mancktelow).

Fig. 5. (a) Individual kink bands merge downward to form a master (décollement-like) zone. (b) Top-to-south displacement is laterally transferred between en echelon kink bands 1, 2 and 3. (c) Intersection of two kink bands at locality 6 (photo is subparallel to slaty cleavage plane, view is towards the north). This intersection (*i.l.*) is colinear with north–south trending culminations and depressions of the highly curved kink bands (e.g., Fig. 3). The curvature of the kink bands' surfaces is not due to a later east–west folding event after kink band formation. The colinearity of these structural elements is consistent with minor east–west contraction during propagation and merging of these two kink bands.

difficult to establish for the "Y" shaped intersection. It is likely that the kink bands were forming contemporaneously and either the two kink bands converged or an individual bifurcated at the junction during their (its) lateral propagation. Alternatively, the two kink bands might have formed at different times, such that the orientation and geometry of the earlier band controlled the orientation of the later kink, forcing it to merge asymptotically.

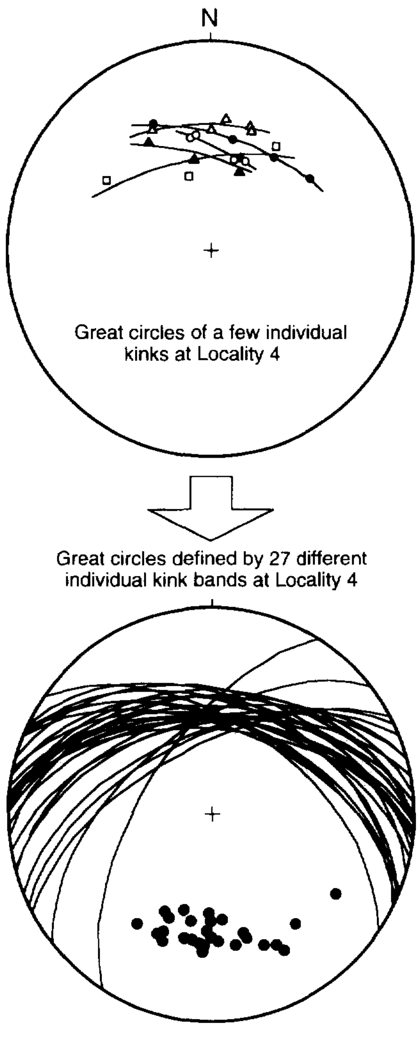


Fig. 7. Orientation measurements taken along individual kink bands also define great-circle girdles similar to those recorded in the stereonets of Fig. 6. Poles to kink bands measured along five highly curved, individual kink bands (top stereonet) and a summary of measurements made for 27 kink bands at locality 4 (lower stereonet) define the north-dipping, east–west striking great circle girdles.

2.4. *Penecomtemporaneous kinking of differently oriented kink bands*

The nonuniform orientation of the kink bands at Somport could be interpreted as being the product of several distinct kink-forming events, or having formed during one kink-forming event when the stress and incremental strain fields rotated relative to the slaty cleavage. The following observations, however, support the hypothesis that most of the kink bands are broadly contemporaneous. First, all three types of kink band junctions described above are present and show conflicting age relationships between kink bands of different orientations in the same outcrop. Secondly, many individual kink bands exhibit pronounced curvature resulting in cylindrical culminations and depressions (Fig. 3). The axial zones of the culminations and depressions are colinear with the intersection zones produced at the "*T*", "Y" and "X" shaped junctions for the same kink bands (Fig. 5c). The simplest explanation for the colinearity of these structural elements is that the kink bands formed penecontemporaneously. Thirdly, it is very common that two kink bands with different orientations merge at "Y" shape junctions to form a single band with an orientation intermediate between the two kink bands. Therefore, we conclude that the kink bands at Somport formed during a single kink-forming event.

2.5. *Direction of slip within individual kink bands*

In order to quantify the direction and magnitude of slip accommodated within individual kink bands, passive markers are needed. Unfortunately, the Somport slate is essentially devoid of passive markers apart from sparse reduction spots at the six study localities. We have documented the tangential and longitudinal rotations experienced by six elliptical reduction spots that were fortuitously transected by kink bands (exposed on single S1 cleavage planes; Fig. 9). Excluding one reduction spot, the magnitude of slip perpendicular to the kink domain is approximately three to four times the magnitude of slip parallel to the kink band–cleavage intersection.

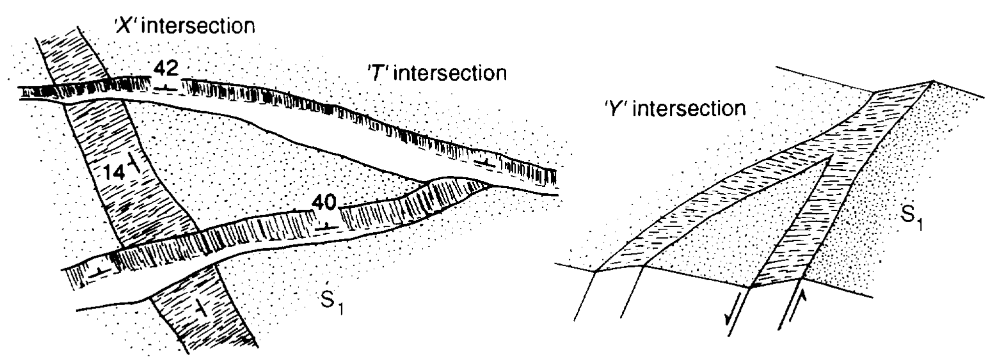
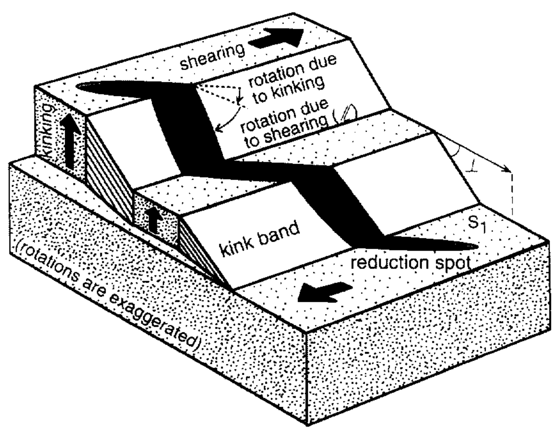


Fig. 8. Relative chronology determined from cross-cutting relations between kink bands in the Somport slate (sketched from outcrop at locality 5). Younger kink bands either cross-cut and displace older kink bands (to form an "X" shape intersection) or abut against older kink bands (to form a "T" shape intersection). A third type of intersection is formed by the merger of two kink bands to form one kink band of intermediate orientation (thus forming a "Y" shape intersection). Although the "Y" shape intersection is most common in the kink bands of Somport, the relative chronology between kink bands at such an intersection is unclear.

One possible consequence of slip parallel to the kink band–cleavage intersection is the lateral accumulation or loss of material in the axial zones of the culminations and depressions. Based on measurements of six highly curved kink bands at locality 4 and corroborated by observations of numerous other curved kink bands, the width of kink band domains (as measured perpendicular to the domains) do vary laterally, but these variations are not systematically related to position on the curved kink band surfaces (Fig. 10). We conclude from our limited data set on the rotation of reductions spots and lateral variations in the thicknesses of domains that the dominant slip direction within the kink bands was subperpendicular to the local kink band–slaty cleavage intersection.

2.6. *Strain compatibility problems*

The curvature of the kink bands must have been established during the incipient stage of their formation and lateral propagation. Subsequent displacement during kinking should have resulted in east–west stretching or shortening along the curved kink band surface because slip within the kink bands was



No.	⊥	∥	direction	ratio
1	32°	12°	west	40%
2	13°	11°	west	85%
3	27°	2°	east	5%
4	17°	7°	east	40%
5	24°	6°	west	25%
6	28°	7°	east	25%

Angular displacement of reduction spots perpendicular (⊥) and parallel (∥) to fold axes

Fig. 9. Deflection of passive reduction spots from unkinked to kinked domains. Approximately two-thirds to three quarters of total deflection recorded by the reduction spots was due to displacement perpendicular to the kink band fold hinge, while the remainder of the displacement responsible for the deflection of the reduction spots was parallel to the kink fold hinge (resulting in deflection of reduction spots either towards the east or west).

Widths of six kink bands relative to position on culminations and depressions

		A	B	C	D	E	F
Kink band	1	1.4	-	1.5	1.6	1.6	-
	2	2.0	-	2.4	2.4	2.4	-
	3	0.9	0.5	0.7	-	-	-
	4	1.6	1.0	1.4	0.8	-	-
	5	1.1	-	1.5	1.5	1.8	-
	6	-	-	-	1.8	1.2	2.2
		A/C	**B/C**	**C/C**	**D/C**	**E/C**	**F/E**
Kink band	1	0.9	-	1.0	1.1	1.1	-
	2	0.8	-	1.0	1.0	1.0	-
	3	1.3	0.7	1.0	-	-	-
	4	1.1	0.7	1.0	0.6	-	-
	5	0.7	-	1.0	1.0	1.2	-
	6	-	-	-	1.5*	1.0	1.8

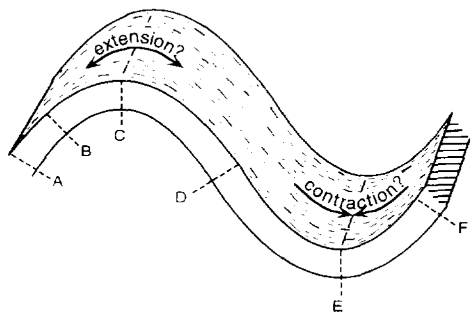


Fig. 10. Widths of six highly curved kink bands from locality 4, as measured perpendicular to the kink band boundary (positions *A–F*). The widths of kink bands are neither constant between positions A to F, nor do they systematically vary across individual kink bands. One possible consequence of slip parallel to the kink domain is the lateral accumulation or loss of material in the axial zones of the culminations and depressions. We observed no mesoscopic features (e.g., fractures, dissolution seams) related to the gain or loss of material in the axial zones.

Table 1
Data collected along E–W and N–S trending transects (as measured parallel to the unkinked slaty cleavage plane) in order to calculate bulk shortening for the kink band systems at localities 4 and 5 (cf. Fig. 4c,d). Displacement in the highly curved, contractional kink bands resulted in bulk constrictional strains at these two localities such that both E–W, subhorizontal and N–S, subvertical lines were shortened up to 3% (calculations applicable to lines lying in the unkinked slaty cleavage planes and bisecting the overall kink band system)

Band	Apparent width (cm)	Apparent dip (°)	Spacing (cm)	l_0 (cm)	l (cm)	
Locality 4 N–S cross-section						
18	4.0	40	90.0	94.0	93.1	
20	4.0	35	28.0	32.0	31.3	
–	2.0	30	10.0	12.0	11.7	
–	2.0	30	13.0	15.0	14.7	
23	5.0	46	29.0	34.0	32.5	
65	3.0	40	9.0	12.0	11.3	
–	12.0	28	10.0	22.0	20.6	
–	0.5	30	5.0	5.5	5.4	
29	2.0	35	32.0	34.0	33.6	
30	2.5	41	27.0	29.5	28.9	
63	3.0	35	5.5	8.5	8.0	
64	1.0	30	12.5	13.5	13.4	
–	2.2	35	4.0	6.2	5.8	
–	3.0	35	5.0	8.0	7.4	
60	2.0	34	25.0	17.0	16.7	
59	2.5	40	25.0	27.5	26.9	
				sum = 343.2	334.4	stretch = 0.974
Locality 4 E–W cross-section						
31	4.0	10	30.0	34.0	33.9	
63	14.0	10	40.0	54.0	53.8	
30	12.0	20	60.0	72.0	71.3	
–	14.0	0	100.0	114.0	114.0	
67	11.0	4	50.0	61.0	61.0	
69	4.0	16	115.0	119.0	118.8	
				sum = 454.0	452.8	stretch = 0.997

Table 1 (continued)

Band	Apparent width (cm)	Apparent dip (°)	Spacing (cm)	l_o (cm)	l (cm)	
Locality 5 N–S cross-section						
A	1.7	23	3.0	4.7	4.6	
B	1.0	20	1.0	2.0	1.9	
C	0.5	36	5.0	5.5	5.4	
D	0.6	34	7.3	7.9	7.8	
E	0.4	28	2.4	2.8	2.8	
F	0.6	15	4.1	4.7	4.7	
G	1.5	31	5.0	6.5	6.3	
H	1.3	30	2.7	4.0	3.8	
I	0.8	24	1.7	2.5	2.4	
J	1.2	28	4.5	5.7	5.6	
K	0.7	30	2.1	2.8	2.7	
L	0.3	23	2.6	2.9	2.9	
M	1.5	22	1.1	2.6	2.5	
N	0.9	27	5.6	6.5	6.4	
				sum = 61.1	59.7	⇒ stretch = 0.977
Locality 5 E–W cross-section						
O	1.7	19	23.6	25.3	25.2	
P	0.7	18	21.0	21.7	21.7	
Q	2.0	76.9	8.9	11.4		
R	1.4	9	10.0	11.4	11.4	
				sum = 67.3	67.1	⇒ stretch = 0.998
Locality 5 E–W (2nd) cross-section						
S	2.5	18	3.2	5.7	5.6	
T	2.1	13	3.9	6.0	5.9	
U	1.1	11	5.0	6.1	6.1	
V	0.9	15	16.2	17.1	17.1	
W	0.8	11	3.7	4.5	4.5	
X	3.3	10	10.0	13.3	13.2	
				sum = 52.7	52.4	⇒ stretch = 0.994

dominantly perpendicular to the local kink band–cleavage intersection. The magnitude of stretching or shortening would depend on the location of the "neutral surface" in the kink band (i.e. surface of no finite extension or contraction). If the lower (inner) arc in a kink band culmination was the "neutral surface", then the foliation across the entire kink band domain would have been extended perpendicular to the colinear "zone axis" and slip direction of the kink. Conversely, if the upper (outer) arc of a kink band culmination was the "neutral surface", then the foliation in the kinked domain would have been shortened. The highly curved segments of kink bands at Somport should have experienced several percent of east–west extension perpendicular to the axis of the cylindrical culminations and depressions during their formation. Although we examined the foliation surfaces of many strongly curved bands at Somport, we did not observe any structures (e.g., microfracturing, dissolution seams, secondary kink bands) that would have accommodated lateral extension or contraction. Due to sampling difficulties of strongly curved kink domains, we are unable to comment on microstructural accommodation mechanisms. We conclude there was no large strain compatibility problem that resulted in visibly-observable accommodation mechanisms or microscale accommodation processes were involved.

2.7. Displacement due to kinking

In order to quantify the magnitude of contraction accommodated by the anastomosing kink band network, we systematically measured kink band orientations, interlimb angles, and spacing between adjacent kink bands for localities 4 and 5 (Fig. 4c,d; Table 1). We assumed in these calculations an idealized cozonal geometry for the network, that displacement was accommodated entirely by simple shear with the shear plane parallel to the local kink band boundary and shear direction oriented perpendicular to the local kink fold axis. The total displacement accommodated by the kink band network can be calculated by integrating the displacements across each kink band, from which bulk shortening for the outcrops can be determined (Table 1). Calculated N–S shortening parallel to the unkinked foliation plane is ~ 3% and E–W shortening is less than 1% for localities 4 and 5. These displacements, which resulted in subvertical and subhorizontal E–W contraction in the planes of symmetry to the cozonal kink bands, are indicative of bulk constrictional strains for these two localities.

3. Generalized model for kink band geometry

It is generally accepted that kink bands occur either as a monoclinal, coplanar set or two sets of kink bands that are conjugately arranged. The kink bands in the Somport slate are neither. For many kink bands at Somport, the intersection between the kink band and the slaty cleavage is strongly curved by 30° or more, rather than being linear as in simple monoclinic or conjugately arranged kink bands. In addition, the intersection between kink bands of Somport are oriented in *two* directions (E–W and N–S), rather than one direction as is commonly observed for many conjugately arranged kink bands. It has been shown, however, that the intersection lineations and fold hinges of conjugate kink bands need not be colinear if the kink bands are oriented obliquely to each other on the cleavage plane (e.g., Ramsay, 1962; Dewey, 1965; Ramsay and Huber, 1987). This situation arises when the intermediate stress axis is oblique to the cleavage plane during kink band formation. For such kink bands, termed conjugate kink folds with crossing fold axes, the kink band–slaty cleavage intersection and the intersection between kink bands can be oriented in at least three directions, but the traces of individual kink bands on the cleavage surface are still linear. This geometry can only occur when there are two sets of kink bands with opposite sense of displacement. The Somport kink bands cannot be interpreted as conjugate kink folds with crossing fold axes because all the kink bands show the same top-to-the-south displacement and the traces of the kink bands on the slaty cleavage plane are strongly curved.

3.1. Proposed model

Given that the existing geometric–kinematic models for kink band formation cannot adequately explain the kink bands at Somport, we propose a model that is derived from models developed for brittle faults and brittle–ductile shear zones. Kink bands are similar to brittle faults and brittle–ductile shear zones in that they are localized zones of deformation that accommodate most, if not all, of the imposed displacement while the surrounding rock body is lesser deformed or undeformed by the same deformation event. In addition, many conjugate kink bands are geometrically and kinematically similar to conjugate faults, albeit the obtuse dihedral angle rather than the acute dihedral angle of conjugate kink bands faces the maximum bulk shortening direction (Paterson and Weiss, 1966; Anderson, 1968, 1974; Clifford, 1968; Weiss, 1968).

The number and orientation of fault sets that accommodate slip during a single deformation are dependent on the displacements imposed on the rock body. This relation has been documented in experiments (Oertel, 1965; Reches and Dietrich, 1983) and proposed from natural fault systems (Aydin, 1977; Reches, 1978; Krantz, 1988). Up to four sets of faults develop during bulk coaxial, non-plane-strain deformations such that the three mirror planes of symmetry are coincident with the principal planes of bulk finite strain. Conjugate faults are particular to coaxial, plane-strain deformation. During bulk non-coaxial deformation, the number of fault sets are reduced to two and one for non-plane and plane strain deformations, respectively. This model has been extended to explain the geometry of en echelon vein arrays in brittle–ductile shear zones (Kirschner and Teyssier, 1994).

We suggest, based on the similarities between structures, that the models developed for brittle faults and brittle–ductile shear zones are applicable to kink bands, albeit the angular relationships between the four sets of kink bands would be different from those of orthorhombic fault patterns just as the geometry of conjugate kink bands differs from that of conjugate faults. Thus, four sets of kink bands develop during bulk coaxial, non-plane-strain deformations; while, two sets of kink bands develop during bulk non-coaxial, non-plane-strain deformations (Fig. 1). Monoclinal and conjugate sets of kink bands are unique to non-coaxial and coaxial plane-strain deformations, respectively. The coaxiality of the deformation will depend on the disposition of the stress field relative to the anisotropic layering: noncoaxial deformation and asymmetrical development of kink bands being favored when the principal stresses are inclined to the anisotropic layering.

The dynamics involved in the contemporaneous development of up to four sets of kink bands is surely more complex than that of brittle faulting (which is still not entirely understood; cf. Reches, 1983; Johnson, 1995) given the additional mechanical constraints imposed by the anisotropy of the slaty cleavage. There is obviously a need for theoretical and experimental work on kink band formation that takes into account non-plane-strain deformations. In addition, it will be necessary to investigate the importance of local stress field reorientation in the vicinity of overlapping kink bands' tips during their lateral propagation. This stress field reorientation might result in overlapping kink bands curving and terminating into one another (Fig. 11), similar to what occurs between overlapping dilatant fractures (e.g., Pollard et al., 1982, fig. 13 of that paper; Olson and Pollard, 1991). Although local stress reorientation possibly accounts for some of the curvature in the more closely spaced kink bands at Somport, it is difficult to imagine that the stress field was significantly modified between narrow (< 3 cm wide), highly curved kink bands that are widely spaced (up to 1 m spacing).

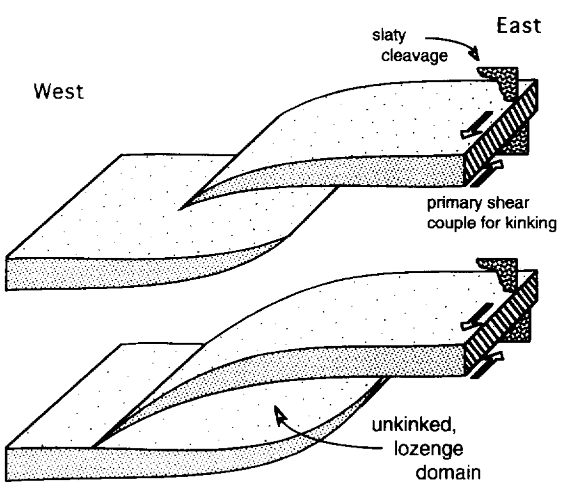


Fig. 11. The curvature exhibited by some overlapping, closely spaced kink bands might have been due to stress field reorientation in the local vicinity of the kink bands' tips during their lateral propagation and linkage. This reorientation would be similar to what occurs between overlapping, curved dilatant fractures (cf., Olson and Pollard, 1991).

3.2. Application of model to Somport

The kink bands at Somport developed during a single non-coaxial, non-plane-strain deformation event that resulted in vertical and horizontal E–W contraction and subhorizontal N–S extension (Fig. 3). This deformation resulted in highly curved kink bands that accommodated top-to-the-south displacement. The principal directions of the imposed bulk strain must have been oriented obliquely to the main anisotropy plane in the rock in order to account for the absence of kink bands with top-to-the-north displacement.

There is no direct evidence for the absolute age of kink band development at Somport, though they probably formed before the end of Pyrenean contraction, as they are locally cut by subhorizontal veins with steep calcite fibers, and at one locality they appear rotated by a minor thrust fault (locality 4). The kink bands post-date the formation of the Eocene–early Oligocene large folds and slaty cleavage of the Somport formation that formed at low-grade metamorphic conditions, under a cover of some 6 to 8 km of sedimentary rocks (Teixell, 1992). The vertical contraction could have been due to orogenic collapse towards the foreland of the Pyrenean axial culmination (Verbeek, 1978). Apart from a system of normal faults localized in upper Cretaceous rocks at the crest of the Axial Zone antiformal culmination, 20 km to the northwest of the Somport area (Teixell, 1990), additional evidence for vertical contraction has not been found in other more competent formations in the region.

4. Conclusions

A system of contractional kink bands in the Somport slate (central Pyrenees) exhibit a geometry that cannot be explained in terms of traditionally accepted models for monoclinal and conjugately arranged sets. The highly curved kink bands, which form an anastomosing network, accommodated top-to-the-south displacement that resulted in both subvertical and E–W subhorizontal contraction and N–S subhorizontal extension. A model is proposed for kink band systems that correlates kink band geometry and kinematics with imposed bulk displacement. This model predicts that four sets of kink bands develop during bulk non-plane-strain, coaxial deformations when the principal stress and incremental strain axes are symmetrically disposed about the slaty cleavage. Correspondingly, only two sets of non-conjugate, monoclinal kink bands develop during bulk non-plane-strain, noncoaxial deformations. Monoclinal and conjugate sets of kink bands are restricted to noncoaxial and coaxial, plane-strain deformations, respectively. This model is a natural extension of models that have been proposed for brittle faulting and brittle–ductile shear zones.

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