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Graphic derivation of the local sense of shear strain components in stretched walls of lithotectonic boundaries

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Abstract—Lithotectonic boundaries (LTBs) are deformed interfaces between rock masses such as sheared strata, midcrustal thrust slices or sutured microcontinents. Structural analysis of strained LTB walls have focussed attention on rock cuts through the foliation normal and mineral lineation direction, but this practice is commonly inappropriate for investigating the tangential shear strain (γ). A simple graphic technique is introduced whereby one may derive the sense of large shear strain components in two sections across an LTB wall segment; one section parallel to the lineation direction, the other normal to the foliation. The orientation of the strain ellipse is used on each section to deduce the sense of its shear strain component by visual inspection.

The technique is applicable to metamorphic rocks with *L–S* mineral fabrics, but without reliable gauges of large incremental or total longitudinal strain. If the factor of prolateness/oblateness of the strain ellipsoid is unknown, then the γ direction cannot be fixed within an angle of $<90°$ on the LTB surface (cf. accompanying paper by R. J. Lisle, *Journal of Structural Geology*, **20,** 969–973). However, the γ direction may be accurately determined if an LTB cross section fortuitously contains the normal to foliation as well as the mineral lineation direction. Similarly, the γ direction can be determined if the local strain ellipsoid corresponds to an oblate or prolate spheroid. Where the ellipsoid is nearly spheroidal, one can therefore discern which of the two shear strain components under consideration has the larger magnitude. This proves advantageous in assessing the sense of Alleghanian tangential shear below the Brevard fault zone (Grandfather Mountain area), southern Appalachians. Here γ has the sense of a ductile thrust, >1 km into the stretched footwall. Close to the fault zone, however, γ has a large sinistral component, unless the LTB dip is $>40°$. © 1998 Elsevier Science Ltd. All rights reserved

INTRODUCTION

Coherent and incoherent lithotectonic boundaries (LTBs) such as sutures between former microcontinents or mid-crustal stretching faults (Means, 1989, 1990; Duebendorfer and Black, 1992; Hajnal *et al*., 1996) have been favourite targets of field-based geological research. In many parts of orogenic belts, incoherent LTBs are poorly exposed, however, and defy attempts by field geologists to unravel their kinematic history. Good outcrop is commonly found in LTB walls, but their ductile deformation may predate the LTBs, or bear no simple relationship to slip vectors on the LTB surface.

A connection between ductile faulting and the strain of LTB walls may be evident in structural patterns displayed on geologic maps. (This point is illustrated in a subsequent section dealing with the footwall of the Brevard fault zone, Southern Appalachians.) On typical stretching faults, however, the slip vector changes systematically with position, and the rate of change depends largely on the tangential longitudinal strain of the walls (Means, 1989; Duebendorfer and Black, 1992; Hajnal *et al*., 1996). Like the LTB slip, tangential shear strain (γ, ψ) may vary in direction, sense and magnitude throughout curved LTB walls of any size, and therefore needs to be specified for individual localities (Fig. 1; Cobbold, 1983). Moreover, the local slip vector need not be parallel to the γ vector in adjacent wall rocks (Fig. 1c), especially if an incoherent LTB has negligible sliding friction and mechanically anisotropic wall rocks in which the weakness plane is initially oblique to the boundary surface.

Consider a half stretching fault (Means, 1989, p. 893) with perfect ease of sinistral slip and one rigid wall (Fig. 2). The other wall is homogeneously stretched and dextrally sheared, whereby the original orientation of the weakness plane (e.g. a pre-existing schistosity) determined the sense of tangential shearing. This is a hypothetical example of tangential shear strain without tangential shear stress (Schwerdtner *et al*., 1965), and poses a potential problem for structural analysts. The LTB trace of *actual* weakness planes will be inclined rather than normal to the stretching direction (as implied in Fig. 2), and this leads to an obliquity between the vectors of slip and tangential shear strain rather than a reversal in sense. Such obliquity would be difficult to detect, at strained LTBs, by employing the graphic technique outlined in the present paper. The technique relies on the principal directions of wall rock strain, and uses the orientation of schematic strain ellipses in deriving the sense of shear strain components on two sections across the local LTB surface. This requires that the LTB dip be known, to a first approximation, from drilling, vibroseismic profiling or other geophysical work.

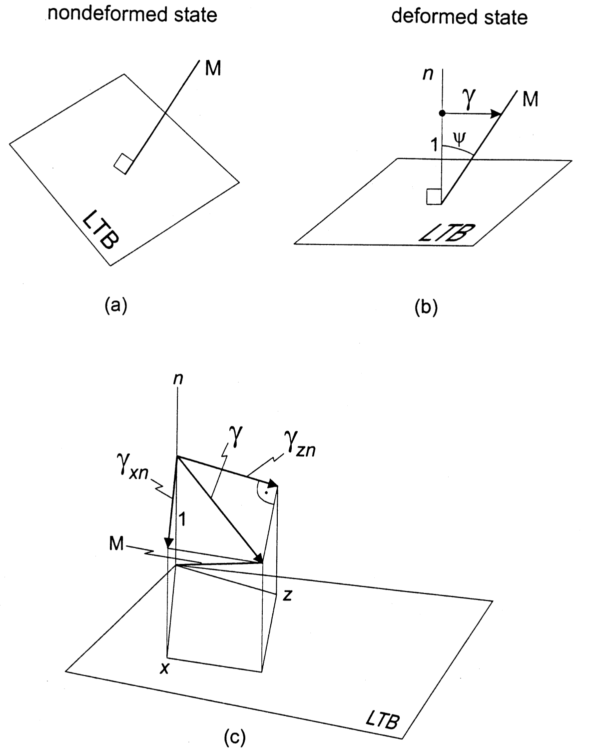

Fig. 1. Tangential shear strain at one side of a small element in a lithotectonic boundary (LTB). (a) M = material line perpendicular to LTB surface before deformation, (b) n = normal of deformed LTB surface, ψ = shear angle of M, (c) γ = tangential shear strain with components γ_{xn}, γ_{zn} on cross-sections Xn and Zn, x, z = directions of shear components.

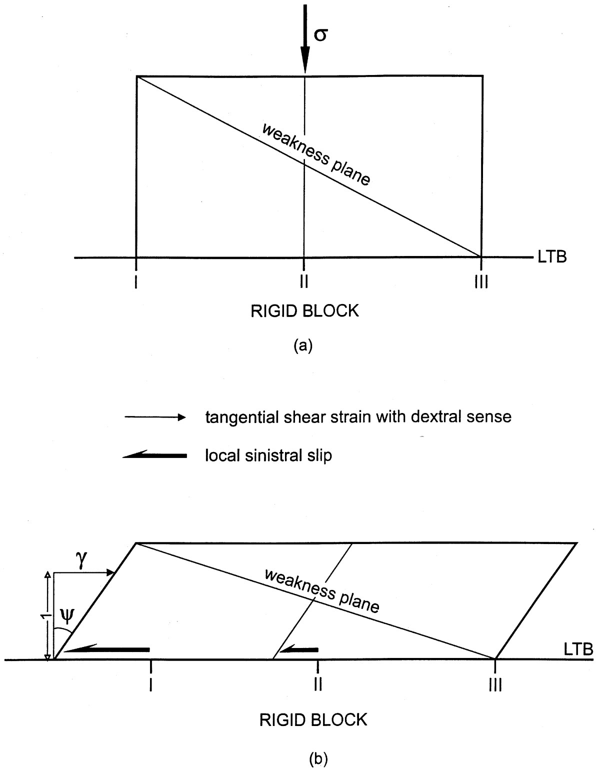

Fig. 2. Locally homogeneous deformation in the ductile wall of a half stretching fault (Means, 1989). I, II, III are marker points on the rigid wall. The absense of sliding friction on the LTB surface and an oblique mechanical anisotropy lead to tangential shear strain (γ, ψ) with dextral sense. The sinistral slip varies with the distance on the LTB surface (half stretching fault).

BACKGROUND AND PRACTICAL PROBLEMS

'Shear' has a variety of meanings in mechanics, engineering and structural geology, where it is used as a noun as well as an adjective. Shear strain is a geometric property of individual material lines in states of continuous deformation with finite or infinitesimal magnitude (Jaeger, 1962; Ramsay, 1967; Ramsay and Huber, 1983; Lister and Snoke, 1984; Hatcher, 1995). Common metamorphic rocks contain a partial record of several, apparently successive deformations, which may be regarded as finite increments of the total ductile deformation. The present paper deals with large shear strains (γ) tangential to an LTB segment (Fig. 1). Note that γ is a vector quantity related to the obliquity of the strained material line M, initially normal to the LTB segment. The vector has components (γ_{xn} and γ_{zn}) which are generally nonorthogonal but nonetheless vital for the technique outlined herein. Slip and shear strain of finite magnitude provide no definite clue to the shear-induced vorticity and other elements of the deformation path of ductile rocks, a principal focus of research in modern structural geology (Flinn, 1962; Ramsay and Huber, 1983; Simpson and Schmid, 1983; Lister and Snoke, 1984; Passchier and Simpson, 1986; Passchier, 1987). Effects of shear-induced vorticity are commonly investigated on outcrop surfaces or in thin sections containing the foliation normal and mineral lineation direction (Park, 1983, p. 71; Davidson, 1984; Passchier *et al.*, 1990; Hanmer and Passchier, 1991, p. 24). These structural elements are approximately parallel to the local directions of maximum shortening (Z) and elongation (X), respectively, and lie in the principal plane that contains the line of maximum finite shear strain. Exclusive focus on this principal plane, however, can be problematic for the analysis of vorticity as well as tangential shear strain.

In most structures recently studied by the author and his coworkers, for example, the normal (Y) to the X–Z plane is inclined to n at an angle of ρ (Tables 1 & 2). This implies that the X–Z plane (Figs 1 & 3) is not an LTB cross-section and therefore inappropriate for the analysis of tangential shear strain. An obliquity between Y and n also means that γ does not lie in the X–Z plane, and this confronts structural analysts with an important problem: how to determine the γ direction where $\rho \ll 90°$ (Tables 1 & 2). A graphic solution of the problem is detailed in the accompanying paper by Lisle (1998), given some knowledge of the strain state. In typical wall rocks with L–S mineral fabrics

Table 1. Values of dip and ρ at LTBs under study

Part of Orogen	LTB	Study Area	Strained rock mass	Geologic prediction of LTB dip (°)	Geophys. estimate of LTB dip (°)	Local ρ-value (°) based on geophysical data	Geophysical method	References
Western Trans-Hudson Orogen (Reindeer Zone)	La Ronge–Rottenstone domain boundary, near Shield edge	Eastern Clam Lake, west of La Ronge	Ohaninyank pluton (hbl.gran.)	89NW	45NW	50	Vibro-seismic reflection profiling	Morris (1963), Lewry and Slimmon (1985), Hajnal *et al.* (1996), Coté (1996)
			Ohaninyank pluton, qtz. monzonite	87SE	45NW	44		
		Churchill River	Trout Lake pluton	70NW,SE	45NW	26,64		
Kenoran Orogen, NW Ontario, Red Lake region	Uchi–English River subprovince bundary	Chase Lake	amphibolite units	45–85 S	30 S	60	Gravity ground survey and modelling	Runnell (1978), Stone (1981), Borowik and Schwerdtner (1996)
		Longlegged Lake	amphibolite silver	75–88 S	30 S	25		
	Woman–Confederation tectonic assemblage boundary	Western Confederation Lake greenstone belt	Woman assemblage	28W	77E	30	Bedding attitude in marble unit	Pryslak and assistants (1969, 1970), Thurston (1985)
			Confederation assemblage	58W	77E	57		

(Flinn, 1965), however, only the principal directions can be determined to a first approximation (Schwerdtner *et al.*, 1977). Nonetheless this information suffices for deducing the sense of γ_{xn}, γ_{zn} if not the sense of γ (Figs 1 & 3). After treating the general situation, special geometric cases will be considered: (i) γ_{xn}, γ_{zn} are approximately parallel to the lines of strike and dip, respectively, on the LTB surface, (ii) the acuate bisectrix between the components is approximately parallel to the strike or dip line, (iii) X, Z lie in the same LTB cross-section and (iv) a wall rock segment is apparently devoid of mineral foliation (Flinn's L tectonite) or mineral lineation (Flinn's S tectonite).

GENERAL ORIENTATION OF PRINCIPAL STRAIN DIRECTIONS

Figure 1 shows oblique components of tangential shear strain (γ_{xn}, γ_{zn}) for a hypothetical LTB segment that ends up to be subhorizontal. Consider next the general case of an inclined LTB surface, and arbitrarily oriented structures in the wall rocks (Fig. 3). The principal planes of finite strain are oblique to n, and the attitude of the n–M plane and its γ vector is unknown. However, γ will have finite components parallel to x, z if X, Z do not lie on the LTB surface (Fig. 3). Moreover X, Z must be the long and short axes, respectively, of their cross-sectional strain ellipses.

Table 2. Local ρ-values in ductile deformation zones

Part of Orogen	Host structure	Ductile deformation zone	Area of investigation	ρ-value (°) based on geological data	ρ-value (°) based on geophysical data	References
Northeastern Penokean Orogen	Sudbury Basin	South Range shear zone	domain 1	80	88	Shanks and Schwerdtner (1991); Milkereit *et al.* (1992), Dressler (1984)
			domain 2	90	87	
			domain 3 of Shanks and Schwerdtner (1991, fig. 7)	74	70	
Southern Appalachians (s > c. Segment)	Chauga Belt, Inner Piedmont Province	Brevard fault zone	Northwestern parts of South Carolina	60–75 (drilling)	65–75	Cook *et al.* (1979), Coruh *et al.* (1987), Edelman *et al.* (1987)

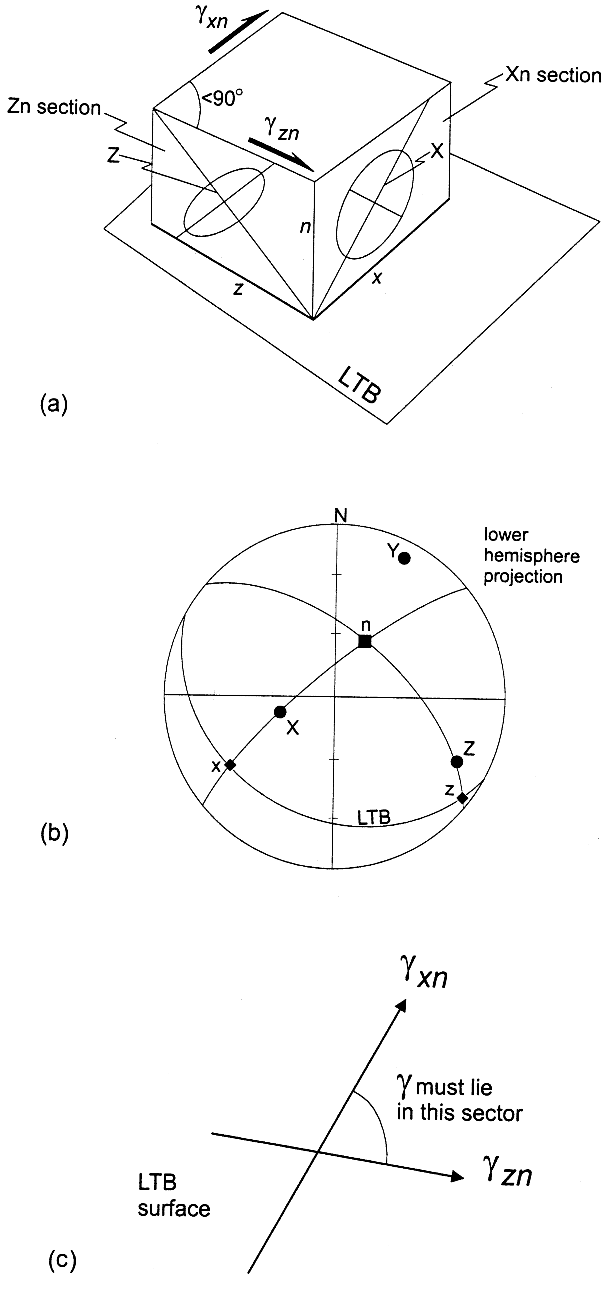

Fig. 3. Schematic strain ellipses on cross-sections through the lineation direction (X) and foliation normal (Z), respectively, whereby x, z are cross-sectional projections of X, Z on the LTB surface (a). Angular relationships between X, Y, Z and x, n, z in lower-hemisphere stereographic projection (b). Directions of componental tangential shear (magnitude unknown), with arrows indicating relative displacement of the hanging wall (c).

In Fig. 3, γ_{xn} has the sense of a sinistral reverse fault and γ_{zn} the sense of a sinistral normal fault. Use of the adjectives normal, reverse, dextral and sinistral (Fig. 4) is problematic, however, because the initial attitude of an LTB may differ greatly from its final attitude. The arrows in Fig. 3(a) specify directions of componental shear displacements in the hanging wall (Fig. 3c), and therefore indicate the sense of γ_{xn}, γ_{zn}. However, the magnitude of the components is unknown so that the γ direction may lie anywhere within the acute angle between x and z on the LTB surface (cf. accompanying note by Lisle, 1998).

In fortuitous situations, the analyst can find the sense of strike shear and/or dip shear of γ (special cases i, ii). A plane through X, Z and n (special case iii) constitutes a principal cross-section, for which the angle $\rho = 90°$. This implies that the γ direction is fortuitously parallel to the intersection line between the cross-section and the LTB surface. The same relationship is obtained if the strain ellipsoid degenerates into a prolate or oblate spheroid, in which any equatorial radius may be regarded as a principal direction (special case iv). Therefore, the γ direction is parallel to the intersection line between the LTB surface and the principal cross-section through the unique axis of the spheroid (lineation direction in L tectonites, foliation normal in S tectonites). In wall rocks with very strong lineation and very weak foliation, the larger of the two shear strain components (Figs 1 & 3) will be in the cross-section containing the lineation. By contrast, in wall rocks with very weak lineation and very strong foliation, the larger of the two shear strain components will be in the cross-section through the foliation normal. This simple qualitative rule permits the identification of LTB walls in which strike shear predominates over dip shear or vice versa.

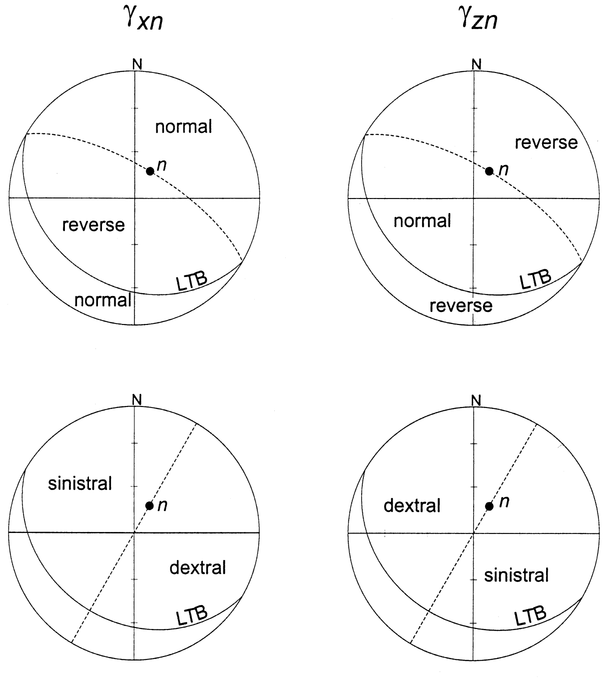

Fig. 4. Fields of different shear-strain sense for principal directions X, Z not shown in lower-hemisphere stereographic projection.

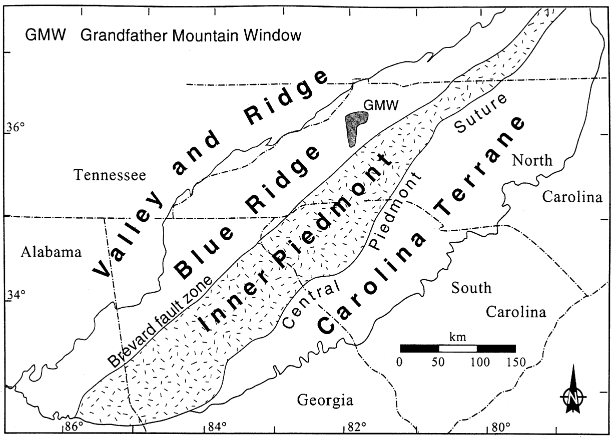

Fig. 5. Structural provinces of the southern Appalachians (modified from Davis, 1993, p. 18). GMW = Grandfather Mountain window.

SENSE OF SHEAR COMPONENTS AT A SEGMENT OF THE BREVARD FAULT ZONE

In the southern Appalachians, the LTB between the Blue Ridge and Inner Piedmont provinces (Fig. 5) is marked by the Brevard fault zone, a major Taconic or Acadian dislocation reactivated during the Alleghanian orogeny (Jonas, 1932; King, 1955; Reed and Bryant, 1964; Sinha *et al.*, 1987; Hopson and Hatcher, 1988; Hatcher and Goldberg, 1991). The Alleghanian reactivation created a 1–3 km wide zone (Fig. 6) characterized by phyllonites and other retrograded mylonitic rocks with greenschist-facies mineral assemblages. Retrograde effects are discernible also in the granitoid gneisses of the fault-zone walls, and attest to Alleghanian strain (Reed and Bryant, 1964; Edelman *et al.*, 1987; Hopson and Hatcher, 1988). This explains the gradational borders of the Brevard fault zone and problems in finding objective criteria of fixing the boundaries (Roper and Dunn, 1973; Edelman *et al.*, 1987; Hopson and Hatcher, 1988).

In western North Carolina, the footwall of the Brevard fault zone contains the Grandfather Mountain window (Figs 5 & 6), within a frame of variously deformed rocks of the Blue Ridge and Tablerock thrust sheets (Reed and Bryant, 1964; Reed *et al.*, 1970; Hatcher, 1995, p. 389). Two groups of autochthonous rocks occur in the window, (i) metasedimentary and metavolcanic rocks with prograde greenschist-facies metamorphic signature and (ii) heterogeneously strained retrograded granitoids and related gneisses (Reed and Bryant, 1964; Reed *et al.*, 1970, fig. 1). The respective prograde and retrograde metamorphic processes are thought to be coeval, at the peak of the Alleghanian orogeny.

Despite structural and lithologic complexity in the Grandfather Mountain area, the Alleghanian strain pattern of the footwall to the Brevard fault zone is remarkably regular, and points to a direct connection between ductile faulting and tangential shear strain (Reed *et al.*, 1970). Mineral foliation strikes northeasterly and dips southeasterly in much of the window and its frame, but the attitude of mineral lineation on the foliation surface (as opposed to the intersection trace of bedding and other types of lineations) varies systematically with distance to the Brevard fault zone (Reed and Bryant, 1964; Hatcher, 1995, p. 389). Trend lines of mineral lineation drawn by eye through the field of lineation arrows (Reed and Bryant, 1964, and unpublished own data) pass without refraction across internal lithologic and structural boundaries (Fig. 6). This first-order relationship was recognized by Reed, Bryant and coworkers, and led to a conceptual kinematic model for the main Alleghanian deformation in the Grandfather Mountain area (Reed *et al.*, 1970, fig. 2). The model envisages simultaneous sinistral

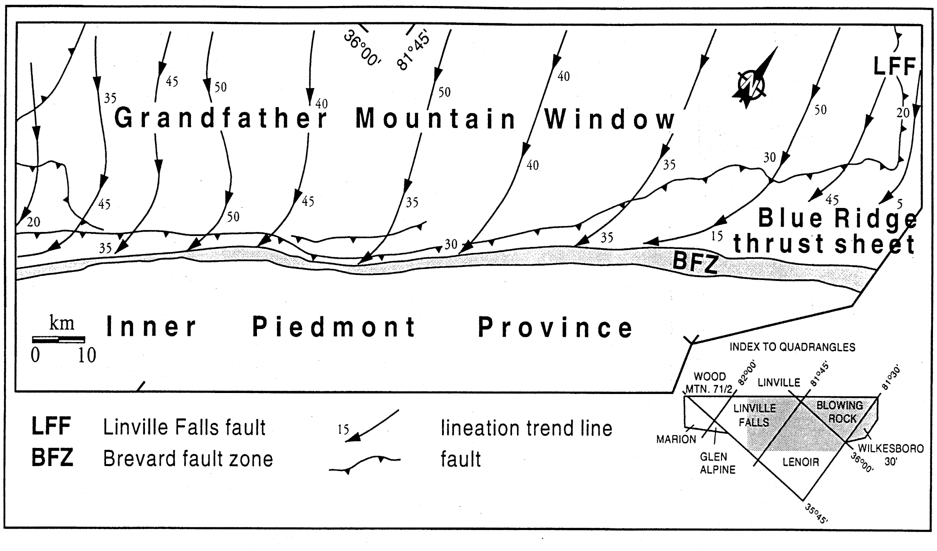

Fig. 6. Structural map pattern of the Grandfather Mountain area (modified from Reed and Bryant, 1964, plate 5). The lineation trend lines attest to a connection between faulting and tangential shear strain of the footwall.

Table 3. Attitudes of *L–S* fabrics used in shear-sense analysis

Locality	Foliation attitude	Lineation attitude
Grandfather Mountain window and northeastern relic of Blue Ridge thrust sheet	N30E/55SE	N155 S/50SE
Blue Ridge thrust sheet southeast of Linville Falls fault	N40E/40SE	N180(due south)/28 S

movement on the Brevard fault zone and sinistral thrust shear in much of the footwall, whereby the sinistral component decreases toward the NW. The possibility of concomitant NE–SW stretching was not considered by Reed *et al.* (1970), despite abundant supporting evidence. For example, $S \gg L$ mineral fabrics (Flinn, 1965) predominate in the window, and closely-spaced discoidal boudins (derived from concordant granitoid sheets) occur in mylonitic Blue Ridge gneisses at the Brevard fault zone. The proximity of neighbour boudins attests to modest, NE–SW stretching rather than NE–SW, progressive simple shearing of very large magnitude. (Shear-induced rotation and pull-apart of originally oblique granitoid sheets would have created large gaps between adjacent boudins.)

Reed *et al.* (1964, 1970) seem to hold that the mineral lineation attitude is indicative of the local movement direction (*a*) or, at least, the direction of tangential shear strain (γ). The present technique does not rely on the *a* lineation concept, but provides independent information about the degree of subparallelism between the γ vector and the lineation direction.

Shear-sense determination

On a regional scale, the reactivated Brevard fault zone may be regarded as a SE-dipping, strained LTB surface (Fig. 1). The present dip of the fault zone is best known in South Carolina from seismic reflection work and shallow drilling (Cook *et al.*, 1979; Hopson and Hatcher, 1988; Edelman *et al.*, 1987; Coruh *et al.*, 1987). At a depth of < 8 km, the dip angle is 15–35°, whereas the dominant foliation has an average dip of about 45° in Brevard phyllonite and adjacent rocks (Roper and Justus, 1973; Edelman *et al.*, 1987, p. 799). If the dominant foliation resulted from joint straining of diverse rocks in the Blue Ridge and Inner Piedmont provinces, then thrust shear was a major component of the ductile deformation.

Reed and Bryant (1964), Reed *et al.* (1970) and Hatcher (personal communication) judge that the Brevard fault zone dips more steeply at the Grandfather Mountain window. This prompts the use of two dip magnitudes (15°, 45°) in stereoplots depicting the general attitude of *L–S* fabrics in window and thrust sheet (Table 3, Figs 6–8).

At some localities in the western window, foliation strikes parallel, and mineral lineation trends normal, to the Brevard fault zone (Fig. 6; Reed and Bryant, 1964; Hatcher, 1995, p. 389). Here the plane through the lineation direction and foliation normal corresponds to a principal cross-section whose trace is the dip line of the LTB surface, i.e. the value of ρ (Tables 1 & 2) is 90°. This is indicative of thrust shear without a strike-shear component. At most other localities within the window (Table 3) and northeastern relic of the Blue Ridge thrust sheet, oblique components of shear strain parallel to *j*, *k* have the sense of *sinistral* thrust faults, but oblique components parallel to *l*, *m* have the sense of *dextral* thrust faults (Fig. 7). The LTB dip line lies in the acute angles between *j* and *m* and between *k* and *l*, respectively. Without knowing shear strain magnitudes, the γ direction (Fig. 1) is unconstrained within the acute angle between *k* and *l* or *m* and *j*. The dip shear must be reverse, but the amount of the strike shear is uncertain for both options of LTB dip (Fig. 7).

Pervasively strained rocks in the western window are characterized by prominent foliation and weak mineral lineation, and qualify as $S \gg L$ tectonites that border on purely foliated varieties (Flinn, 1965). Moreover, the linear component of *L–S* fabrics is generally overestimated when judging the degree of prolateness/oblateness in the field (Schwerdtner *et al.*, 1977). Shape fabrics defined by strained primary objects in various rock types (clay balls in meta-arkosic rocks, amygdules in metavolcanic rocks and small mafic xenoliths in granitoid gneiss) are dominantly oblate. The oblateness not only attests to the parallelism between principal strain directions and mineral fabric directions (Reed and Bryant, 1964), but also corroborates the value of $S \gg L$ mineral fabrics as indicators of lattening-type strain. Evidently, the Alleghanian strain ellipsoid approaches an oblate spheroid at many localities in the western window. This means that the strike shear component must be small in the LTB dip option of 15°, but could be relatively large in the 45° option (Fig. 7a). Here, dextral thrust shear is a distinct possibility, although pure thrust shear cannot be ruled out (cf. Lisle, 1998).

In the strip between the Linville Falls fault and the Brevard fault zone, mineral lineation plunges to the south at most localities (Fig. 6). A representative attitude of the *L–S* fabric (Table 3) and two possible LTB dip values are used for determination of the sense of shear strain (Fig. 8). Only the result for the low-dip option (shear directions *k*, *l*) is considered reliable. The component of shear strain parallel to *l* has the sense of a thrust with a small dextral component, and the *k*-component has the sense of sinistral thrust. The γ direction (Fig. 1) is again unconstrained within the acute angle between *k* and *l* (cf. Lisle, 1998). The tangential shear strain, therefore, has the sense of a pure

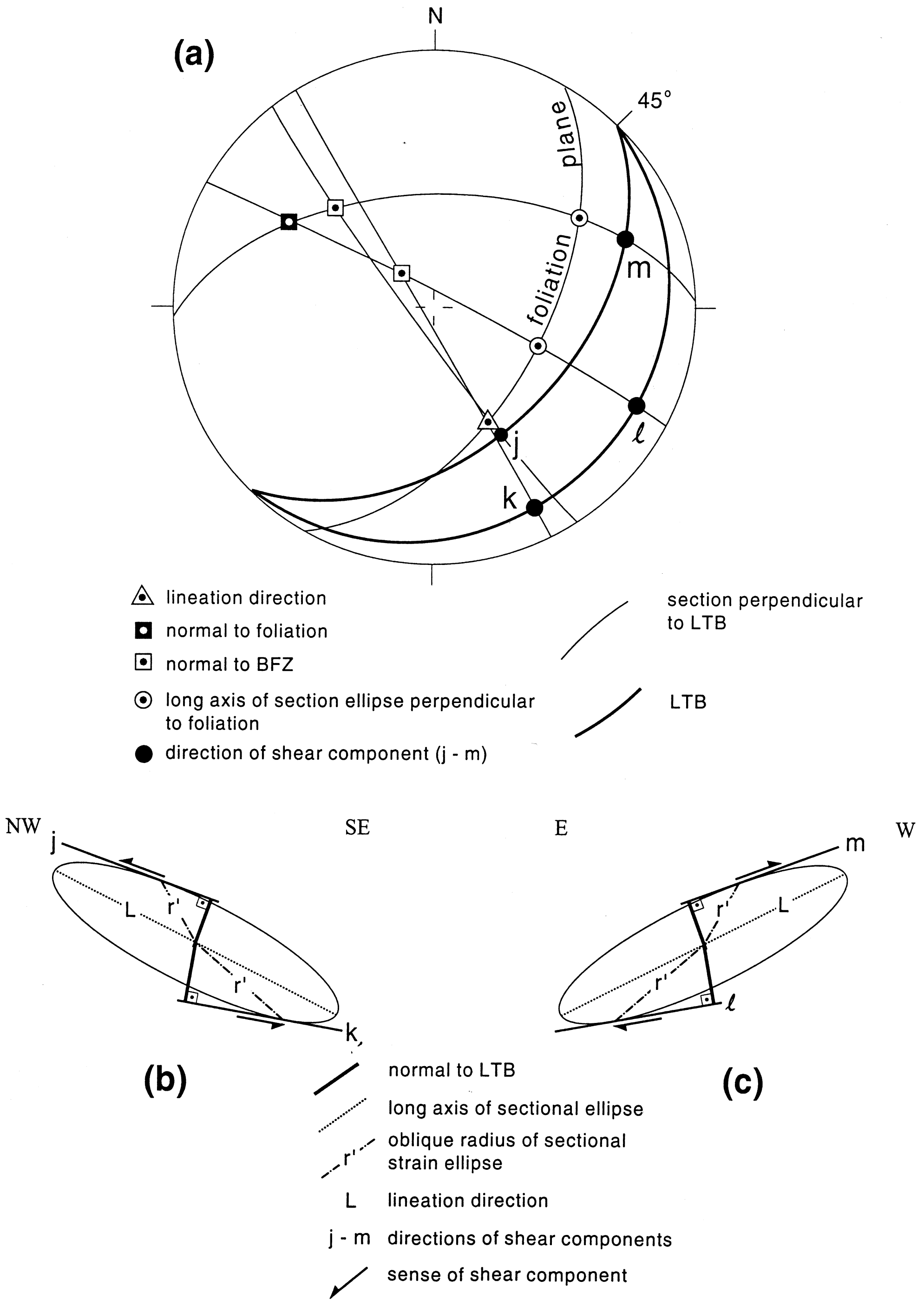

Fig. 7. (a) Equal-angle stereographic projection (lower hemisphere) of mineral fabric directions representative of the Grandfather Mountain window and northeastern relic of Blue Ridge thrust sheet (Table 3, Figs 5 & 6). Two LTB dip options (15°, 45°) represented by two LTB surfaces and two LTB normals. This results in tangential shear directions *j*, *k*, *l*, *m*. (b) and (c) Schematic cross-sectional strain ellipses viewed in a perpendicular downward direction. The shear strain sense for tangents *j*, *k* corresponds to sinistral thrusting, that for *l*, *m* to dextral thrusting. *L* is parallel to *X* of Fig. 3(a) (see text).

thrust or a sinistral thrust. The possibility of sinistral transcurrent shear (Reed *et al.*, 1970) can be ruled out in the footwall.

Line *j* in the 45° dip option (Fig. 8a) fortuitously parallels the γ direction because it lies in a principal cross section ($\rho = 90°$). The γ direction is subparallel to the lineation direction, and has the same sense as a dextral normal fault (Fig. 8b). However, the sense of strike shear and dip shear reverses if one lowers the LTB dip by $\geq 5°$. Judging from the results of shallow drilling and vibroseismic profiling in northwestern South Carolina (Cook *et al.*, 1979; Edelman *et al.*,

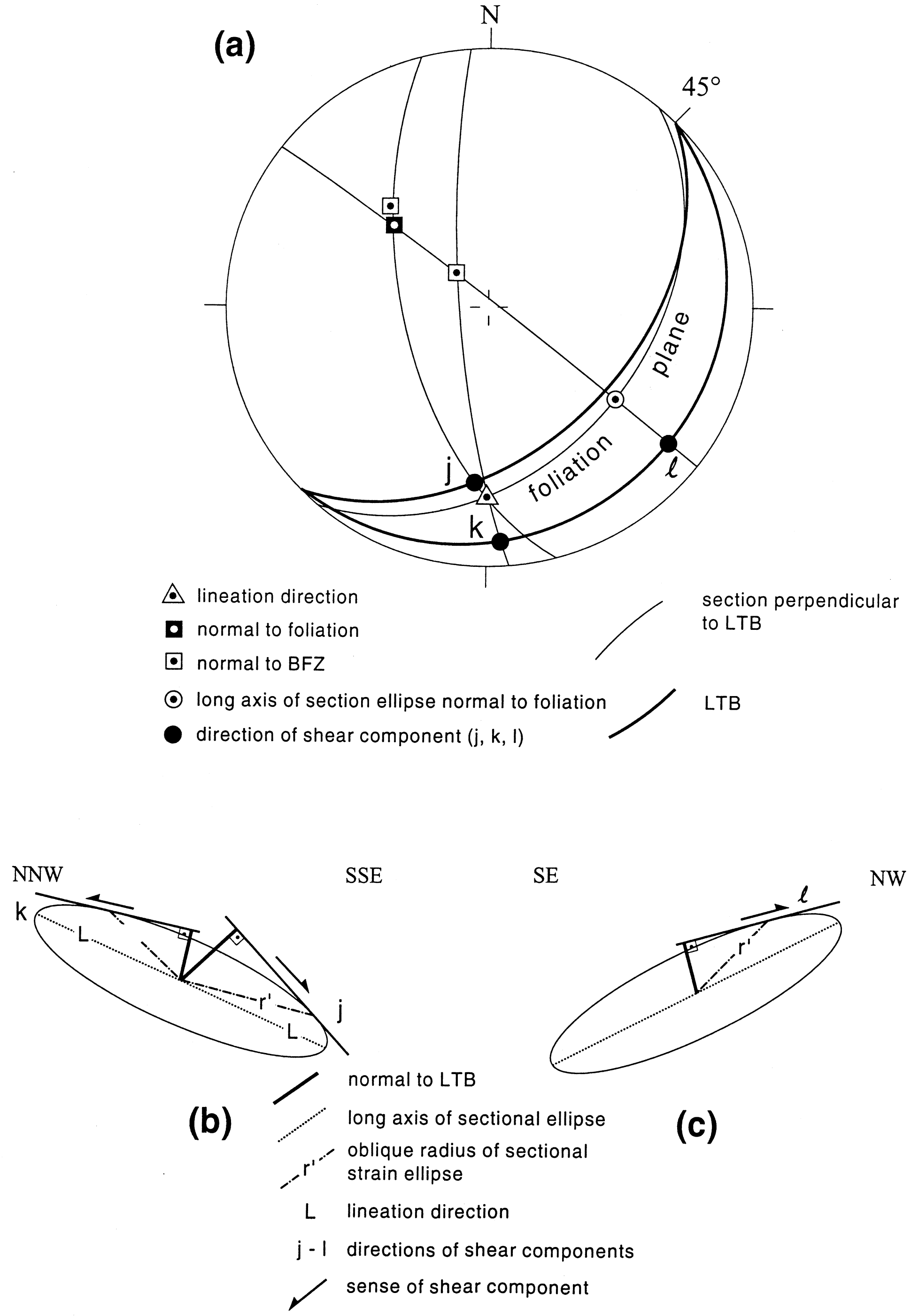

Fig. 8. (a) Equal-angle stereographic projection (lower hemisphere) of mineral fabric directions representative of the Blue Ridge thrust sheet southeast of Linville Falls fault (Table 3, Fig. 6). Two LTB dip options: 15°, 45°, as in Fig. 7. (b) and (c) Schematic cross-sectional strain ellipses viewed in a perpendicular downward direction. The shear strain sense for tangent l is close to that of a pure thrust, but the shear sense for tangent k is that of a sinistral thrust. Finally, the shear strain sense for tangent j is that of a dextral normal fault. The j direction is effectively parallel to the γ vector, L is parallel to X (Fig. 3).

1987; Coruh *et al.*, 1987), the southeasterly dip of the Brevard fault zone does not exceed 40°.

Sense of movement on the regional scale

The idea of subhorizontal Alleghanian movement in the Brevard fault zone is widely accepted in the geologic literature, whereby most workers favour scenarios of dextral transcurrent displacement (Reed and Bryant, 1964; Bobyarchick and Edelman, 1988; Hatcher, 1995, p. 171). However, Reed *et al.* (1970) present plausible arguments in favour of sinistral displacement, and it is possible that rocks within and adjacent to the Brevard fault zone record the effect of two subhorizontal Alleghanian events: a large sinistral deformation followed by dextral ductile faulting. (In addition, two episodes of brittle type thrusting are recognized by Edelman *et al.*, 1987, toward the end of the Alleghanian orogeny in South Carolina.)

Results of the present analysis of tangential shear strain in mylonitic rocks just below the fault zone (Fig. 8) provide qualified support for the hypothesis of sinistral thrust shear (Reed *et al.*, 1970, fig. 2). More specifically, in the LTB dip option of 15° the bisector of the range angle for the γ direction implies tangential shear strain with sinistral thrust sense. The same result would be obtained for a dip option of 30–40° (rather than the 45° option and its unrealistic normal-shear component).

Insufficient knowledge prevents the use of the prolateness/oblateness of the mineral fabric for constraining the possible orientation of the γ vector at the fault zone. The linear fabric component seems to be strong in places ($L > S$ tectonites), but this may not hold for the entire strip of Blue Ridge gneisses between Linville Falls thrust and the fault zone.

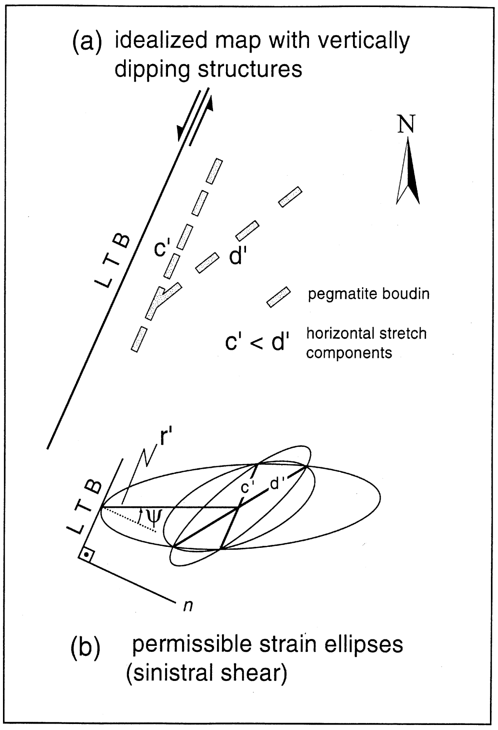

Fig. 9. Use of differently stretched, conjugate dikes (*c*′, *d*′) (a) for constraining the orientation of sectional strain ellipses in a cross section (horizontal plane) that does not contain a principal direction. The horizontal section ellipse is indeterminate (Brace, 1961), but the sense of obliquity with respect to *n* and the LTB trace may nonetheless be found. (b) The sense of componental shear corresponds to the obliquity sense of the strain ellipses, *r*′ = oblique radius in one possible schematic ellipse.

SHEAR SENSE OF A SINGLE ARBITRARY COMPONENT

The foliation of gneissic rocks is commonly cut by narrow dykes of granite pegmatite (< 5 m thick), which may be folded and/or pulled apart. The dilation of the host rocks associated with dyke emplacement can be regarded as part of a strain increment at scales of many metres. Dyke deformation amounts to a further strain increment affecting the host rocks. This increment may have (i) produced a new foliation/mineral lineation in the host rocks or (ii) strengthened or weakened pre-existing mineral fabrics. Because the mineral fabric in (ii) is the net effect of several increments, it need not indicate a principal direction of the deformation imposed on the dykes. This represents a situation in which the analyst may have to be content with determining the sense of one shear component, in an arbitrary section across an LTB segment.

Consider the hypothetical case of a vertical LTB and wall rocks with disrupted vertical dykes. Assume that the pegmatite was emplaced into conjugate fractures, which resulted in many bifurcating dykes. Subsequent deformation produced rectangular boudins with inclined parallel axes, whereby ENE-striking boudins (*d*′ in Fig. 9a) were more widely separated, on horizontal outcrops, than NNE-striking boudins (*c*′ in Fig. 9a). This information may be used to construct oblique ellipses of minimum horizontal strain in the wall rocks, three of which are shown in Fig. 9(b). (It is assumed tacitly that the disruption of all dykes commenced at the same time. However, a ‘head-start’ of NNE–SSW dykes would not alter the shear sense implied by the ellipse orientation.) An infinite number of ellipses could be drawn (Brace, 1961), but all strike more easterly than the strained LTB, and indicate the same sense of tangential shear strain.

A field example of boudiné conjugate dykes similar to those of Fig. 9 has been encountered in the inner Trans-Hudson orogen (Schwerdtner and Hirsekorn, 1995). The strain increment has regional significance, and will be evaluated in a separate article.

DISCUSSION AND CONCLUSIONS

Lithotectonic boundary (LTB) is the family name of coherent and incoherent structural surfaces that govern the deformation of rock masses (Cobbold, 1983; Treagus, 1983, 1988; Cobbold *et al.*, 1984; Means, 1989). Ductile LTB walls are prone to tangential shearing even while an LTB surface is incoherent. The present article outlines a graphic technique whereby one may determine the sense of large tangential components of shear strain by using common *L–S* mineral fabrics.

At any locality in an LTB wall segment (Fig. 1), the direction of shear strain (γ) will parallel the slip vector if the sliding friction is very large, and the wall rocks are mechanically isotropic. However, without knowing the ratios of principal strain and the value of a prolateness/oblateness parameter of the strain ellipsoid, the direction of the shear strain vector is difficult to determine within an acute range angle on the LTB surface (Figs 3, 7 & 8).

In general, the degree of prolateness/oblateness of the *L–S* mineral fabric will differ from that of the strain ellipsoid (Schwerdtner *et al.*, 1977; Themistocleous and Schwerdtner, 1977; Schwerdtner and Cowan, 1992). This complicates the application of Lisle's (1998) graphic method (which determines the shear strain direction on arbitrary sections through deformed bodies) to LTB walls with *L–S* mineral fabrics.

Vibroseismic profiling and other geophysical work show that the principal plane containing the directions of maximum extension (mineral lineation) and maximum shortening (normal to mineral foliation) is commonly oblique to the LTB surface (Tables 1 & 2). Because the tangential shear strain must be determined in sections perpendicular to the LTB surface (Fig. 1), the shear direction is not expected to lie in the principal plane.

In the graphic technique outlined above, two LTB cross-sections are used for determining the sense of componental shear strain, (i) the cross-section through the lineation direction and (ii) the cross-section through the foliation normal. These are the only cross-sections for which the long axis can be found without the Biot–Fresnel formula (Flinn, 1962). Because the lineation direction and foliation normal are parallel to the largest and smallest diameters of the strain ellipsoid they must correspond to axes of any section ellipse in which they occur. Figure 3 illustrates how the sense of tangential components of shear strain can be determined without knowing the shape of the section ellipses. Note that the use of such ellipses for shear-sense determinations is not restricted to LTB walls with *L–S* mineral fabrics, as shown in an example of stretched, conjugate pegmatite dikes.

The footwall of the narrow Brevard fault zone, in the Grandfather Mountain area, furnishes a good example in which the tangential shear strain is connected to ductile faulting. The fault zone separates the Inner Piedmont Province from the Blue Ridge Province (Fig. 5), and is a Taconic or Acadian LTB apparently reactivated in the Alleghanian Orogeny. Insufficient knowledge of the LTB dip in the Grandfather Mountain area complicates the analysis of shear strain sense (Figs 7 & 8). It can be discerned, nonetheless, that the main component of Alleghanian tangential shear strain has thrust sense in much of the footwall. Adjacent to the fault zone, which is widely regarded as a dextral dislocation, the component of sinistral shear strain may be larger than the dip shear component. This raises the question whether the rocks of the fault zone and adjacent footwall recorded two Alleghanian increments of tangential shear strain, i.e. a large sinistral thrust increment followed by a smaller dextral thrust increment (Reed *et al.*, 1970; Bobyarchick, 1984; Edelman *et al.*, 1987).

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