Journal of Structural Geology 29 (2007) 850–862

JOURNAL OF STRUCTURAL GEOLOGY

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Importance of differentiating ductile slickenside striations from stretching lineations and variation of shear direction across a high-strain zone

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Received 21 April 2006; received in revised form 29 November 2006; accepted 29 December 2006
Available online 21 January 2007

Abstract

Shear direction is an important parameter in the kinematic interpretation of high-strain zones. Recent developments in the study of high-strain zones show that there is no simple relationship between the orientation of stretching lineations and the shear direction and it is difficult to use the former to determine the latter. In contrast, striations on C-surfaces, a product of ductile deformation, form parallel to the shear direction. It is therefore important for the kinematic interpretation of high-strain zones to differentiate such striations from stretching lineations. Ductile striations are much more common in natural high-strain zones than reported in the literature. We discuss how to differentiate the two types of lineations and describe a natural high-strain zone example from the Superior craton of Canada. The striation data show that the shear direction of the high-strain zone varies from subhorizontal to moderately plunging across the strike of the zone. We conclude that well-developed ridge-in-groove type striations are a reliable indicator of the shear direction. We also discuss situations where the orientation of stretching lineations can potentially be used as an indicator of shear direction.

Keywords: Ductile slickenside striation; Stretching lineation; Shear direction; Triclinic transpression; High-strain zone

1. Introduction

Rocks in high-strain zones are generally foliated and/or lineated, and foliation and lineation data play a significant role in the kinematic interpretation of these zones. Two principal types of foliations and two corresponding types of lineations are commonly developed in high-strain zones. The foliations are generally called C- and S-surfaces (Fig. 1; Berthé et al., 1979; Lister and Snoke, 1984). The C-foliation is parallel to the shear-zone boundary and comprises surfaces, or more typically micro-scale zones of high shear strain (relative to adjacent S-domains) which are typically curvi-planar (Fig. 1; Lin and Williams, 1992a). When a rock splits along a C-surface, the outcrop surface appears striated due to its ridge-and-groove morphology (Fig. 1; Lin and Williams, 1992a and references therein), and the "ridge-in-groove" type striations (Lc) are parallel to the shear direction. S-surfaces comprise a shape fabric that is inclined acutely to the C surfaces, and the stretching lineation (Ls) lies in the S-surfaces (except in true L-tectonites). The S and Ls fabrics are often assumed to be parallel to the $\lambda_1\lambda_2$ plane and the λ_1 direction, respectively, of the finite strain ellipsoid (where $\lambda_1 > \lambda_2 > \lambda_3$ are the three principal stretches). In reality, S-surfaces commonly lie somewhere between the $\lambda_1\lambda_2$ planes of the instantaneous and finite strain ellipsoids (the orientation depending

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0191-8141/$ - see front matter
doi:10.1016/j.jsg.2006.12.006

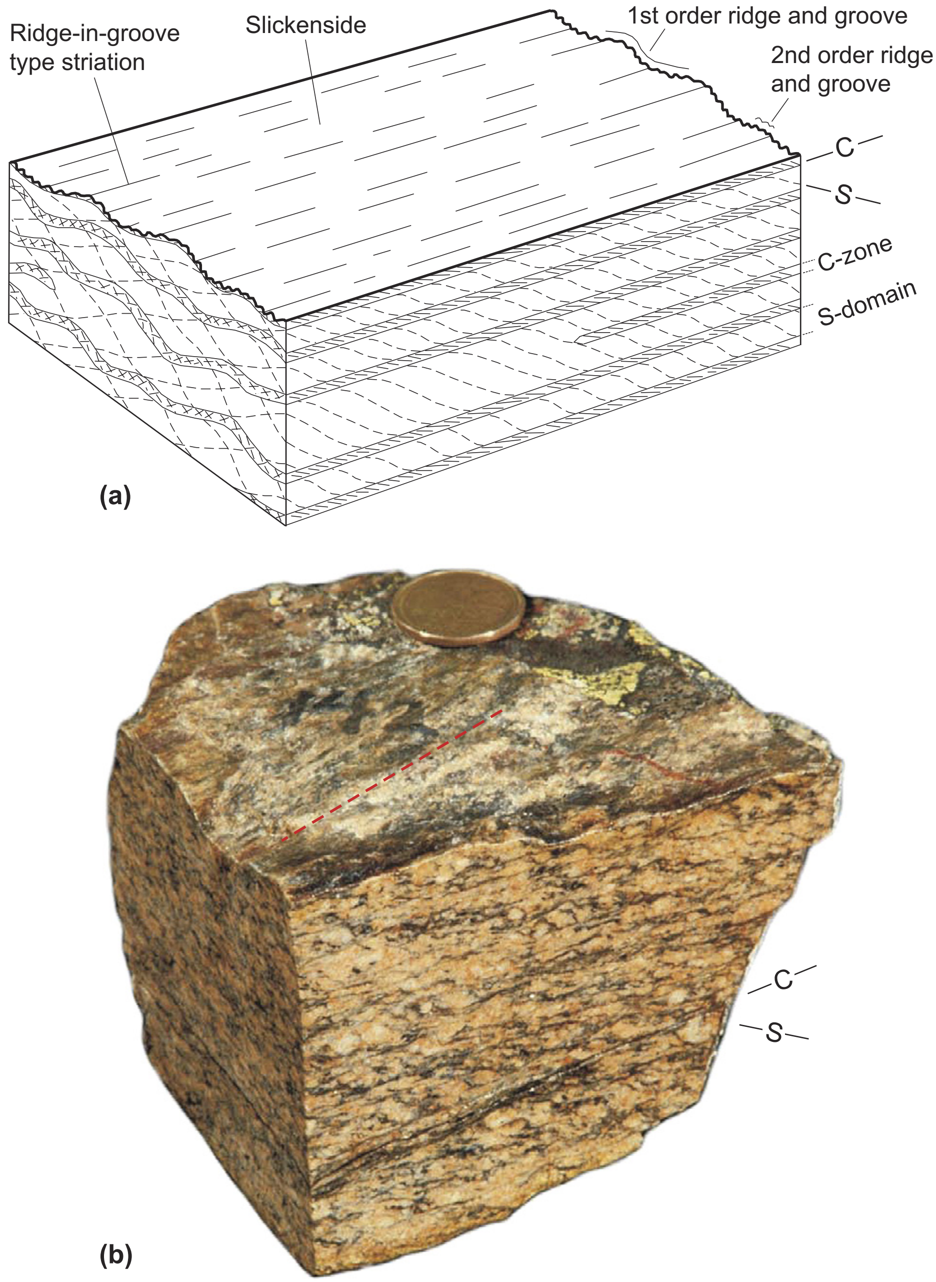

Fig. 1. (a) Schematic diagram showing the structures of a typical S-C mylonite (modified from Lin and Williams, 1992a). C-surfaces (zones) are parallel to the shear zone boundary, and surfaces exposed by parting along the C-surfaces are slickensides. Ridge-in-groove type striations on the slickensides are parallel to the shear direction. Stretching lineations (not shown) are developed on S-surfaces. (b) Hand sample of a granitic S-C mylonite from the Roper Lake shear zone in the Canadian Appalachians (Lin and Williams, 1992a). The top surface is a slickenside exposed by parting along a C-surface.

on the relative rates of development and recovery of the fabric; cf. the steady-state foliation (Means, 1981; Lister and Snoke, 1984)), and the stretching lineation (Ls) lies at the intersection of S and the $\lambda_1\lambda_3$ plane.

A key task in the kinematic interpretation of many high-strain zones is to determine their shear directions. Traditionally this is done using Ls fabrics which are assumed to indicate the 'transport' (more precisely 'shear') direction and thus to have a kinematic significance similar to that of Lc. However, this long-held assumption is based on the simple shear model (Ramsay and Graham, 1970; Ramsay, 1980), and recent developments in the study of high-strain zones show that it is not generally applicable to general high-strain zones such as transpressional and transtensional zones. This is especially true in high-strain zones with a triclinic flow geometry where the relationship between stretching lineations and shear directions is more complex (see below). On the other hand, the ductile slickenside striations (Lc) form parallel to the local shear direction (see later discussion). Therefore, Lc may be very useful for kinematic interpretation of high-strain zones and it is important to differentiate Lc from Ls.

Although both S- and C-surfaces are commonly present in high-strain zones, Lc data are much less commonly reported than Ls data (for examples see Berthé et al., 1979; Lin and Williams, 1992a and references therein; Lin et al., 1998). Our experience is that Lc fabrics are much more common than reported in the literature. It is likely that many field geologists do not differentiate the two types of lineations, because of either a lack of appreciation of the importance or the difficulty of doing so. Both types of lineations may have been simply reported as "stretching lineations".

In this paper, we first review the recent development in the study of high-strain zones, emphasizing the difficulty of using stretching lineations to infer the shear direction. We then discuss how to distinguish Lc from Ls. Finally, we present a description of a natural high-strain zone and show how differentiating the two types of lineations can lead to recognition of new phenomena as well as kinematic insights into a high-strain zone.

2. Kinematic frameworks of high-strain zones

Fig. 2a–c shows the general flow geometry ("movement picture" of Turner and Weiss, 1963) of *a domain* in a high-strain zone undergoing a flow with both a boundary-parallel simple shear component and a boundary-normal pure shear component. The shear strain rate is represented by $\dot{\gamma}$, and the pure shear component has three principal strain rates $\dot{\varepsilon}_a, \dot{\varepsilon}_b$, and $\dot{\varepsilon}_c$. The shear direction makes an angle φ with the $\dot{\varepsilon}_a$ direction (Fig. 2c; Jiang and Williams, 1998; Lin et al., 1998). These parameters can vary from one domain to another. If $\dot{\varepsilon}_a = \dot{\varepsilon}_b = \dot{\varepsilon}_c = 0$, the deformation of the domain is simple shear (Fig. 2d). Otherwise it is a general shear (a thinning zone if $\dot{\varepsilon}_b < 0$, and a thickening zone if $\dot{\varepsilon}_b > 0$; Jiang and Williams, 1998). In the general shear case, if $\varphi = 0$ or 90° or $\dot{\varepsilon}_a = \dot{\varepsilon}_c$, the flow geometry is reduced to monoclinic symmetry (Fig. 2e); otherwise, it has triclinic symmetry (Fig. 2c). The flow geometry of simple shear also has monoclinic symmetry. It should be noted that simple shear and pure shear are independent components and the cases of $\varphi = 0°$ or 90°, or $\dot{\varepsilon}_a = \dot{\varepsilon}_c$ are probably rare. Therefore, the flow geometry of general shear is expected to be generally triclinic, as concluded by Lin et al. (1998) and Jiang and Williams (1998) as a result of theoretical modeling and examination of natural examples (see also Jiang et al., 2001; Lin and Jiang, 2001). A special case not discussed here is pure shear ($\dot{\gamma} = 0$), where the flow geometry has orthorhombic symmetry.

3. Foliation (S) and stretching lineation (Ls) patterns in high-strain zones: model predictions

In recent years, significant progress has been made in theoretical modeling of high-strain zones. A major effort has been made to predict the foliation (S-surface) and stretching lineation (Ls) patterns in various kinematic types of high-strain zones, assuming that the S-surface is parallel to the local $\lambda_1\lambda_2$ plane and the Ls is parallel to the λ_1 direction (e.g. Sanderson and Marchini, 1984; Fossen and Tikoff, 1993; Fossen et al., 1994; Robin and Cruden, 1994; Dutton, 1997; Jones et al., 1997; Passchier, 1997, 1998; Jiang and Williams, 1998; Jones and Holdsworth, 1998; Lin et al., 1998; Teyssier and Tikoff, 1999; Jiang et al., 2001; Czeck and Hudleston, 2003; Bailey et al., 2004; Jones et al., 2004).

Theoretical modeling has shown that the symmetry of the S/Ls fabric (*strain geometry*) in a high-strain zone corresponds to that of the *flow geometry*, so long as the latter does not change during deformation (i.e. the flow is steady) (Fig. 2f–h). In simple shear high-strain zones, Ls and poles to S all plot parallel to the vorticity-normal section (VNS) – the section parallel to the shear direction and perpendicular to the shear zone boundary, which is also the symmetry plane (Fig. 2g). In monoclinic transpressional or transtensional zones, they either plot parallel to the VNS or parallel to the vorticity vector, and the VNS is still the symmetry plane (Fig. 2h). In triclinic high-strain zones, Ls varies continuously between the VNS and the vorticity vector and there is no symmetry plane, as illustrated in Fig. 2f by means of a transpressional example where $\dot{\varepsilon}_b = -\dot{\varepsilon}_c$, $\dot{\varepsilon}_a = 0$, and $\varphi = 20°$. It should be noted that apparent monoclinic strain geometry can potentially occur in domains within a high-strain zone with a triclinic flow geometry where the $\dot{\gamma}/\dot{\varepsilon}_b$ ratio is high and the finite strain is below a certain value (see Lin et al., 1998). On the other hand, perfectly monoclinic transpression (or transtension) without even infinitesimal perturbations is rare in nature, if it occurs at all, and the "lineation switch" (from horizontal to vertical when the strain increases to a critical value), theoretically predicted for transcurrent transpression (Fig. 2h; Fossen and Tikoff, 1993; Tikoff and Greene, 1997), is unlikely to be common in natural high-strain zones (Jiang, 2005). Jiang (2005) demonstrated that even an infinitesimally small deviation from the perfect condition of monoclinic symmetry would lead the λ_1-axis (the "lineation") to rotate progressively, rather than "switching" instantaneously, from horizontal to vertical as strain increases.

3.1. Variation in orientation of stretching lineations and deformation path partitioning in transpressional zones

Variation in the orientation of Ls in a transpressional high-strain zone can be due to any of the following:

(1) *Variation in the simple shear/pure shear ratio:* As emphasized and discussed by Lin et al. (1998) and Williams et al. (2006), simple shear tends to be localized and pure shear tends to be widely distributed (see also Tikoff and Teyssier, 1994; Jones and Tanner, 1995). The result is that the simple shear/pure shear ratio generally varies across a high-strain zone, a phenomenon referred to as deformation path partitioning by Lin et al. (1999). As is evident from Fig. 2f–h (in particular Fig. 2f), such variation can lead to significant variation in the orientation of Ls. This is further discussed below.
(2) *Variation in strain:* Strain in high-strain zones is generally heterogeneous, and it is well known that the orientation of Ls can vary with strain. This is most evident in triclinic high-strain zones (e.g. Fig. 2f), but also occurs in monoclinic transpressional and transtensional shear zones

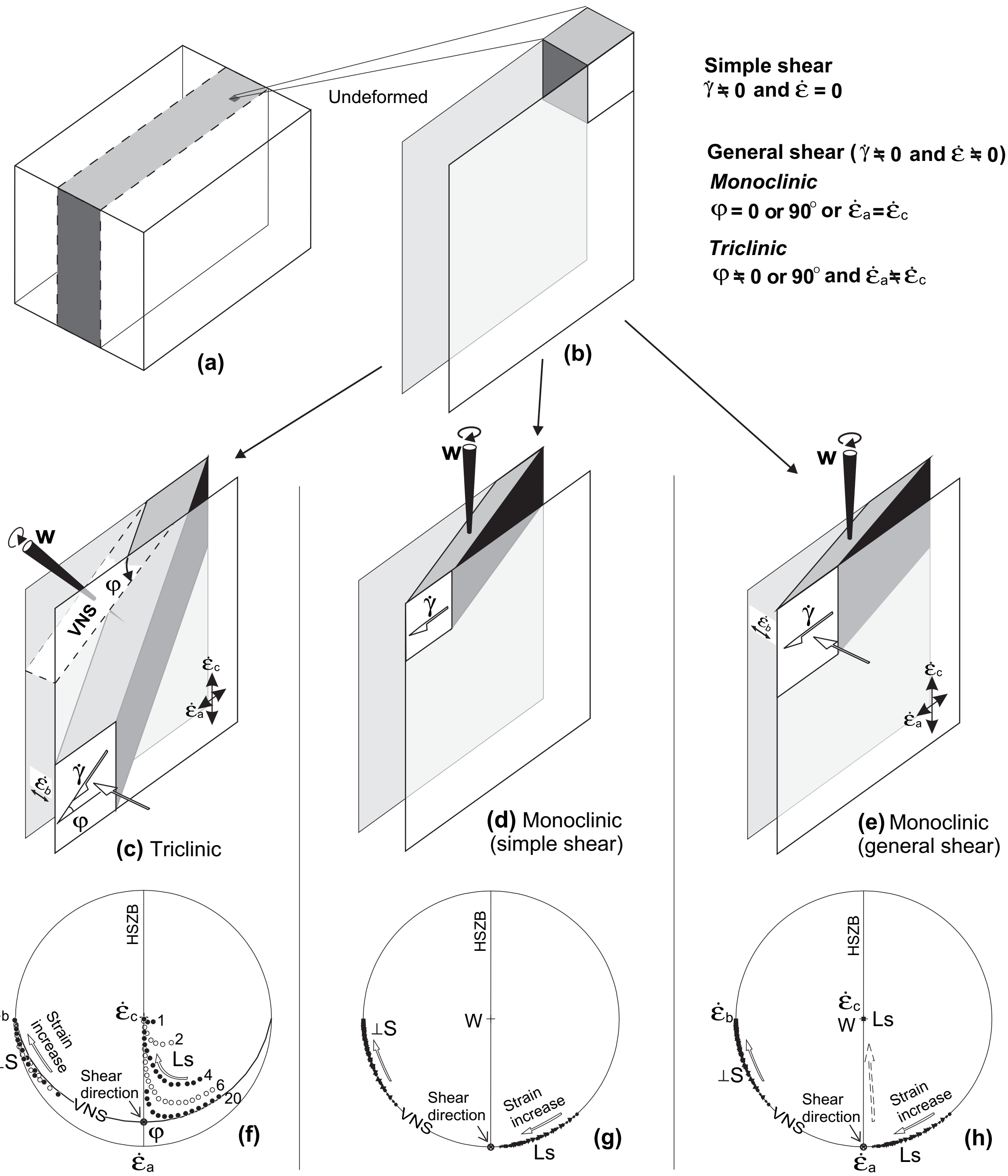

Fig. 2. Flow geometries of high-strain zones and resulting strain patterns (modified from Lin et al., 1998 and Jiang and Williams, 1998). (a) A high-strain zone; and (b) a domain in the zone in the initial (undeformed) state. (c) The domain in the final (deformed) state resulting from triclinic transpression ($0° < \varphi < 90°$), with both a boundary-parallel simple shear component and a boundary-normal pure shear component. $\dot{\gamma}$: shear strain rate; $\dot{\varepsilon}_a$, $\dot{\varepsilon}_b$ and $\dot{\varepsilon}_c$: the three principal components of the pure shear; φ: the angle between the shear direction and the $\dot{\varepsilon}_a$ direction; **W**: vorticity; VNS: vorticity-normal section (the section parallel to the shear direction and perpendicular to the shear zone boundary). (d) The domain in the final state resulting from simple shear, with monoclinic symmetry. (e) The domain in the final state resulting from a monoclinic transpression ($\varphi = 0°$). Other monoclinic situations (not shown) are $\varphi = 90°$ and $\dot{\varepsilon}_a = \dot{\varepsilon}_c$. (f)–(h) Equal-area lower-hemisphere projections showing variation and evolution with time of stretching lineations (Ls, subparallel to λ_1) and poles to S-foliations (⊥S, subparallel to λ_3) in an isochoric transpressional shear zone with constant strike length ($\dot{\varepsilon}_a = 0$) (from Lin et al., 1998). (f) Triclinic transpression ($\varphi = 20°$). Numerals 1, 2, 4, 6 and 20 are values of $\dot{\gamma}/\dot{\varepsilon}_b$ ratio. (g) Simple shear, with monoclinic symmetry. (h) Monoclinic transpression ($\varphi = 0°$). HSZB: high-strain zone boundary. White arrows indicate the evolution with time (increasing finite strain) for different $\dot{\gamma}/\dot{\varepsilon}_b$'s. The dashed white arrow in (h) indicates "switch" of orientation of stretching lineations from horizontal to vertical.

(e.g. Fig. 2h), and even in zones of simple shear (e.g. Lin and Williams, 1992b).

(3) *Variation in angle* φ: Lineation orientation varies with the φ value which is evident from figures 8–11 of Jiang and Williams (1998) and figure 9 of Lin et al. (1998). The variation in φ can be due to variation in shear direction and/or variation in orientation of $\dot{\varepsilon}_a$, both of which can occur within a single high-strain zone. The latter has been discussed by Czeck and Hudleston (2003, 2004). The former is discussed later in this paper with an example.

Fig. 3 illustrates a model for the distribution, localization and partitioning of deformation across a high-strain zone, based on theoretical considerations discussed above (see also Lin et al., 1998; Williams et al., 2006) and field observations, and illustrated with an example of a vertical triclinic transpressional zone of $\dot{\varepsilon}_b = -\dot{\varepsilon}_c, \dot{\varepsilon}_a = 0$ and $\varphi = 20°$. The main features of the model are: (1) pure shear is distributed over a broader region whereas simple shear is localized into a narrower high-strain zone; and (2) the resulting simple shear/pure shear ratio varies significantly across the zone. In the central domain, the $\dot{\gamma}/\dot{\varepsilon}_b$ ratio is high, so that the deformation may approach simple shear and Ls plunges shallowly (Fig. 3b). Here the $\dot{\gamma}/\dot{\varepsilon}_b$ ratio may be so high that for the Ls to be steeply plunging or vertical, unrealistically high strain may be required (cf. Williams et al., 2006). In the marginal domain, the $\dot{\gamma}/\dot{\varepsilon}_b$ ratio is low and Ls plunges steeply to vertically (Fig. 3b). In the transitional domain, Ls may vary from moderately to steeply plunging to vertical. The plunge of lineations thus varies across the zone. The variation can be continuous, as observed in the Roper Lake shear zone (Lin et al., 1998) and the Southern Knee Lake shear zone (Lin and Jiang, 2001). It should be noted that simple shear can be localized into a single high-strain zone (e.g. in the Roper Lake shear zone; Lin et al., 1998) or into a set or multiple sets of zones (see Figure 13 of Lin et al., 1998), and such partitioning can occur from sample scale (e.g., between C-zones and S-domains in Fig. 1) to orogen scale (Figure 13 of Lin et al., 1998). We believe that the geometry and kinematics of the White Mountain shear zone as described by Sullivan and

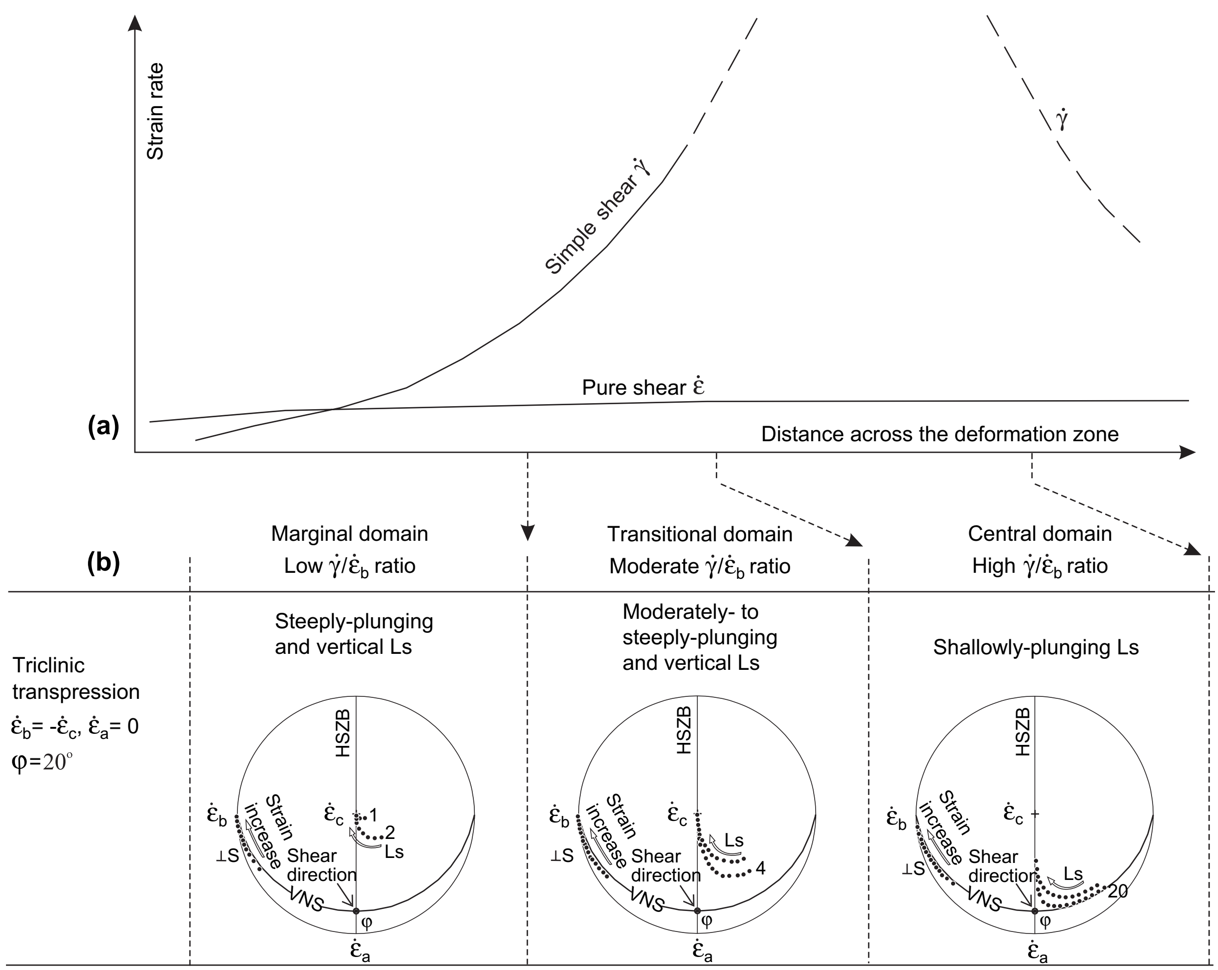

Fig. 3. (a) Schematic diagram showing the distribution, localization and partitioning of deformation across part of a transpressional high-strain zone. The boundary-normal motion results in crustal shortening and thickening (pure shear) which is distributed over a wide region and is not significantly localized. The boundary-parallel motion resulting in simple shear ($\dot{\gamma}$) is localized into the narrow high-strain zone. The simple shear/pure shear ratio varies significantly across the zone. (b) Equal-area lower-hemisphere projections showing varying Ls patterns across a triclinic transpressional zone (with $\dot{\varepsilon}_b = -\dot{\varepsilon}_c$ and $\dot{\varepsilon}_a = 0$, and $\varphi = 20°$), corresponding to varying simple shear to pure shear ratio shown in (a). HSZB: high-strain zone boundary. White arrows indicate increasing finite strain. Numerals 1, 2, 4 and 20 are values of $\dot{\gamma}/\dot{\varepsilon}_b$ ratio.

Law (2007) is consistent with the triclinic model described here, with their simple shear-dominated and pure shear-dominated domains being equivalents of the central and the marginal domains, respectively, as described here and in Lin et al. (1998, for the Roper Lake shear zone).

It should be emphasized that partitioning of deformation as shown in Fig. 3a is probably a general phenomenon. In cases like this, *the overall strain geometry of a high-strain zone (in particular its potential triclinicity) can only be fully understood when structures in the different domains are considered together*.

3.2. Relationship between orientation of stretching lineations and shear direction

The above review shows that the relationship between the orientation of stretching lineations and the shear direction of a high-strain zone is not straightforward; significant variation in the orientation of stretching lineations can occur even in a high-strain zone with a constant shear direction and, in some cases, the shear direction can vary across the zone. Therefore, it is generally difficult to use the orientation of stretching lineations to infer the shear direction, unless it can somehow be demonstrated that the *flow geometry* of the high-strain zone concerned has monoclinic symmetry. In the latter case, the shear direction is parallel to the orthogonal projection of the stretching lineation on the high-strain zone boundary, i.e. the intersection of the symmetry plane and the zone boundary (Lin and Williams, 1992b).

An important inference from the discussion of the localization of the simple shear component (Fig. 3) is that where the shear strain is high (e.g., at the centre of many high-strain zones), the deformation is probably close to simple shear. In addition, if the orientation of the stretching lineation is more or less constant across a high-strain zone, or poles to the S-foliation (and the high-strain zone boundary, if known) and the stretching lineation define a great-circle (girdle), as discussed in Lin and Williams (1992b), it is likely that either the deformation is close to simple shear or, in the case of general shear, the shear direction is subparallel to the principal stretching direction ($\dot{\varepsilon}_a$) of the flow and the flow geometry is of monoclinic symmetry. In this case, it is important that data from both the high-strain domains near the centre and the low-strain domains near the margins are considered together. In both cases, the shear direction may be inferred from the orientation of the stretching lineation by the method of Lin and Williams (1992b). In any case, caution is needed when the stretching lineation is used to infer the shear direction, and the shear direction thus inferred should be tested independently, where possible, e.g., by using the ductile striations discussed below.

4. Differentiation of ductile slickenside striations (Lc) from stretching lineations (Ls)

As discussed above, it is generally difficult to use the orientation of stretching lineations to determine the shear direction. Kuiper et al. (in press) demonstrated that the relationship between the orientation of sheath folds and the shear direction is also a complicated one. In contrast, striations on C-surfaces (Lc) are parallel to the shear direction at the time of formation and, if not modified by subsequent rotation, give a reliable shear direction. Therefore, in the kinematic interpretation of high-strain zones, it is useful to recognize Lc and differentiate it from Ls.

Differentiation between Lc and Ls is often possible, if given special attention. The S-foliation and the lineation lying in its surface (Ls) are defined by deformed markers such as ellipsoidal grains, mineral aggregates or pebbles. In contrast, the C-surfaces are shear surfaces or more commonly narrow (typically only a few grains wide) shear zones. The zones are generally finer-grained than the intervening S domains (Fig. 1a) and fine-grained layer silicates (e.g., micas), if present, commonly occur as thin layers along the centres of the C-zones (Fig. 4e; see also Lin and Williams, 1992a, Fig. 3). The zones are a product of strain localization and they have undergone a greater shear strain than adjacent S domains. C-surfaces (zones) are typically curvi-planar (Lin and Williams, 1992a) and S-surfaces in the intervening S domains are inclined to C and curve between adjacent C-zones (Fig. 1). C-surfaces (zones) are thus more discrete and more continuous than S-surfaces. Due to these features, C is weaker and easier to part along and thus outcrop surfaces are more likely parallel to C than S. Because of the larger shear strain and resultant stronger fabric and finer grain size, surfaces exposed parallel to C are commonly smooth and shiny and have the appearances of slickensides. The striations on such surfaces (ductile slickensides) are often of the "ridge-in-groove" type (Fig. 4a–d), reflecting the curviplanar feature of the C-surfaces (zones) (see Lin and Williams, 1992a, for a more detailed description and interpretation of such striations). The above features of C-surfaces (zones) are best known in the type of S-C mylonites described by Berthé et al. (1979) and Lin and Williams (1992a), which are developed in previously isotropic and medium-grained granites. They are also present in other rock types and can be used to help to differentiate C-surfaces from S-surfaces even in situations where only one foliation is well developed (Fig. 4d,e).

A C-zone being a micro-scale shear zone itself, the fabric within it can be essentially the same as that within the S-domain, with a shape foliation and stretching lineation. But due to concentration of shear strain, the deformation within the C zones is practically a simple shear (see above). Therefore, if the shape foliation is subparallel to the C-foliation at high shear strains, the stretching lineation within the C-zone is expected to be subparallel to the shear direction. The fine, second-order linear features on exposed C-surfaces (developed on the first-order ridges and grooves; Lin and Williams, 1992a, p. 316) can be traces of the stretching lineation and/or second-order ridges and grooves (Fig. 1). Because they are both subparallel to the shear direction, their differentiation is not essential for the current purpose.

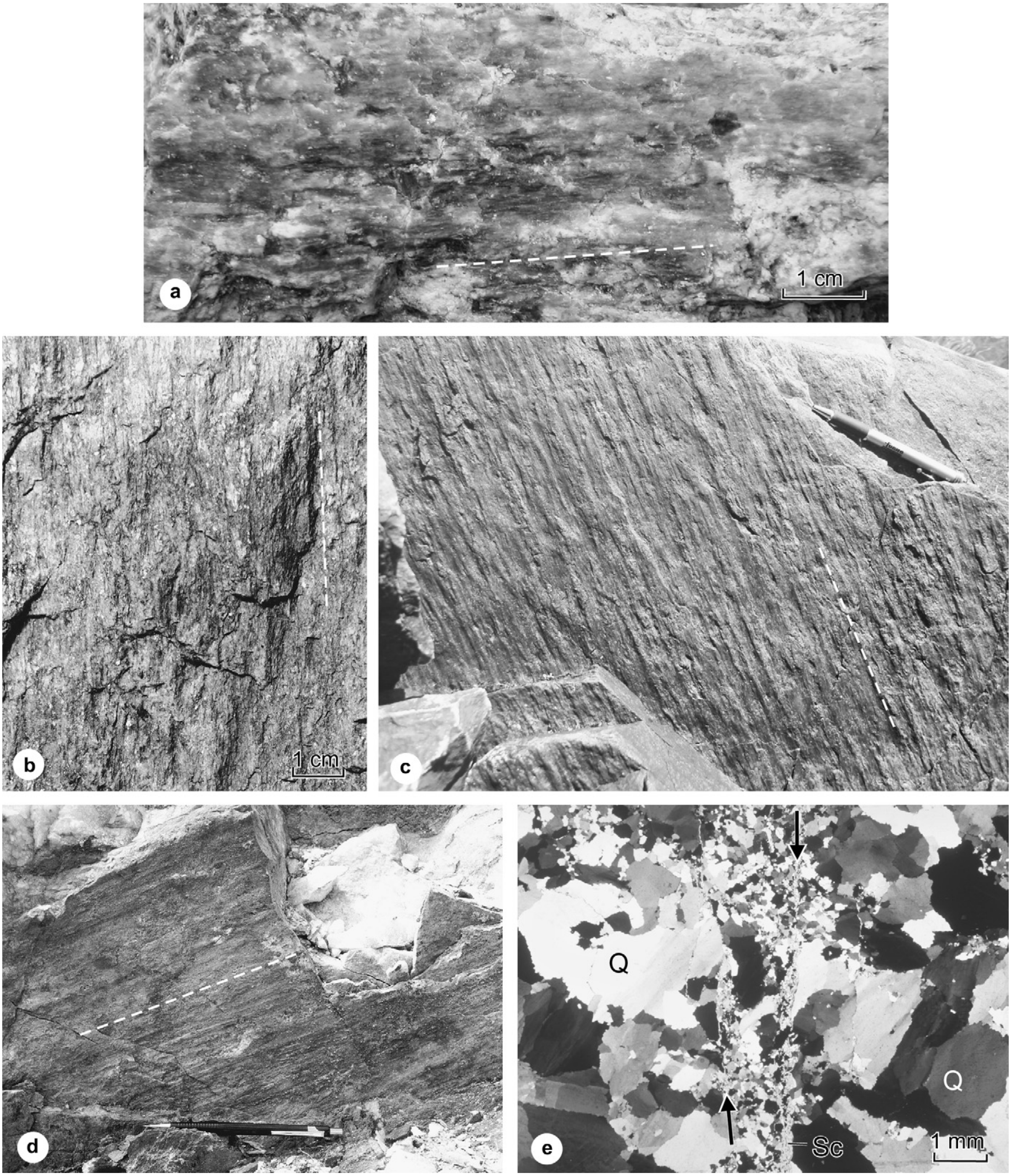

Fig. 4. Examples of ridge-in-groove-type striations on exposed C-surfaces (ductile slickensides) from: (a) a deformed granite in the South Armorican shear zone (cf. Berthé et al., 1979); (b) a deformed granite in the Roper Lake shear zone in the Canadian Appalachians (from Lin and Williams, 1992a); (c) a deformed granite from a shear zone along the northern margin of the Pukaskwa intrusive complex in the Superior craton, east shore of Lake Superior, Canada, and (d) a deformed quartz vein from a shear zone in the Superior Province, Canada (from Lin and Corfu, 2002). Both S and C-surfaces are well developed in rocks represented in (a), (b) and (c). Only C-surfaces are developed in rocks represented in (d). (e) Photomicrograph of the quartz vein shown in (d), showing the ductile deformation features. The section is parallel to the striations and perpendicular to the slickensides (C-surfaces). C-surfaces (arrowed) are zones of stronger ductile deformation. Note the concentration of sericite along the C-surfaces. Q: quartz; Sc: sericite.

4.1. Discussion

A potential complication in using striations to infer the shear direction is that the striations may rotate after their formation. Rotation can occur if the high-strain zone is overprinted by later deformation. This is not unique to the situation discussed here and is not considered further. Rotation can also occur if the host high-strain zone is undergoing significant boundary-parallel stretching synchronous with boundary-parallel shearing. In the case of a transpressional zone of $\dot{\varepsilon}_b = -\dot{\varepsilon}_c$ and $\dot{\varepsilon}_a = 0$, the rotation due to boundary stretching is given by $\tan(\varphi_f) = \exp(\dot{\varepsilon}_c t)\tan(\varphi_i)$, where φ_i and φ_f are the angles between the striation and the $\dot{\varepsilon}_a$ direction before and after rotation, respectively, $\dot{\varepsilon}_c$ is the strain rate, and t is time. φ_i is equal to φ in Fig. 2c. It is evident that rotation of striations only occurs in triclinic high-strain zones ($\varphi_i \neq 0$ or 90°) and is related to the pure shear component only. If rotation does occur and the striations are continuously being rotated away from the shear direction as they are being formed, no well-developed ridge-in-groove type striations are expected to occur. This is especially true for the ridge-in-groove type striations similar to those described by Lin and Williams (1992a), which are developed in previously isotropic, medium- to coarse-grained rocks (e.g., granite in the case of Lin and Williams, 1992a) and formation of which needs significant amount of finite strain. The latter is because well-developed C-surfaces, in which the curvi-planar/ridge-in-groove geometry is developed, only develop after significant amount of shear strain (Berthé et al., 1979). Therefore, well-developed ridge-in-groove type striations suggest that insignificant rotation has occurred and the striations are a reliable indicator of the shear direction.

C′-surfaces (shear bands), where present, may represent another potential complication. Differentiation between C and C′ surfaces is not always easy, but is often possible. C′-surfaces are oblique to the high-strain zone boundary and are not as continuous as C-surfaces. It is therefore not very likely that rocks will part along C′-surfaces as continuously as along C-surfaces. It should be noted that striations on C′-surfaces, if present, have kinematic significance similar to those on C-surfaces, in that they are parallel to the shear direction on the C′-surface.

5. Variation in orientation of ductile slickenside striations and shear direction across the Gods Lake Narrows high-strain zone

As an example of how differentiating Lc from Ls can be essential for sound kinematic interpretation of high-strain zones, the Gods Lake Narrows high-strain zone in the northwestern Superior craton of Canada is described.

5.1. General geological setting

The Superior craton, to a first approximation, consists of a series of east-west trending "subprovinces" of supracrustal rocks (greenstone belts) and granitoid rocks. It contains some of the best-preserved evidence for plate tectonics-like processes in the Archean being characterized by regional scale horizontal motion (drift) of "plates" or "microplates" ("horizontal tectonism" in Archean geology), and the subprovinces are interpreted as a series of microcontinents, remnant arcs, oceanic terranes and accretionary prisms (Percival et al., 2006, and references therein). The northwestern Superior craton is characterized by narrow greenstone belts surrounded and intruded by voluminous granitoid plutons (Fig. 5a). The plutons mostly occur in open domes whereas greenstones generally occur in narrow synclinal keels, a geometry recognized in many Archean cratons. Such a dome-and-keel geometry is commonly interpreted as a result of density inversion (Rayleigh-Taylor-type instabilities), inherent between denser volcanic sequences (greenstones) and underlying less dense sialic material (granitoids), which leads to buoyant rising of granitoids (diapirism) and sinking of greenstones (sagduction) ("vertical tectonism" in Archean geology; Lin, 2005, and references therein).

Also occurring in the northwestern Superior craton are approximately east-southeast-trending high-strain zones (Fig. 5a). These regional scale high-strain zones are spatially coincident with narrow greenstone belts and have oblique slip. The strike-slip component is consistently dextral and is a result of the regional scale horizontal motion or the plate tectonics-like processes mentioned above (Lin, 2005; Parmenter et al., 2006; and references therein). The dip-slip component is consistent in the sense that it always shows pluton-side-up/greenstone-side-down sense of shear and is a result of diapirism and sagduction as mentioned above (Lin, 2005; Parmenter et al., 2006). Lin (2005) and Parmenter et al. (2006) concluded that the geometry and kinematics of this part of the Superior craton is a result of synchronous (and potentially interactive) regional scale dextral horizontal shearing and diapirism/sagduction at the late stages of Neoarchean cratonization.

The Gods Lake Narrows high-strain zone described below is one of the approximately east-southeast-trending high-strain zones in the northwestern Superior craton. It is part of a major high-strain zone that separates the Oxford-Knee-Gods Lake greenstone belt to the north from granitoid intrusions (including gneisses) to the south (Fig. 5a,b). In the Gods Lake Narrows area of this study (Fig. 5b), the granitoid immediately south of the high-strain zone is an ca. 10 km-wide felsic gneiss complex. The supracrustal rocks north of the high-strain zone consist of three units: the ca. 2883 Ma Gods Lake group, the ca. 2720 Ma Gods Lake Narrows group and the ca. 2705 Ma Oxford Lake Group. The Gods Lake group here is predominantly massive and pillowed basalt with local felsic to intermediate volcanic rocks. The Gods Lake Narrows group consists of siltstone, sandstone, pebbly sandstone, polymictic conglomerate, and locally chert-magnetite iron formation, ironstone and argillite. The Oxford Lake Group is a sub-aerial sequence of polymictic conglomerate with sandstone lenses. It lies unconformably on the Gods Lake group, and the Gods Lake Narrows group is in sheared contact with it.

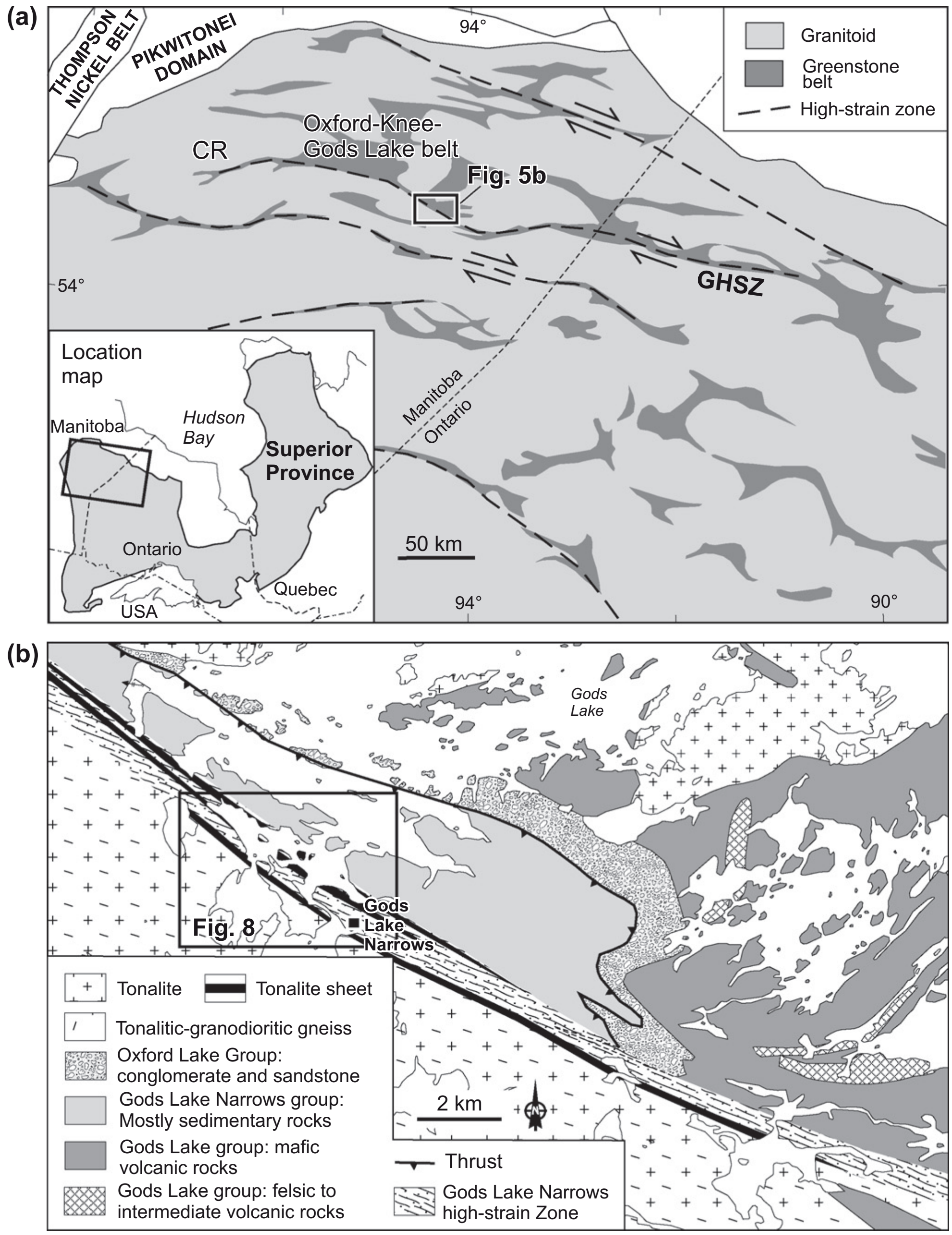

Fig. 5. (a) Map showing tectonic setting of the Gods Lake Narrows high-strain zone (GHSZ) in the northwestern Superior Province. CR: Carrot River greenstone belt. (b) Simplified geological map of the Gods Lake Narrows area.

5.2. Internal geometry and kinematics

In the Gods Lake Narrows high-strain zone, supracrustal rocks of the greenstone belt and numerous tonalite sheets (the 3 mappable ones are shown in Fig. 5b) are strongly deformed (Fig. 6a). In the Gods Lake Narrows area the mylonite zone associated with the high-strain zone is approximately 1 km wide.

Rocks in the high-strain zone are well foliated and mostly well lineated. Both S-foliations with Ls and C-foliations with Lc are present. Differentiation between S/Ls and C/Lc is commonly possible, using the method discussed above. Locally an S/Ls fabric is defined by deformed clasts (Fig. 6b). In the S-C mylonites, the rocks typically part along the C-surfaces, and striations of the ridge-in-groove type are well developed on the exposed surfaces (Fig. 7). Both the S- and C-foliations strike east-southeasterly and dip steeply to the south-southwest, and the stretching lineations and the striations vary from subhorizontal to moderately plunging (Fig. 8). Well-developed shear sense indicators, such as S-C/S-C′ structures and drag folds (or modified buckle folds; cf. Williams et al., 2006), indicate dextral movement with a south-over-north (i.e. pluton-side-up/greenstone-side-down) dip-slip component (Fig. 6b–e). A Dextral sense of shear is also evident from the regional map pattern seen in Fig. 5b

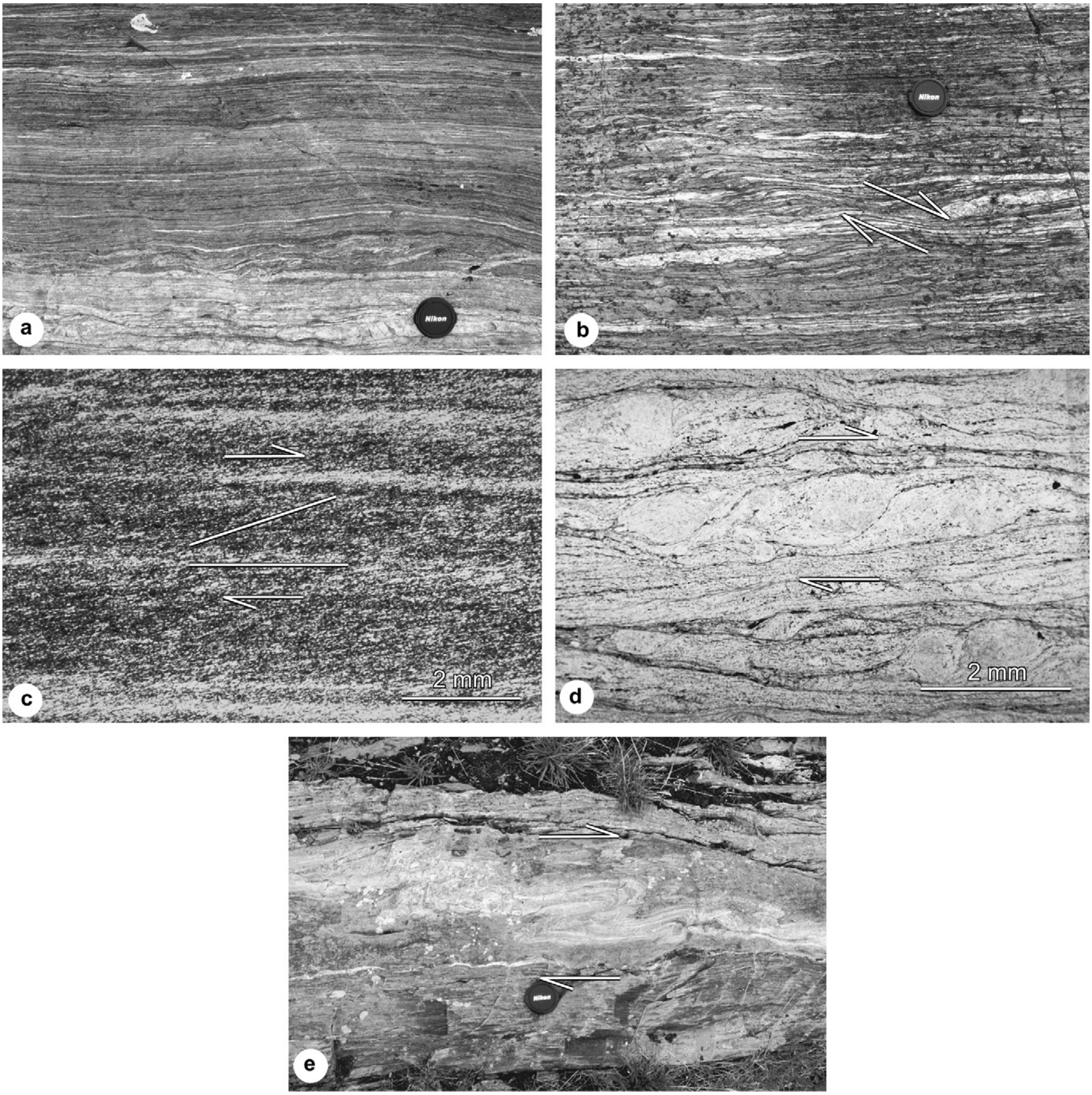

Fig. 6. Field photos and photomicrographs from the Gods Lake Narrows high-strain zone. (a) Extremely deformed rock (mylonite). (b) Deformed conglomerate. The deformed clasts define the local S-foliation and stretching lineation. Note the shear band (C′) indicating dextral shear. (c) A quartz mylonite with C and S domains and an oblique shape fabric in the S domains indicating dextral shear. Cross nicols. (d) S-C structure in deformed tonalite indicating dextral shear. Plane light. (e) Drag folds or modified buckle folds indicating dextral shearing. All surfaces are approximately horizontal.

(e.g., the Z-fold defined by the geometry of the Oxford Lake Group, and the ‘‘drag’’ shown by the geometry of the felsic-intermediate volcanic rocks in the Gods Lake group).

The ridge-in-groove type striations in the Gods Lake Narrows high-strain zone are subhorizontal to shallowly plunging near the northern margin of the zone, and their plunges gradually increase to moderately plunging near the southern margin of the zone (Figs. 7 and 8). The data indicate that the shear direction of the high-strain zone varies gradually from subhorizontal to moderately plunging from the northern to the southern margin of the zone.

In the Gods Lake Narrows high-strain zone, the striations and the stretching lineations have similar orientations, and both vary across the zone in a similar pattern. It should be emphasized that such similarity in the orientation of the two types of lineations does not in any way diminish the importance of differentiating the two. If the two types of lineations were not differentiated and both were mapped simply

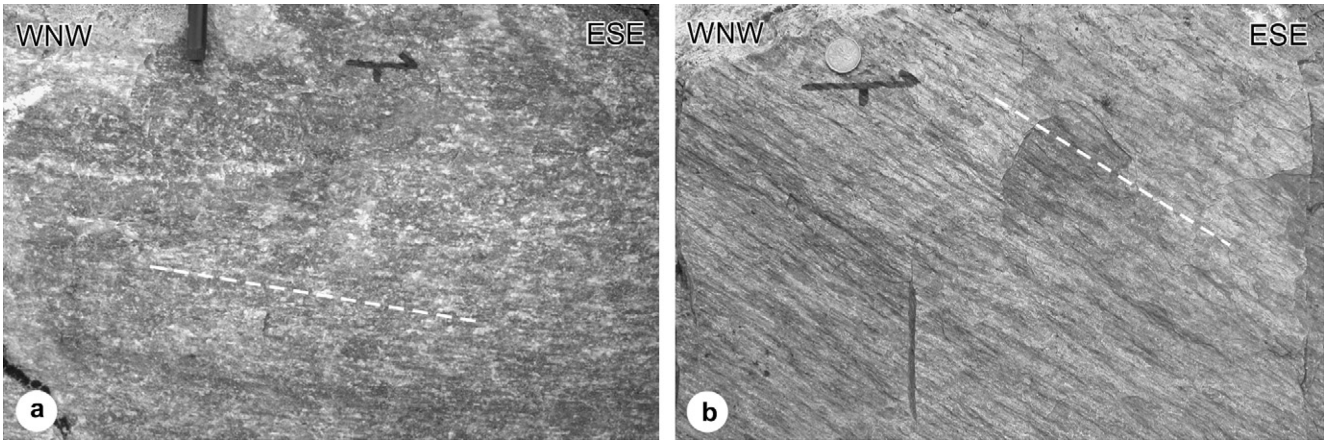

Fig. 7. Two examples of ridge-in-groove type slickenside striations from the Gods Lake Narrows high-strain zone. They plunge shallowly in (a) and moderately in (b). Both surfaces dip steeply to the south-southwest. Pen in (a) and coin in (b) for scale.

as the stretching lineation, the variation in the orientation of shear direction across the zone might not be recognized because variation in the orientation of stretching lineations across a high-strain zone can occur in a zone with a constant shear direction, as discussed above (e.g., Figs. 2f and 3) and observed in the Roper Lake shear zone (Lin et al., 1998).

5.3. Discussion

In many natural high-strain zones, lineation plunges vary across the strike (e.g. Caron and Williams, 1988; Holdsworth, 1994; Goodwin and Williams, 1996; Lin et al., 1998; Jiang et al., 2001; Lin and Jiang, 2001; Czeck and Hudleston,

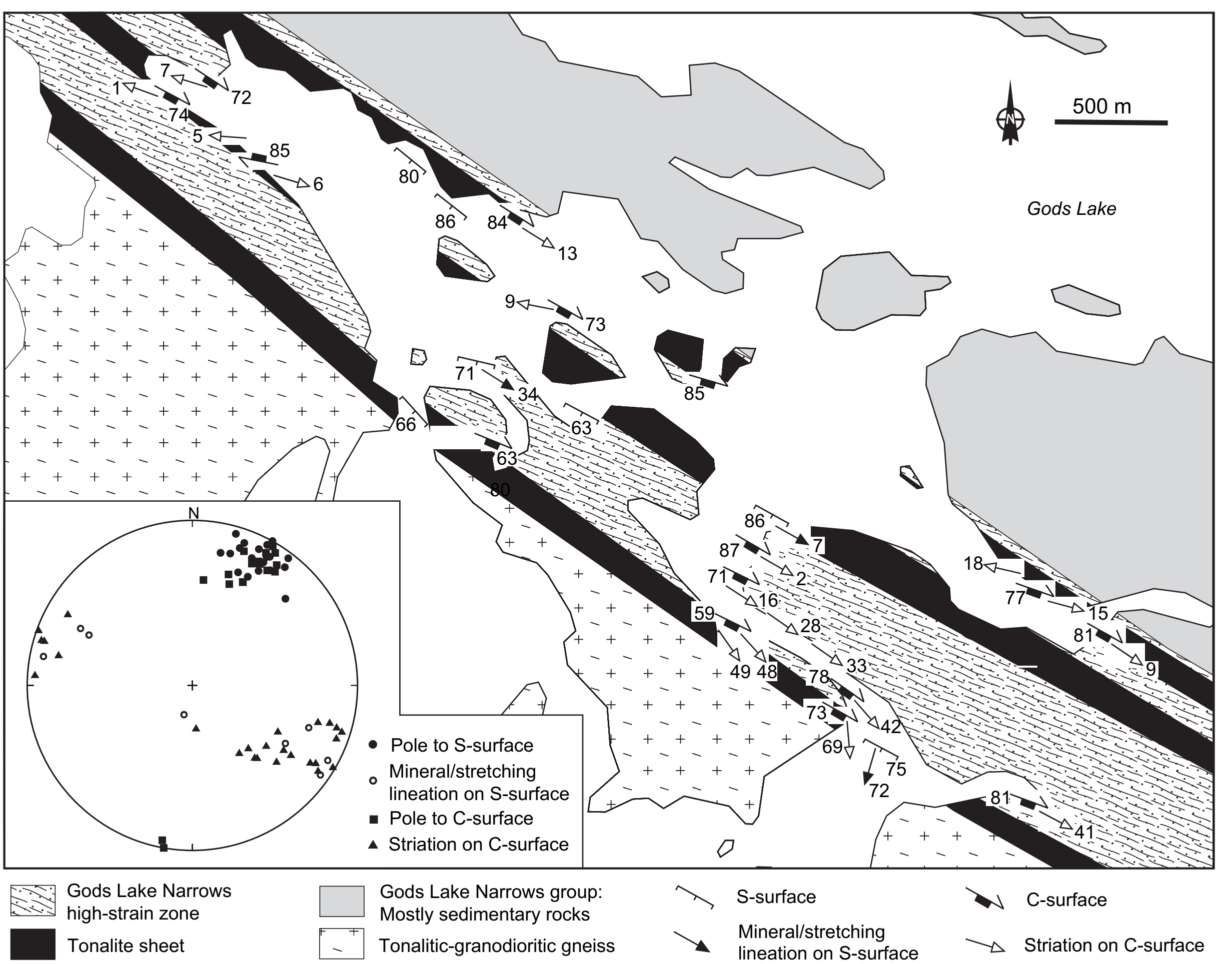

Fig. 8. A simplified structural-geology map of the Gods Lake Narrows area. Inset is an equal-area lower-hemisphere projection of structural data from the Gods Lake Narrows high-strain zone.

2003; Lin, 2005). In the Southern Knee Lake shear zone of Lin and Jiang (2001), they are true stretching lineations defined by the long axes of deformed clasts in conglomerates. The variation in plunge is interpreted as resulting from a triclinic flow geometry, presumably with a more or less constant shear direction across the zone, although the latter was not directly constrained due to the lack of striations. In the Roper Lake shear zone of Lin et al. (1998), stretching lineations and striations are both present and are differentiated. The striations and thus the shear direction do have a more or less constant orientation, indicating that the variation in the pitch of stretching lineations across the zone is probably due to a triclinic *flow geometry* although the local *strain geometry* can be approximately monoclinic, a situation similar to that shown in Fig. 3.

In the Gods Lake Narrows high-strain zone described here, the shear direction is defined by striations and its variation across the zone in unambiguous. The variation is gradual across the zone. This observation and the fact that there is no evidence for one shear direction overprinting another indicate that the variation is a result of a single generation of deformation. Such a variation indicates that the ratio of the strike-slip to the dip-slip component varies across the zone.

As discussed above, the high-strain zones in the northwestern Superior craton have been interpreted as having resulted from synchronous diapirism/sagduction and regional scale dextral horizontal shearing (Lin, 2005; Parmenter et al., 2006). More specifically, the Gods Lake Narrows high-strain zone is the eastern extension of a high-strain zone at Carrot River to the west (called the southeastern subzone of the Carrot River high-strain zone in Lin, 2005) (Fig. 5a) that has been interpreted as a product of such a synchronous process (see Lin, 2005 for detail). In such a scenario, the dip-slip and the strike-slip components are the results of two independent processes: diapirism/sagduction (due to density inversion) and regional scale horizontal shearing respectively. Although they occur synchronously in the same high-strain zone, they can be distributed differently across the zone, which readily explains the variation in the ratio of the strike-slip to the dip-slip component across the zone.

6. Concluding remarks

Striations (Lc) and stretching lineations (Ls) have different kinematic significance. Striations are parallel to the *in-situ* shear direction, whereas stretching lineations are approximately parallel to the maximum axis of the finite strain ellipsoid for at least a finite increment of strain. There is generally no simple relationship between the orientations of these two types of lineations. It is therefore essential for kinematic interpretation of high-strain zones to differentiate the two. The authors' experience indicates that ductile striations are probably much more common than reported in the literature. We ourselves have not always differentiated the two types of lineations. Their differentiation is not always easy, but is often possible if an attempt is made.

Acknowledgments

We all gratefully acknowledge financial support in the form of Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery grants for our work in general and financial and logistical support from the Manitoba Geological Survey and NSERC Lithoprobe for Lin's work on the Superior craton in Manitoba. We also gratefully acknowledge constructive reviews by Hideo Takagi and Pierre-Yves Robin.

References

Bailey, C.M., Francis, B.E., Fahrney, E.E., 2004. Strain and vorticity analysis of transpressional high-strain zones from the Virginia Piedmont, USA. In: Alsop, G., Holdsworth, R.E., McCaffrey, K.J.W., Hand, M. (Eds.), Flow Processes in Faults and Shear Zones. Geological Society, London, Special Publications, vol. 224, pp. 249–264.

Berthé, D., Choukroune, P., Jegouzo, P., 1979. Orthogneiss, mylonite and non coaxial deformation of granite: the example of the South Armorican shear zone. Journal of Structural Geology 1, 31–42.

Caron, A., Williams, P.F., 1988. The kinematic indicators of the Love Cove Group in the northeastern Newfoundland. Geological Association of Canada Program with abstracts 13, p. A17.

Czeck, D.M., Hudleston, P.J., 2003. Testing models for obliquely plunging lineations in transpression: a natural example and theoretical discussion. Journal of Structural Geology 25, 959–982.

Czeck, D.M., Hudleston, P.J., 2004. Physical experiments of vertical transpression with localized, nonvertical extrusion. Journal of Structural Geology 26, 573–581.

Dutton, B.J., 1997. Finite strains in transpression zones with no boundary slip. Journal of Structural Geology 19, 1189–1200.

Fossen, H., Tikoff, B., 1993. The deformation matrix for simultaneous simple shearing, pure shearing and volume change, and its application to transpression-transtension tectonics. Journal of Structural Geology 15, 413–422.

Fossen, H., Tikoff, B., Teyssier, C., 1994. Strain modeling of transpressional and transtensional deformation. Norsk Geologisk Tidsskrift 74, 134–145.

Goodwin, L.B., Williams, P.F., 1996. Deformation path partitioning within a transpressive shear zone, Marble Cove, Newfoundland. Journal of Structural Geology 18, 975–990.

Holdsworth, R.E., 1994. Structural evolution of the Gander-Avalon terrane boundary: a reactivated transpression zone in the NE Newfoundland Appalachians. Journal of the Geological Society, London 151, 629–646.

Jiang, D., 2005. Problems with transpression and transtension. Geological Association of Canada-Mineral Association of Canada Abstracts 30, p. 97.

Jiang, D., Williams, P.F., 1998. High-strain zones: a unified model. Journal of Structural Geology 20, 1105–1120.

Jiang, D., Lin, S., Williams, P.F., 2001. Deformation path in high-strain zones, with reference to slip partitioning in transpressional plate-boundary regions. Journal of Structural Geology 23, 991–1005.

Jones, R.R., Holdsworth, R.E., 1998. Oblique simple shear in transpression zones. In: Holdsworth, R.E., Strachran, R.A., Dewey, J.F. (Eds.), Continental Transpressional and Transtensional Tectonics. Geological Society, London, Special Publications, vol. 135, pp. 35–40.

Jones, R.R., Tanner, P.W.G., 1995. Strain partitioning in transpression zones. Journal of Structural Geology 17, 793–802.

Jones, R.R., Holdsworth, R.E., Baily, W., 1997. Lateral extrusion in transpression zones. Journal of Structural Geology 19, 1201–1217.

Jones, R.R., Holdsworth, R.E., Clegg, P., McCaffrey, K., Tavarnelli, E., 2004. Inclined transpression. Journal of Structural Geology 26, 1531–1548.

Kuiper, Y.D., Jiang, D., Lin, S. Relationship between non-cylindrical fold geometry and the shear direction in monoclinic and triclinic shear zones. Journal of Structural Geology, in press. doi:10.1016/j.jsg.2007.01.009.

Lin, S., 2005. Synchronous vertical and horizontal tectonism in the Archean: Kinematic evidence from a synclinal keel in the northwestern Superior Craton, Manitoba. Precambrian Research 139, 181–194.

Lin, S., Corfu, F., 2002. Structural setting and geochronology of auriferous quartz veins at the High Rock Island gold deposit, northwestern Superior Province, Manitoba, Canada. Economic Geology 97, 43–57.

Lin, S., Jiang, D., 2001. Using along-strike variation in strain and kinematics to define the movement direction of curved transpressional shear zones: an example from northwestern Superior Province, Manitoba. Geology 29, 767–770.

Lin, S., Williams, P.F., 1992a. The origin of ridge-in-groove slickenside striae and associated steps in an S-C mylonite. Journal of Structural Geology 14, 315–321.

Lin, S., Williams, P.F., 1992b. The geometrical relationship between the stretching lineation and the movement direction of shear zones. Journal of Structural Geology 14, 491–497.

Lin, S., Jiang, D., Williams, P.F., 1998. Transpression (or transtension) zones of triclinic symmetry: natural example and theoretical modeling. In: Holdsworth, R.E., Strachran, R.A., Dewey, J.F. (Eds.), Continental Transpressional and Transtensional Tectonics. Geological Society, London, Special Publications, vol. 135, pp. 41–57.

Lin, S., Jiang, D., Williams, P.F., 1999. Discussion on transpression and transtension zones. Journal of the Geological Society, London 156, 1045–1048.

Lister, G.S., Snoke, A.W., 1984. S-C mylonites. Journal of Structural Geology 6, 617–638.

Means, W.D., 1981. The concept of steady state foliation. Tectonophysics 78, 179–199.

Parmenter, A.C., Lin, S., Corkery, M.T., 2006. Structural evolution of the Cross Lake greenstone belt in the northwestern Superior Province, Manitoba: implications for relationship between vertical and horizontal tectonism. Canadian Journal of Earth Sciences 43, 767–787.

Passchier, C.W., 1997. The fabric attractor. Journal of Structural Geology 19, 113–127.

Passchier, C.W., 1998. Monoclinic model shear zones. Journal of Structural Geology 20, 1121–1137.

Percival, J.A., Sanborn-Barrie, M., Skulski, T., Stott, G.M., Helmstaedt, H., White, D.J., 2006. Tectonic evolution of the western Superior Province from NATMAP and Lithoprobe studies. Canadian Journal of Earth Sciences 43, 1085–1117.

Ramsay, J.G., 1980. Shear zone geometry: a review. Journal of Structural Geology 2, 83–89.

Ramsay, J.G., Graham, R.H., 1970. Strain variation in shear belts. Canadian Journal of Earth Sciences 7, 786–813.

Robin, P.-Y.F., Cruden, A.R., 1994. Strain and vorticity patterns in ideally ductile transpressional zones. Journal of Structural Geology 16, 447–466.

Sanderson, D.J., Marchini, W.R.D., 1984. Transpression. Journal of Structural Geology 6, 449–458.

Sullivan, W.A., Law, R.D., 2007. Deformation path partitioning within the transpressional White Mountain shear zone, California and Nevada. Journal of Structural Geology 29, 583–598.

Teyssier, C., Tikoff, B., 1999. Fabric stability in oblique convergence and divergence. Journal of Structural Geology 21, 969–974.

Tikoff, B., Greene, D., 1997. Stretching lineations in transpressional shear zones: An example from the Sierra Nevada Batholith, California. Journal of Structural Geology 19, 29–39.

Tikoff, B., Teyssier, C., 1994. Strain modeling of displacement-field partitioning in transpressional orogens. Journal of Structural Geology 16, 1575–1588.

Turner, F.J., Weiss, L.E., 1963. Structural Analysis of Metamorphic Tectonites. McGraw-Hill, New York, 545 p.

Williams, P.F., Jiang, D., Lin, S., 2006. Interpretation of deformation fabrics of infrastructure zone rocks in the context of channel flow and other tectonic models. In: Law, R., Searle, M., Godin, L. (Eds.), Channel Flow, Ductile Extrusion and Exhumation of Lower-mid Crust in Continental Collision Zones. Geological Society, London, Special Publications, vol. 268, pp. 221–235.