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An outline of shear-sense analysis in high-grade rocks

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Abstract

Ductile shear zones are important in tectonic reconstructions as a source of information on the relative motion of large crustal blocks or plates in the geological past. Methods to interpret fabric in ductile shear zones were mostly developed for low grade rocks where overprinting relations are usually well preserved. However, high grade shear zones are common and dominate in many Precambrian terrains. High grade shear zones should be analysed in a different way from low grade zones. The plane on which shear sense markers should be observed, the vorticity profile plane, is more difficult to find than in low grade shear zones. The most reliable shear sense markers in high grade shear zones are shear bands, mineral fish, mantled porphyroclasts, sigmoids and asymmetric boudins.

Keywords: High-grade rocks; Shear sense; Shear zone

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1. Introduction

Structural geology is the science of reconstructing the deformation history of rocks using geometries on the microscopic to kilometre-scale, which usually formed in the course of a long history and by complex deformation processes. Detailed analysis of all aspects of rock deformation is rarely possible from what is usually sparse data, but there is often much pressure on scientists to provide kinematic models for large-scale tectonic reconstructions. As a result, there is much misuse and over-interpretation of structural data and it is important to know where the limits of available methods are. Since the development of modern structural geology in the second half of the twentieth century, most studies on structures such as folds, lineations and shear criteria have focussed in low-grade metamorphic crustal rocks. This preference reflects the fact that such rocks provide the most spectacular geometries on a scale visible in outcrops or thin section and are, therefore, the most attractive subjects of structural research. As a consequence, the majority of published literature describes methods and interpretations derived from low-grade field examples. High-grade rocks on the other hand have been studied extensively in terms of metamorphic petrology and geochemistry, but less commonly from a structural point of view and few text books are concerned with their peculiarities. The main reason for this asymmetry is that high-grade rocks often lack clear fabric geometries, and are difficult to interpret. Many scientists have tried to simply extrapolate low-grade classic geometries to higher grade environments, but this may lead to erroneous results (Passchier et al., 1990). However, an understanding of high-grade rocks is fundamental for large scale tectonic interpretation of the Precambrian granulite terranes that occupy a large part of the Earth's surface. Shear zones in particular are amongst the more important structures in high-grade rocks as places of preferred accommodation of deformation and the relative movement between crustal blocks. This paper is a short guideline which reviews the use of shear sense indicators in high-grade shear zones, taking into account the idiosyncrasies of this tectonic environment.

2. Nature of flow conditions in high grade rocks

In the upper crust the partitioning of periodic ductile flow leads to inhomogeneous deformation of markers such as bedding, veins and older foliations. This produces well-known structures used for kinematic analysis such as folds, shear bands

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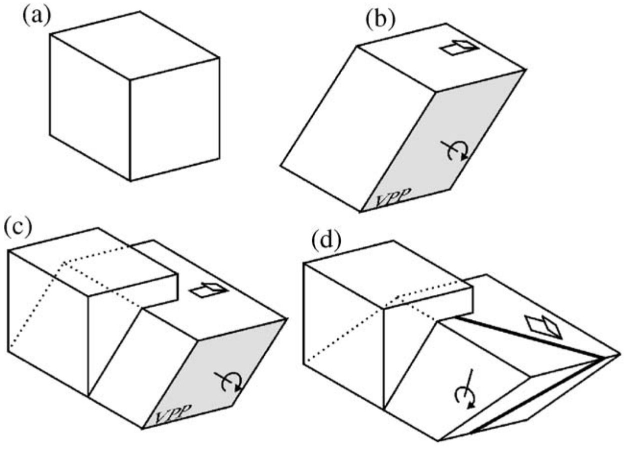

Fig. 1. The change in shape of a volume of rock (a) depends on ductile flow type. In non-coaxial flow this is defined by the vorticity vector, the vorticity profile plane (VPP) normal to this vector, and its orientation to stretching directions in the rock. Basic types of flow leading to changes in shape are (b) simple shear with no stretch in the plane of the shear zone; (c) general monoclinic flow with stretching directions parallel or normal to the vorticity vector and (d) triclinic flow, where the vorticity vector is oblique to stretching directions.

and boudins. Partitioning of flow also means that high and low strain domains develop and relicts of previous deformation events may be preserved in less deformed domains (Fig. 1). In other words, low grade deformed rocks are ideal to reconstruct tectonic history and kinematics. In high strain domains the geometry of flow is commonly influenced by the surrounding wall rock, which can be either rigid or slowly deforming. This restricts the number of possible flow geometries and commonly leads to flow conditions with high symmetry like simple shear or other monoclinic or even orthorhombic flow types (e.g. Jiang and Williams, 1998; Passchier, 1998; Fig. 1). The geometry of high-symmetry flow types is easy to describe, has been investigated in a large number of physical and numerical experiments, and tends to change little or predictably with time (Passchier, 1998; Tikoff and Fossen, 1999).

Flow in the deep crust affecting high grade rocks (HGR) may be partitioned less and on a larger scale than in the upper crust, probably because dislocation creep, diffusion creep and grain boundary migration are easier in most minerals under these conditions. In such cases, flow geometry is not restricted by weakly or non-deforming wall rocks. It can have a low symmetry (e.g. triclinic), can change significantly with time (Jiang and Williams, 1998; Lin et al., 1998; White and Mawer, 1992; Jiang et al., 2001) and can have wedge-shaped and complex geometries (Bird, 1991; Royden et al., 1997; Shen et al., 2001; Beaumont et al., 2001; Grujic et al., 2002; Searle and Szulc, 2005). Since high-grade rocks deform pervasively, domains where older structures can be preserved are few or absent, meaning that most of the archive recording evidence for earlier stages of the deformation process is lost. As an additional factor, high temperatures in the lower crust lead to static recrystallisation and partial melting that contribute to the overgrow and annihilation of small scale older features. Also, since grain size in these rocks is coarser than in the upper crust, deformation domains are wider and structures therefore tend to be larger in size. These factors imply that the structure in HGR is not easily studied in thin section or scanning electron microscope from isolated samples collected in the field. A single small outcrop of low grade slate can contain much of the information required for regional kinematic interpretation, but in a high grade terrain much larger outcrops or sets of outcrops are needed. Therefore, detailed field mapping of structures in an area of moderate to good outcrop is crucial for a correct analysis and interpretation of structures in high-grade rocks.

3. Fabric in high grade rocks

Foliations in HGR are usually associated with preferred orientation of individual planar minerals such as micas or hornblende (grain foliation; Fig. 2) or of mineral aggregates (aggregate foliation). Several foliations can be present as part of the fabric in a rock, usually inclined to other foliations at a small angle. Compositional layering, shape fabrics and mineral preferred orientations tend to dominate, while pressure solution cleavage and crenulation cleavage are rare or absent (Passchier et al., 1990).

Lineations are amongst the most important structures in HGR. There are two main groups of lineations (Piazolo and Passchier, 2002; Fig. 2): *trace lineations* such as intersection lineations between foliations and layering, and *object lineations*, which are built from discrete elongate volumes of material. Object lineations are the most important in HGR, as the only lineations that can easily be interpreted in a kinematic framework. Trace lineations can result from the intersection of random planes and therefore may have no intrinsic geological meaning. Thus, clear identification of relevant lineations is essential in any attempt of kinematic interpretation.

Object lineations (Piazolo and Passchier, 2002) can be subdivided into two types; *aggregate-* and *grain-lineations* (Fig. 2). Grain-lineations are defined as lineations formed by individual prolate single grains of a mineral species with similar long axis

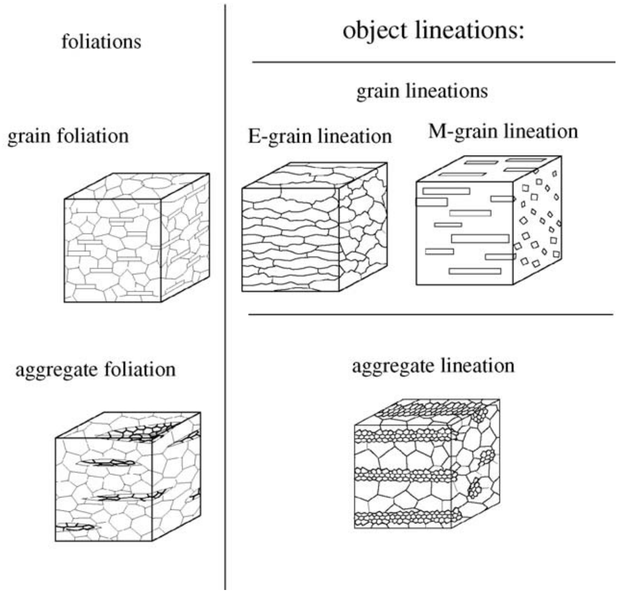

Fig. 2. Terminology used in this paper for common types of foliations and lineations in high grade rocks.

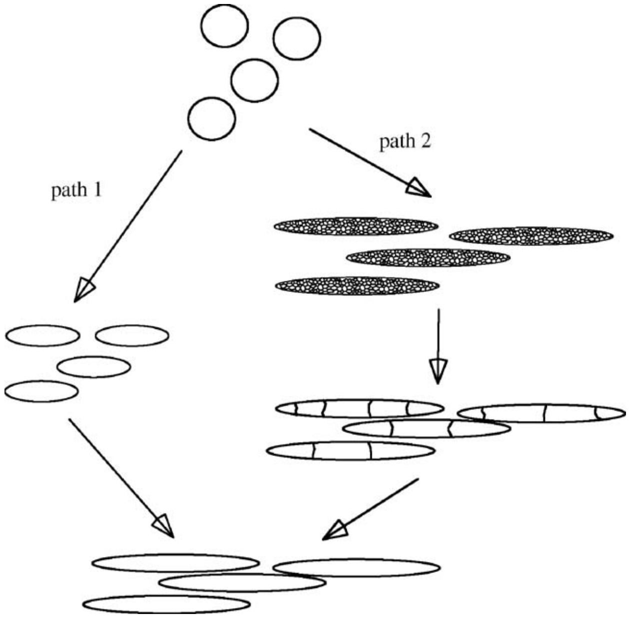

Fig. 3. Development of an E-grain lineation by two different paths. Stretching of grains by dislocation or diffusion creep can produce elongate monocrystalline ribbons (path 1) but this can also happen by deformation and dynamic recrystallisation to small grain size to form an aggregate lineation, which then evolves to an E-grain lineation by grain boundary migration (path 2).

orientation. This definition includes elongate deformed crystals of minerals that are normally equidimensional, e.g. long thin quartz and calcite grains (E-grain lineations), but also single undeformed crystals that present an elongate shape such as sillimanite, tourmaline and pyroxene (also known as mineral lineations or M-grain lineations; Fig. 2). Aggregate-lineations are defined by prolate aggregates of grains of the same or several different mineral species, in which individual grains have a smaller aspect ratio than the aggregate (Figs. 2 and 3). Aggregate lineations develop by deformation and dynamic recrystallisation of large single grains to a finer grain size (Piazolo and Passchier, 2002; Fig. 3). This implies that aggregate lineations can only develop if the original grain size of the rock exceeds the dynamically recrystallised grain size (Piazolo and Passchier, 2002). HGR usually have a large dynamically recrystallised grain size, probably because of low flow stress, and recrystallised grain size continues to increase after deformation at high temperature, a process known as static recrystallisation (Evans et al., 2001). As a result, aggregate lineations are second in importance to grain lineations in HGR and many highly strained rocks that lack grain lineations may seem undeformed (Piazolo and Passchier, 2002). M-grain lineations can develop by rotation of older single grains or new growth in a preferred orientation. In most cases, individual grains show typical crystal faces of the mineral involved. E-grain lineations can form by stretching of large individual grains without recrystallisation (Fig. 3), but in HGR they are more likely to develop from originally large grains by deformation, recrystallisation and subsequent static growth of one of the crystals until the whole aggregate consists of just one single grain (Hippertt et al., 2001; Fig. 3).

4. Identification of shear zones

Flow in lower crustal rocks can be extremely complex and lead to the development of large scale folds and domes, which can intersect and define interference patterns (e.g. Zhang et al., 1994; Dirks et al., 1997). Although such structures have an interest of their own, they are not likely to have been of major importance for large-scale tectonics, since they do not accommodate relative motion of major crustal fragments or plates. Ductile shear zones do accommodate such plate motion and are characterised by prolonged concentration of non-coaxial (rotational) flow in a relatively narrow planar domain. This means that within the shear zone, fabrics tend to be simpler and stronger than those found in the wall rock, lacking for instance complex folding, while the non-coaxial nature of the flow favours the development of highly asymmetric structures.

Major shear zones in high grade rocks can be recognised as domains with relatively uniform pervasive planar mylonitic foliations parallel or at a small angle to the shear zone boundary on scales up to hundreds of kilometres (Fig. 4). Although most shear zones are high strain zones, the amount of strain in itself is not a good criterion to identify a shear zone because bulk strain can be higher in the wall rock if it predates the shear zone; the shear zone can also represent only the first stages of deformation,

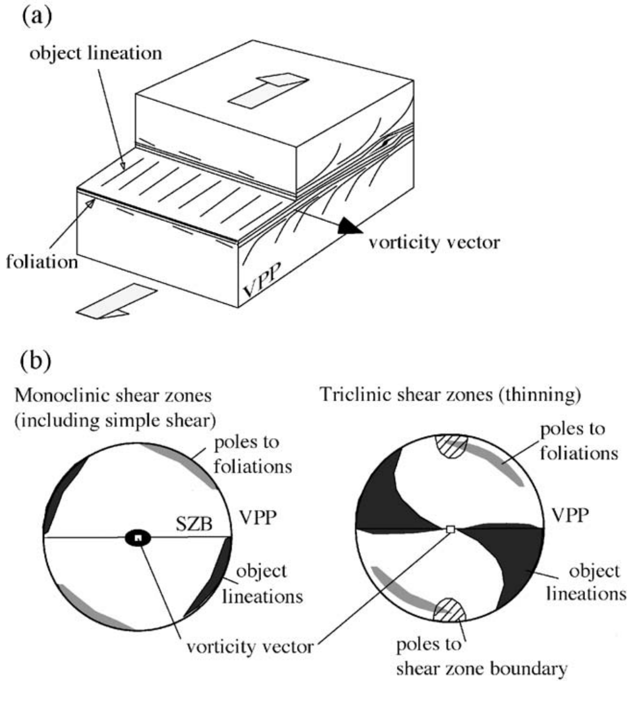

Fig. 4. (a) Block diagram showing the geometry of a ductile shear zone formed in simple shear with associated object lineation and foliation, and the flow vorticity vector. The vorticity profile plane (VPP) is normal to the vorticity vector (parallel to the lineation and normal to the foliation in the shear zone in this case); (b) stereograms illustrating how monoclinic and triclinic deformation histories in shear zones can be distinguished. A monoclinic shear zone has poles to foliations and to the shear zone boundary in or close to the VPP. Object lineations are parallel or, more rarely, normal to the VPP. Most (thinning) triclinic shear zones have poles to the foliation at a small angle to the VPP, but lineations in variable orientations, mostly highly oblique to the VPP in the dark grey domain.

with lower accommodated strain. Similarly, despite the fact that linear fabrics are a common feature in shear zones, presence of lineations is not an argument in favour of the identification of shear zones. The development of lineations is also heavily dependent on the characteristics of the undeformed rock and, therefore, is possible to have a high strain shear zone without any clear example of lineation (Piazolo and Passchier, 2002). Asymmetric structures, such as most shear sense indicators, are a common feature of high strain shear zones developed in strongly non-coaxial flows. However, certain types of flow or lithological characteristics may prevent the development of asymmetric objects, even in non-coaxial flow and therefore absence of asymmetry is not a rebuttal of the presence of shear zones.

5. Conditions of shear zone activity

The metamorphic conditions at which a ductile shear zone in a high grade terrain was active can be assessed from the minerals that are stable in the fabric, and the deformation behaviour of quartz, feldspars and other minerals in the rock. In low grade rocks, feldspar undergoes brittle deformation and develops core and mantle structures (Passchier and Trouw, 2005), Under high grade conditions both quartz and feldspar will deform by dislocation and diffusion creep, and develop homogeneous deformed elongate single crystals and ribbons or, more commonly, aggregates of recrystallised grains (Olesen, 1998; Lafrance and Scoates, 1996; Altenberger and Wilhelm, 2000; Rosenberg and Stünitz, 2003). Garnet shows ductile behaviour only at very high grade conditions (Ji and Martignole, 1994; Prior et al., 2000, 2002). Recrystallisation mechanisms and slip systems in quartz, feldspar and other minerals are also temperature dependent and can be used to assess metamorphic conditions during the deformation (Stipp et al., 2002; Passchier and Trouw, 2005). A review of quartz and feldspar microstructures, as well as other minerals typical for specific metamorphic grades, can be found in Passchier and Trouw (2005).

It is important to identify the conditions at which certain fabrics are formed because reactivation of shear zones is common in high grade rocks. This is due to the long periods of time required to uplift shear zones to the present day erosion level, during which the shear zone may have been continuously or intermittently active. In most cases, only parts or some branches of a shear zone system are reactivated (Fig. 5c,d); if fabric in these sections is misinterpreted to represent activity during the high grade stage of its motion, the overall large scale tectonic interpretation can be flawed (Fig. 5c). An example is the known presence of brittle fault rock like cataclasite and pseudotachylyte transecting older fabrics in high grade shear zones (Grocott,

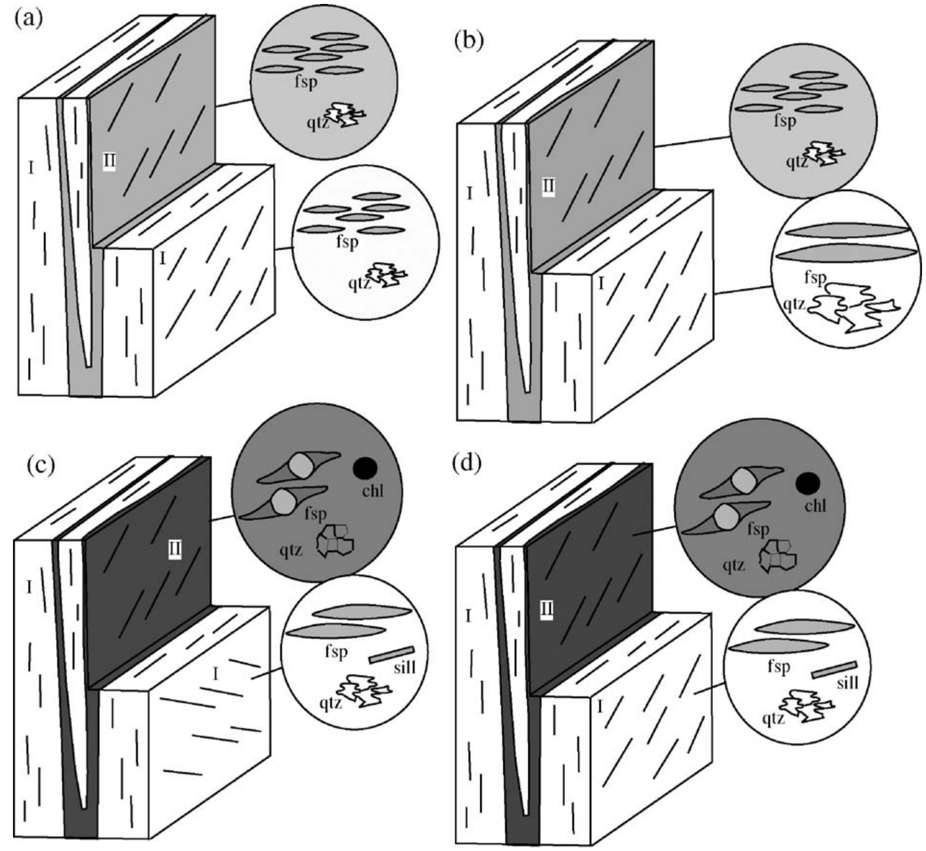

Fig. 5. Many shear zones in high grade rocks contain alternating domains of different fabric. This can be due to (a) two lithologies being deformed together at the same metamorphic grade; (b) one lithology being deformed locally more strongly then elsewhere, leading to smaller grain size; (c) one lithology being deformed first at high grade (I), the other at low grade (II), but in two different tectonic settings leading to two orientations of the object lineations; this situation is sometimes confused with triclinic flow; (d) as (c), but in one tectonic setting where shear direction did not change with a decrease in metamorphic grade; as a result, lineations are in the same direction in both domains.

1977; Scholz, 1988). In the most common scenario these structures develop late at upper crustal conditions, but pseudotachylyte can form occasionally at deep crustal level (e.g. Clarke and Norman, 1993; White, 2004). Analysis of mineral phases in the pseudotachylyte will reveal the real metamorphic conditions of its development.

6. Kinematic analysis of shear zones in high grade rocks

Shear zones with planar shape and bounded by little or non-deforming wall-rocks have a relatively simple flow geometry that is reflected in laterally uniform fabrics, which can be used for kinematic interpretations (Fig. 1). An essential characteristic of ductile shear zones is that wall rocks are displaced parallel to the shear zone boundary and that the magnitude of this displacement exceeds any stretching or shortening within the wall rocks. As a result, rocks in the shear zone are more strongly deformed and are affected by rotational or vortical flow, characterised by a vorticity vector (Figs. 1 and 4a). Because of the dominance of the shear motion, this vector will be parallel or close to parallel with the shear zone boundaries. The plane normal to this vorticity vector is known as the Vorticity Normal Surface (Jiang and Williams, 1998) or the Vorticity Profile Plane (VPP; Robin and Cruden, 1994; Passchier, 1998) and is usually normal or at a high angle to the shear zone boundary. The intersection of the VPP and the shear zone boundary represents the *shear direction*, the direction of motion of crustal blocks on both sides of the shear zone. If the directions of shortening and extension in the plane of the shear zone are parallel or normal to the VPP, the shear zone has monoclinic flow symmetry (Fig. 1c); if they are oblique, the symmetry is triclinic (Fig. 1d; Jiang and Williams, 1998). For the analysis of high grade shear zones it is necessary to identify the VPP, the shear direction and the shear sense from the rock fabric (Fig. 4b).

It is usually difficult to determine with certainty whether a shear zone segment operated by monoclinic or triclinic flow. Shear zones with approximately monoclinic symmetry are most reliable to interpret, and are discussed here. If the wall rock of a shear zone is undeformed, flow must have been simple shear and the VPP will be parallel to the object lineation and normal to foliations in the zone (Fig. 4a). The same applies if the wall rock is deformed before or after shear zone development. This can be recognised from overprinting relations, mineral dating, or by a different metamorphic grade of deformation in wall rock and shear zone. If the wall rock deformed at the same time as shear zone activity, a detailed analysis should be made of lineations and foliations in the shear zone and in the adjacent wall rock, and of the orientation of the shear zone boundary. The VPP can be found normal to the shear zone boundary and to foliations in the shear zone if these fabrics have an approximately monoclinic symmetry (Fig. 4b; Passchier, 1998; Jiang and Williams, 1998; Fig. 4a). In most cases, the VPP is parallel to object lineations in the shear zone, but monoclinic shear zones segments with lineations normal to the VPP are theoretically also possible in the lower crust (Dias and Ribeiro, 1994; Passchier, 1998; Tikoff and Fossen, 1999). Although the orientation of the VPP can usually be established as described above, it is always necessary to check the results; outcrops parallel to the VPP should contain the best developed asymmetric structures as described below.

In thinning triclinic shear zones, lineations might be oblique to the VPP (Fig. 4b) and, object lineations and foliations in the wall rocks may be oblique to those in the shear zone. The VPP in such cases can only be established approximately as the surface that contains the best developed asymmetric structures.

Complex monoclinic or triclinic shear zones can be confused with polyphase shear zones, where multiple deformation phase lineations might be oblique to each other (Fig. 5c). In these circumstances, analysis of metamorphic conditions during deformation in different segments will be useful to identify such situations (Fig. 5c,d).

7. Shear sense indicators

The use of shear sense indicators for determining shear sense has been well established for use in low-grade mylonites for several decades (Berthé et al., 1979; Platt and Vissers, 1980; Simpson and Schmid, 1983; review in Passchier and Trouw, 2005). For HGR, there is less information available and although some of the same shear sense indicators occur as in low grade rocks, there are also important differences.

Small scale structures in HGR that can be used as shear sense indicators in the field include shear bands, isolated objects, asymmetric boudins, flanking folds, tension gash veins and the relation of folded and boudinaged veins. Such structures should be observed in the VPP and correctly classified. Folds, however, are dangerous to use since their asymmetry seems to have no clear simple relationship with shear sense of flow in the rock, even when seen on the VPP.

A useful tool in HGR is the asymmetry of crystallographic preferred orientation patterns in quartz and other minerals, but since this cannot be applied in the field it is not discussed here (review in Passchier and Trouw, 2005).

7.1. Shear bands

In HGR, shear bands can occur in weakly foliated rocks and on a larger (decimetric to metric) scale than in low-grade rocks. Commonly, melt accumulated along the shear band planes (Fig. 6a; White, 2004). Shear sense is identified from the geometry of the shear band deflection of the older foliation in the same way as this is done for deflection of layering into any fault or shear zone (Fig. 7). The commonly large size of shear bands in HGR is a difficulty if only part of the structure is exposed or if only a single orientation of out crop surfaces is available. Since shear-band interpretation relies on a cross-section effect, it is in all cases important to determine the exact orientation of the fabric elements in and around the shear band before it can be used as a shear sense indicator (Fig. 7). For example, if shear bands developed in approximately monoclinic flow with minor stretching normal to the VPP, correct interpretation is possible on VPP-outcrop surfaces parallel to the object lineations and normal to the foliation in the host rock and the shear band. Observations on outcrop surfaces of other orientation, even if these show apparently classic shear bands, may give wrong results (Fig. 7;

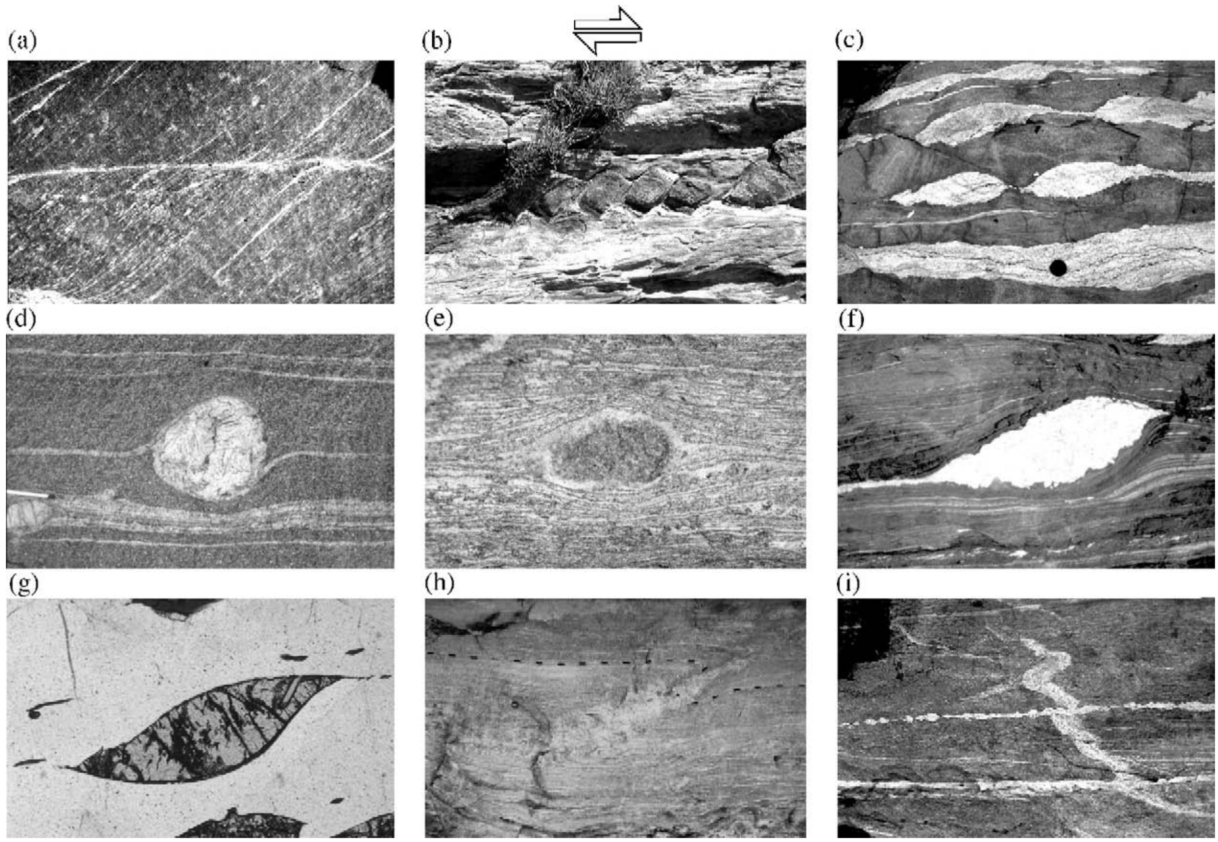

Fig. 6. Photographs of some typical structures that can serve as shear sense indicators in high-grade rocks; (a) shear bands with a central melt vein in mylonitised gneiss. Ponte Brolla, Ticino, Switzerland. Width of view 2 m; (b) domino-type asymmetric boudinage in a calcsilicates. Cadaques, NE-Spain. Width of view 1 m; (c) shear band type asymmetric boudinage in granitic gneiss. Ticino, Switzerland; (d) delta-type mantled porphyroclast in mylonitised granite. Shaw Batholith, Pilbara, Australia. Width of view 20 cm; (e) garnet crystal in gneiss, surrounded by tails of plagioclase. Copacabana beach, Rio, Brazil. Width of view 10 cm; (f) lozenge-shaped pegmatitic sigmoid isolated in gneiss. Ticino, Switzerland. Width of view 50 cm; (g) diopside fish in quartz matrix from high grade gneiss. Varginha, southern Minas Gerais, Brazil. Width of view 1.5 mm; (h) flanking fold in gneissic layering on anatectic melt vein CE. This type has positive slip and over-roll as in Fig. 10a. Sri Lanka. Width of view 3 m; (i) boudinaged and folded veins in a granitic gneiss. Ticino, Switzerland. Width of view 1 m. This geometry is not typical for any shear sense, but the distribution of orientation of a large number of this type of veins may be. Shear sense is dextral in all cases and some photos have been reversed for the purpose.

Passchier and Williams, 1996). Once the shear sense for a shear band has been established, it is necessary to determine if it is representative for bulk flow in the rock: if shear bands form on some pre-existing surface or structure, they may give a shear sense opposite to the bulk shear sense in a way similar to planes separating domino-type boudins described below.

7.2. Asymmetric boudins

One of the most common types of potential shear sense indicators in gneissic terrains are asymmetric boudins (Figs. 6b, c, and 8). These can have a complex three dimensional shape but are in many cases monoclinic, with symmetry axis normal to the VPP, usually normal to the object lineation and parallel to the foliation. Shape of boudins in the VPP may be complicated, but can be roughly defined by a few parameters such as length–width ratio of individual boudins, the angle Θ between the inter-boudin plane and the long axis of the boudins, and separation of the boudin, normalised against boudin width (Goscombe and Passchier, 2003; Fig. 8). Based on these parameters, three main types can be defined: *symmetric*, *domino type* and *shear-band*

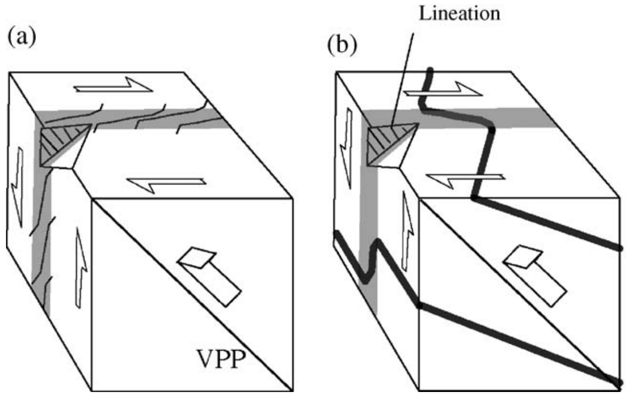

Fig. 7. Problems of section for shear bands and ductile shear zones in general. (a) A ductile shear zone with simple shear flow in an originally isotropic rock will develop sigmoidal foliation patterns which can be used to infer shear sense correctly on any rock face, even if not parallel to the lineation and VPP; (b) a ductile shear zone that transects an older foliation or layering will develop deflection of those older structures which is unreliable as a shear sense indicator, unless the precise orientation of fabric elements in the rock with respect to the VPP are known.

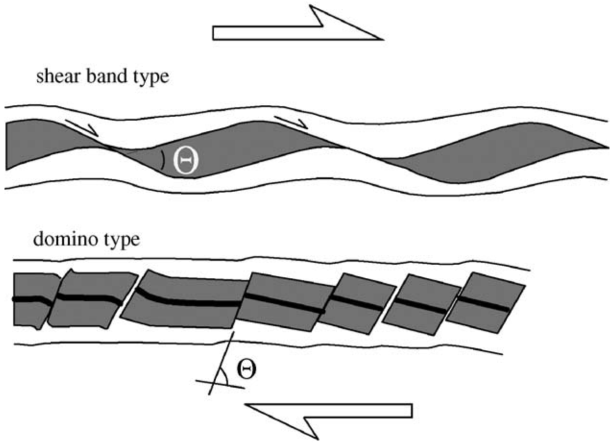

Fig. 8. Two main types of asymmetric boudins. Shear band-type boudins are long and thin, with a small angle between the inter boudin plane and the boudin surface (*Θ*), and considerable negative slip between boudins and negative lift of the boudin tips; domino-type boudins are stubby, with a high angle between the inter boudin plane and the boudin surface (*Θ*), minor slip between the boudins and commonly positive lift and negative slip of marker layers in the boudins.

type boudins, distinguished mostly by the angle *Θ* (Goscombe et al., 2004; Fig. 8). Symmetrical boudins cannot be used as shear sense indicators, unless they are part of sets of deformed veins (see below).

In *domino-type boudins* (Blumenfeld, 1983; Simpson and Schmid, 1983; Ramsay and Huber, 1983; Hanmer and Passchier, 1991; Swanson, 1992; Goscombe and Passchier, 2003) the inter-boudin surface is at a high angle *Θ* to the outer surface and is discrete and sharp. Domino-type boudins have rhomb shapes with low aspect ratios, typically with angular boudin edges and straight or slightly curved inter-boudin surface. Lateral displacement along the inter-boudin surface is small and since there is low extension of the enveloping surface, complete isolation of boudins is uncommon. Flanking folds may occur in layering in domino boudins along the inter-boudin surface, usually with positive lift and negative slip geometry (Coelho et al., 2005) also described as “antithetic drag” (Hudleston, 1989; Passchier, 2001). In all domino-type boudins, vergence of interboudin surface inclination is as shown in Fig. 8.

Shear-band boudins (Ramsay, 1967; Goldstein, 1988; Lacassin, 1988; Hanmer and Passchier, 1991; Swanson, 1992; Goscombe and Passchier, 2003) have asymmetric, rounded rhomb-, lens- or sigma-shapes with tapering wings and high aspect ratio. The inter-boudin surface is usually curved and develops as a fault or narrow ductile shear zone with associated ductile grain-refinement (Fig. 8). The degree of apparent block rotation is typically lower than for domino-type boudins. Dilation across the inter-boudin surface and vein-infill are rare. On the other hand, lateral displacement is considerable and consequently, extension of the layer enveloping surface is also high. Negative slip and lift (drag) on the inter-boudin surface is a diagnostic feature of shear-band boudins and is responsible for the typical, tapering sigma shapes of the boudin blocks (Coelho et al., 2005; Passchier, 2001). In all shear-band boudins, vergence of inter-boudin surface inclination is as shown in Fig. 8.

Asymmetric boudins can be reliable shear sense indicators if two criteria apply: 1) inter-boudin planes should be normal or at least highly oblique to the VPP and 2) boudin trains should be oriented at a small angle to the shear zone boundary, which usually means at a small angle to the foliation (Goscombe and Passchier, 2003). Boudin trains at a high angle to the shear zone boundary may also contain asymmetric boudins, but these are usually unreliable as shear sense indicators (Goscombe and Passchier, 2003).

7.3. Isolated asymmetric objects

Isolated asymmetric objects occur in a number of shapes and geometries, as shown in Fig. 9. There are five basic types common in HGR: mantled porphyroclasts; strain shadows; mineral fish, sigmoids and grains with asymmetric reaction rims. Although these objects have superficially the same shape, they develop by different mechanisms and should therefore be given separate names.

7.3.1. Mantled porphyroclasts

Mantled porphyroclasts or mantled objects (Figs. 6d,e, and 9a) consist of an isolated core-object, usually a single crystal of feldspar, hornblende or pyroxene, and a dynamically recrystallised mantle with trails derived from the grain. In HGR, mantled objects can be decimetric or metric in scale where the central object is a large single crystal or a rock fragment such as part of a vein. The resulting core–mantle geometries can be described as

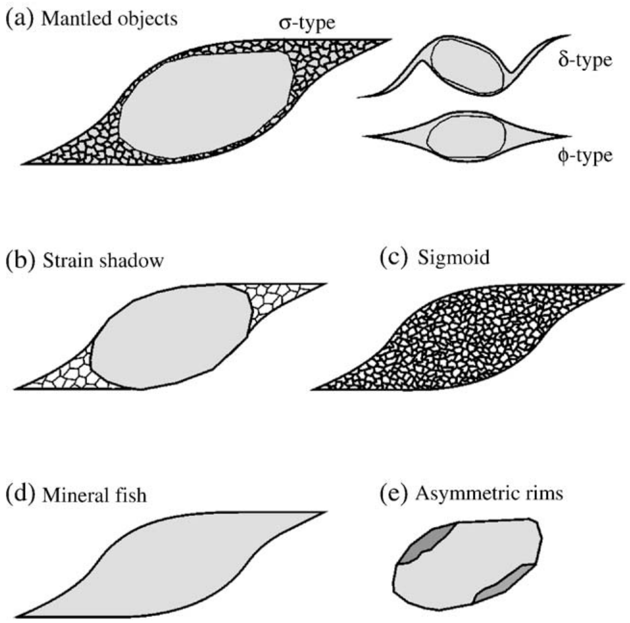

Fig. 9. Basic types of isolated objects that can be used to determine sense of shear in high grade rocks. All dextral shear sense. (a) Mantled objects have a weakly deformed singe crystal as core and a mantle of polycrystalline trails derived from the core by recrystallisation and/or reaction; (b) strain shadows consist of a rigid core and polycrystalline trails on both sides which derive from the wall rock; (c) sigmoids have the shape of a sigma-type mantled object but lacks the central rigid core; (d) mineral fish are monocrystals in the shape of a sigma-type mantled object; (e) asymmetric reaction rims on a rigid single crystal can occur in opposite quadrants to the trails on (a) and (b).

sigma-, delta- or phi-type (Passchier and Simpson, 1986; Passchier and Trouw, 2005). Sigma-types form when the core object is irrotational in the kinematic frame or if abundant recrystallised material is produced during deformation; delta-types develop when the core-object rotates rapidly and little recrystallised material is produced (Passchier and Trouw, 2005). In HGR, phi-type symmetric mantled objects dominate, probably due to rapid recrystallisation in non-coaxial flow. Phi-type mantled porphyroclasts cannot be used to determine shear sense due to their orthorhombic symmetry and lack of stair-stepping of the trails.

Folds developed in layering with variable thickness can resemble delta objects but can be distinguished by the unusual length of the trails, which is in fact part of the layering, and absence of a core object. Such structures should be interpreted as folds, and could give the wrong shear sense if identified as mantled objects.

7.3.2. Strain shadows

Strain shadows (Fig. 9b) develop when flow around rigid objects, such as isolated mineral grains or boudins, causes local detachment of the matrix from the object, especially if the rheological contrast with the host rock is significant (Durney and Ramsay, 1973; Köhn et al., 2000). The space created by this deflection can be filled with material that migrates from the wall rock to these low pressure areas. Some examples typical for HGR include mafic boudins with trails of quartz or granitic melt, or ilmenite trails around feldspar grains. With progressive deformation, these structures may develop geometries that resemble sigma-objects in shape. However, this similarity is only geometrical since the trails of mantled objects are built on material dynamically recrystallised from the core with minimal volume change, whereas in strains shadows they derive from the surrounding matrix with local volume increase. Although development is different from mantled objects, experimental data suggest that strain shadows can be interpreted in a similar way as shear sense indicators (cf. Figs. 6 and 7 in Marques and Coelho, 2001).

7.3.3. Sigmoids

Sigmoids are isolated, centimetre to metre scale, lozenge-shaped lenses of a composition different from that of the host rock (Figs. 6f; and 9c). These structures are different from mantled porphyroclasts because they lack a rigid central grain. Common types in HGR are sigmoid lenses of mafic rock in granitic gneiss, of quartz in gneiss, or gneiss lenses in marble, but many other combinations of lithologies have been observed. In many cases, the sigmoids are mantled by a thin veneer of anatectic melt which may trail out over a long distance in the wall rock parallel to the foliation. The exact formation mechanism of these structures is still unknown, but many of them may have formed as shear-band boudins which have become so much separated that they are now isolated in a single outcrop, and which have been changed in shape during the separation process. Currently available data suggest that sigmoids have the same geometry with respect to shear sense as sigma-type mantled objects. Care must be taken that they are observed in the VPP, because the 2D geometry of sigmoids can vary substantially in different sections.

7.3.4. Fish

Many large single crystals in rocks have the shape of an elongate sigma-object, but consist of internally undeformed and isolated crystals in a more fine-grained matrix (Figs. 6g and 9d). Such structures, known as *mineral fish*, have been observed for mica (Eisbacher, 1970; Fig. 9d), feldspar, hornblende, pyroxene, garnet, kyanite, sillimanite and a number of other minerals (Passchier and Trouw, 2005). They are named after the constituent mineral, for example feldspar fish, mica fish or garnet fish. Mineral fish are though to form by slip on the flat surfaces of the structure and are thought to remain relatively stable in orientation during ductile deformation. The typical shape is obtained by a combination of dissolution, growth and possibly some internal deformation (Eisbacher, 1970; Lister and Snoke, 1984; ten Grotenhuis et al., 2002; Mancktelow et al., 2002; Ceriani et al., 2003). Mineral fish are usually tilted against the general sense of shear and sometimes develop a small recrystallised trail that can be interpreted as trails in sigma objects. Studies of mineral fish in rocks that contain other independent shear sense criteria suggest that they are good shear sense criteria.

7.3.5. Grains with asymmetric reaction rims

In high grade rocks, reaction rims can be relatively common either as a monomineralic moat or a polymineralic corona of

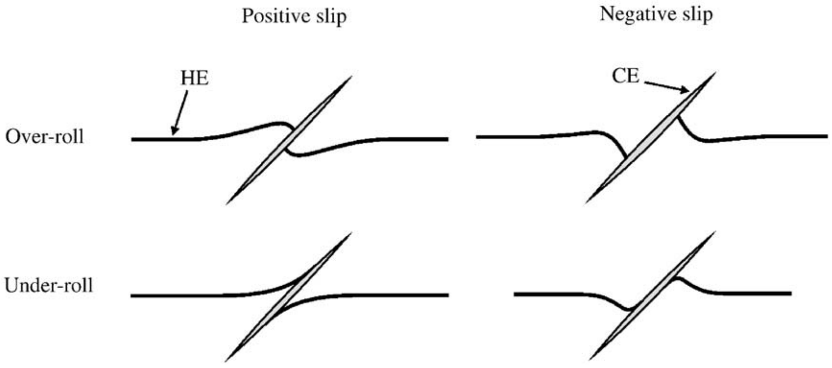

Fig. 10. Flanking structures consist of a host element (HE) such as layering, dykes or a foliation cut by a central element which can be an intrusion, shear zone or fault (CE). In high grade rocks, there is commonly slip on the CE during ductile flow in the wall rock, which leads to development of flanking folds, flanking the CE. There can be four basic geometries, depending on the amount of slip and roll. Only the type at top left can presently be used to determine shear sense. Further explanation in text.

reaction products surrounding certain minerals such as garnet or pyroxene. Polymineralic reactions rims are usually coronas with lamellar or tube-shaped intergrowth of phases, which may be asymmetrically arranged, occurring only in the direction of instantaneous shortening axes (Fig. 9e). A common example present in HGR is myrmekite growth on K-feldspar porphyroclasts (Simpson and Wintsch, 1989). Asymmetric reaction rims can occur in combination with fine grained trails in sigma-type mantled porphyroclasts, but can also occur on single grains without such trails.

7.4. Flanking structures

Many HGR rocks contain shear zones or veins (named central element, CE) which cut older and more pervasive elements such as layering, foliations or older vein sets (host element, HE). When folds are developed in the HE in a zone adjacent to the CE, such folds are known as *flanking structures* (Passchier, 2001; Figs. 6a, h, and 10). The geometry of flanking structures varies according to: *tilt*, the orientation of the CE with respect to the main foliation; *lift*, the far-field displacement of the HE; *slip*, the off-set of the HE observed in the CE; and *roll*, the sense and degree of curvature of the HE (Coelho et al., 2005). The combination of these geometric parameters results in 27 theoretical geometries for flanking structures (Coelho et al., 2005), which can be reduced to four basic settings illustrated in Fig. 10 (Wiesmayr and Grasemann, 2005) with zero lift, neutral roll and ignoring the special cases of no slip (cf. n-type flanking structures Passchier, 2001). Each of these four geometries has a mirror image that can developed under the same flow conditions and, therefore, their use as isolated shear sense indicators is problematic (Wiesmayr and Grasemann, 2005). Nevertheless, flanking structures have some potential to be used as shear sense indicators in specified settings. Wiesmayr and Grasemann (2005) have shown that if a shear zone formed in monoclinic transpression, flanking structures with positive slip, over-roll and a left dipping central vein (Fig. 10) indicate dextral shear sense. Also, if several veins of originally different orientation are present in a shear zone, the combined geometry of flanking structures along them can be used as a shear sense indicator (Wiesmayr and Grasemann, 2005).

7.5. Melt tension gashes and veins

Structures very similar to trains of sigmoidal tension gashes in low grade rocks can be observed in some HGR, but filled with anatectic melt material. Any rock can develop fractures and open veins if the fluid pressure is high enough, and this also applies to partial melt present in rocks. During deformation, fractures may open allowing melt to concentrate in tension gashes that can be interpreted in a similar way as quartz or calcite-filled tension gashes in low grade rocks (Passchier and Trouw, 2005): Z-shape of the veins indicates dextral shear sense, and S-shape sinistral sense.

7.6. Folded-boudinaged vein distribution

If a volume of undeformed rock was intruded by planar elements such as veins or dykes, in several orientations, their behaviour in progressive deformation (folding, boudinage, or a sequence of both; Fig. 6i) is dependent on their original orientation with respect to the shortening or extension field of the subsequent deformation. This determines if the vein or dyke will be folded or boudinaged, respectively (Fig. 6i; Fig. 5.29 in Passchier and Trouw, 2005). If a planar element in the rock rotates from the shortening to the extension field of flow, the result will be folding followed by boudinage. The reverse scenario, folded boudin trails, is uncommon and usually does not develop in a single deformation event. The combined orientation of folded and boudinaged (and boudinaged folded) planar elements can be used to determine shear sense as outlined in Passchier and Trouw (2005).

8. Conclusions

Shear zones in high grade terrains have a number of peculiarities which require a different approach from those in low grade terrains. The main difference is that it is not always straightforward to find the VPP and that the number of shear sense indicators that can be used is limited. The monoclinic or triclinic nature of the shear zone and the orientation of the VPP can usually be found from orientation data of fabric elements in the shear zone and its wall rocks. High grade shear zones are commonly overprinted by low grade fabrics and it is easy to confuse polyphase fabrics as effects of complex monoclinic or triclinic flow. Shear sense indicators in high grade shear zones, with the exception of mineral fish, tend to be large and have to be observed in outcrop. The most common ones are shear bands, asymmetric boudins, isolated asymmetric objects and flanking structures.

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References

Altenberger, U., Wilhelm, S., 2000. Ductile deformation of K-feldspar in dry eclogite facies shear zones in the Bergen Arcs, Norway. Tectonophysics 320, 107–121.

Beaumont, C., Jamieson, R.A., Nguyen, M.H., Lee, B., 2001. Himalayan tectonics explained by extrusion of a low-viscosity crustal channel coupled to focused surface denudation. Nature 414, 738–742.

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

Bird, P., 1991. Lateral extrusion of lower crust from under high topography, in the isostatic limit. Journal of Geophysical Research 96 (6), 10275–10286.

Blumenfeld, P., 1983. Le "tuilage des megacristaux", un critere d'ecoulement rotationnel pour les fluidalites des roches magmatiques; Application au granite de Barbey. Bulletin de la Societe Geologique de France 25, 309–318.

Ceriani, S., Mancktelow, N.S., Pennacchioni, G., 2003. Analogue modelling of the influence of shape and particle/matrix interface lubrication on the rotational behaviour of rigid particles in simple shear. Journal of Structural Geology 25, 2005–2021.

Clarke, G.L., Norman, A.R., 1993. Generation of pseudotachylyte under granulite facies conditions, and its preservation during cooling. Journal of Metamorphic Petrology 11, 319–335.

Coelho, S., Passchier, C., Grasemann, B., 2005. Geometric description of flanking structures. Journal of Structural Geology 27, 597–606.

Dias, R., Ribeiro, A., 1994. Constriction in a transpressive regime: an example in the Iberian branch of the Ibero-Armorican arc. Journal of Structural Geology 16, 1543–1554.

Dirks, P., Zhang, J., Passchier, C.W., 1997. Exhumation of high-pressure granulites and the role of lower crustal advection in the north China craton near Datong. Journal of Structural Geology 19, 1343–1358.

Durney, D.W., Ramsay, J.G., 1973. Incremental strains measured by syntectonic crystal growths. In: DeJong, K.A., Scholten, R. (Eds.), Gravity and Tectonics. Wiley, New York, pp. 67–95.

Eisbacher, G.H., 1970. Deformation mechanics of mylonitic rocks and fractured granites in Cobequid mountains, Nova Scotia, Canada. Geological Society of America Bulletin 81, 2009–2020.

Evans, B., Renner, J., Hirth, G., 2001. A few remarks on the kinetics of static grain growth in rocks. International Journal of Earth Sciences 90, 88–103.

Goldstein, A.G., 1988. Factors affecting the kinematic interpretation of asymmetric boudinage in shear zones. Journal of Structural Geology 10, 707–715.

Goscombe, B.D., Passchier, C.W., 2003. Asymmetric boudins as shear sense indicators — an assessment from field data. Journal of Structural Geology 25, 575–589.

Goscombe, B.D., Passchier, C.W., Hand, M., 2004. Boudinage classification: end-member boudin types and modified boudin structures. Journal of Structural Geology 26, 739–763.

Grocott, J., 1977. The relationship between Precambrian shear belts and modern fault systems. Journal of the Geological Society of London 133, 257–262.

Grujic, D., Hollister, L.S., Parrish, R.R., 2002. Himalayan metamorphic sequence as an orogenic channel: insight from Bhutan. Earth and Planetary Science Letters 198, 177–191.

Hanmer, S., Passchier, C.W., 1991. Shear-sense indicators: a review. Geological Survey of Canada 90.

Hippertt, J., Lana, C., Takeshita, T., 2001. Deformation partitioning during folding of banded iron formation. Journal of Structural Geology 23, 819–834.

Hudleston, P.J., 1989. The association of folds and veins in shear zones. Journal of Structural Geology 11, 949–957.

Ji, S., Martignole, J., 1994. Ductility of garnet as an indicator of extremely high temperature deformation. Journal of Structural Geology 16, 985–996.

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.

Köhn, D., Hilgers, C., Bons, P.D., Passchier, C.W., 2000. Numerical simulation of fibre growth in antitaxial strain fringes. Journal of Structural Geology 22, 1311–1324.

Lacassin, R., 1988. Large-scale foliation boudinage in gneisses. Journal of Structural Geology 10, 643–647.

Lafrance, B.E.J., Scoates, J.S., 1996. Synemplacement recrystallization and deformation microstructures in the Poe Mountain anorthosite, Wyoming. Contributions to Mineralogy and Petrology 122, 431–440.

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

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

Mancktelow, N.S., Arbaret, L., Pennacchioni, G., 2002. Experimental observations on the effect of interface slip on rotation and stabilisation of rigid particles in simple shear and a comparison with natural mylonites. Journal of Structural Geology 24, 567–585.

Marques, F.O., Coelho, S., 2001. Rotation of rigid elliptical cylinders in viscous simple shear flow: analogue experiments. Journal of Structural Geology 23, 609–617.

Olesen, N.Ø., 1998. Plagioclase porphyroclasts in a high-temperature shear-zone. In: Snoke, A., Tullis, J., Todd, V.R. (Eds.), Fault related rocks — a photographic atlas. Princeton University Press, New Jersey, pp. 506–507.

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

Passchier, C.W., 2001. Flanking structures. Journal of Structural Geology 23, 951–962.

Passchier, C.W., Simpson, C., 1986. Porphyroclast systems as kinematic indicators. Journal of Structural Geology 8, 831–843.

Passchier, C.W., Trouw, R.A.J., 2005. Microtectonics, Second edition. Springer-Verlag, Berlin.

Passchier, C.W., Williams, P.R., 1996. Conflicting shear sense indicators in shear zones; the problem of non-ideal sections. Journal of Structural Geology 18, 1281–1284.

Passchier, C.W., Myers, J.S., Kröner, A., 1990. Field Geology of High-Grade Gneiss Terrains. Springer-Verlag.

Piazolo, S., Passchier, C.W., 2002. Controls on lineation development in low to medium grade shear zones: a study from the Cap de Creus peninsula, NE Spain. Journal of Structural Geology 24, 25–44.

Platt, J.P., Vissers, R.L.M., 1980. Extensional structures in anisotropic rocks. Journal of Structural Geology 2, 397–410.

Prior, D.J., Wheeler, J., Brenker, F.E., Harte, B., Matthews, M., 2000. Crystal plasticity of natural garnet: new microstructural evidence. Geology 28, 1003–1006.

Prior, D.J., Wheeler, J., Peruzzo, L., Spiess, R., Storey, C., 2002. Some garnet microstructures: an illustration of the potential of orientation maps and misorientation analysis in microstructural studies. Journal of Structural Geology 24, 999–1001.

Ramsay, J.G., 1967. Folding and Fracturing of Rocks. McGraw-Hill, New York, pp. 103–109.

Ramsay, J.G., Huber, M.I., 1983. The Techniques of Modern Structural Geology. Volume 1: Strain Analysis. Academic Press.

Royden, L.H., Burchfiel, C., King, R.W., Wang, E., Chen, Z., Shen, F., Liu, Y., 1997. Surface deformation and lower crustal flow in Eastern Tibet. Science 276, 788–790.

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

Rosenberg, C.L., Stünitz, H., 2003. Deformation and recrystallization of plagioclase along a temperature gradient: an example from the Bergell tonalite. Journal of Structural Geology 25, 389–408.

Scholz, C.H., 1988. The brittle–plastic transition and the depth of seismic faulting. Geologische Rundschau 77, 319–328.

Searle, M., Szulc, A., 2005. Channel flow and ductile extrusion of the high Himalayan slab — the Kangchenjunga–Darjeeling profile, Sikkim Himalaya. Journal of Asian Earth Sciences 25, 173–185.

Shen, F., Royden, L.-H., Burchfiel, B.-C., 2001. Large-scale crustal deformation of the Tibetan Plateau. Journal of Geophysical Research 106, 6793–6816.

Simpson, C., Schmid, S.M., 1983. An evaluation of criteria to deduce the sense of movement in sheared rocks. Bulletin of the Geological Society of America 94, 1281–1288.

Simpson, C., Wintsch, R.P., 1989. Evidence for deformation-induced K-feldspar replacement by myrmekite. Journal of Metamorphic Geology 7, 261–275.

Stipp, M., Stünitz, H., Heilbronner, R., Schmid, S.M., 2002. The eastern Tonale fault zone: a “natural laboratory” for crystal plastic deformation of quartz over a temperature range from 250 to 700 °C. Journal of Structural Geology 24, 1861–1884.

Swanson, M.T., 1992. Late Acadian–Alleghenian transpressional deformation: evidence from asymmetric boudinage in the Casco Bay area, coastal Maine. Journal of Structural Geology 14, 323–341.

ten Grotenhuis, S.M., Passchier, C.W., Bons, P.D., 2002. The influence of strain localisation on the rotation behaviour of rigid objects in experimental shear zones. Journal of Structural Geology 24, 485–499.

Tikoff, H., Fossen, H., 1999. Three dimensional reference deformations and strain facies. Journal of Structural Geology 21, 1497–1512.

White, J.C., 2004. Instability and localization of deformation in lower crust granulites, Minas fault zone, Nova Scotia, Canada. In: Alsop, G.I., Holdsworth, R.E., McCaffrey, K.J.W., Hand, M. (Eds.), Flow Processes in Faults and Shear Zones, Geological Society of London, Special Publications, vol. 224.

White, J.C., Mawer, C.K., 1992. Deep-crustal deformation textures along megathrusts from Newfoundland and Ontario: implications for microstructural preservation, strain rates and strength of the lithosphere. Canadian Journal of Earth Sciences 29, 328–337.

Wiesmayr, G., Grasemann, B., 2005. Sense and non-sense of shear in flanking structures with layer-parallel shortening: implications for fault-related folds. Journal of Structural Geology 27, 249–264.

Zhang, J.S., Dirks, P.H.G.M., Passchier, C.W., 1994. Extensional collapse and uplift in a polymetamorphic granulite terrain in the Archaean and palaeo-Proterozoic of north China. Precambrian Research 67, 37–57.