PERGAMON

Journal of Structural Geology 26 (2004) 155–161

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.com/locate/jsg

Apparent shear-band geometry resulting from oblique fold sections

Ondrej Lexa[a,*], John Cosgrove[b], Karel Schulmann[a]

[a]*Institute of Petrology and Structural Geology, Charles University, Prague, Czech Republic*
[b]*Department of Earth Sciences and Engineering, Royal School of Mines, Imperial College, London SW7 2BP, UK*

Received 1 May 2002; received in revised form 1 February 2003; accepted 4 April 2003

Abstract

Small-scale shear zones inclined at intermediate angles to an earlier anisotropy are often observed in deformed rocks. They are traditionally described as shear-bands, C-bands, extensional crenulation cleavage or normal kink-bands formed as a result of extension along the anisotropy. Their asymmetries are widely used to describe the large-scale kinematics of deformation and the deformational history of a given area. We demonstrate that when various three-dimensional fold structures are observed on two-dimensional outcrop surfaces or in thin section, they can appear geometrically identical. We have developed a simple technique that allows the geometrical evaluation of any section across a cylindrical fold of arbitrary geometry. The ranges of planar sections on which a fold exhibits shear-band like geometry are presented on a stereographic projection in order to simplify the determination of critical orientations. We demonstrate that for any fold geometry, there are two distinct groups of sections showing shear-band like geometry with opposite 'senses of shear' criteria systematically arranged around the axial plane and which are inclined at a high angle to the major anisotropy. We provide a field example from Western Carpathians, where kinematic analysis, mainly based on apparent extensional shear-bands, led to overemphasis of the role of post-orogenic extension on the final structural pattern of the belt.

Keywords: Shear-band geometry; Oblique fold sections; Small-scale shear zones

1. Introduction

Small-scale shear zones inclined at intermediate angles to a previous anisotropy are commonly observed in deformed rocks. They are traditionally presented as shear-bands (White, 1979), C′-bands (Ponce and Choukroune, 1980), extensional crenulation cleavage (Platt, 1979, 1984; Platt and Vissers, 1980), asymmetric boudinage, asymmetric folds or normal kink-bands (Dewey, 1965; Cobbold et al., 1971; Cosgrove, 1976) formed as a result of extension along the older anisotropy or shortening normal to the anisotropy. Their 'sense of shear' and geometrical relations are widely used to describe the large-scale kinematics of deformation (Berthé et al., 1979; Simpson and Schmid, 1983; Lister and Snoke, 1984) or the tectonic settings of the deformational history (Platt and Vissers, 1980; Behrmann, 1987).

Shear bands may resemble the compressional crenulation cleavage but develop by extension of the older foliation rather than by shortening (Passchier and Trouw, 1996). This led some authors to use the terms compressional (CCC) and extensional (SBC) crenulation cleavages (Platt and Vissers, 1980). Passchier and Trouw (1996) presented a summary of differences between these two contrasting structures. Their main argument for distinction between both kinds of structures is the angle of CCC with the older foliation, which generally ranges between 45 and 90°, while for SBC the angle to earlier foliation is less than 45°. However, the angular distinction between CCC and SBC is not always valid. The compressional crenulation cleavage changes the geometry in the profile section towards the hinge direction of the folded domain, so that the internal rotation becomes less than 45° and may be easily misinterpreted as an SBC (Price and Cosgrove, 1994, p. 263, Fig. 10.50).

From a kinematic point of view, CCC develops at a high angle to bulk shortening while SBC represents a single shear plane at small angle to the foliation (Passchier and Trouw, 1996). In order to interpret the kinematic significance of both kinds of structures, they have to be observed in plane,

* Corresponding author. Tel.: +420-22195-1531; fax: +420-22195-1524.

E-mail address: lexa@natur.cuni.cz (O. Lexa).

0191-8141/03/$ - see front matter © 2003 Elsevier Ltd. All rights reserved.
doi:10.1016/S0191-8141(03)00072-5

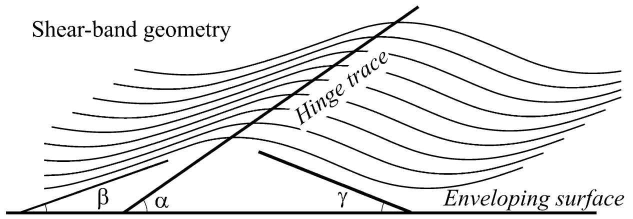

Fig. 1. Shear band geometry and definition of angles α, β and γ according to Platt and Vissers (1980).

perpendicular to the intersection of CCC and SBC with the older foliation.

With the advent of modern kinematic analysis in structural geology in the early 1980's, the *XZ* plane of finite strain ellipsoid became extremely important. This plane is traditionally defined as a plane parallel to the stretching lineation and perpendicular to the foliation. However, the stretching lineation in phyllites or phyllonites can be difficult to define, and it can be easily confused with corrugations or intersection lineation. Moreover, the presence of well-defined shear bands on a rock surface in the field is in many cases considered a satisfactory indicator to consider this surface as an *XZ* plane. Because, shear bands are such noticeable structures and their kinematic significance is straightforward, these structures have been widely used as first order kinematic indicators in many orogenic belts (Behrmann, 1987).

This paper aims to demonstrate that: (1) distinguishing between CCC and SBC is not always an easy task, (2) unless this is fully appreciated there is a great danger of misinterpretation when the shear bands are used as kinematic indicators, and (3) the CCC and SBC can appear identical when seen on flat outcrop surfaces or in thin sections.

2. Geometrical characteristics of oblique sections of folds

Folding or flow partitioning are commonly presented in two dimensions while geological structures are three-dimensional (3D) features. In order to justify the use of the two-dimensional (2D) analyses to investigate a three-dimensional problem, certain assumptions are made. Because the displacement fields predicted by the 2D-theory are limited to a plane (usually one of the principal planes of the strain ellipsoid), it is assumed that displacement is identical in any parallel plane and therefore that the resulting fold structures are cylindrical. As a result, the axes of the folds are perpendicular to the plane of the displacement field. Based on these assumptions we will consider 2D sections normal to the fold axes to be 'true' sections and all other sections 'apparent'.

Geometrically, shear-bands can be characterized by three angles α, β and γ (Fig. 1), corresponding to the relative angles of the limbs, hinge trace and enveloping surface (Platt and Vissers, 1980). In order for the fold or flexure profiles to have shear-band geometry, α should have a value between 10 and 50°, while β and γ should range between 10 and 25°, so that the interlimb angle exceeds 130°. Platt and Vissers (1980) show that these angles are mean values from observations in the field, for example from the Betic movement zone (Behrmann, 1987). We will show that for a given fold profile in the 'true' section (i.e. a section normal to the fold axis; Fig. 2) there is a specific range of 'apparent' sections (i.e. a section oblique to the fold axis; Fig. 2) in which the fold profiles satisfy the geometrical criteria of shear-bands.

Apparent sections through three-dimensional cylindrical, coaxial folds can be treated as fold axis parallel projections of 'true' fold section onto the section plane. When $ax + by + cz = 0$ is the equation of a section plane and (p, q, r) is the vector parallel to the fold axis in an arbitrarily chosen reference frame, then the coordinates $[x\ y\ z]$ of points in a 'true' section and the coordinates $[x'\ y'\ z']$ of points on an 'apparent' section are related to each other by matrix equation:

$$[x\ y\ z]\begin{bmatrix} \frac{bq+cr}{D} & \frac{-ap}{D} & \frac{-ar}{D} \\ \frac{-bp}{D} & \frac{ap+cr}{D} & \frac{-br}{D} \\ \frac{-cp}{D} & \frac{-cq}{D} & \frac{ap+bq}{D} \end{bmatrix} = [x'\ y'\ z']$$

where $D = (ap + bq + cr)$.

The 2D coordinates on the chosen section are obtained as coefficients of linear combinations of any two perpendicular unit vectors coplanar with the section plane. We developed a simple MATLAB® script, which visualises any section profile across a given fold geometry and determine the three angles α, β and γ (Fig. 1) for the oblique section profile. Using this script we can examine any section across a fixed fold geometry and determine which of them satisfies the geometric requirements for shear-bands. The results are presented in a stereographic projection (Figs. 3 and 4) sharing the area containing poles to sections that satisfy the shear-band criteria. The area of sections exhibiting shear-band like geometry is shaded on the basis of the interlimb angle α (Fig. 1).

Sections through symmetrical folds generally have fold profiles with an asymmetric geometry (Fig. 3) and the planes on which the apparent fold geometry satisfies the shear-band criteria fall into two distinct groups separated by the fold axial plane. These two groups contain poles to sections on which shear-band geometry exhibit opposing asymmetry, i.e. opposing 'shear-sense' criteria. The area of these domains on a stereographic projection, i.e. the range of orientations of section planes in space that display shear-band geometries is related to the interlimb angle of the symmetrical folds, so as the interlimb angle increases towards 180°, the range of suitable sections displaying shear-band geometry increases.

Sections across asymmetric folds that display shear-band

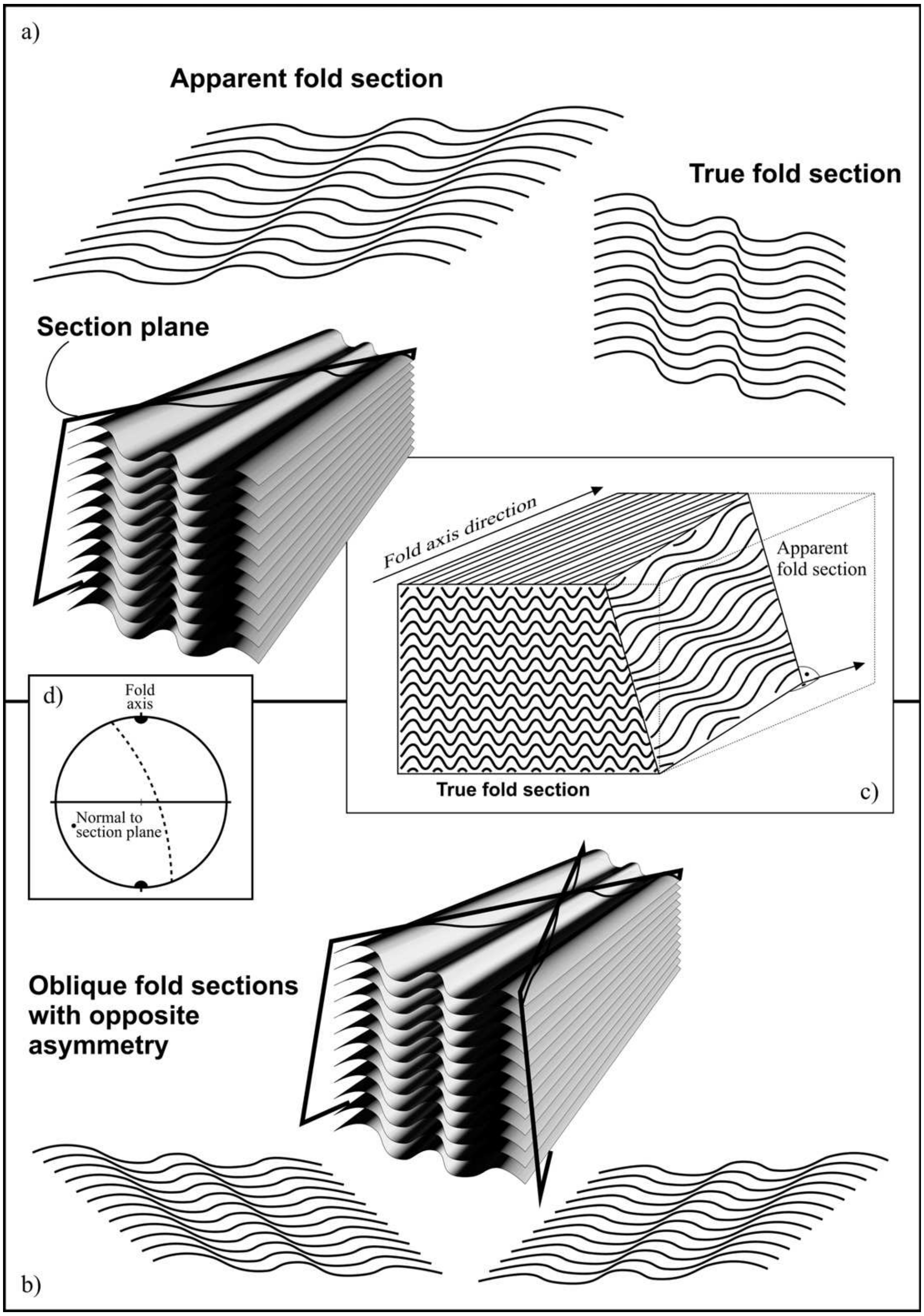

Fig. 2. (a) Block diagrams of folded anisotropy and 'apparent' fold sections showing shear-band geometries. (b) Orientation of apparent fold sections exhibiting opposite sense of shear criteria. (c), (d) Principle of presentation of 'apparent' fold sections in stereographic projection.

geometries are shown in Fig. 4. It can be seen that the range of sections suggesting a sinistral and dextral 'sense of shear' is unequal in this example and a preferred enlargement of one group occurs. This asymmetry is controlled by the angle between the fold axial plane and the main anisotropy (Fig. 4).

3. Geological example

In the Vepor basement of the Central Western Carpathians, a flat-lying mylonitic foliation containing a well-developed stretching lineation is affected by late

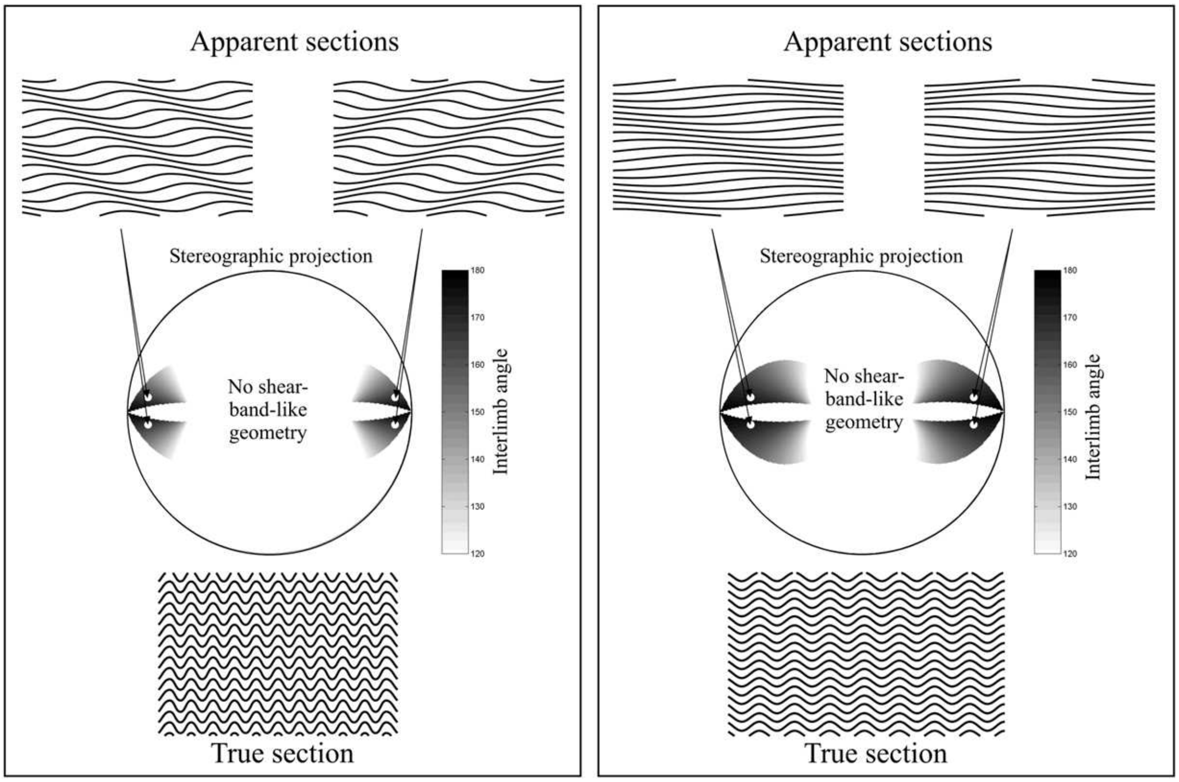

Fig. 3. Stereographic projection showing influence of interlimb angle. The range of section planes showing shear-band geometry increases with interlimb angle of folds affecting main anisotropy.

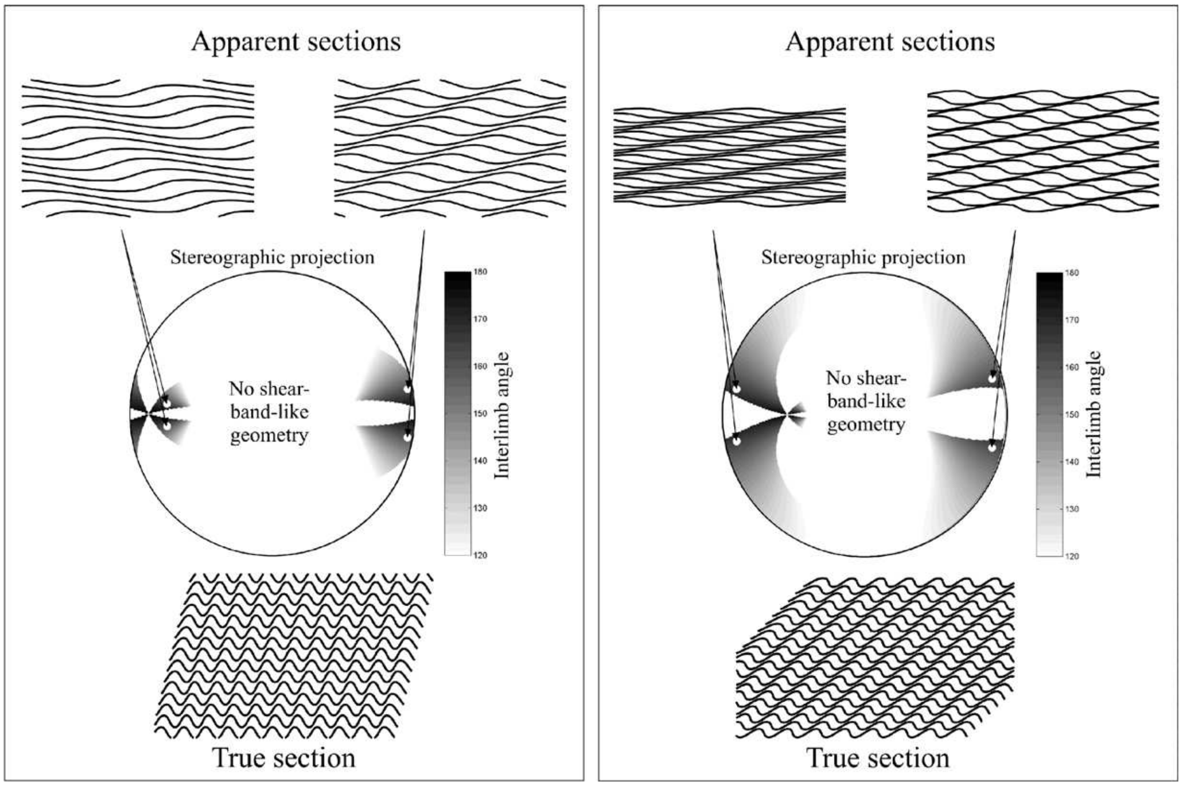

Fig. 4. Stereographic projections showing influence of angle between fold axial plane and main anisotropy. The probability of occurrence of opposite shear criteria decreases with decreasing angle of axial plane and plane of main anisotropy.

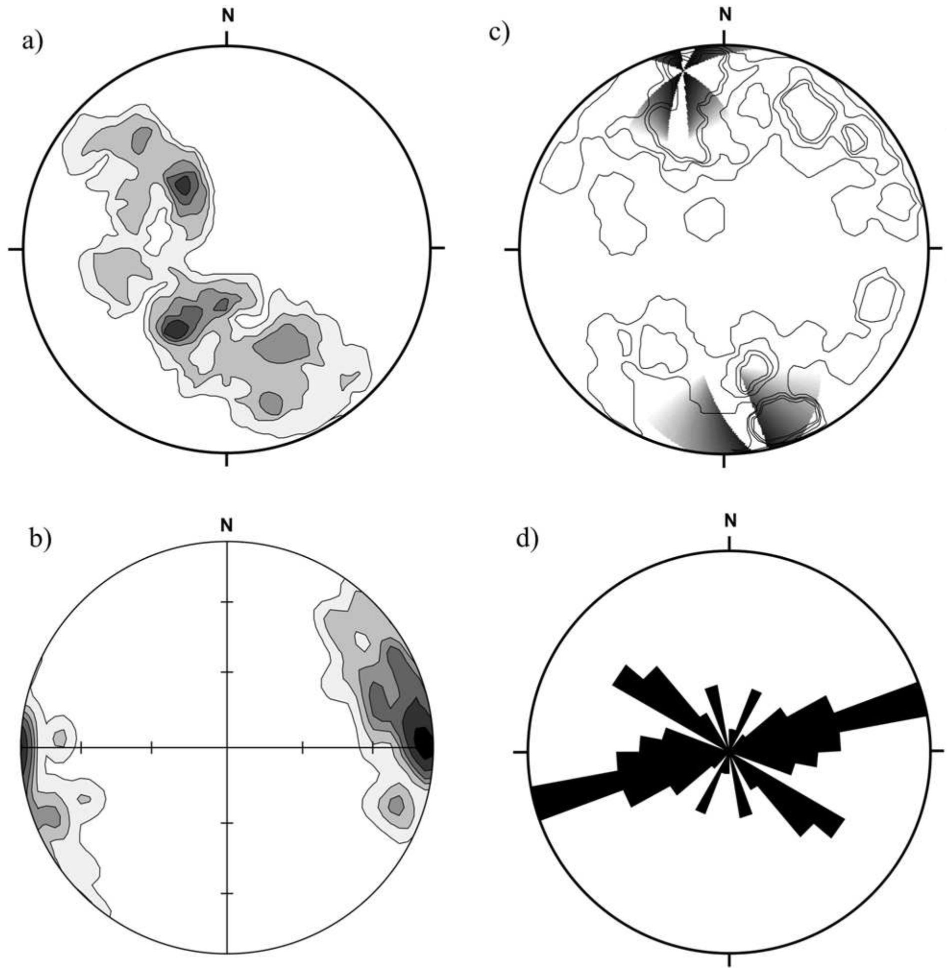

Fig. 5. Structural elements from studied area. (a) Poles to main Alpine metamorphic anisotropy showing girdle distribution around the axis sub-parallel to hinges of late Alpine folds—116 measurements; (b) orientation of stretching lineation—68 measurements; (c) distribution of poles to main fracture systems developed in studied area (Hók et al., 2001) overlaid by shaded areas indicating 'apparent' fold sections in which shear-band geometry can be observed; (d) rose diagram of main fracture directions in studied area (Hók et al., 2001). Note that a main maximum of fracture orientations coincides with orientations of apparent fold sections. All data are plotted on Schmidt net and projected from lower hemisphere. In (a) and (b), the contour levels are even multiples of standard deviation.

folding, which generated a crenulation cleavage. The fold axes are generally sub-parallel to the stretching lineation (Fig. 5). Most of the studies on the kinematic and tectonic evolution of this region are based on the use of shear-bands and asymmetric porphyroclasts as kinematic indicators. These studies have resulted in the generally accepted model of post-orogenic, orogen-parallel extension (Plašienka et al., 1999; Lupták et al., 2000; Janák et al., 2001). In contrast to the interpretation given by previous workers in which the major extensional deformation post-dates the episode of compression, a study by these authors shows that extension was the first Alpine deformation in the area and that this pre-dates the compressional stage of tectonic evolution (Lexa et al., 2003). The extensional phase is highly asymmetrical and locally non-coaxial. The majority of the studied outcrops show that we are dealing with oblique sections across small-scale folds, which are likely to be misinterpreted as shear-bands (Fig. 6).

In order to evaluate the probability of encountering oblique sections with shear-band like geometry in a particular field area, we need to identify the dominant geometries of the small-scale folds and, moreover, we have to understand the distribution of surfaces on which the structures are observed. It should be pointed out that the majority of observations are from natural rather than man-made outcrops, where the orientation of the exposed surfaces is controlled mainly by fractures (typically joints). In addition, sections that are sub-parallel to the lineations are specifically selected as being appropriate for the study of kinematic indicators. We plotted the range of sections with shear-band like geometry, the range of naturally occurring fractures and the distribution of lineations on a stereographic projection (Fig. 5c), which shows that there is a high probability of systematically observing oblique sections across the small-scale folds showing opposite shear-band geometries. We propose that such field observations led some authors

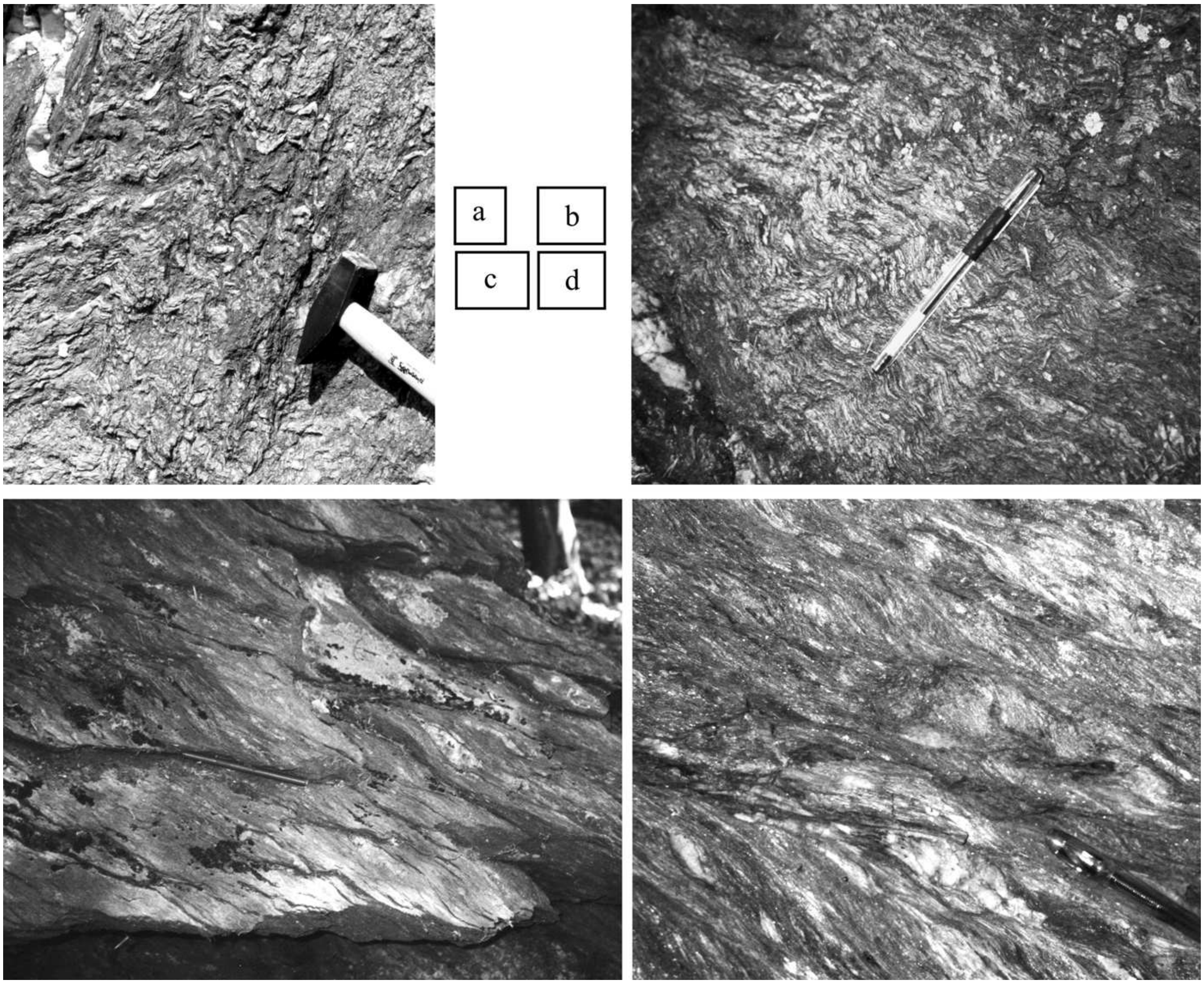

Fig. 6. Field photos of late folding and crenulation cleavage affecting early Alpine fabric in the Vepor micaschists of the West Carpathians. True fold sections (a) micaschists in the Mútnik area; (b) micaschists in the Katarínska huta area. Apparent fold sections showing shear-bands geometry (c), (d) Katarínska huta. Axial plane: 326/75; fold axis: 52/14; and general outcrop surface: 318/65.

(e.g. Siman et al., 1996) to interpret the extensional tectonics in Vepor basement to be symmetrical.

4. Discussion and conclusions

Shear-bands and folds can generate identical geometries when seen on a flat exposure surfaces in some orientations. These geometries can lead to misinterpretation of folds as shear bands and to erroneous structural and kinematic interpretation.

The ambiguity arises since oblique sections through small-scale folds in anisotropic materials have identical geometries to *XZ* finite strain sections through shear-band bearing rocks. Misinterpretations are most likely in areas of multiple deformations when earlier fabrics are folded. Determination of the *XZ* section in phyllonites and phyllites is often complicated by the presence of microscopic corrugations on foliation surfaces, which may be easily confused with stretching lineation. These corrugations are commonly associated with gentle folds of a larger scale. Particularly in this case, geologists would tend to look for kinematic criteria in sections in which the larger folds would generate profiles similar to shear band geometry.

In order to be confident that the geometry displayed on a 2D exposure surface is related to true shear-bands and can therefore be used as a valid kinematic indicator, it is essential to know the 3D geometry of the structure and the orientation of the exposure surface with respect to fold axes and lineations. For this reason, systematic studies of fracture and joint systems in folded areas should accompany kinematic analyses.

Acknowledgements

We are grateful to the Geological Survey of the Slovak Republic for significant financial support during the initial stages of our research. This work has been also supported by the Grant of Charles University Agency No. 216/1999/B-GEO. The salaries of K. Schulmann and O. Lexa were covered from the grant of the Ministry of Education No. 24313005.

References

Behrmann, J.H., 1987. A precautionary note on shear bands as kinematic indicators. In: Cobbold, P.R., Gapais, D., Means, W.D., Treagus, S.H. (Eds.), Shear Criteria in Rocks. Journal of Structural Geology 9(5–6). Pergamon, Oxford–New York, International, pp. 659–666.

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

Cobbold, P.R., Cosgrove, J.W., Summers, J.M., 1971. Development of internal structures in deformed anisotropic rocks. Tectonophysics 12, 23–53.

Cosgrove, J.W., 1976. The formation of crenulation cleavage. Journal of the Geological Society of London 132 (Part 2), 155–178.

Dewey, J.F., 1965. Nature and origin of kink-bands. Tectonophysics 1 (6), 459–494.

Hók, J., Lacika, J., Madarás, J., Kohút, M., Nagy, A., Ivanička, J., Siman, P., Král', J., Töröková, I., 2001. Neotektonický a geomorfologický vývoj študijných lokalít – 1. časť. Projekt: Vývoj hlbinného úložiska vyhoreného jadrového paliva a vysokoaktívnych Ra – odpadov v podmienkach Slovenskej republiky pre obdobie 1998–2000. Úloha: Výber lokality. Číslo etapy: VYL-01-00. Štátny geologický ústav Dionýza Štúra, Bratislava. Manuskript–archív ŠGÚDŠ, Bratislava, pp. 1–171.

Janák, M., Plašienka, D., Frey, M., Cosca, M., Schmidt, S.T., Lupták, B., Méres, S., 2001. Cretaceous evolution of a metamorphic core complex, the Veporic unit, Western Carpathians (Slovakia): P–T conditions and in situ Ar-40/Ar-39 UV laser probe dating of metapelites. Journal of Metamorphic Geology 19 (2), 197–216.

Lexa, O., Schulmann, K., Ježek, J., 2003. Cretaceous collision and indentation in SW part of West Carpathians:view based on structural analysis and numerical modeling. Tectonics, accepted.

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

Lupták, B., Janák, M., Plašienka, D., Schimdt, S.T., Frey, M., 2000. Chloritoid-kyanite schists from the Veporic unit, Western Carpathians, Slovakia: implications for Alpine (Cretaceous) metamorphism. Schweizerische Mineralogische Und Petrographische Mitteilungen 80 (2), 213–223.

Passchier, C.W., Trouw, R.A.J., 1996. Microtectonics, Springer-Verlag, Berlin, Heidelberg.

Plašienka, D.a., Janák, M., Lupták, B., Milovskú, R., Frey, M., 1999. Kinematics and metamorphism of a Cretaceous core complex: the Veporiuc Unit of the Western Carpathians. Physics and Chemistry of the Earth (A) 24 (8), 651–658.

Platt, J.P., 1979. Extensional crenulation cleavage. In: Cobbold, P.R., Ferguson, C.C. (Eds.), Description and Origin of Spatial Periodicity in Tectonic Structures; Report on a Tectonic Studies Group Conference. Journal of Structural Geology 1. Pergamon, Oxford–New York, International, pp. 95–96.

Platt, J.P., 1984. Secondary cleavages in ductile shear zones. Journal of Structural Geology 6 (4), 439–442.

Platt, J.P., Vissers, R.L.M., 1980. Extensional structures in anisotropic rocks. Journal of Structural Geology 2 (4), 397–410.

Ponce, d.L.M.I., Choukroune, P., 1980. Shear zones in the Iberian Arc. In: Carreras, J., Cobbold, P.R., Ramsay, J.G., White, S.H. (Eds.), Shear Zones in Rocks. Journal of Structural Geology 2(1/2). Pergamon, Oxford–New York, International, pp. 63–68.

Price, N.J., Cosgrove, J.W., 1994. Analysis of Geological Structures, Cambridge University Press, Cambridge.

Siman, P., Johan, V., Ledru, P., Bezák, V., Madarás, J., 1996. Deformation and P–T conditions estimated in “layered migmatites” from southern part of Veporicum crystalline basement (Western Carpathians, Slovakia). Slovak Geological Magazine 3–4/96, 209–213.

Simpson, C., Schmid, S.M., 1983. An evaluation of criteria to deduce the sense of movement in sheared rocks. Geological Society of America Bulletin 94 (11), 1281–1288.

White, S., 1979. Large strain deformation; report on a Tectonic Studies Group discussion meeting held at Imperial College, London on 14 November 1979. Journal of Structural Geology 1 (4), 333–339.