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ANALYSIS OF MOVEMENTS IN BRITTLE SHEAR ZONES

MIROSLAV COUBAL[1)] and JIŘÍ MÁLEK[2)]

[1)] Institute of Geology, Academy of Sciences of the Czech Republic
Rozvojová 135, 165 02 Prague 6, Czech Republic

[2)] Institute of Rock Structure and Mechanics, Academy of Sciences of the Czech Republic
V Holešovičkách 41, 182 09 Prague 8, Czech Republic

ABSTRACT. Two basic groups of shear faults are distinguished in this paper: non–determined faults and determined faults. In non–determined faults, the orientations of the movement directions [illegible] regional stress tensor. Some faults within the brittle shear zones are referred to as determined. Movement directions on determined faults depend on the geometry of the shear zone deformation. Non–determined faults can be used for the computation of paleostress tensor parameters while determined faults can be used for the estimation of the orientations of the shear zone wall and of the movement on this wall.

KEYWORDS: slickensides, brittle shear zone, kinematic analysis

1. INTRODUCTION

Numerical analysis of movements on shear faults, frequently referred to as slickensides, is carried out with the main purpose to determine the paleostress tensor parameters. Paleostress analysis of fault–slip data commonly do not distinguish between faults deforming the rock mass at more or less constant frequency, and faults concentrated into brittle shear zones.

Methods of paleostress analyses assume that the movement direction on a shear fault is defined [illegible] in the text below, the movement orientation on faults within a brittle shear zone may be affected by several other factors, such as the presence of uneven planes of the individual faults, the presence of faults insufficiently separated from the shear zone wall and also the necessity of subcompatible deformation of the zone as a whole. Such faults contain traces of movements, the directions of which do not precisely correspond to the shear stress direction, defined by paleostress tensor parameters. Movement directions found on these planes have, relative to the predicted shear stress direction, orientations closer to the direction of the resulting movement on a shear zone wall.

The deflection of movement directions on faults comprising a brittle shear zone can be used for the determination of its kinematic character. Exposed brittle shear

zones of different sizes are often encountered during geological mapping. Orientations of planes
the shear zone can be usually measured but the general orientation of the shear zone walls
approaches to the solution of this problem have been presented in the literature so far.
placements on the individual faults comprising a brittle shear zone. Marrett and Allmendinger (1990) described a technique of stress tensor determination from the P–axes and T–axes of the individual faults. Cladouhos and Allmendinger (1993) determined
ments. Coubal and Málek (1995) proposed a procedure for the determination of principal parameters of brittle shear zones, based on the assumption of linearity of the relation between the stress in an evenly fractured body and the resulting deformation of the body. It is assumed that the brittle shear zone deformation is composed of simple shear and pure shear components of deformation, which are orientated orthogonally to the

This paper discusses the influences on movement directions on individual faults within britt
as the possibilities of their use for the determination of the kinematic character of the zone as a whole.

2. Shear Fault — its Nature and Slip Orientation

A shear fa
curred subparallel to its plane. Magnitude of the translation component in the direction perpendicular to the fault plane is generally negligible relative to the translation component along the fault plane.

Shear movement on the fault plane can be recorded using different kinematic indicators (e.g. Angelier, 1994; Doblas, 1998), most frequently using striae. The orientation
plane. Methods
gelier, 1994) are based on the relation between paleostress tensor (T), fault plane orientation (n — unit normal to the fault plane) and the vector of stress acting upon this plane (σ).

$$\sigma = T \cdot n \,. \tag{1}$$

Most of the methods of paleostress analysis assume that fault planes have a perfectly planar shape and that striae orientations on these planes are identical with the orientation of shear component of vector σ. Equation (1) implies that planes of different orientat
also that
fault
faults. Irregularities of the shape of fault planes are most frequently cylindrical or dish–shaped (Fig. 1). We suggest that their origin is connected with reactivation of the system
teristic

(e.g. Angelier, 1994; Doblas, 1998). A fault plane composed of several particular surfaces of different
in the model scheme.

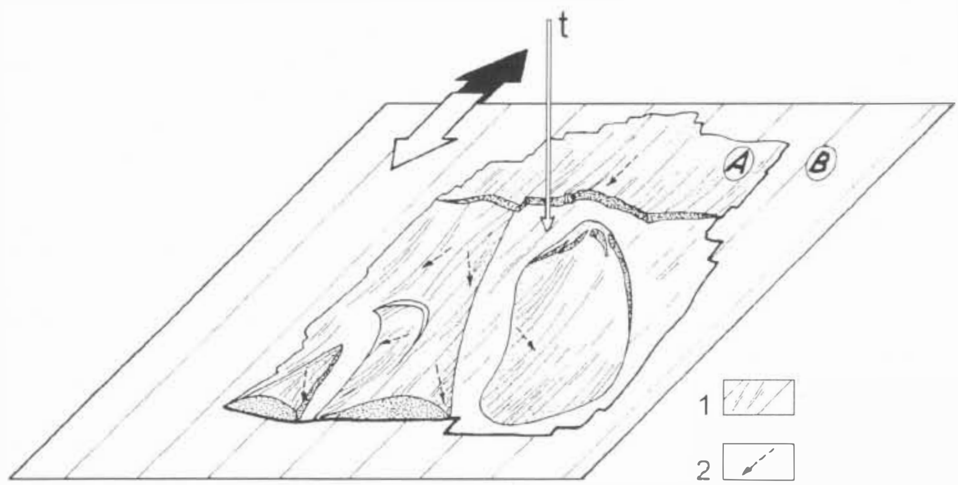

FIG. 1. Slip on subhorizontal slickenside of non–planar geometry with cylindrical or dish–shaped irregularities (A). 1 — striae, 2 — dips of particular planes, B — plane approximating the slickenside, t — stress acting to slickenside plane

Both uneven and composite fault planes can be characterized as a single continuous fault plane, composed of segments of different orientations. Equation (1) implies that the shear movements on these segments should be of different orientations. This is, however, impossible as uneven and composite faults often separate blocks, which show no internal deformation.

As the
the particular planes have the same azimuth as the resulting movement on the composite
direction on the particular planes is defined by the intersection of these planes with a plane perpendicular to the approximated plane and containing a vector of the resulting movement along the composite fault. Orientations of the above mentioned movements along particular planes need not correspond to the shear stress orientation defined by the spatial relation of these planes to paleostress field T acting in the ambience of the composite

An illustrative example of a disproportion between predicted and real striae directions on these planes is shown in Fig. 1. The composite slickenside displayed is composed of many particular planes with a variety of dip orientations. The plane approximating this composite slickenside dips very gently, near horizontally. The effect of a uniaxial, vertically orientated regional stress T resulted in a uniform shear along the composite plane. Therefore, striae on all particular planes have the s azimuth. This contradicts equation (1), according to which the striae orientations should be close to dip orientations of particular

Striae produced by this mechanism may adversely affec of paleostress analysis. The described situation is an example of how movement on a whole plane affects movements on particular planes.

We suggest that an analogous mechanism takes effect also within higher order structures, i.e. brittle shear zones.

3. Kinematics of a Brittle Shear Zone

Brittle within which the intensity ambience. A number of types of the typical examples is a zone, bilaterally bounded by prominent discontinuity or fracture surfaces from the undeformed blocks outside the zone (Ramsay and Huber, 8

Another typical example are zones of concentrated ruptures, the density of which continuously decreases towards the two blocks separated by the zone. In this case the term shear zone wall denotes an axial plane of the zone.

The magnitude of relative displacement of the blocks separated by the zone need not be large. Then, such str ing. Nevertheless, large displacements along brittle shear zones are very common. Regionally important faults, visualized in geological maps. Their study shows that these faults are fractured zones metres to tens of metres wide with a displacement frequently reaching hundreds of metres or even first thousands of metres.

This paper deals with brittle shear zones originated in cold regime only, i.e. under conditions where no ductile deformation of rocks occurred either within or outside the zone. Deformations of magmatic and metamorphic rocks by such zones were produced only after the end of thermal processes. The approach, which is presented in this paper, is f ties. Kinematic modelling of brittle shear zones starts with the assumption that the relative displacement the zone itself occurred are considered rigid and their brittle deformation including the shear zone walls is considered negligible.

Principles of deformation for brittle shear zones parallel those for ductile shear zones with the exception that translation of particles is not continuous but mediated by displacements along individual faults within the zone (Ramsay and Huber, 1987). Orientations of the individual faults and movements on these faults may vary, but the sum of all movements must equal the resulting movements of blocks separated by the zone. In this case, particles are represented by blocks of rocks bounded by the faults within the brittle shear zone. If the particle size is small relative dimensions of the zone, deformation characteristics of the brittle shear zone should be close (Wojtal, 1989) to ductile shear zone deformation (Fig. 3).

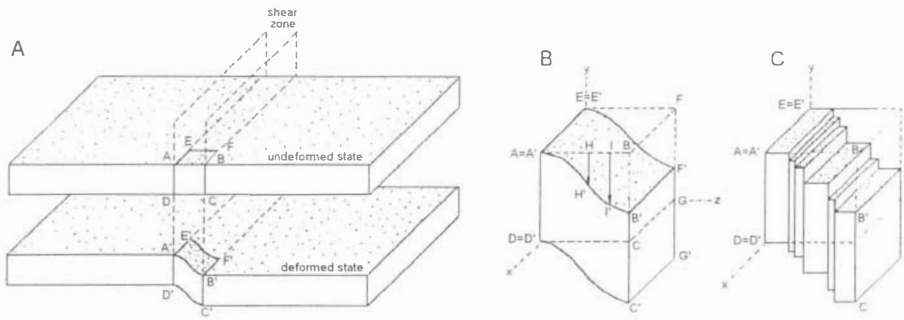

FIG. 2. Shear zone with simple shear deformation geometry. A — initial situation. B — ductile development, C — brittle development mediated by faults of general orientation of shear zone

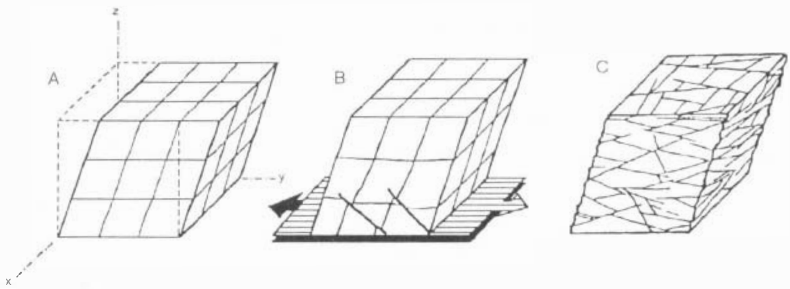

FIG. 3. Shear zone (A) in ductile (B) and brittle (C) development

As it has been proved by Ramsay
a shear zone can be decomposed into three
het
neous deformation affecting both the shear zone and its walls. Movements of distinct particles in simple shear deformati
same time, to the movement on the shear zone wall (Fig 4A). Particle movements in the volume change are parallel
Particle movements in homogeneous deformation are not parallel to one another and have general orientation with

Compression perpendicular to the zone wall may be indicated by tectonic clays orientated and by intensive brecciation of rocks within the zone. In most of the brittle shear zones, however, there are no signs arguing or a significant shortening of the original width of the zone.

Extension in the direction perpendicular to the zone wall is much similar. Veins and fillings indicative of this extension are found in many brittle shear zones. Their thickness usually varies in the order of millimetres to
metres in only exceptional cases (e.g., ore veins).

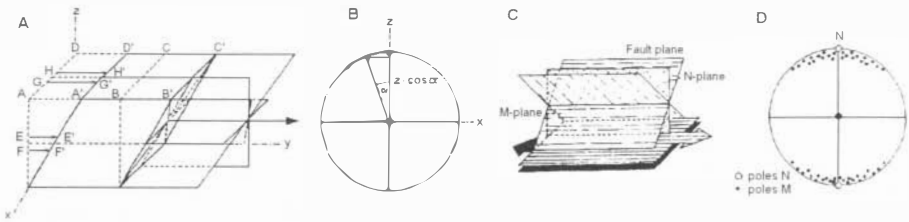

Fig. 4. Simple shear mediated by group of individual faults, whose intersection line is identical with the movement vector on the shear zone wall. A — situation. B — dependence of movement vector length along fault plane on the angle between

planes and N–planes. D — location of poles to M–planes and

The above mentioned facts suggest that the magnitude

nimal in the case of brittle shear zones. A yet smaller contribution to the finite deformation of brittle shear zone is represented by uniform homogeneous deformation affecting both the shear zone and its wall. This is explained by the fact that zones originated in cold regime usually separate blocks showing only a low degree of deformation or no deformation at all. Regional faults with drag folds are an exception.

The text below is based on the statement that most of the brittle shear zones, and the regional faults in particular, are dominated by simple shear deformation component (i.e. translation of blocks parallel to the brittle shear zone walls). The magnitude of other components of finite deformation of the zone is usually significantly lower; their

An M–plane is defined as a plane constructed

and containing its striation line (Arthaud, 1969). An N–plane is defined as a plane containing a striation

the shear zone wall. In the text below, constructed planes referred to as M–planes and N–planes are used for the graphical analysis of movements on faults within the brittle shear zones.

4. Movements on Faults in a Brittle Shear Zone

For the solution of the brittle shear zone kinematics, it is critical to know what movements occurred on differently orientated individual faults within a brittle shear zone, the finite deformation of which is near to simple shear. A reverse formulation of the problem finds a wider application in geological practice: the use of known movements on the individual faults within a brittle shear zone for the determination of principal kinematic characterist

wall and the movement along this wall.

The first problem can be solved from two different viewpoints — the viewpoint of finite deformation of the zone and the viewpoint of paleostress analysis.

4.1. *Finite Deformation Viewpoint*

In this viewpoint, the individual faults will be reactivated in such way, that the movements along these faults produce a simple–shear type of the finite deformation of the zone and the rock massif deformed by the zone remains roughly compatible even after the deformation. This example of deformation and the related assumptions were discussed by Ramsay and Huber (1987).

One of the simple shear features is the parallelism of the particle movements while in the ductile shear zones their length changes continuously (Fig. 2B). In brittle shear zones, the movement of particles is mediated by fault planes (Fig. 2C).

If a deformation strictly conformable to simple shear took place in a shear zone, the movements of particles would be mediated only by those fault planes, whose intersection line is identical with the movement vector on the shear zone wall. Their M–planes intersect in the same line and their N–planes are parallel to the plane of symmetry of the finite deformation of the zone (Fig. 4C). Striae orientations on the above specified fault planes is identical with the particle movement orientations and also with the movement vector on the shear zone wall. Let us examine the difference between lengths of movement vectors of the neighbouring particles separated by these fault planes (Fig. 4). In case the length of movement vector between two neighbouring particles does not reach over a certain value given by the rheology of the rock, elastic or other ductile deformation may occur and no fault may originate.

In contrast, faults separating particles with the greatest difference in movement vector lengths will be reactivated most frequently. The appearance of the particle movement vector (u, v, w) for simple shear

$$
\begin{aligned}
u &= 0\,, \\
v &= \gamma \cdot z\,, \\
w &= 0\,.
\end{aligned}
\tag{2}
$$

indicated that the mutual relative movement vector length of two particles is determined only by the difference in their z–coordinate. Around a chosen point inside the element, neighbouring particles separated by the above described bundle of fault planes lie on a unitary–radius circle on xz–plane (Fig. 4B). The difference of movement vectors of the chosen particle and its neighbour is defined by the relation

$$
\begin{aligned}
\mathrm{d}u &= 0\,, \\
\mathrm{d}v &= \gamma \cdot \mathrm{d}z \cdot \cos\alpha\,, \\
\mathrm{d}w &= 0\,,
\end{aligned}
\tag{3}
$$

where α is the angle between the connection line of the two particles and z–axis.

The distribution of particle movements in simple shear deformation implies that the most frequently reactivated planes are the faults parallel to the shear zone wall. The least frequently planes are the faults close to the yz–plane of the chosen reference frame (Fig. 4D).

Movements on individual faults, which do not correspond to the above mentioned bundle in their orientation, lead to the finite deformation of a zone different from simple shear. If the movements are of low magnitude, they may be compensated by rock compressibility (Fig. 3B), as it has been demonstrated in modelling of the origin of Riedel shears (Riedel, 1929; Tchalenko, 1970). Deformation of a brittle shear zone of simple shear type may be formed by movements on different oriented faults only if complementary faults are created at the same time (Ramsay and Huber, 1987). Both situations may occur when displacement magnitudes on individual faults are small relative to the brittle shear zone size.

Fig. 5 shows two generally orientated sets of individual faults with movements induced by the movement of shear zone walls. The walls are represented by rigid blocks and the dilation of the zone perpendicular to its walls is compensated by rock compressibility. Even such deformation follows the rule that projections of striae on individual faults onto the shear zone wall are parallel to the movement along the zone. Projection planes are perpendicular to the shear zone wall, thus corresponding to the above declared N–planes. In other words, the following rule holds even for those individual faults, whose orientations do not correspond to those of the planes of the above mentioned bundle: their N–planes are parallel to one another, while their M–planes do not intersect in one line.

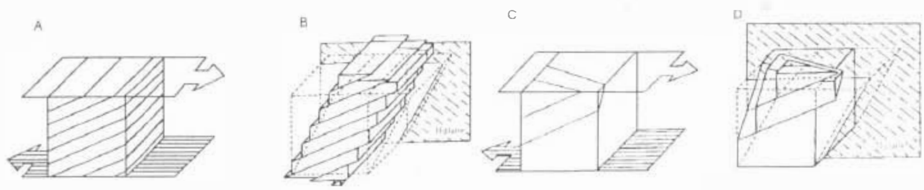

FIG. 5. Movements on simple system of individual faults of general orientation to shear zone. Explanation in text

If the finite deformation of a brittle shear zone is close to simple shear, those individual faults, whose planes intersect in a line identical with the movement vector on the shear zone wall, should be preferably reactivated. Maximum displacement should occur on faults parallel to the shear zone wall. The displacement magnitude on individual faults having orientations different from that of the shear zone wall should decrease as a function of the difference in orientation. In terms of the finite deformation of the zone, striae orientation on the individual faults should be close to the projection of the movement vector on the shear zone wall onto the planes of the individual faults using a projection plane perpendicular to the shear zone wall. In a stereographic projection, the poles to striae should lie on an arc, which is geometrically identical with the simple shear plane of symmetry. Also the N–planes of the individual faults should be identical with this plane.

4.2. *Paleostress Analysis Viewpoint*

According to the elementary presumptions of the paleostress analysis method (Angelier, 1994), the orientation of movement on a shear fault depends only on its spatial relation to the regional stress tensor. Then, the movements on individual faults are only controlled by the orientations of fault planes, being independent of the orientation of the shear zone wall and the movement along the wall. Their M–planes, with the exception of specific cases (Vergely et al., 1987), do not intersect in one line, and their N–planes are not parallel to one another.

The problem of this viewpoint is that it allows — at a specific model distribution of several individual faults — the development of non-compatible deformations of the brittle shear zone (especially large open spaces), which contradicts geological field observations (Ramsay and Huber, 1987). This problem, however, is probably merely theoretical. Stress field becomes affected (Means, 1977; Pollard and Segall, 1987) around prominent inhomogeneities such as brittle shear zones. It can be stated that the regional stress field around these zones is affected in such a way that it has a linear relation to the finite deformation of the zone, which is nearly compatible (Coubal and Málek, 1995). In such cases, the maximum shear stress originates on two sets of individual faults. One of them is parallel to the shear zone wall and the other one is perpendicular to the movement vector on the shear zone wall. M–planes and N–planes of these faults are identical, perpendicular to the shear zone wall, and contain the vector of movement along the shear zone wall. Considering that the brittle shear zone separates two rigid blocks, the maximum movements would probably occur on individual faults parallel to the shear zone wall.

Both of the above mentioned viewpoints agree on the idea that the movement on a brittle shear zone wall corresponds to its orientation relative to the regional stress tensor. However, they substantially diverge from each other in the degree of the effect regional stress had on movements on individual faults within the zone.

As for finite deformation, the role of regional stress is negligible as the movements on individual faults are determined by the movement orientation on the shear zone wall. Analogical case is the movement orientation on particular plane of composite and non–planar slickensides. Orientation of particular plane relative to regional stress field is also of little importance in this case.

Movement orientations on individual faults reactivated in accordance with this model only reflect the orientation of relative movement of the two blocks separated by the shear zone. As such, they can be reasonably used to determine kinematic characteristics of the zone. In contrast, their use in paleostress analysis produces misleading results. In real brittle shear zones, this group of faults should primarily include individual faults formed close to the shear zone wall and faults subparallel to the shear zone wall with large displacement magnitudes. In addition, it may include faults branching off of the faults mentioned above and being insufficiently separated from them. An important geometrical feature of these reactivated faults is the parallelism of their N–planes and also the parallelism of the latter to the plane of finite deformation of the zone (i.e., simple shear). In this paper, the new term is introduced and such reactivated faults are referred to as determined faults.

In the viewpoint of paleostress analysis, movements on faults within the brittle shear zone only reflect regional stress state and show no relation to the kinematics of the zone. Such reactivated faults are further referred to as non–determined. This group includes faults bounding perfectly detached rock blocks within the brittle shear zone as well as individual faults forming broad zones, individual faults in zones with small movements along shear zone walls, associated faults outside the shear zones and at shear zone terminations.

An important indicator of the kinematics of brittle shear zones are the movement magnitudes on the determined as well as non–determined planes. The largest movements may occur on those individual faults whose orientations are close to the shear zone wall; this is particularly true for brittle shear zones with large movements along their shear zone walls. From this viewpoint, it is essential that field measurements include registration of direct and indirect movement magnitude indicators as well as registration of orientations of ruptures with no movement and terminating ruptures.

5. Field Study of Kinematics of Brittle Shear Zones

To test the model presented above, striated faults were analysed at several localities, where important brittle shear zones are exposed — usually regionally significant faults with large displacement magnitudes. Such localities were selected, where the orientation of both the shear zone wall and the movement on the wall could be measured. The results of the analysis are shown in Fig. 6 and generally correspond with the postulated assumptions. The data were summarized in Fig. 7 to emphasize the generally applying features of brittle shear zones. During summarization all the studied brittle shear zones were rotated: brittle shear zone wall strikes N–S and dips 90°, movement on brittle shear zone wall is vertical with left–block–down displacement (dextral sense of movement).

As implies from Fig. 7A, simple shear is really dominant in the studied brittle shear zones, i.e. orientation of most striae on individual faults approaches the orientation of movement on shear zone wall. A significant number of poles to planes of individual faults lie on an arc with an increased frequency of fault planes close to the shear zone wall (Fig. 7C). Besides, poles to many individual faults are concentrated on an arc which represents a plane containing vector of movement on the shear zone wall and being normal to the shear zone wall. These faults are Riedel shears, which can be commonly found in brittle shear zones (Riedel, 1929; Tchalenko, 1970).

M–plane poles of the most frequently reactivated faults are concentrated in one field of the stereoplot (Fig. 7B) which means that the intersections of M–planes form an arc to a belt centered by this field.

These intersection belts originated by mutual intersections of similarly orientated M–planes. Fig. 6 clearly shows that the plane of the belt of M–plane intersections is usually identical with the plane containing two numerically determined principal axes of paleostress tensor as well as the movement vector on the shear zone

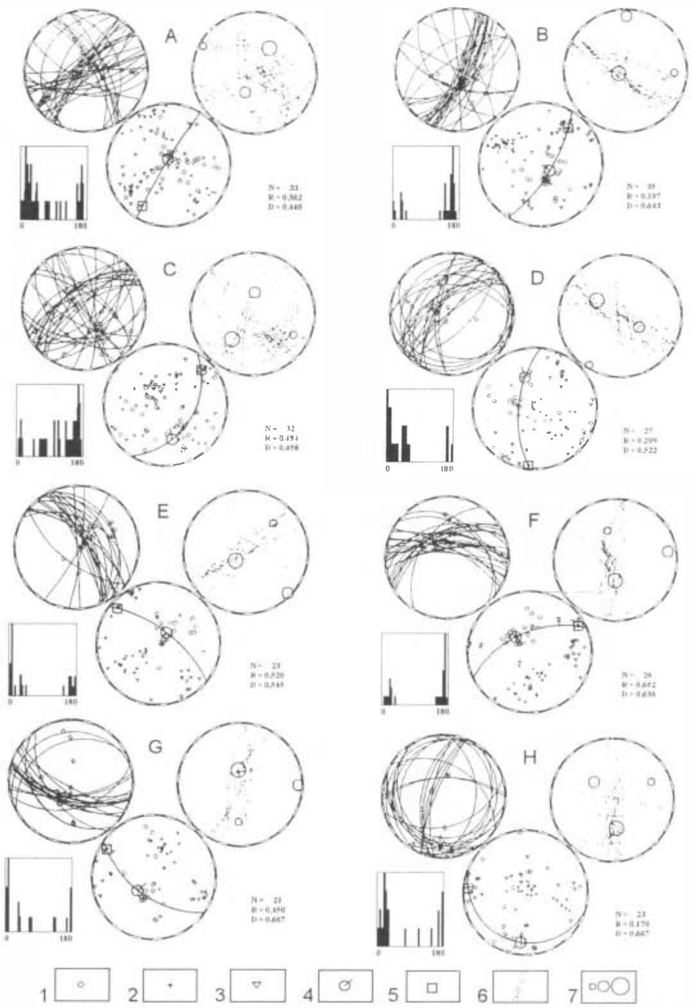

FIG. 6A. Application of the method to different regionally important faults with known orientations of shear zone wall and movement on this wall from the North Bohemian Basin, Lusatian Fault, Krkonoše Piedmont Basin and České středohoří Mts. 1 — striae, 2 — poles to fault planes, 3 — poles to M-planes, 4 — orientation of the movement on shear zone wall calculated from stress tensor, 5 — N-plane pole maximum concentration, 6 — M-plane intersections, 7 — calculated principal stresses, full line arc — shear zone wall determined by the method

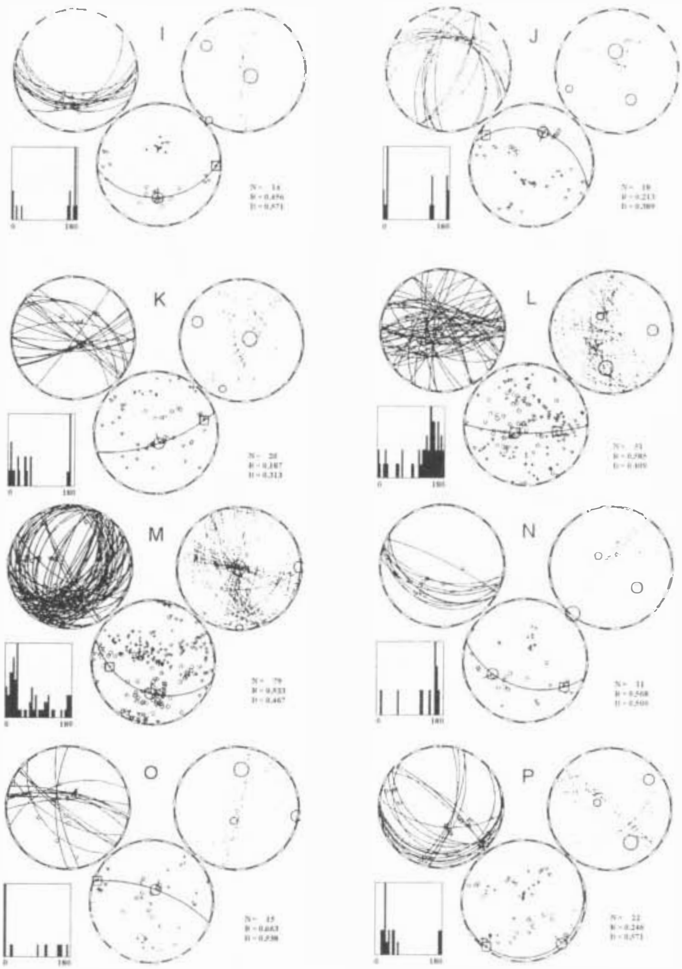

FIG. 6B.

wall. Diagrammatic visualization of intersections of M-planes is advantageous in sets with a lower number of measured individual faults because the zoning of the intersections is obvious.

The orientations of N-planes are also evaluated for the studied brittle shear zones in histograms in Fig. 6. The histogram shows frequencies of normal lines to N-planes in the plane of the shear zone wall, which is known at the given localities. Angular coordinates on the horizontal axis of the histogram were chosen in a manner attributing the value of 90° to the movement direction on the shear zone wall. This direction is also known for the given localities. Prominent maxima of frequencies of normal lines to N-planes for the values of 0° and 180° indicate that this model appropriately describes the kinematics of brittle shear zones. It also documents a high frequency of determined individual faults in the studied zones. This is also shown in Fig. 8 for summarized data.

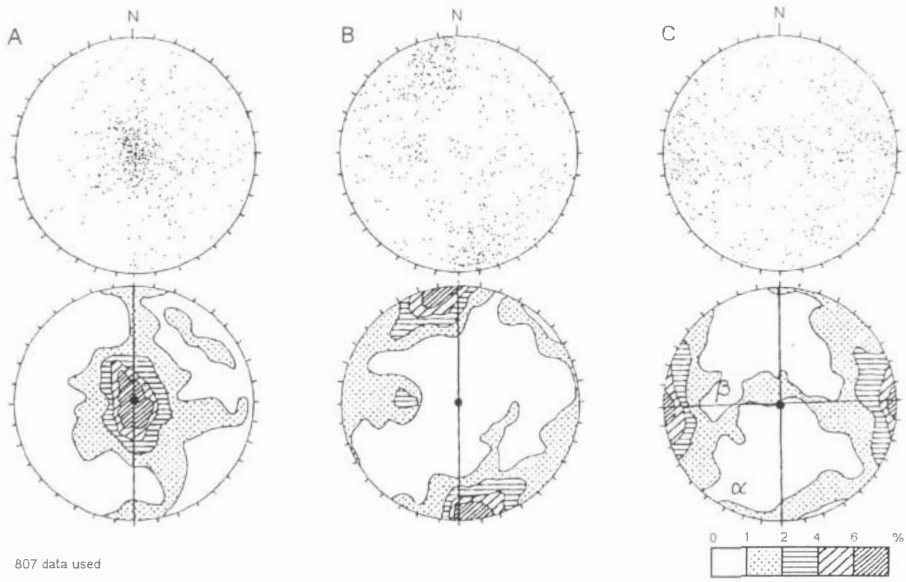

FIG. 7. Results of measurements within shear zones shown in Fig. 6 rotated so that the shear zone wall and movement on this wall were identical. A — striae, B — poles to M–planes, C — poles to individual fault planes

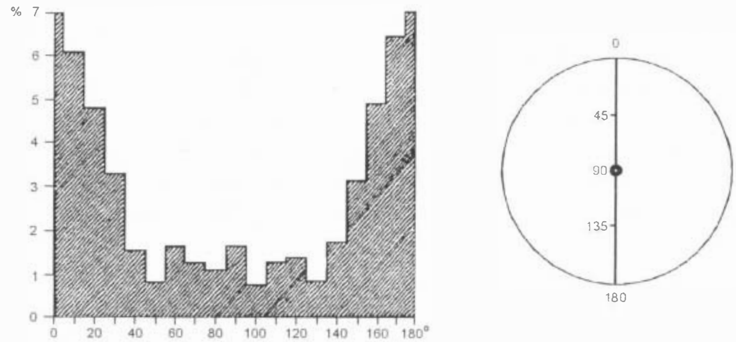

FIG. 8. Dependence of N–plane frequency on the deviation of their direction relative to the movements on shear zone walls for data shown in Fig. 7

6. GEOMETRICAL PRINCIPLES OF DETERMINED PLANE SEPARATION

In accordance with the above described principle, two basic types of shear planes may coexist: determined and non–determined planes. Frequency ratio of both types at a studied locality is determined primarily by its position relative to a possible brittle shear zone: frequency of non-determined planes is directly proportional to increasing distance from the zone axis.

Movement orientation along faults of both groups is affected by different factors, hence, a simple application of paleostress analysis by slickensides within a brittle shear zone can produce insufficient results. The above described method aims at separating both fault groups and describing: paleostress tensor parameters on the basis of non-determined planes, shear zone wall orientation and orientation of movement on this wall on the basis of determined planes. The parallelism of N-planes of differently oriented slickensides is considered as the significant feature of determined fault planes. This criterion is tested during numerical analysis.

Knowledge of the shear zone wall orientation is substantial for the use of the method. Three different situations are possible.

A. The orientation of the shear zone wall can be directly measured in an outcrop or constructed from two linear elements, e.g. fault trace in the field and drag axis (Ramsay and Huber, 1987).

B. Only the fault trace in the field is known, which is the most common case. As demonstrated in Fig. 7A most striae on determined planes in the stereoplot are cumulated around the principal shear projection. This reflects the orientation of the most frequently reactivated faults in fault belts. Most of them — according to Fig. 7C — belongs either to the bundle fitting the simple shear mechanism the best — then, the striae should be parallel to the movement on the shear zone wall — or, to the bundle described by Tchalenko (1970). Here, the striae lie on Riedel shears and P-shears, which are orientated symmetrically with respect to the wall of the originating brittle shear zone. In this case the shear zone wall is constructed as containing the trace of the fault and running through the field with maximum striae concentration.

C. No linear element of the shear zone wall is known (e.g. a fault in monotonous sediments being difficult to locate by geological mapping). Figs. 7B and 7C clearly show, that the poles to M-planes belonging to both groups of faults are cumulated in one area of the stereoplot on an arc representing the shear zone wall. The shear zone wall is, in this case, constructed as a plane running through the centre of the maximum striae concentration area and the centre of the maximum M-plane poles concentration area.

In fault belts, M-plane poles of the preferentially reactivated faults have a similar orientation as N-plane poles, i.e. they lie on the principal fault arc in the proximity of the pole to the shear zone wall symmetry plane. This empirical knowledge is used for shear zone wall construction.

In the following step, it is tested which of the faults can be ranked among the determined ones. After the orientation of the shear zone wall has been determined, N-planes can be constructed for all faults of the respective set. The faults the N-plane poles of which are cumulated along with most M-plane poles in the proximity of the shear zone wall arc are considered determined and are excluded from the computation. If there are more areas of cumulation of N-plane and M-plane poles obtained in the proximity of the shear zone wall arc, this is considered to be a result of movements in several phases and the whole problem is solved as a polyphase one.

The above described constructions have been completed for 16 faults with good results (Fig. 6).

The phenomenon of stereoplot striae cumulation occurs also in the case described by Vergely et al. (1987) and under the influence of radial stress. In these cases M–plane poles are distributed along the whole length of an arc centred by the striae cumulation field and the N–planes are not parallel to one another. Grouping of M–plane and N–plane poles is thus a diagnostic feature. Most of the M–plane poles should cumulate along the principal fault arc which is an evidence for correct determination of principal fault orientation.

The determined and non–determined planes cannot be distinguished on the basis of the above given criteria in the only single case: the bundle of fault planes intersecting in one line is reactivated in such a manner that the striae lie on a plane normal to this line.

7. Numerical Principles of Fault Movement Analysis

First methods for stress tensor determination based on slickenside measurements were of graphic nature, however, computers started to be used shortly thereafter. Inversion of the stress tensor is a typical inverse problem (Tarantola, 1987), which is moreover complicated in case of the presence of several tectonic phases (Angelier et al., 1982; Angelier, 1984; Angelier, 1994). The problem is also complicated by the presence of the determined fault planes. As it has been shown above, the movement orientation on these planes is not controlled by the stress tensor but the brittle shear zone kinematics. The determined planes must be recognized before the entire calculation, otherwise they produce outliers in the data set and strongly bias the calculated stress tensor parameters.

If simplified, the movement during a single tectonic phase along preexisting non–determined fault planes can be considered as controlled by a spatially homogeneous stress tensor at a given locality. Then, the movement direction is the same as the direction of tangential stress component acting upon the fault plane. This can be expressed by the equation:

$$ks = T \cdot n - (n \cdot T \cdot n)n\,, \qquad (4)$$

where s is a unit vector — direction of slickenside, n is a unit vector — normal to i–th plane, T is stress tensor, k is a scalar constant and $\cdot$ denotes the scalar product.

In more advanced methods, the slickenside is considered to be potentially formed only on those faults, where the amplitude of tangential stress is greater than the friction on fault planes:

$$(T \cdot n - (n \cdot T \cdot n)n) \cdot s > \tau n \cdot T \cdot n\,, \qquad (5)$$

where τ is the coefficient of friction.

This means that only some of the preexisting faults with specific orientations are activated. The inclusion of friction in the inverse problem solution imposes additional constraints on the computation.

It should be also taken into account that the sense of movement can be determined in only some of the slickensides in the field. In addition, pertinence to a particular tectonic phase cannot be distinguished from the field measurements only. Solving a polyphase problem, it is necessary to calculate several stress tensors at the same time, which apply to the individual phases, and to distribute the measured data so that each measurement was attributed to a single phase.

At the beginning of the computation, it is necessary to discriminate between determined and non-determined fault planes. The measurements taken from the determined faults cannot be directly used for stress tensor computation. However, they are helpful in the estimation of the number of tectonic phases. The methods of determined fault discrimination were described in the preceding chapter.

Such formulated polyphase problem with simultaneous recognition of determined faults is solved by the ROCK computer program. This program is derived from the method of Málek et al. (1991), which was supplemented by determined fault discrimination. As the result of the computation, a single stress tensor is obtained for each tectonic phase. The application of the stress tensor to the shear zone wall reveals movement on the shear zone wall which can be compared with the movement direction on the shear zone wall as calculated from the determined fault planes.

8. Conclusion

The observations of slickensides with uneven geometries resulted in the distinguishing of a separate group of shear faults, called determined faults. This term denotes fault planes lying within a higher-order structure and showing insufficient autonomy in relation to this structure. The orientation of movement along these faults is therefore controlled by the kinematics of the higher-order structure, and not by their orientation to the regional stress tensor.

This approach was applied to the study of brittle shear zones with the aim to characterize their kinematics by means of studying movements on individual faults within these zones. Such approach is particularly useful in the study of regionally significant faults (e.g. Lusatian Fault), often having the character of broad fracture zones.

This paper provides basic principles of discrimination between determined and non-determined faults. The determined faults are used for the characteristics of the brittle shear zone kinematics, the non-determined faults are used for the computation of paleostress responsible for the deformation studied.

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References

Angelier J.: 1984. Tectonic analysis of fault slip data sets. *J. geophys. Res.* **89**, 5835–5848.

Angelier J., Tarantola A., Valette B., Manoussis S.: 1982. Inversion of field data in fault tectonics to obtain the regional stress. *Geophys. J. R. astr. Soc.* **69**, 607–621.

Angelier J.: 1994. Fault slip analysis and paleostress reconstruction. In P. L. Hancock (ed.) *Continental Deformation*, 53–100. Exeter: Pergamon Press Ltd.

Arthaud F.: 1969. Méthode de détermination graphique des directions de raccourcissement, d'allongement et intermédiare d'une population des failles. *Bull. Soc. geol. Fr.* **11**, 729–737.

Cladouhos T.T., Allmendinger R.W.: 1993. Finite strain and rotation from fault slip data. *J. Struct. Geol.* **15**, 771–784.

Coubal M., Málek J.: 1995. Stress–strain relation model of brittle shear zones. In H. P. Rossmanith (ed.) *Mechanics of Jointed and Faulted Rocks*, 231–234. Vienna, Balkema.

Doblas M.: 1998. Slickenside kinematic indicators. *Tectonophysics* **295**, 187–197.

Málek J., Fischer T., Coubal M.: 1991. Computation of regional stress tensor from small scale tectonic data. *Publs. Inst. Geophys. Pol. Acad. Sc.* **M–15** (235), 77–92.

Marret R., Allmendinger R.W.: 1990. Kinematic analysis of fault — slip data. *J. Struct. Geol.* **12**, 973–986.

Means W.D.: 1977. *Stress and Strain: Basic concepts of continuum mechanics for geologists.* Springer Verlag , Berlin.

Pollard D.D., Segall P.: 1987. Theoretical displacement and stresses near fractures in rocks with applications to faults, joints, veins, dikes, and solution surfaces. In: *Fracture Mechanics of Rock* (edited by Atkinson B.K.), Academic Press, London, 277–350.

Ramsay J.G., Graham R.H.: 1970. Strain variation in shear belts. *Canad. J. Earth Sc.* **7**, 786–813.

Ramsay J.G., Huber M.I.: 1987. *The techniques of modern structural geology.* Vol.2: Folds and Fractures. Academic Press, London.

Tarantola A.: 1987. *Inverse problem theory. Methods for data fitting and model parameter estimation.* Elsevier, Amsterdam.

Tchalenko J.S.: 1970. Similarities between shear zones of different magnitudes. *Geol. Soc. Am. Bull.* **81**, 1625–1640.

Verglely P., Sassi W., Carey-Gailhardis E.: 1987. Analyse graphique des failles à l'aide des focalisations de stries. *Bull.Soc.geol.France.* **8**, 3, 2, 395–402. Paris.

Wojtal S.: 1989. Measuring displacement gradients and strains in faulted rocks. *J. Struct. Geol.* **11**, 669–678.

Analýza pohybů v křehkých střižných zónách

Miroslav COUBAL a Jiří MÁLEK

V geologické minulosti byla zemská kůra vystavena působení napětí, která zanechala stopy v podobě křehkých a duktilních deformací hornin. Analýzou těchto stop lze rekonstruovat směr působení a tvar tenzoru napětí. Nejčastěji se k tomuto účelu využívají smykové zlomy různých rozměrů, na jejichž plochách je dokumentován směr pohybu prostřednictvím striací.

Dosavadní práce, věnované tomuto tématu, vycházejí z předpokladu, že směr pohybu na smykovém zlomu je dán pouze jeho orientací vzhledem k tenzoru působícího napětí. V předkládané práci je diskutován často se vyskytující případ smykových zlomů s nerovnými plochami. Podle uvedeného předpokladu by na různě orientovaných částech těchto ploch mělo docházet k různě orientovaným pohybům. To však často není možné, protože nerovné zlomy oddělují souvislé, dále neporušené bloky, které se vůči sobě mohou pohybovat jedině jako jeden celek. Z toho vyplývá, že na některých částech nerovných ploch zlomu dochází k pohybu, který nemusí být rovnoběžný se střižnou složkou napětí na této části zlomu. Předpokládáme, že tento mechanismus se uplatňuje i na souboru zlomů, které tvoří křehkou střižnou zónu.

Křehké střižné zóny jsou části horninových těles, které jsou podstatně intenzivněji křehce deformovány než jejich okolí. Pohyb bloku podél zóny je realizován prostřednictvím pohybu na řadě dílčích zlomů. Křehké střižné zóny mohou mít různou velikost, od mikroskopických rozměrů až po regionálně významné zlomy. Směr pohybu na regionálních zlomech často nelze určit přímým pozorováním. V tomto článku je navržen způsob jeho určení na základě směru pohybu na dílčích zlomech, které je tvoří.

Jsou vymezovány dvě základní skupiny smykových zlomů, tvořících křehkou střižnou zónu. Na plochách zlomů první skupiny, označovaných jako nedeterminované zlomy, závisí orientace striací pouze na orientaci jejich ploch vzhledem k tenzoru paleonapětí. Do druhé skupiny patří zlomy, na kterých je orientace striací dána geometrií pohybu na stěně střižné zóny. Pro tyto zlomy zavádíme termín determinované zlomy. Analýzou nedeterminovaných zlomů jsou určovány parametry tenzoru paleonapětí, které způsobilo jejich oživení. Analýzou determinovaných zlomů je určována kinematika křehké střižné zóny, které jsou součástí. Vzhledem k předpokladu, že křehké střižné zóny se deformují především mechanismem prostého střihu, je analýzou determinovaných zlomů určována orientace pohybu na stěnách střižné křehké zóny.

Jsou prezentovány výsledky numerické analýzy paleonapětí a směru pohybu na několika regionálně významných zlomech Českého masívu.