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Slickenside kinematic indicators

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Abstract

A new classification of slickenside kinematic indicators is presented based on 61 criteria. These slickensides have been subdivided into eleven major groups: 'V' or crescentic markings, steps, fractures, trains of inclined planar structures, trailed material, asymmetric elevations, deformed elements, mineralogical/crystallographic orientations, asymmetric plan-view features, asymmetric cavities, and asymmetric folds. This classification constitutes a useful tool for geologists interested in the determination of the shear sense in fault surfaces bearing slickensides. Examples of application of this classification to natural fault surfaces at different scales are presented.

Keywords: classification; slickensides; fault surfaces; kinematic indicators

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1. Introduction

The deduction of the sense of shear on fault surfaces from slickensides has been a usual procedure in structural geology for many years, particularly in the brittle field. Even if these kinematic criteria are key elements in many geodynamic studies (e.g. paleostress reconstructions inferring continental-scale scenarios; Angelier, 1994), the detailed analysis of these indicators is not always fully undertaken. In this sense, it is noteworthy that many textbooks in structural geology lack any real attempt to deal with this subject apart from a brief description of the most obvious criteria (Mattauer, 1976; Davis, 1984; McClay, 1987; Ramsay and Huber, 1987). The classification of the 'brittle' slickenside kinematic criteria has been put forward by Petit et al. (1983), Doblas (1985, 1987), Petit (1987), Mercier and Vergely (1992) and Angelier (1994).

Other alternative types of slickensides have never been included in these classifications: ductile (Doblas, 1987; Means, 1987; Wilson and Will, 1990), hydroplastic (Petit and Laville, 1987), pedogenic (Gray and Nickelsen, 1989), igneous (Smith, 1968; Doblas et al., 1988), antropic (Spray, 1989), neotectonic (Hancock and Barka, 1987; Doblas et al., 1993, 1997a), microscopic (Lee, 1991), etc . . .

The available classifications are clearly insufficient and the time has come to summarize the overwhelming amount of slickenside data which have accumulated through these years. This is precisely what this paper intends to do, suggesting a new classification of the shear sense criteria in slickensides, and describing how this classification might be used in a practical way in some natural fault examples at different scales.

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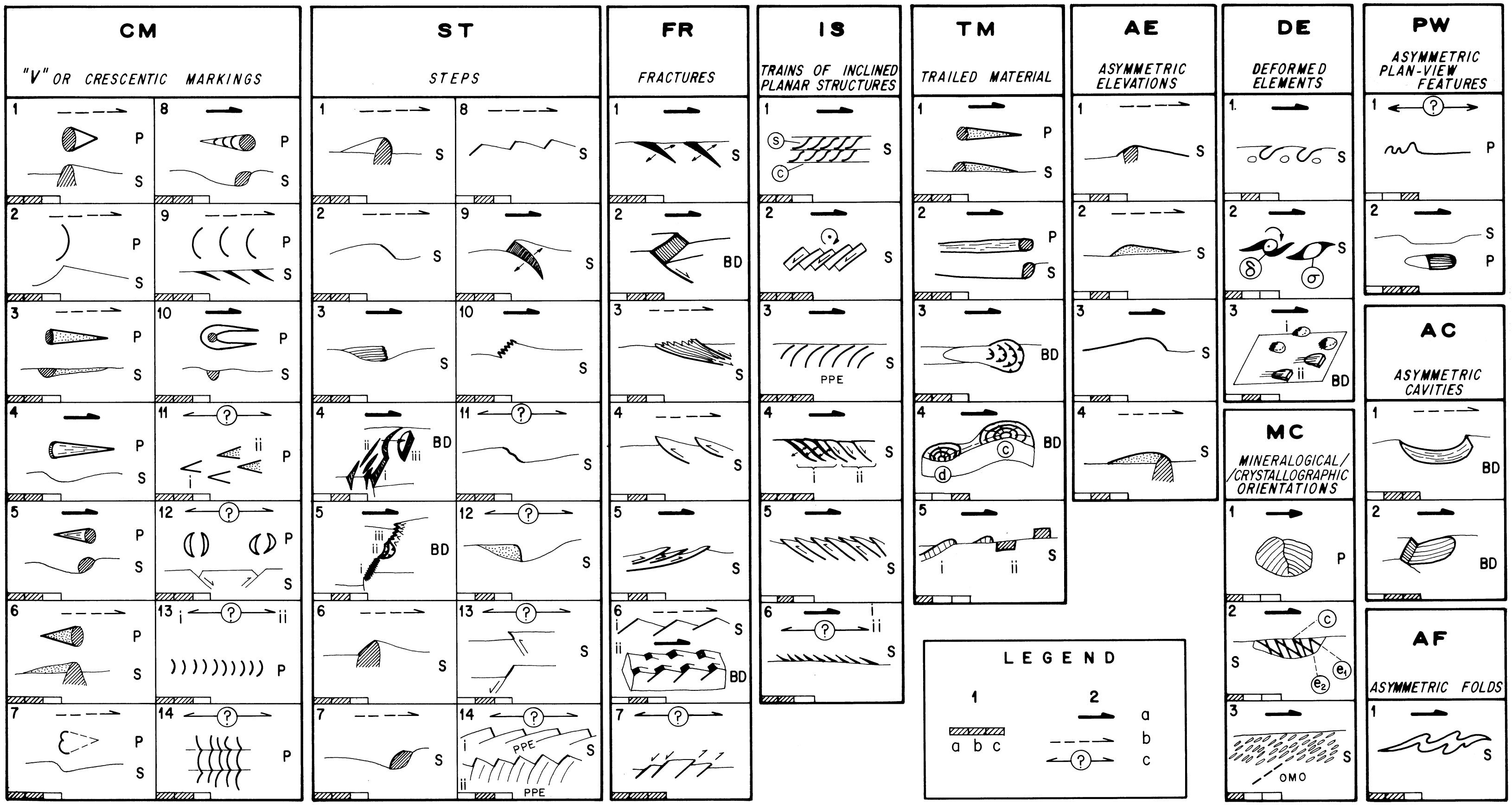


Fig. 1. Classification of slickenside kinematic indicators. See text for complete details. The same numbers and abbreviations shown in this table are used in the text. Legend: *1* = scale of occurrence of the indicators (*a* = microscopic; *b* = tens of millimeters; *c* = metric); *2* = three different types of arrows (pointing in the direction of movement of the missing block) indicate the degree of confidence in each one of the kinematic indicators (*a* = good; *b* = fair; *c* = poor); *BD* = block diagram; *OMO* = oblique mineralogical orientation; *PPE* = previous planar element; *P* = plane; *S* = section.

2. Classification of slickenside kinematic indicators

The following is a new classification of 61 slickenside kinematic indicators, which are subdivided into eleven major groups (Fig. 1). These major groups have been established according to a series of morphological and geometrical characteristics. This classification will depict the approximate scale of occurrence of the different slickenside structures (microscopic to metric), as well as the degree of confidence that might apply to each kinematic indicator: good, fair, or poor. A 'good' criterion should have been recognized as such in the references and/or verified in natural examples during the present researches. A criterion will be considered 'fair' (even if it has been cited in the literature) if it has not been verified in nature during the course of the present work. Finally, a 'poor' criterion will be defined if contradictory shear senses have been either published or observed. The classification shown in Fig. 1 describes the different slickenside kinematic indicators as described below:

2.1. 'V' or crescentic markings (CM)

These markings are found on the slip surfaces of the fault surfaces (CM in Fig. 1). Some of these features have their acute angles or concavities facing against the motion of the opposite block: (1) *Sheltering trails* usually termed 'trails' (Willis and Willis, 1934), 'trailing ridges' (Tjia, 1967), or 'sheltered gouge trails' (Power and Tullis, 1989), are also similar to 'scour marks' in snow (Allen, 1965). These figures result from the sheltering effect of protuberances acting as hard objects. (2) *Stepped crescentic marks* (Willis and Willis, 1934; Tjia, 1968) occur singly (rather than as a series, like chatter marks; Tjia, 1968), and they are formed by secondary shear fractures disrupting some protruding sectors of the fault surfaces. (3) *Debris trails* (Doblas, 1987) correspond to V-shaped streaking of debris away from a visible grain or protuberance. (4) *Gouging/plucking markings* are good indicators in active normal faults, and they are constituted by carrot-shaped features resulting from the gouging effect of grains plucked away (Doblas et al., 1995, 1997a).

Other markings have their acute angles or concavities facing in the opposite direction: (5) *Gouging-grain grooves* (Tjia, 1964, 1967; Jackson and Dunn, 1974; Doblas, 1985, 1987; Spray, 1989), 'molded grooves' (Willis and Willis, 1934), 'prod marks'(Tjia, 1968), or 'microscopic wear grooves' (Engelder, 1974a,b), are carrot-shaped features which represent trails left by moving/grooving grains which are finally indented on the fault surface (they are usually reliable). (6) *Spurs* (Willis and Willis, 1934; Tjia, 1967) or 'triangular patches of gouge' (Norris and Barron, 1969) are formed by fault material piled up against protuberances. (7) *Tectonic flutes* (Dzulynski and Kotlarczyk, 1965; Doblas et al., 1995, 1997a) or 'niches d'arrachement' (Vialon et al., 1976) result from the plucking away of fault material leaving complex concave features behind. (8) *Chatter marks* are good kinematic criteria constituted by trains of curved fractures on the bottom of groove-trails (Tjia, 1967; Willis and Willis, 1934). (9) *Tension gashes* occasionally display crescentic outlines in ground plan (Dzulynski and Kotlarczyk, 1965). (10) *Spoon-shaped depressions* are reliable indicators which have been described around small hard particles in active normal faults (Power and Tullis, 1989).

Finally, some other 'V' or crescentic markings are oriented either way, and thus, they are poor kinematic indicators: (11) Small groups of 'V'-shaped features have been described as: (i) *Scratches and striations* produced by gouging hard particles (Willis and Willis, 1934; Tjia, 1967), and (ii) *bruises* caused by the elongated streaking of debris fault material (Willis and Willis, 1934; Tjia, 1967, 1968; Jackson and Dunn, 1974), also known as 'éléments broyés' (Vialon et al., 1976). (12) A long list of *normal and reverse microfractures* with mostly concave markings has been cited: 'crescentic gouge or fractures', 'sagged grooves', 'lunate fractures', 'lunules tectoniques de plis', 'croissants concaves', etc ... (Harris Jr., 1943; Dzulynski, 1953; Wegman and Schaer, 1957; Paterson, 1958; Tjia, 1968; Mattauer, 1976; Petit et al., 1983; Petit, 1987; Spray, 1989). (13) Similarly, many different *trains of crescentic-shaped fractures* have been described: 'crescentic fractures or gouge', 'curved pinnate secondary shears', 'lunate friction cracks', 'parabolic marks', 'comb fractures', 'arcatures', 'broutures', etc ... (Willis and Willis, 1934; Harris Jr., 1943; Tjia, 1967; Wardlaw et al., 1969; Hancock and Barka, 1987;

Sellier and Bossière, 1993; Angelier, 1994). These trains of crescentic fractures might be oriented with their concavities facing towards the movement of the opposite block [(i) 'arcatures'; Sellier and Bossière, 1993], or in the opposite direction [(ii) 'broutures'; Sellier and Bossière, 1993]. In some case it might be possible to distinguish them: 'arcatures' are formed by sliding and no plucking of fault material occurs, while 'broutures' are related to rolling objects which trigger plucking of fault material (Johnson, 1975; Lawson, 1983; Sellier and Bossière, 1993). (14) The last criterion of this group is constituted by *slickenside chevrons* (Dzulynski and Kotlarczyk, 1965) also called 'cannelures à fissures en chevron' (Vialon et al., 1976), which correspond to relatively broad longitudinal grooves separated by narrow ridges, giving rise to 'V' and concave markings pointing in opposite directions.

2.2. Steps (ST)

Steps are found in sections normal to the fault surfaces in the direction of the movement, and they are usually subperpendicular to the striae (ST in Fig. 1). This criterion is based on the orientation of the risers of steps (which might be defined by planar elements, or asymmetric protuberances or grains), either facing in the same direction that the motion of the opposite block ('positive smoothness criterion', Angelier, 1994; or, 'congruous steps', Norris and Barron, 1969), or the opposite ('negative smoothness criterion'; Angelier, 1994; or, 'incongruous steps'; Norris and Barron, 1969). This criterion might be described as 'the relative amounts of felt friction which occurs when the observer's hand moves in opposite senses on the fault parallel to a slickenside lineation' (Angelier, 1994). A classification of steps including six incongruous varieties produced by frictional-wearing and two congruous ones associated to accretionary growth fibers was suggested by Hancock (1985). However, this is an oversimplification, and the present paper will show that things are much more complex, with at least fourteen different types of steps involving a wide variety of deformation mechanisms.

Several features correspond to the classical 'positive smoothness criterion' (Billings, 1942) which was widely used until recent times: (1) *Spurs* (Willis and Willis, 1934; Tjia, 1967, 1968). (2) *Knobby elevations* (Dzulynski and Kotlarczyk, 1965; Doblas, 1991) or 'slickenside roches moutonnées' (Tjia, 1967, 1968), which are asymmetric elevations formed directly on the wall rock of a fault. (3) *Crystal fibers* are among the best kinematic indicators and they correspond to neoformed minerals growing congruously in shadow zones (Durney and Ramsay, 1973; Hobbs et al., 1976; Mattauer, 1976; Vialon et al., 1976; Petit et al., 1983; Doblas, 1985, 1987, Doblas, 1991; Lee and Means, 1990; Lee, 1991). (4) Three different types of *tension-related detailed features* described in some congruous steps of active normal faults constitute excellent kinematic criteria (Doblas et al., 1995, 1997a): sharp borders (i), tension fractures (ii), and detached fragments (iii).

Other features correspond to a 'negative smoothness criterion' in that the risers of the steps face against the motion of the opposite block (uncongruous steps; Norris and Barron, 1969): (5) Three excellent types of *contraction-related detailed features* have also been described in some incongruous steps of active normal faults (Doblas et al., 1995, 1997a): damaged borders (i), thrusted microflakes (ii), and arrow-shaped microindentations (iii). (6) *Sheltering trails* (Willis and Willis, 1934; Tjia, 1967, 1968; Means, 1987; Power and Tullis, 1989). (7) *Gouging-grain grooves* (Tjia, 1967; Petit et al., 1983; Petit, 1987). (8) *P fractures*, which are also called 'reliefs amont striés' (Petit et al., 1983; Petit, 1987), and constitute secondary striated shear fractures of P orientations. (9) *Tension gashes* are good kinematic indicators (Dzulynski and Kotlarczyk, 1965; Tjia, 1967; Vialon et al., 1976; Petit et al., 1983). (10) *Slickolites* (Arthaud and Mattauer, 1969; Mattauer, 1976; Means, 1987; Hancock, 1985) are formed by oblique stilolized peaks, and they are among the best kinematic indicators.

Finally some steps may correspond to a 'positive' or a 'negative smoothness criterion', and hence they are poor kinematic indicators: (11) *Plucking steps* might be either congruous or incongruous, and many authors have described them (Dzulynski and Kotlarczyk, 1965; Riecker, 1965; Tjia, 1964, 1967; Norris and Barron, 1969; Hobbs et al., 1976; Vialon et al., 1976; Doblas, 1985, 1987; Lin and Williams, 1992). (12) The same happens with *accretion steps* which are formed by the plastering of fault material in shadow zones (Dzulynski and Kotlarczyk, 1965; Tjia, 1967; Norris and Barron, 1969; Spray, 1989). (13) Many varieties of *synthetic and antithetic fractures* have been recognized such as 'secondary pinnate shears', 'Riedel fractures', 'feather fractures', 'failles secondaires F', 'gradins de diaclases pennées', etc ... (Harris Jr., 1943; Rod, 1966; Tjia, 1967; Currie, 1969; Norris and Barron, 1969; Vialon et al., 1976; Petit et al., 1983). (14) The *drag-effect on previous planar elements* might also trigger congruous (i) and incongruous (ii) steps (Vialon et al., 1976). It is only possible to use these steps as reliable kinematic indicators in the case of the congruous steps of SC mylonites (Lin and Williams, 1992).

It might be concluded that the classical 'smoothness-roughness hand' technique of Billings (1942) for determining the sense of shear from the orientation of the risers of the steps may still be used with reliability (see also Rod, 1966) in two specific cases where the following steps predominate: in calcareous rocks deformed in the upper structural levels with congruous steps related to the growth of crystal fibers (criteria ST3; Durney and Ramsay, 1973); and, in strongly deformed SC ductile mylonites where rough congruous steps predominate (criteria ST14i; Lin and Williams, 1992).

2.3. Fractures (FR)

The fractures which might be used as kinematic indicators are observed in sections perpendicular to the fault surface in the direction of the movement (FR in Fig. 1). The criterion in this case is based on the inclination of these fractures. Some of them dip towards the motion of the opposite block: (1) *Tension gashes* are among the best criteria to deduce the sense of shear in slickensides (Dzulynski and Kotlarczyk, 1965; Tjia, 1967; Vialon et al., 1976; Doblas, 1985, 1987; Petit, 1987), including on a microscopic scale (Lee, 1991) with 'flake-like glass in gouge' (Norris and Barron, 1969) or 'microscopic feather fractures, mff' (Friedman and Logan, 1970; Conrad II and Friedman, 1976). (2) *Synthetic hybrid fractures* are good kinematic criteria in active normal faults (Doblas et al., 1995, 1997a,b). They might be called 'hybrid fractures' (following the nomenclature of Hancock, 1985) as they are not truly R1 Riedel fractures (they display angles between 30 and 50º) and they are synthetic and inclined downwards. Meter-scale spoon-shaped varieties are common in neotectonic extensional faults (Doblas et al., 1995, 1997a,b). (3) *Step-like synthetic R1 Riedels with swollen compartments* are typical of hydroplastic faults (Petit and Laville, 1987). (4) *Reverse R2 Riedel fractures* (F1 or R0 fractures of Petit et al., 1983; Petit, 1987).

However, some other fractures are inclined in the opposite direction: (5) *Microthrusts* are among the best kinematic indicators (Doblas, 1987), and may be associated with trailed/thrusted material (criterion TM3; Doblas et al., 1995, 1997a,b). (6) *P fractures* (Petit et al., 1983; Petit, 1987) might be either fair kinematic indicators [when they are found as isolated fractures (i)], or good shear sense criteria [when they are found in groups, and form a pervasive fabric on the fault surface (ii)].

A wide group of *synthetic and antithetic fractures* (7) which are usually found alone, and which have no further specific characteristics, constitute poor kinematic indicators i.e., they may be inclined in any direction (Harris Jr., 1943; Tjia, 1967; Currie, 1969; Norris and Barron, 1969; Engelder, 1974b; Jackson and Dunn, 1974; Vialon et al., 1976; Logan et al., 1979; Petit et al., 1983; Petit, 1987; Lee and Means, 1990; Lee, 1991; Doblas, 1991).

2.4. Trains of inclined planar structures (IS)

A series of very useful criteria is constituted by trains of 'en echelon' inclined planar structures (IS in Fig. 1) that are inclined towards the movement of the opposite block: (1) *SC-type geometries* are constituted by S sigmoids and C shearing planes (P and Y planes in the brittle field) and they are commonly found in highly deformed slickenside fault rocks (Petit et al., 1983; Doblas, 1985, 1987; Petit, 1987; Lee and Means, 1990; Lee, 1991; Crespi, 1993). (2) *Domino-type offset* showing tilted blocks with antithetic fractures (Doblas, 1985, 1987; Lee and Means, 1990; Lee, 1991). (3) *Drag-effect* which bends previous planar elements (Doblas, 1987, 1991; Lee, 1991).

Another group of these criteria is characterized by inclinations in the opposite direction: (4) *Sigmoidal tension gashes* (i), *R1 Riedel or synthetic hybrid fractures* (ii) are also good kinematic indicators forming ‘en echelon’ arrangements (Doblas et al., 1995, 1997a). (5) *Reverse R2 Riedel fractures* have also been described in slickensides (F1 or R0 fractures of Petit et al., 1983; Petit, 1987).

The last criterion has been identified with both inclinations, but as two distinct types: (6) *Slickenside flakes* have been described as partly attached flake-like material dipping in the direction of movement of the missing block, as associated to soft-sediment deformation in near-surface environments (Spray, 1989). This criterion (i) is excellent (even if it is useless from a tectonic point of view) in soft-sediments which have undergone ‘antropic’ mechanical excavation, and which display abundant flakes. However, contrary inclinations (ii) have also been described in isolated microscopic flakes associated to C shearing planes in SC mylonites (Doblas, 1987) or to deformed surfaces generated by glacial abrasion (‘microécailles’; Bossière and Sellier, 1993).

2.5. Trailed material (TM)

The trailing of fault material in the direction of the movement of the opposite block has been shown to be an excellent kinematic indicator (TM in Fig. 1): (1) *Trails of debris* away from a protruding element (Doblas, 1985, 1987). (2) *Trailed grains* accompanying ‘gouging-grain grooves’ and which are characterized by a grain plastered at the end of a gouge trail (Tjia, 1967; Jackson and Dunn, 1974; Mattauer, 1976; Doblas, 1985; Spray, 1989). (3) *Thrusted/trailed material* (Doblas et al., 1995, 1997a,b) constitute flakes of fault material torn away and trailed in the direction of the missing block with frontal microthrusts and tensile fractures (these last features appear also in the back of the thrusted pads). Special cases observed in hydroplastic faults are the ‘tappering grooves’ and ‘thrusted pads’ of Petit and Laville (1987). Similar examples indicative of some kind of kinematic picture are also observed in soft-sediment glacial grooves (Savage, 1972), in synsedimentary erosional flute- or groove-casts (Roberts, 1991), or in still plastic grooved lava (Nichols, 1938). (4) *Culmination/depression figures* (Doblas et al., 1995, 1997b) are meter-scale/oval-shaped features where material has been removed from the depression (d in Fig. 1) and transported by movement on the fault to form the culmination (c in Fig. 1) ahead of the depression. These two last criteria (TM3 and TM4) have been observed in low-angle extensional detachments, and the morphology of the different structures observed under the microscope suggests that they deformed in a macroscopically ductile manner by the process of cataclastic flow, before deformation became localized into fault surfaces (Doblas et al., 1995, 1997b). (5) The last case has been described under the microscope and corresponds to *flexed and torn minerals* (i in Fig. 1; Norris and Barron, 1969; Doblas, 1985) and *grain offsets* (ii in Fig. 1; Lee and Means, 1990; Lee, 1991).

2.6. Asymmetric elevations (AE)

Asymmetric elevations are observed in sections perpendicular to the fault surface in the direction of the movement (AE in Fig. 1). Some elevations have their steep slopes facing the motion of the opposite block: (1) *Sheltering trails* (Tjia, 1967; Gay, 1970). (2) *Triangular patches of gouge* (Norris and Barron, 1969).

Some other elevations have their steep slopes facing in the opposite direction: (3) *Knobby elevations* are considered good kinematic indicators (Dzulynski and Kotlarczyk, 1965; Tjia, 1967). (4) *Spurs* (Tjia, 1967).

2.7. Deformed elements (DE)

A series of elements deformed along fault surfaces constitute excellent kinematic indicators (DE in Fig. 1): (1) *Deformed bubbles in volcanic rocks* displaying a drag-effect in the direction of the movement of the missing block (Angelier, 1994). (2) σ- *or* δ-*type porphyroclasts* have also been observed under the microscope in the wall rocks of faults (Doblas, 1991). (3) *Asymmetric protruding grains* with either damaged frontal parts (i) or polished lee sectors (ii) constitute excellent kinematic criteria in active normal faults (Doblas et al., 1995, 1997a).

2.8. Mineralogical/crystallographic orientations (MC)

Specific mineralogical and crystallographic orientations observed under the microscope constitute reliable shear sense indicators (MC in Fig. 1): (1) *Curved slickenfibers* (Twiss and Gefell, 1990); (2) *E-twin lamellae in calcite* (Laurent, 1987); (3) *Oblique preferred mineralogical orientations* of calcite or quartz (Doblas, 1991).

2.9. Asymmetric plan-view features (PW)

Two different asymmetric/elongated plan-view features exist (PW in Fig. 1): (1) *Tool tracks* have been described as being more sinuous upslope in active normal faults (Hancock and Barka, 1987). However, they are not reliable kinematic indicators as contrary sense have also been observed in similar faults (Doblas et al., 1995, 1997a). (2) The *differential groove polishing* of the frontal part of elongated cavities or grooves constitutes a good kinematic indicator (Willis and Willis, 1934).

2.10. Asymmetric cavities (AC)

Certain cavities found in fault surfaces might be used as shear sense indicators (AC in Fig. 1): (1) *Asymmetric depressions* with their risers facing the motion of the opposite block were described in active normal faults (Hancock and Barka, 1987). These arise from the indentation effect of protuberances or loose material. However, contrary senses have also been observed in some neotectonic faults (Doblas et al., 1995, 1997a). (2) *Asymmetric cavities with congruous steps* have been described in active normal faults and low-angle extensional detachments (Doblas et al., 1995, 1997a,b). These might be constituted by pluck holes, spall marks (similar to the ones described by Hancock and Barka, 1987), and cavities with congruous steps formed by R1 Riedel or synthetic hybrid fractures (Doblas et al., 1995, 1997a,b). Contrary to the previous AC1 criterion, the AC2 indicator arises basically from the plucking away of fault material leaving a congruous step behind.

2.11. Asymmetric folds (AF)

A good criterion is constituted by *asymmetric folds* (AF in Fig. 1) such as the ones described in the 'thrusted pads' of hydroplastic faults (Petit and Laville, 1987), and in deformed minerals at the microscopic-scale (Doblas, 1985, 1987).

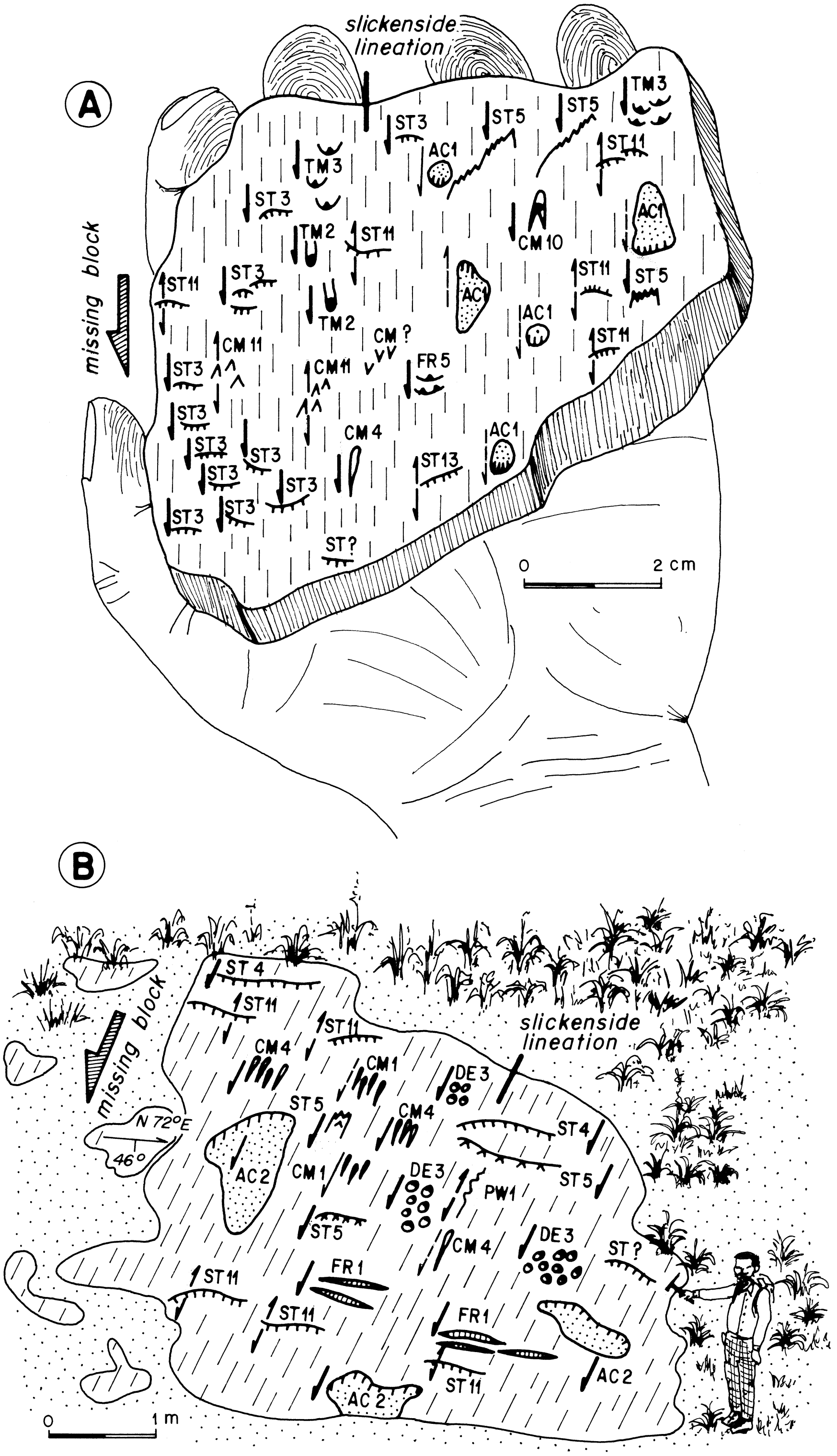
3. Discussion

This paper distinguishes 61 slickenside kinematic indicators, subdivided into eleven groups. Not all the criteria are equally useful as kinematic indicators: thirty four might be considered reliable (slightly more than half of the existing ones; Fig. 1). Additionally, some of the groups of criteria have few good indicators (CM, ST, and AE) as compared to the best groups whose indicators are all reliable (IS, TM, DE, MC, and AF). Slickenside kinematic indicators might be found on a large variety of scales, but some of the groups of criteria are scale-dependent: tens of millimeters (MC) or meters (AE).

Some of the indicators observed in the field might show mixed criteria (for example a step defining a concave marking), and these might be helpful in certain cases. A very important point is that sometimes the validity of a specific kinematic indicator might depend on such factors as the scale of observation, the type of rock, or its abundance. For example, criterion IS6 is only reliable when many of them exist in an outcrop of soft-sediments.

It is very important for the correct application of this classification to undertake a very careful and detailed examination of each one of the slickenside indicators observed in a given fault surface, as it is not enough to recognize a step or a fracture: one should be able to discriminate the exact type of indicator. In this sense, the application of this classification is not always easy, as the observer has to learn to recognize exactly the differences between the many criteria. In some fault surfaces it might even be impossible to obtain valuable kinematic indicators (for example in slightly eroded neotectonic slickenside surfaces), and in these cases one should use a very reliable additional technique: slickenside petrography, or the analysis of thin sections of slickensides (Lee and Means, 1990; Doblas, 1991; Lee, 1991).

Fig. 2 shows two examples of the application of this classification to natural fault surfaces at different scales: a hand-sample, and an outcrop. Several sequential steps should be taken in order to correctly apply this classification and to be able to determine the sense of shear: (1) undertake a general study and representation of the fault surface (attitude, irregularities, lineations, etc . . .); (2) analyze and identify carefully each one of the observed kinematic indi-


A
slickenside lineation
missing block
ST3
ST5
ST5
TM3
TM3
AC1
ST11
ST 3
ST11
TM2
CM10
AC1
ST11
ST 5
ST3
ST11
TM2
AC1
CM ?
ST11
CM 11
CM11
FR5
ST3
ST3
ST3
ST3
ST3
ST3
ST3
CM4
AC1
ST13
ST?
0
2 cm
B
ST 4
ST11
ST11
missing block
CM4
CM1
DE3
slickenside lineation
N 72°E
46°
ST5
CM4
ST4
AC2
CM1
DE3
PW1
ST5
ST5
CM 4
DE3
ST ?
ST11
FR1
ST11
FR1
AC2
ST11
AC 2
0
1 m

cators, and represent them in a detailed structural map. Even the indicators which are not definitive as kinematic criteria should be depicted, as they might reveal other important data (conditions of deformation, etc . . .); (3) suggest the most probable sense of shear of the missing block. It should be mentioned that the deduced sense of motion of a given fault surface corresponds only to one slickenside lineation. Many fault surfaces display several lineations resulting from different movements in more than one direction. In these cases, the detailed kinematic analysis exposed in the present paper should be carried out with every slickenline. The fact that several movements often occur on a single slip surface introduces a series of complications for the correct kinematic interpretation: the last movement will overprint the previous criteria; late-stage coatings usually conceal the initial slickensides; etc . . . A particularly complex case arises where movement has occurred in both senses parallel to a single lineation, a situation which seems to be common according to the premises of inversion tectonics. In this case, one might find contradictory senses of movement and the kinematic scenario might be impossible to unravel.

This morphological and geometrical classification, which is essentially based on certain asymmetric characteristics of the slickenside features does not intend to specifically address the question of the deformation mechanisms. However, it should be mentioned that the main mechanisms described in the literature are the following: (1) frictional wear and surface polishing (Hancock and Barka, 1987); (2) pressure-solution slip with generation of fibrous crystals (Durney and Ramsay, 1973); (3) streaking/trailing of gouge material (Tjia, 1968); (4) strain alignment of clay particles in soils (Gray and Nickelsen, 1989); (5) plastic yielding and strain alignment (Will and Wilson, 1989); (6) cataclastic flow (Doblas et al., 1995, 1997b); etc . . .

Some of the criteria described here seem to belong to very specific environments, and thus they might be considered indicative of these conditions: hydroplastic faults (FR3, and some indicators included within TM3 and AF1), active normal faults (FR2, PW1, AC1, and some indicators included within ST4, ST5, DE3, and AC2), low-angle extensional detachments (TM4, and some indicators included within TM3, and AC2), etc . . .

The detailed analysis of slickenside features appears to be a very promising field of study, and experimental work might be highly rewarding, in particular regarding seismic versus aseismic detailed features (Means, 1993), or small-scale 'V'-shaped markings in grooves. In this sense, it is important to note that this field of study gains a lot from the analysis of other friction surfaces completely unrelated to tectonic stresses: glacial abrasion planes, surfaces triggered by the mechanical excavation of rock (Spray, 1989), or synsedimentary structures.

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Fig. 2. Examples of application of the classification of slickenside kinematic indicators to a hand-sample (A) and an outcrop (B). The terminology of the indicators corresponds to the one shown in Fig. 1. The degree of confidence in each one of the kinematic indicators is depicted by different types of arrows (see also Fig. 1). A question mark is shown when an indicator has not been clearly identified. The true scale of the criteria has been exaggerated in both examples in order to highlight them.

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