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Criteria for the sense of movement on fault surfaces in brittle rocks

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Abstract—This paper gives a detailed description of the use of minor structures on fault planes in various brittle rocks as indicators of the sense of relative movement. The main kinds of structures described involve sets of repeated secondary fractures (striated or not) which intersect the slip plane in a direction roughly perpendicular to the slip direction. Some of the most frequent criteria are new; their reliability is established in the field and by comparison with both previous and new experiments. It is shown that some of the rarer structures probably correspond to neo-rupture in intact rock, most probably at the tip of pre-existing joints, while the most frequent structures are generated by friction on joints, with very little sliding. The possible seismic origin of some structures is discussed.

INTRODUCTION

THE DETERMINATION of direction and sense of movement on faults is a basic requirement during brittle tectonics analysis. It is indispensable in establishing the kinematics of faults of various scales or the geometry of faulted ore bodies, especially in cases where the slip cannot be determined from the offsets of geological structures. With recent computer methods which give some characteristics of paleostress tensors from measurements of fault striation (Carey & Brunier 1974, Angelier 1975, Etchecopar *et al.* 1981, Armijo *et al.* 1982), slip-sense determination is also necessary. A most useful way of determining direction and sense is the direct observation of fault surfaces which may show not only striation but also minor structures indicating the sense of relative movement (sense criteria).

Original morphological descriptions of corresponding structures are rare in the geological literature (Dzulinski & Kotlarczyk 1965, Tjia 1971, Hobbs *et al.* 1976, Elliott 1976). This paper gives descriptions of such structures based on field observations of faults in the Alpine High Atlas Mountains of Morocco (Petit 1976), where there is a very dense fault network linked to the Tizi n'Test Fault zone (Mattauer *et al.* 1972, Proust *et al.* 1977). In the excellent outcrops of this semi-arid region, more than 4000 fault planes were observed in different rocks: granite, gneiss, volcanics, sandstone and limestone (Petit *et al.* 1983). In addition, slickensides formed in incompletely lithified sandstones, and morphological and microstructural comparisons between 'hydroplastic' and 'brittle' fault structures formed in the corresponding indurated sandstone, have been described (Petit & Laville 1987). Some of the features given in this paper have already been described (in French) by Petit *et al.* (1983); they have subsequently proved useful in other regions. The present paper re-describes these features, together with new observations and interpretative elements.

The observations were strictly limited to fault surfaces, excluding those completely covered with gouge or with pronounced planar anisotropies in the rock (especially cleavage). Detailed field descriptions are mainly confined to features visible to the naked eye or with a hand lens. The microstructures will be described in a separate publication. The reliability of the shear-sense criteria can be checked when different criteria are used for the same fault plane (related to the same movement). Within a strike-slip regime, the slickensides of conjugate faults show structures indicating opposite senses. If several tectonic phases are responsible for different structures linked to several striation orientations on the same surfaces, the corresponding stress states can be determined by computer methods (Etchecopar *et al.* 1981). During field observations mechanical interpretations of the structures were borne in mind to help define the criteria, although the conclusions were mostly based on evaluations of experimental data.

There is a wide variety of secondary structures associated with faults. The factors controlling their formation could be: (i) the presence and geometry of pre-existing joints; how fault marks due to friction on pre-existing joints may be distinguished from those from shear of intact rocks will be discussed; (ii) the physical properties of the rock involved (composition, porosity, mechanical properties); or (iii) conditions of stress (relative or absolute values) and strain (amount of slip, strain rate, possible seismic movements).

TERMINOLOGY FOR DESCRIPTION

Terminology that has been used for description of repeated secondary fractures and for steps on fault surfaces is presented below. An important feature commonly observed is the presence of secondary repeated fractures of the same type, making an angle with the mean fault plane, some being regular en-échelon fractures. In view of the present lack of adequate terminology, it is essential to provide one for these fractures and

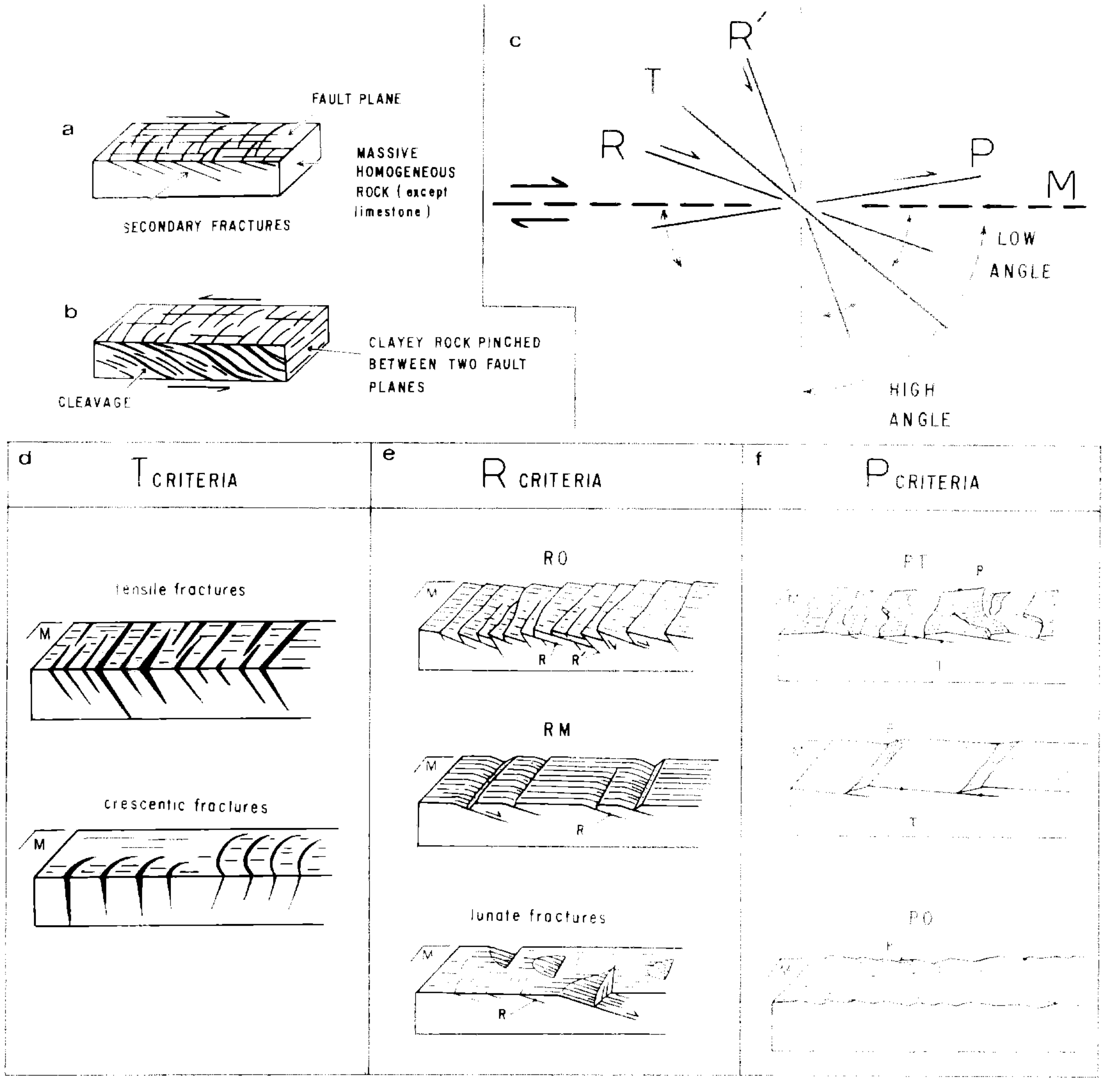

Fig. 1(a) and (b). Structures of comparable aspect but opposite sense. (c) Terminology for description of elementary secondary fractures in a shear context, and for corresponding criteria (see text). (d)–(f) Main types of criteria based on repetitive secondary fractures.

their features. To avoid lengthy non-genetic descriptive terms such as 'right stepping non-striated fractures in a left lateral shear' or 'striated secondary fractures dipping in the direction of movement of the opposite block', a terminology is suggested (Fig. 1c) based mainly on Riedel-type experiments as used in classic works of Tchalenko & Ambraseys (1970), Wilcox *et al.* (1973) and others. These terms are intended only to describe the geometrical position of the observed elementary fractures in a shear context, but not to imply that the structures observed can be explained mechanically by Riedel type experiments, especially for structures linked to friction (see below).

It is convenient to divide structures corresponding to repetitive secondary fractures into three groups (Fig. 1 d–f): *group T*, including types showing only repetitive T fractures (from tension, but see below) and no secondary shear fractures, *group R*, including all types showing secondary synthetic shear fractures (striated) of R orientation, and *group P*, including all types showing secondary shear fractures (striated) of P orientation. The morphological difference between these three groups can easily be seen in the field. Within groups R and P one can distinguish important morphological types with a second letter: O, if only R or P secondary shear fractures are present; M, if the main or mean fault plane is completely striated and T, if non-striated secondary fractures are observed (Fig. 1 e & f). As shown later, the fractures called R, here, are striated and make small angles with the average fault plane similar to those usually observed in Riedel-type experiments. R′ will be used in the description for high angle antithetic secondary shears. A problem arises with repeated apparently non-striated T fractures dipping at various angles to the fault wall in the direction of the missing block. Further discussion will show that some T fractures have not been initiated as macroscopic extensional fractures, so group T in the broader sense must embrace non-striated fracture sets of whatever mechanical origin, possibly older than the shearing, dipping in the direction of movement of the missing block.

Norris & Barron's terminology (1968) will be used for the observed steps: accretion steps (risers formed in added gouge or crystallized material), and fracture steps (risers cut in solid rock), of incongruous (risers facing the movement of the opposite block) and congruous (opposite case) types.

SHEAR-SENSE STRUCTURES NOT LINKED TO SECONDARY FRACTURES

Striation due to a ploughing element (Fig. 2a)

Striation occurs from an element (a rock or gouge fragment or mineral grain) which is obviously harder than the wall it striates, although it may be of the same material. During friction it forms deep striae (grooves) terminated at the final ploughing element position. The end of the plough mark points towards the movement of the missing wall (Dzulinski & Kotlarcyzk 1965, Tjia 1971 and Hancock 1985; Tjia introduced the term 'prod marks', while Hancock referred to 'tool marks'). This feature can be integrated with the more general case of 'asperity ploughing' (Means 1987). This clear type of striation is mainly present in limestone.

Crystallization linked to irregularities of the fault surface (Fig. 2b)

Irregularities on the fault surface exhibit local crystallization generally of fibrous minerals (quartz, epidote, etc., in magmatic rocks, calcite in limestone). They appear as a set of steps (accretion steps) whose risers are more or less perpendicular to the general striation and face in the same direction. These accretion steps are congruous (i.e. risers facing towards the movement of the missing block) where euhedral crystal faces are observed on the risers (Elliott 1976, fig. 13, Hobbs *et al.* 1976, fig. 7.12) (Fig. 2b1) or where crystallization formed during, or after, the opening of domino-type structures (Gamond 1983) (Fig. 2b2). This feature is very common in limestone and sometimes associated with stylolites (Arthaud & Mattauer 1969, fig. 1d), but is also found in igneous rocks (Blès & Gros 1980) where it implies high temperature fluid circulation. The sense is not clear if the slickensides are too thickly coated with the crystalline material. In this case Laurent's method for calcite (1987) can lead to shear-sense determination.

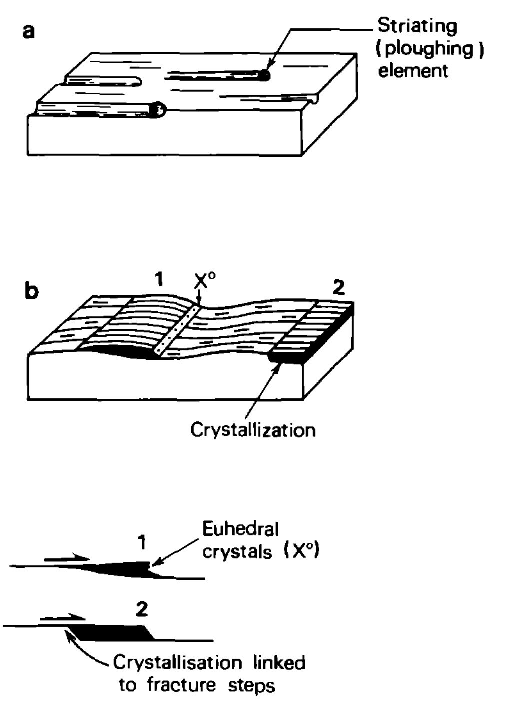

Fig. 2(a). Striation due to a ploughing element (asperity ploughing); (b): crystallization on the lee side of asperities (see text).

SHEAR-SENSE STRUCTURES INVOLVING SECONDARY FRACTURES

T criteria:

The mean fault plane (M) is fully striated. Secondary fractures are not striated, so they are of T type. They can make an angle of 30° to about 90° with the main fault plane (Fig. 1d) (see also 'comb fractures', Hancock & Barka 1987). They can be open or infilled with any mineral and either planar or curved when viewed as traces on the fault plane; in the latter case the $\widehat{TM}$ angle is about 90° and the curved T fractures make a crescentic shape on the M plane. Crescents are never found alone but are usually aligned, at least along a short distance, their horns pointing in the direction of movement of the missing block. These criteria clearly correspond to the 'crescentic fractures' associated with glacial scratches (Harris 1943, Masson & Baud 1974). However, they are sometimes found associated with faults, especially bedding plane faults (Wegmann & Schear 1957), or fault planes in Languedoc limestone (Fig. 3a). Nothing equivalent to 'chatter marks' (Harris 1943) due to aligned spalling or flaking of the fault surface were observed.

R criteria:

The mean fault plane is joined by repeated secondary striated fractures in secondary R shear attitude dipping at a small angle to the fault wall (Fig. 1e). Their intersection with the mean fault plane is more or less perpendicular to the slip direction. Two main types are observed.

RO (R only) type. There is no mean striated fault plane (Figs. 1e and 3b top). The distance between R shears is very small and regular and their surfaces are very slightly striated. The fault surface is serrated in profile due to the intersection of two sets of secondary shears, R and R', whose orientation with respect to the mean plane is indicated in Fig. 4(a). This type is rare and has only been observed in fine-grained sandstone. It seems to be an original feature corresponding to a planar view of an en-échelon zone cut through the middle.

RM type. The main fault plane is fully striated (Figs. 1e and 5a). The R fractures are visible because of the non-tectonic rupture of the tip of the dihedron formed

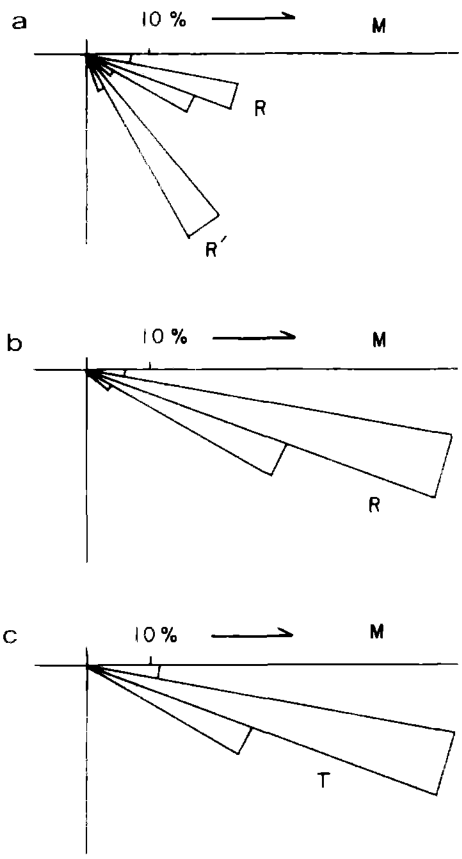

Fig. 4. Angle between secondary fractures and the main or mean fault plane (M). (a): R and R′ in RO structure (from the outcrop shown in Fig. 3b); (b) R in RM structure; (c) T in PT structure (from Fig. 7b).

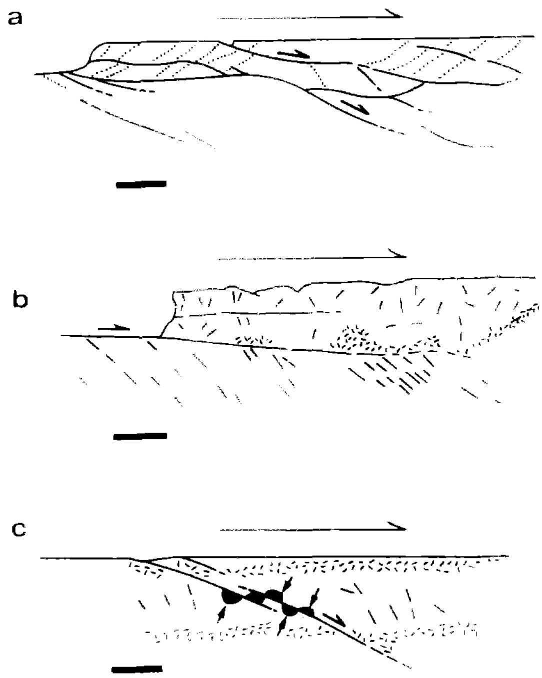

Fig. 6. Sketches from sections parallel to the striation and perpendicular to fault plane through micro-R shears in sandstone. Long dashes indicate transgranular fractures, short ones crushed grains. In (a) black dots indicate alignment of clay and oxides in compartments of more or less crushed grains in porous sandstone; in (c) small arrows outline the amount of slip in sheared quartz grains. Scale lines are (a) 1 mm; (b) 0.1 mm; (c) 0.3 mm.

by R and M surfaces, so that the rupture surface determines incongruous fracture steps. These R fractures are irregularly distributed on the surface, some well apart, some very close together, and of varying size. They make small angles with the M plane (Fig. 4b). They occur from centimeter scale in sandstones to meter scale in igneous rocks. Seldom found in limestones, this structure led to sense determination on about half of the fault planes, in sandstone as well as in igneous rock. Figures 1(a) & (b) illustrate a possible confusion. In spite of its importance, this structure has apparently been described very little, except for one aspect of the R fractures: their concave curvature towards the main plane, so that their intersection with the M plane is also concave and indicates the sense of movement (Figs. 1e and 5b). A comparable feature was referred to as 'lunate fractures' by Harris (1943); it seems to be similar to tectonic 'chevron marks' illustrated by Elliott (1976, fig. 11, p. 30).

In fine-grained sandstone some shiny apparently smooth slickensides are of RM type: under a hand lens, they show micro-R shears, some being micro-'lunate fractures', typically formed in a layer of several millimetres thick crushed grains. In general thin sections cut perpendicular to the shear plane and parallel to the striation (Fig. 6) show that micro-R shears are frequently observed on M surfaces, and are thus homologous with macroscopic R shears. As shown in Fig. 6 (a) & (b), the associated incongruous microsteps can correspond to the broken tip of the dihedral angle between M and R. In Fig. 6(c), the tip is not yet broken. The RM dihedron is often formed of more or less crushed grains so that these micro-steps are not typical fracture steps.

P criteria:

The fault plane is always incompletely striated and looks very different from other types of slickensides (Fig. 1f), which could explain why this feature has never been described or used before. The striation, or at least a bruised surface, appears localized on the side of asperities facing the movement of the missing block. Two types can be seen:

PO (P only) type. The non-striated (protected) surfaces of the asperities (lee side) do not dip into the wall (Figs. 3b, bottom, and 7a).

PT type. The more or less planar non-striated surface clearly dips into the wall at a small angle. P surfaces are more developed and striated than PO types (Fig. 7b & c and 8a). The tip of the dihedron formed by P and T surfaces has been broken to form many small steps. Some of the more striated P surfaces show shallow steps always ascending in the direction of the missing block, sometimes associated with micro-R shears (Fig. 8b). The latter are sometimes observed dipping under the risers when steps are present.

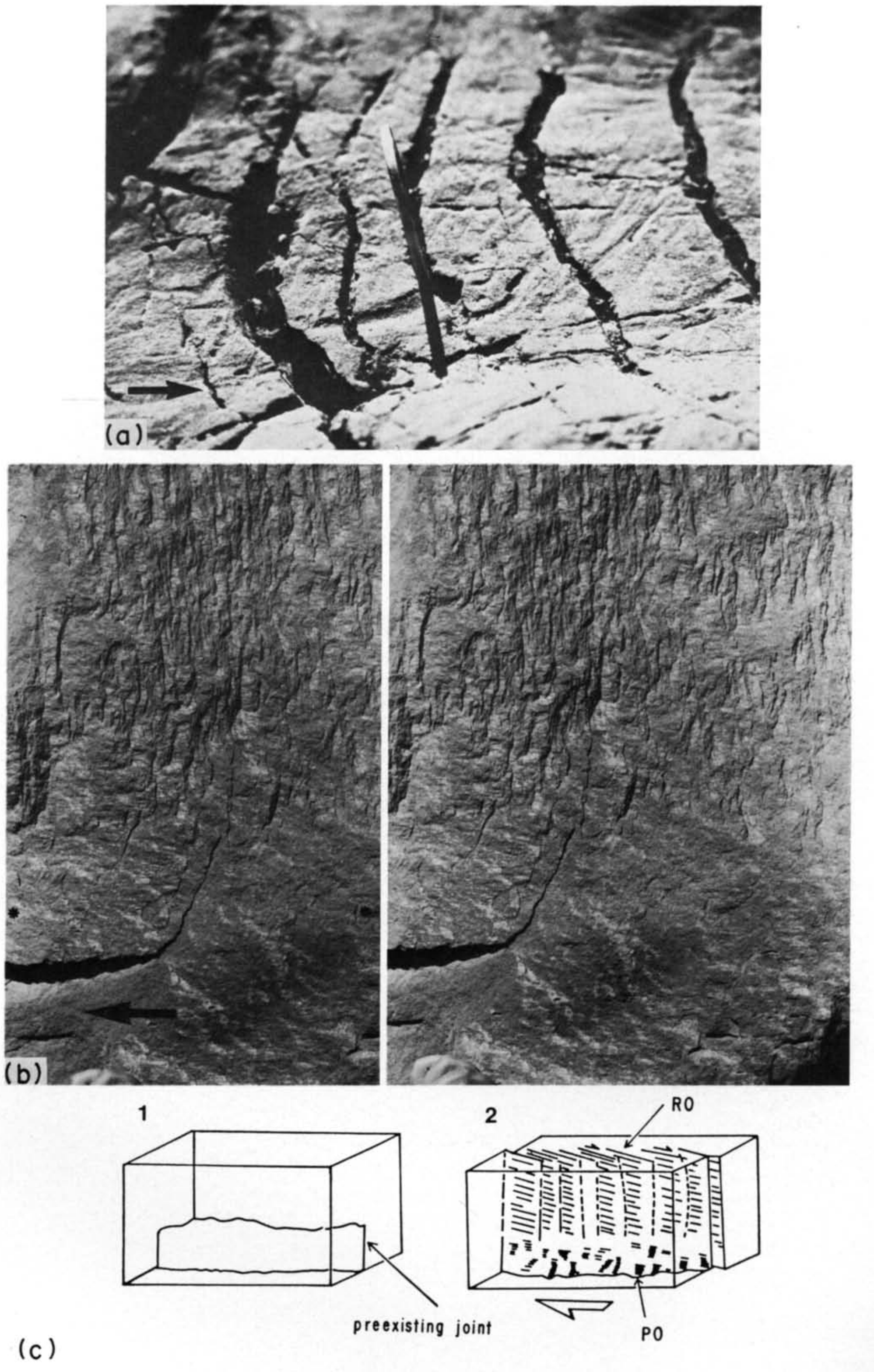

Fig. 3(a). Crescentic fractures (T fractures) in Languedoc Jurassic limestone. (b) Stereo pair of a right lateral strike-slip fault in red Triassic High Atlas sandstone (Morocco). Upper part shows RO structure: the fault surface corresponds to splitting throughout a brittle shear zone formed of en-échelon secondary shears dipping inside the wall. Lower part shows a PO structure indicating the same slip sense. Some PT structures are visible in the transition zone between RO and PO. Black stars are aligned along the trace of bedding plane on the fault surface. Arrows indicate sense of movement of missing block. Scale line is 10 cm. (c) RO structure developed from the tip of a pre-existing joint explaining the features illustrated in (b); 1—before shearing, 2—after shearing.

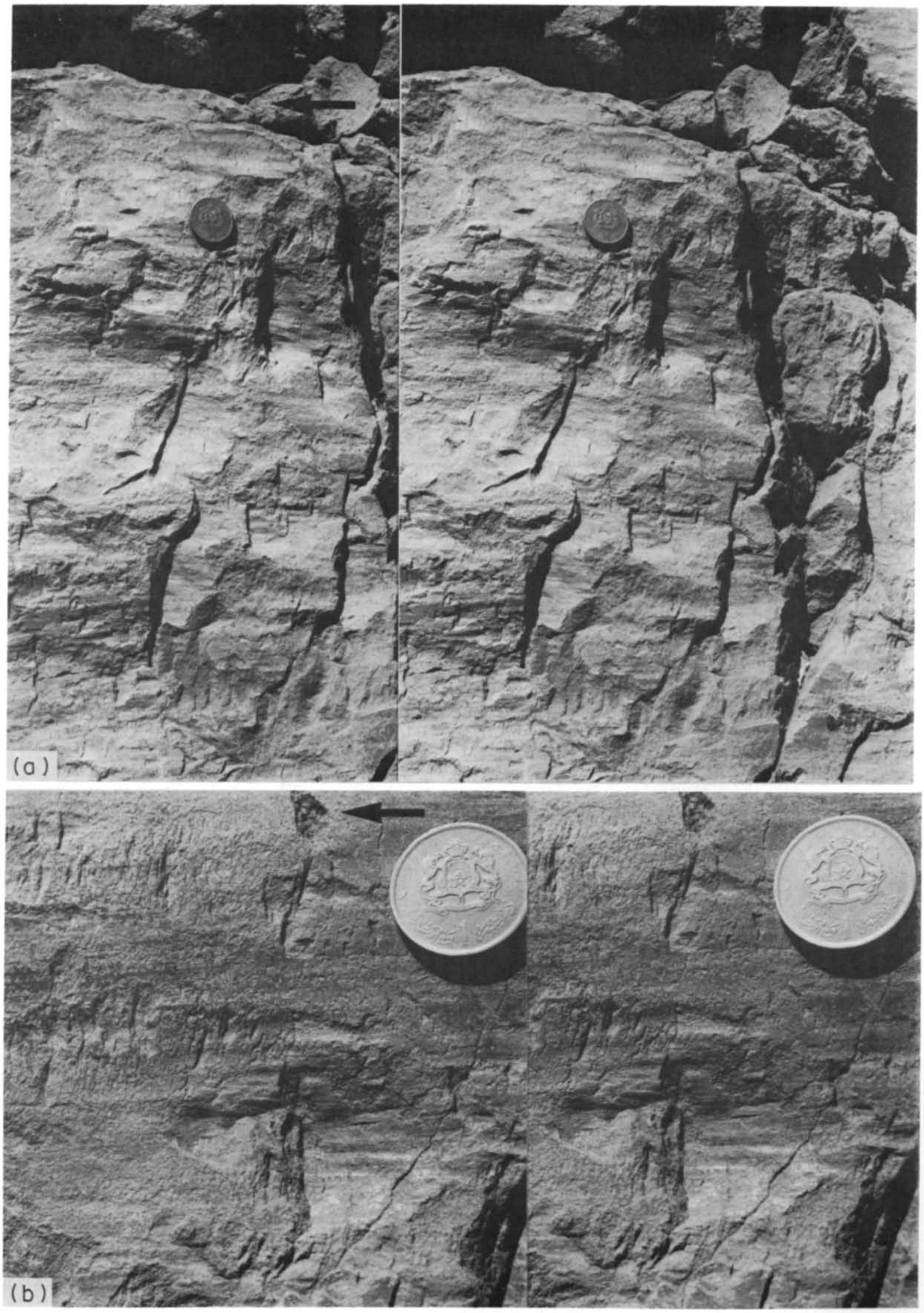

Fig. 5. Stereo pairs for fault structures in the Triassic High Atlas sandstone, Morocco. (a) RM structure on a right lateral strike-slip fault; (b) Details of the same fault showing a lunate fracture (bottom right; here the tip of the dihedron formed by R and M surfaces has been broken) and transition to micro-R shears (left) occurs. Arrows indicate sense of movement of missing block.

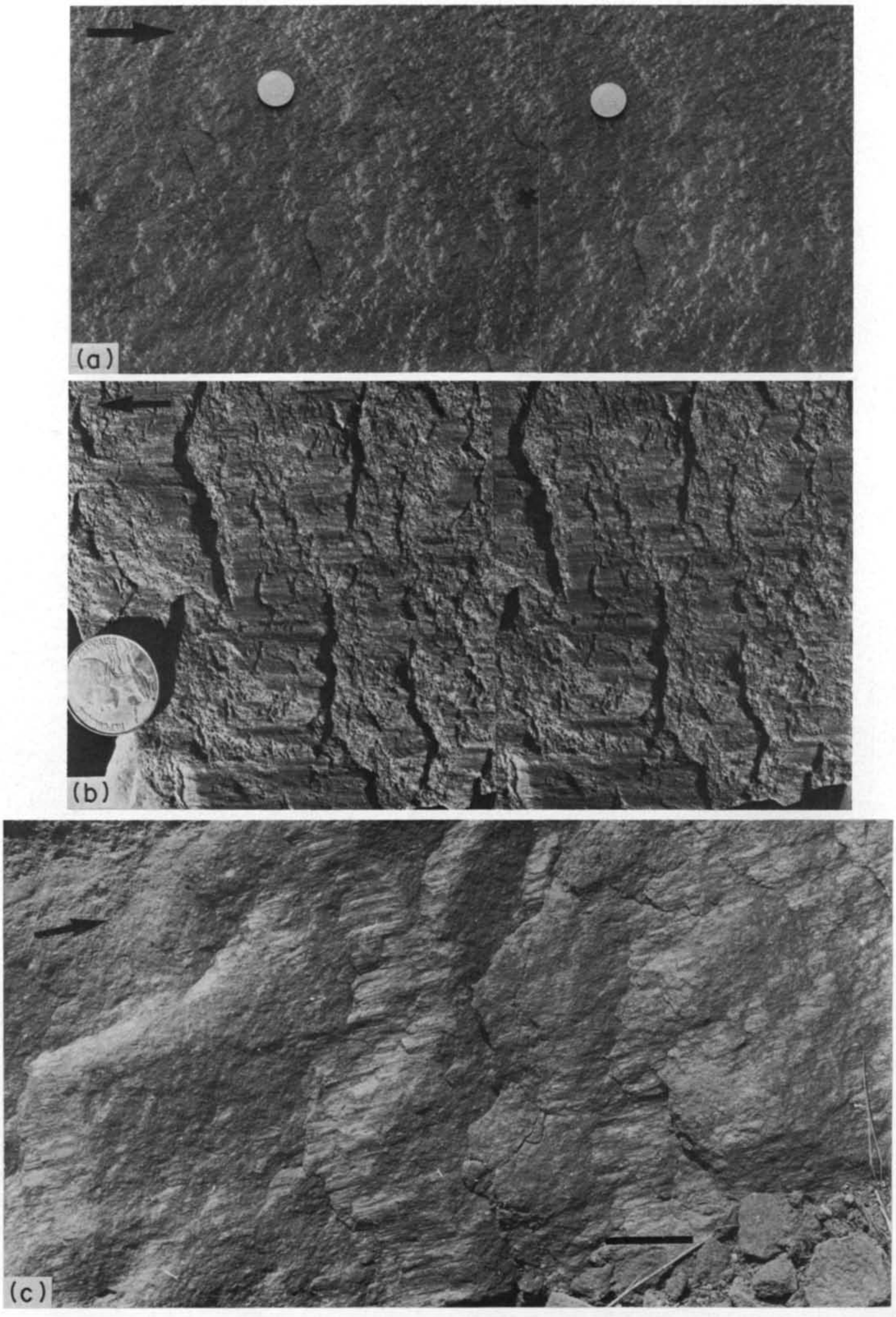

Fig. 7. P criteria from the red Triassic High Atlas sandstone. (a) Stereo pair: PO structure indicating a small displacement (striation only visible with a hard lens), left-lateral strike-slip fault; (b) stereo pair: PT structure. P surfaces have been worn by friction; (c) PT structure (with P/T surface ratio about 1) on a left lateral strike-slip fault. Scale lines are 2 cm. Arrows indicate sense of movement of the missing block.

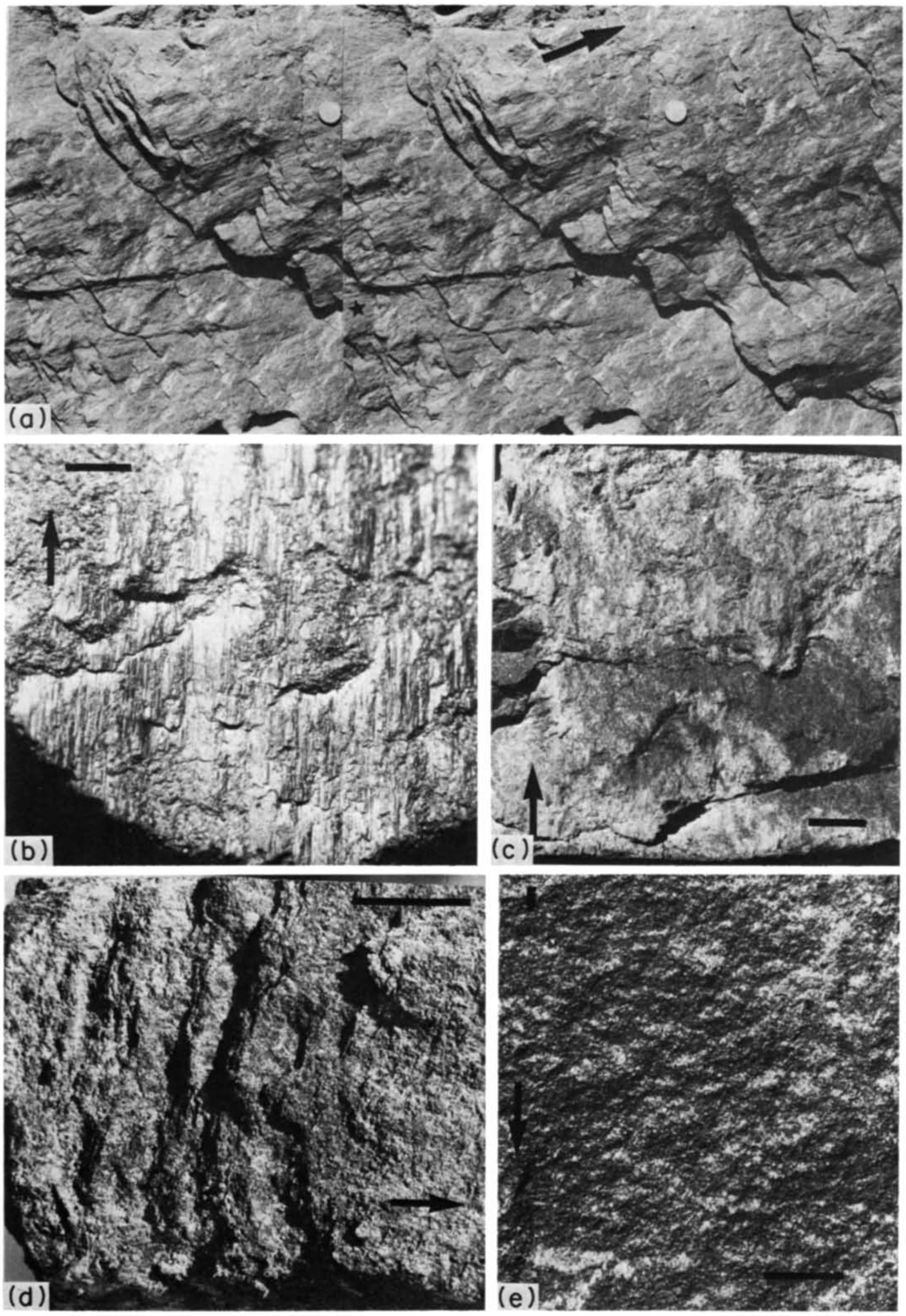

Fig. 8(a). PT structure with well developed T fractures, on a left-lateral strike-slip fault in the red Triassic High Atlas sandstone (Morocco). Black stars are aligned along the trace of bedding plane on fault surface. Arrows indicate sense of movement of missing block. (b) Detail of a natural P surface of PT structure. (c)–(e): Sheared surfaces in red sandstone after shear box tests. (c) Oblique view of sheared surface formed in intact specimen, showing reconstitution of PT structure at low normal stress. P fractures appear whitened and striated, T fractures are not, and dip into the specimen; compare with Fig. 7(c). (d) Detail of surface of a specimen after shear test at high normal stress in intact specimen (same rock as in c), showing slightly striated and tight R fractures dipping into the specimen. Reconstitution of RO criteria; compare with Fig. 3(b, top). (e) Pre-cut surface (see text) after a 2 mm relative displacement showing reconstitution of PO criteria. Scale lines are (b) 1 mm; (c)–(e) 1 cm. Arrows indicate sense of movement of missing block.

The P criteria were first used in red, fine-grained sandstone; the striated side of asperities (the striation is sometimes only visible with a hand lens) appear as whitened patches due to crushing of quartz grains, and thus form a striking contrast with the red non-striated sides. The PO type has been extensively found because P surfaces appear on very tiny asperities, for example on plumose structures, or on the irregularities of any pre-existing joints. The formation of this criterion implies very small slips roughly of the same order of magnitude (generally millimetres in sandstone) as the width of the patch in the direction of movement. Otherwise the striation would have been more extensive and could have led to a fully striated slickenside. These PO criteria have been commonly observed in various magmatic rocks, where the patches are more typically linked to larger often wavy asperities, with chlorite or oxides often present on the lee side. The PT types have been observed less often, and mainly in sandstone on a centimetre scale. These criteria exhibit a variety of morphologies because of the varying ratio P/T (apparent surfaces), which can be from about 1 (Fig. 7c) to 1/5 (Fig. 8a). The smaller the inclination of T fractures with respect to the mean plane, the smaller the ratio. In some cases, the P surfaces have been worn down until they are parallel to the mean plane (Fig. 7b). As shown in Fig. 3(b), RO, PT and PO criteria are mutually consistent. Transitions between PO and PT structures have often been observed.

MECHANICAL INTERPRETATION

Although the criteria presented here are of immediate use for field geologists, the mechanical origin of the corresponding structures is also of interest, as it may give some indication of the stress and strain conditions involved in fault formation. Thus the first basic requirement is to be able to distinguish between structures formed by rupture in intact rock and those produced by sliding on a pre-existing joint.

Comparison with tests in intact rock

Shear box tests. These seem well-adapted to the reconstruction of fault plane marks due to ruptures in intact samples, because the shear plane is imposed by the box and can thus imitate fracture formation at the tip of a pre-existing fracture subjected to a shear movement. Gamond's work (1983, 1985, 1987) is apparently the only application of such tests aimed at recreating geological structures linked to shear in intact brittle materials. Although his experiments were done on an over-consolidated varved clay, the structures obtained at low normal stress in dilatant conditions (i.e. with the sample allowed to extend parallel to the imposed constant normal stress, Gamond 1983, fig. 7) are very similar to PT structures described here with a P/T surface ratio of about 1. The fractures appearing first are low-angle T fractures in the present terminology, as they are not striated (see Discussion). P fractures are formed next by the rupture of bridges between T features.

The same geometrical succession was obtained in my preliminary shear tests on rocks which produced structures closely resembling the PT field examples (Fig. 8c). The tests were carried out with a 500 kN (normal and shear maximum forces) conventional direct shear machine on indurated red Permian sandstone from the Lodève basin (Languedoc, Southern France), on dry specimens 8 × 8 cm in section at room temperature. Before peak stress (τ = 52 MPa, σ_n = 24 MPa, i.e. for values corresponding in this experiment to a very low value of σ_3), T fractures formed first, and the rupture of bridges between them occurred in an explosive way at peak stress. Although a certain amount of elastic stress is stored in the machine during loading, so that explosive rupture can be expected (the machine is a 'soft' conventional one with hydraulic loading), this type of rupture could occur in the Earth's crust, suggesting that the most regular PT structures could be indicators of microseismic events.

In my experiments, RO type structures (i.e. very tight and regularly spaced slightly striated fractures with a serrated profile) were obtained by shearing in specimens (Fig. 8d) subjected to high normal stresses (τ = 100 MPa, σ_n = 80 MPa.) At low normal stress, en-échelon fractures appeared before peak stresses, but rupture at peak stress was not so brutal. The resulting features resemble those observed by Gamond (1985) in non-dilatant conditions (i.e. with no possible extension parallel to the increasing normal stress). The general tendency is for the formation of numerous secondary striated R shears instead of a few isolated non-striated fractures inducing large open dominoes with P fractures. These observations suggest that in shear box tests an increasing normal stress inducing less dilatant conditions could lead progressively from PT type to RO type structures with tighter and shorter striated secondary fracture. If this is true, some of the observed R and T en-échelon fractures could have a common mechanical origin (Fig. 9a & b). Gamond (1983) discussed this, with different terminology, and concluded that the non-striated fractures (T in this paper), were in fact Riedel shear fractures that opened during the sliding of P fractures. As Gamond emphasized, in non-dilatant conditions the shear zone tends to be narrower and void formation is inhibited.

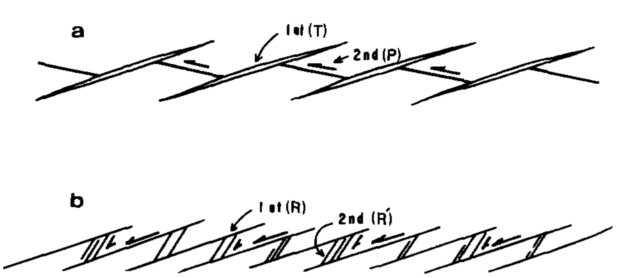

Fig. 9. Formation of types of secondary fractures in direct shear experiments in intact specimens (see text). (a) At low normal stress; (b) at high normal stress. 1st and 2nd indicate chronology of the corresponding fractures.

This tendency is only possible if an important relative movement occurs on closed R fractures, thus inducing friction. Moreover, rupture along the imposed shear zone is easier because bridges between fractures are closer. So it would be possible for RO and some types of PT structures (when the P/T surface ratio is about 1) to correspond to newly formed fault surfaces, RO, indicating high normal (or differential) stress and PT rupture at low normal (or differential) stress, both with very small slips.

Triaxial tests. Although this type of experiment is commonly carried out, only a few morphological descriptions of fracture surfaces have been published and the observations are mainly confined to the step problem. The evidence of fracture steps (generally perpendicular to the striation and formed in intact rock) facing the movement of the opposite block was clearly shown experimentally in marble (Paterson 1958, plate 2) and in other rocks by Currie (in written comments to Norris & Barron 1968). These steps have been presented as possible criteria for determining the sense of movement on natural faults. Paterson's experimental secondary fractures seem to be irregular en-échelon fractures of R type, the steps being due to the rupture of bridges between them. Thus the whole feature could be more or less similar to RO structures before the formation of R shear fractures. On the other hand, the structures described by Paterson and the detailed features of natural P surfaces in Fig. 8(b) have striking similarities. This analogy confirms the formation of some P shears of PT structures from rupture in bridges of intact rock (Fig. 9a).

Comparison with friction tests on pre-cut specimens

Shear box tests. On the same shear box testing machine as above, friction tests were carried out on specimens with an uneven fracture surface caused by previous splitting under uniaxial loading: the two parts were fitted together and the block fixed in the shear box so that the splitting plane corresponded to the imposed shear plane. The result obtained for σ_n = 28 MPa with 2 mm displacement is given in Fig. 8(e). Comparison with the natural example of Fig. 3(b, bottom), and 7(a) shows a very similar aspect and the same distribution of striated patches on the side of asperities facing the movement of the moved block. This emphasizes that PO structures are reliable criteria and probably formed on pre-existing joints. These experiments suggest that P surfaces could form even in low normal stress conditions and for very small slips.

Triaxial tests. Many previous friction tests have been done on saw-cut specimens, but one should not expect to find clear geological analogies, especially to tests using polished surfaces, because natural pre-existing joints are typically uneven. However, some types of indurated (welded) gouge observed on pre-cut specimens (Friedman *et al.* 1974) could also be found on P surfaces of the PO criteria, but this would need more investigation. No natural equivalent of 'microscopic wear grooves' (Engelder 1974) or of tapered grooves as described by Currie (written comments in Norris & Barron 1968) have been found in the field.

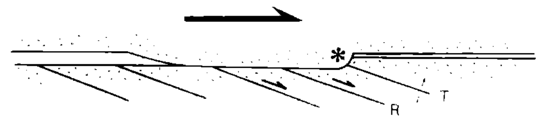

Fig. 10. Possible mechanisms for formation of secondary R fractures in RM criteria by frictional penetration at the front of hardened material (star). T: tension fracture formed first, R: shears formed by relative movement on previous fractures due to local stress field reorientations.

Fracture induced by cutting tools. Although the mechanisms involved are not purely frictional, interesting comparisons can be made with Friedman's experiments (1983) on the fracturing of rocks due to a ploughing mining tool. On the bottom of the furrow dug by the tool he observed among other features a set of repetitive tension factures dipping at an average angle of 16° in the direction of movement of the tool. Their geometry is comparable to those of R fractures of RM structures (Fig. 4b). A similar mechanism could explain the formation of some of the secondary R fractures by friction (Fig. 10a), but this implies a hardness contrast between the two walls. It could be explained by the formation of a wide front zone of hardened material (crystallized gouge) which acted as the tool in forming first the tension fractures. The shearing movement on these fractures could be due to stress reorientation during the continuing relative movement.

Hertzian fracture tests. Among the T criteria, the 'crescentic fractures' (Figs. 1d, bottom, and 3d) clearly correspond to experimental repetitive Hertzian fractures obtained by the circular sliding contact of an element harder than the frictioned material, for example a steel ball on glass (MacClintock 1953) or a hemisphere of sapphire on silicon monocrystal (Barquins 1973). Individual cracks correspond to fragments of Hertzian cones whose axes (perpendicular to the surface if no displacement) are tilted in the direction of movement. The formation of these cracks is predicted by Lawn (1967); they are due to tension stresses formed at the back of the contact area and are linked to stick–slip.

Criteria for neorupture in intact rocks

Previous experimental data in both shear box and triaxial tests strongly suggest that RO and PT structures (if the P/T surface ratio is about 1) are formed in intact rock, the differences between them indicating, respectively, high or low normal stress conditions. Both types imply formation of en-échelon fractures (regularly spaced fractures of the same type) at pre-peak stresses in intact rocks. As shown in rock by Pollard *et al.* (1982) and Granier (1985), such en-échelon cracks can be formed starting from the tip of a parent crack, i.e. an isolated pre-existing joint in a homogeneous rock submitted to a shear movement in well-defined stress conditions. Such a model implying stress concentration at the crack tip can be applied to the structures in Fig. 3(b) and explained in 3(c), where the fault surface showing en-échelon RO structures appears to have formed from the tip of a pre-existing fracture corresponding to the zone now showing PO structures linked to friction. Thus field observations seem consistent with mechanical data. This RO, PO association has been very seldom observed on the field, for reasons given later. PT structures (if the P/T surface ratio is about 1) could be formed in the same way. A problem arises with the frequent PT structures where T surfaces are more developed than P, as in Fig. 8(a). This could be because P and T fractures are not necessarily formed during a single shearing movement. P fractures could be formed by compressive rupture limited by bridges in any older, even irregular, en-échelon fracture set of any origin.

Criteria for friction on pre-existing joints

The shear box data presented here give good evidence for the formation of PO structures from friction even at low σ_n on an irregular pre-existing joint. The transition observed from PO to PT structures (irregular types) could be explained by the formation of some kind of T fractures during friction due to tensile stresses developing at the base of the P side of asperities subject to friction. This, however, remains speculation. The frictional origin of tensile fractures corresponding to T criteria is clear, at least in the case of crescentic fractures where Hertzian-type stresses are involved. On the other hand, it has not been experimentally proven that RM structures originate from friction on a pre-existing joint, even if cutting tool experiments suggest a possible origin of R shears. One can speculate that RM structures could be generated by the continuing relative movement on RO structure and corresponding wearing, but in this case the formation of accretion steps is likely to occur, while the field examples show that the risers of macroscopic steps are always due to fracture in rock. Moreover, R fracture distribution seems much more irregular than one would expect from RO structures, so this type of formation for RM structures seems unlikely.

DISCUSSION AND CONCLUSION

The abundance of PO, RM and the irregular forms of PT structures have been noticed in the field, as well as the scarcity of RO and regular PT ones. This can be explained by the fact that the former (corresponding to friction on pre-existing joints) are more frequently formed than the latter (due to neo-rupture), because friction does not need such high stress levels as neo-rupture. But that does not imply a separate tectonic phase, because stress concentrations inducing neo-rupture can occur at the tips of pre-existing, non-interconnected joints. The corresponding geometry is probably not very frequent.

An idea of the amount of slip involved on faults implying friction on pre-existing joints can be obtained from the amount of striated surfaces. PO and irregular PT structures imply slips of less than a centimeter, while slip is greater for RM structures. Some examples in sandstone showed completely striated surfaces corresponding to a decimeter slip. Normal stress dependence is likely only in the case of neorupture for the most regular forms of PT structures (low σ_n) and for RO structure (high σ_n).

Microseismic events have been inferred by comparison with experiments during the formation of PT structures in intact rocks. Such events could also be generated by friction, at least in the case of Hertzian structures involving stick–slip.

Most of the examples presented are found in fine-grained sandstone because of the presence on faults of numerous secondary fractures of various kinds. This can be explained by the possibility of extensive intragranular micro-fracturing. The amount of porosity present in this sandstone encourages the formation of extensional fractures because of stress concentrations on pores and at grain contacts (Dunn 1973). Thus, once microfractures are well developed, through-going shear can occur and fracture strength is decreased. If porosity is very low, as in quartzites, one can expect the formation of long tensile fractures which would inhibit the formation of minor shears to a varying degree. In the sandstone described, a small amount of highly deformable material in the matrix such as clay minerals or calcite can also help shear formation, as they facilitate sliding at grain boundaries. However, RM structures implying a lot of friction and secondary shear formation were found in low porosity rocks such as granite or various volcanic rocks. But the best examples were found in faults linked to major strike-slip zones where much higher deviatoric stresses can be expected. In these cases micro-fractures are observed, too, but associated with a certain amount of plastic deformation in grains.

While comparison with previous experiments helps understand the formation mechanisms of some of these structures, others will need more specific experiments for their reconstitution. Two problems are (i) can secondary shear fractures be formed by friction and (ii) how do stress and strain influence the type of rupture in various rocks, in shear box tests? Experiments must be carried out on the same material as the equivalent structure on the field, otherwise comparisons will be rendered inaccurate because of the strong influence of the physical properties of the rocks involved on the type and conditions of rupture.

The results of experiments, combined with accurate descriptive data from natural faults should lead to a better understanding of shear-sense criteria in fractured rocks.

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