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Aspects of analysing brittle structures

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Abstract

Brittle mesofractures and allied structures permit far-, mid- and near-field palaeostress directions to be determined depending on whether the structures are uniformly or symmetrically orientated and distributed throughout large homogeneous terrains (e.g. platforms), deformation zones (e.g. thrust-fold belts, graben fields) or narrow tracts (e.g. the hanging- and footwalls of faults respectively). Faults, veins and stylolitic seams are generally the most rewarding structures to analyse. In platforms lacking these kinematic indicators it is necessary to survey joints. They are arranged in either well ordered sets or joint spectra, the latter comprising a coaxial continuum of extension and hybrid fracture orientations, generally enclosing a maximum dihedral angle of 45°.

Even apparently simple populations of orthogonal extension joints build up cumulatively as a consequence of alternating failure events on surfaces at right angles to each other. Such roughly contemporaneous orthogonal sets may be the result of repeated 90° switches in the directions of effective minimum stress axes, or they might indicate that extension fractures can be initiated almost simultaneously perpendicular to both minimum and intermediate stress axes. The abundance of vertical and steep extension and hybrid (transitional tensile) joints in many platforms shows that jointing is favoured when brittle rocks enter an environment in which differential stresses are small and the effective minimum stress is both tensile and horizontal.

PREAMBLE

This note outlines some observations and ideas that have been made or arisen since the first author's (HANCOCK 1985) review of premises and procedures employed in recording and analysing brittle structures. Outcrop- and sample- scale (i.e. mesoscopic) structures, especially joints, are highlighted and the majority of examples are selected from weakly deformed sedimentary terrains which were extending horizontally when the fractures were formed. Examples are also mainly of Cenozoic age and, where possible, from neotectonic provinces. Two advantages of selecting relatively young mesofractures as examples are that it is more straightforward to correlate them with well-dated tectonic phases and they are less likely to have had their original characters modified.

DYNAMIC AND KINEMATIC COMPATIBILITY

Roughly coeval structures initiated in a uniformly orientated stress field can be regarded as dynamically compatible with each other. Dynamic compatibility does not, however, rule out the possibility of there having been temporal or spatial variations of differential stresses during structure initiation, or the influence of material properties. Thus, for example, a quartz arenite might respond to the stress regime illustrated in *fig. 1a* (σ_1' taken as being vertical) by the formation of a set of vertical extension veins. By contrast, a limestone might deform in a nonbrittle manner by developing horizontal stylolite seams with vertical interlocking teeth (*fig. 1b*). Likewise, the association of a set of vertical extension veins with an orthogonal set of horizontal stylolite seams (*fig. 1c*) is dynamically compatible with an association comprising conjugate normal faults (*fig. 1d*). Compatibility between the associations is achieved despite the

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improbability of them being precisely contemporaneous; shear failure requiring a larger differential stress than tensile failure. Precise contemporaneity is equally unlikely where an assemblage of all four sets occurs in conjuction (*fig. 1e*). Isolated single sets of extension fractures can give rise to ambiguous palaeostress interpretations. For example, from the veins illustrated in *fig. 1a* it is reasonable to infer that σ'_3 was horizontal during their formation but without supplementary information, such as the orientation of hackle-mark axes it is not possible to know whether σ'_1 was vertical, horizontal or obliquely inclined. If σ'_1 was vertical the veins are dynamically compatible with the normal faults shown in *fig. 1*, but if σ'_1 was horizontal, vertical strike-slip faults would be compatible with them.

Dynamic comptability between fractures does not necessarily imply kinematic compatibility. The development of the single set of extension fractures shown in *fig. 1a* will cause elongation normal to the set (i.e. parallel to the X strain direction) but no motion or change in length parallel to the plane of the fracture set. By contrast, the conjugate brittle normal faults, dynamically compatible with them, result not only in elongation parallel to their obtuse bisector but also shortening parallel to their acute bisector (Z in *fig. 1d*). The above discussion of brittle faults assumes they are conjugate in the sense employed by ANDERSON (1942), that is, the faults intersect parallel to σ'_2 and strain is plane. According to ANGELIER (1984) the criteria which should be fulfilled if two fault sets are to be classified as comprising conjugate brittle fractures are: (1) slickenside lineations on faults in both sets should be normal to the direction of their mutual intersect (the *B* axis direction in seismological terms), (2) senses of motion should be symmetrical about the acute bisector between the sets and such that it is parallel to the shortening direction and (3) the value of the dihedral angle (2θ) enclosed by the faults should be consistent with the material properties of the rock. The third qualification means that 2θ should be equal to 90-Φ (Φ being the angle of internal friction and hence the orientations of faults predictable on the basis of the Navier-Coulomb shear failure criterion for brittle, mechanically isotropic rocks. The first two criteria are determinable from field observations but assessing the third requires rock-mechanics tests and assumptions to be made about confining and fluid pressures at the time of failure. ANGELIER (1984) calls sets quasi-conjugate if they satisfy only the first two criteria.

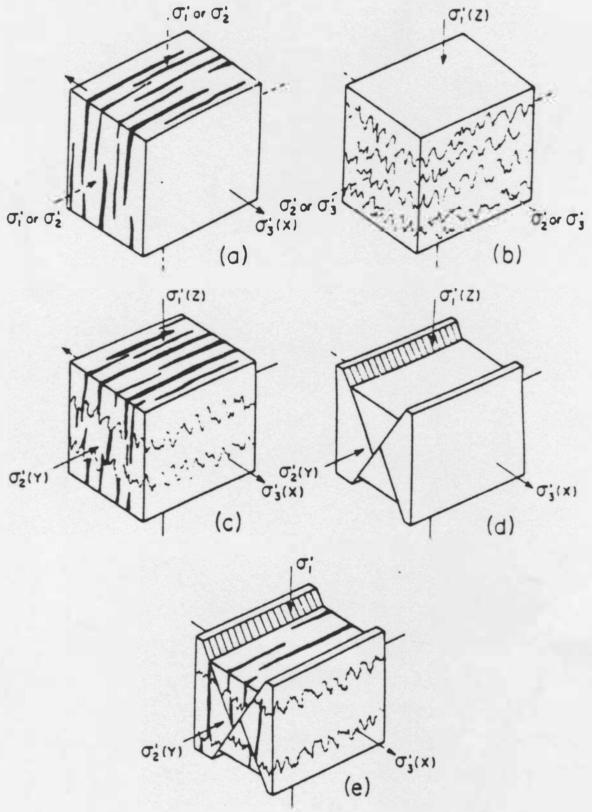

Fig. 1 - Brittle structures illustrating the concepts of dynamic and kinematic compatibility. (*a*) Vertical extension veins. (*b*) Horizontal stylolite seams with vertical interlocking teeth. (*c*) Roughly coeval vertical extension veins and horizontal stylolite seams. (*d*) Conjugate «Andersonian» normal faults. (*e*) Roughly coeval extensional veins, stylolites and conjugate normal faults. σ'_1, σ'_2, σ'_3 - maximum, intermediate and minimum effective principal stress axes (effective stress [σ'_i] being total stress [σ] less fluid pressure [p]); X, Y, Z - greatest, intermediate and least principal strain axes. See text for discussion.

When assessing dynamic and kinematic compatibility, additional complications are introduced if the influence of preexisting discontinuities on shearing is considered (e.g. BOTT 1959), or if strain is not plane. RECHES (1983, *fig. 1b*) has proposed that three or four symmetrically arranged fault sets can form in a three-dimensional strain field provided suitably orientated preexisting cracks or flaws are present.

Deformation is likely to be coaxial in a pure shear environment (*fig. 2a*), but in a simple shear environment it is non-coaxial (*fig. 2b*). This means that during simple shear the *X* and *Z* strain axes rotate away from σ_3 and σ_1 axes as inferred from fault geometry and senses of dis-

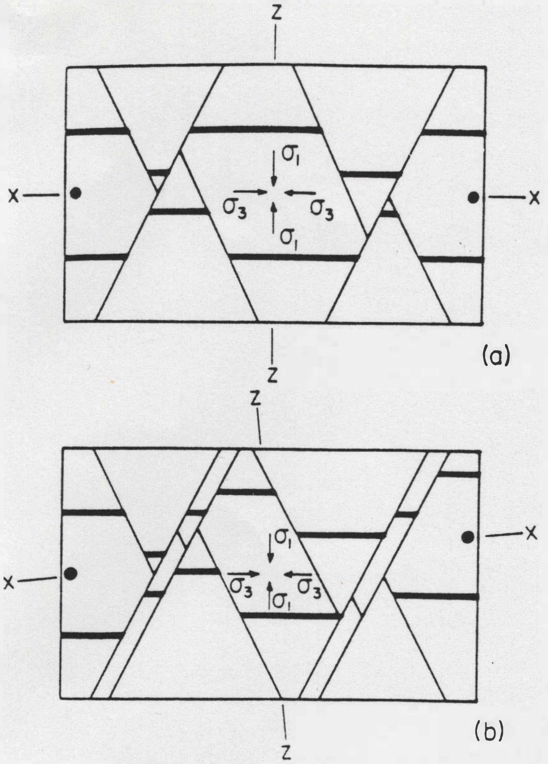

Fig. 2 - (*a*) Coaxial deformation (i.e. pure shear) resulting from the equal development of conjugate fault sets. (*b*) Non-coaxial deformation (i.e. simple shear) resulting from the unequal development of conjugate fault sets, σ_1, σ_2, σ_3, X, Y, Z as in *fig. 1*.

placement. An implication of this conclusion for the field geologist is that unless the net displacements on all faults in both conjugate sets are known it is not possible to determine precisely the orientations or magnitudes of *X* and *Z*, although it is possible to infer the orientations and relative magnitudes of σ_3' and σ_1' axes.

JOINT SPECTRA

Where faults, veins, en échelon crack arrays and solution seams are lacking or scarce it is necessary to survey joints as substitutes for the kinematically more-diagnostic structures. On the basis of field relationships or statistical tests each joint is generally allotted to a set, and the sets interpreted in terms of whether they are thought to comprise extension, hybrid or shear fractures. At most localities allotment to sets is straightforward, but a few localities somewhat arbitrary decisions have to be made so that each member of a group of coaxial (used here in the sense of possessing mutual intersects) joints is assigned to a well-defined set. Among the possible explanations for why allotment can be difficult two are discussed here. Firstly, every non-parallel coaxial joint at a locality is a representative of a «set» consisting of a single surface. Such a situation could arise if, during a failure sequence, there were numerous small angular rotations of σ_1 and σ_3 axes and each joint was an extension fracture initiated in the $\sigma_1\sigma_2$ principal plane. For this explanation to apply to an observed assemblage of joints there should be field evidence in favour of each joint being an extension fracture of slightly different age to its neighbours but nevertheless initiated during the same generation of failure events. Secondly, the widely held axiom that all joints resulting from the action of a uniformly orientated stress field always belong to well-ordered sets is not always valid. Consider the classes and attitudes of joints that could be formed in a small, lithologically homogeneous rock mass that is experiencing a sequence of failure events in a uniformly orientated stress field within which the effective differential stress $(\sigma_1' - \sigma_3')$ is varying with time (*fig. 3*). Assuming a composite failure envelope is appropriate to describe stress conditions during fracture initiation in a brittle, mechanically isotropic rock (*fig. 3d*), whether extension, hybrid or shear joints are formed will depend on the value of $(\sigma_1' - \sigma_3')$ with respect to the magnitude of the tensile strength (T) of the rock (*figs. 3a-c*). If, with time, $(\sigma_1' - \sigma_3')$ varied continuously, but not always progressively, from more than 8T to less than 4T (or *vice versa*) it is possible that instead of sets of extension, hybrid or shear joints being formed a continuum of coaxial joint orientations enclosing a 2θ angle of about 60° could build up (*fig. 3e*). The symmetry axis of such a continuum would permit the orientation of σ_2' to be estimated knowing the joints to be coaxial about the σ_2' direction. HANCOCK (1986a) has proposed calling a continuum of dynamically compatible coaxial joints a joint spectrum. Field examples of complete joint spectra comprising extension and shear fractures plus a wide spread of hybrid fractures have not been described, but partial spectra consisting of extension joints and hybrid joints enclosing a maximum acute angle of 45° are not uncommon (HANCOCK 1986a).

An instructive example of a partial joint spectrum within 30 m of well- ordered conjugate sets is exposed in a 40-cm-thick Jurassic dolostone occupying the core of a gentle dome

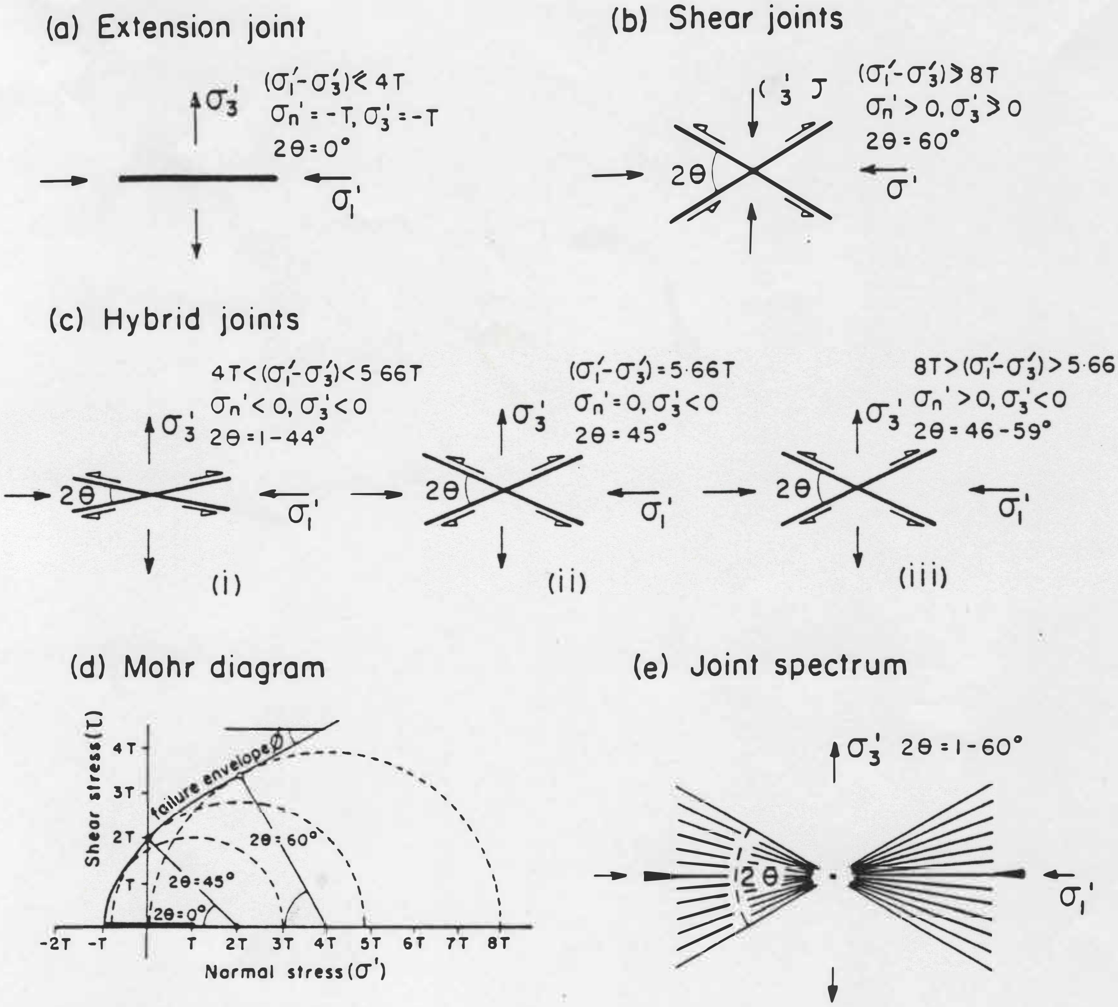

Fig. 3 - Stress conditions during the formation of (*a*) extension joints, (*b*) shear joints and (*c*) three subclasses of hybrid joints assuming that a composite failure envelope of the type shown in (*d*) is appropriate to describe failure conditions. (*e*) Cartoon of an imaginary joint spectrum comprising coaxial extension, hybrid and shear joints shown at 10° intervals in a continuum of directions intersecting at a common point. 2θ. conjugate shear angle; T, tensile strength; $(\sigma'_1-\sigma'_3)$, differential stress. Other symbols as in *fig. 1*. From HANCOCK (1986a, *fig. 1*).

at Kimmeridge Bay, Dorset, England. The joints cut the flat central portions of small overlapping thrust sheets, but are younger than connecting cross-joints. *Figure 4a* is an oblique view of the conjugate sets (statistically perpendicular to bedding) exposed as traces on the top surface of the dolostone. In *fig. 4b* the traces are plotted as intersection lineations. The well-ordered sets enclose a 2θ angle of 37° about a 170°- trending acute bisector. The traces illustrated in *fig. 4c* do not belong to conjugate sets but, as *fig. 4d* shows, define a continuum of intersection lineations enclosing a maximum angle of 39° about a symmetry axis trending 163°. Some of the traces visible in *fig. 4c* are en échelon cracks in arrays that enclose a 2θ angle of 44° about an acute bisector whose trend is within 1° of that of the spectrum symmetry axis. There was probably a minor component of sinistral shear along the array trending 189° and a minor component of dextral shear along that trending 145°. The conjugate joints and conjugate en échelon crack arrays shown in *figs. 4a* and *b* and *figs. 4c* and *d*, respectively, are interpreted as comprising hybrid fractures (2θ = 37 and 44°), formed when $(\sigma_1-\sigma_3)$ approached 5.7T and the effective normal stress (σ'_n) across each fracture was just less than zero (*fig. 3c*, part i). The partial spectrum illustrated in *figs. 4c* and *d* is interpreted as consisting of some extension joints and many hybrid joints at angles between about 10 and 20° with the direction of σ'_1 at the time of their initiation.

The most probable reason for the develop-

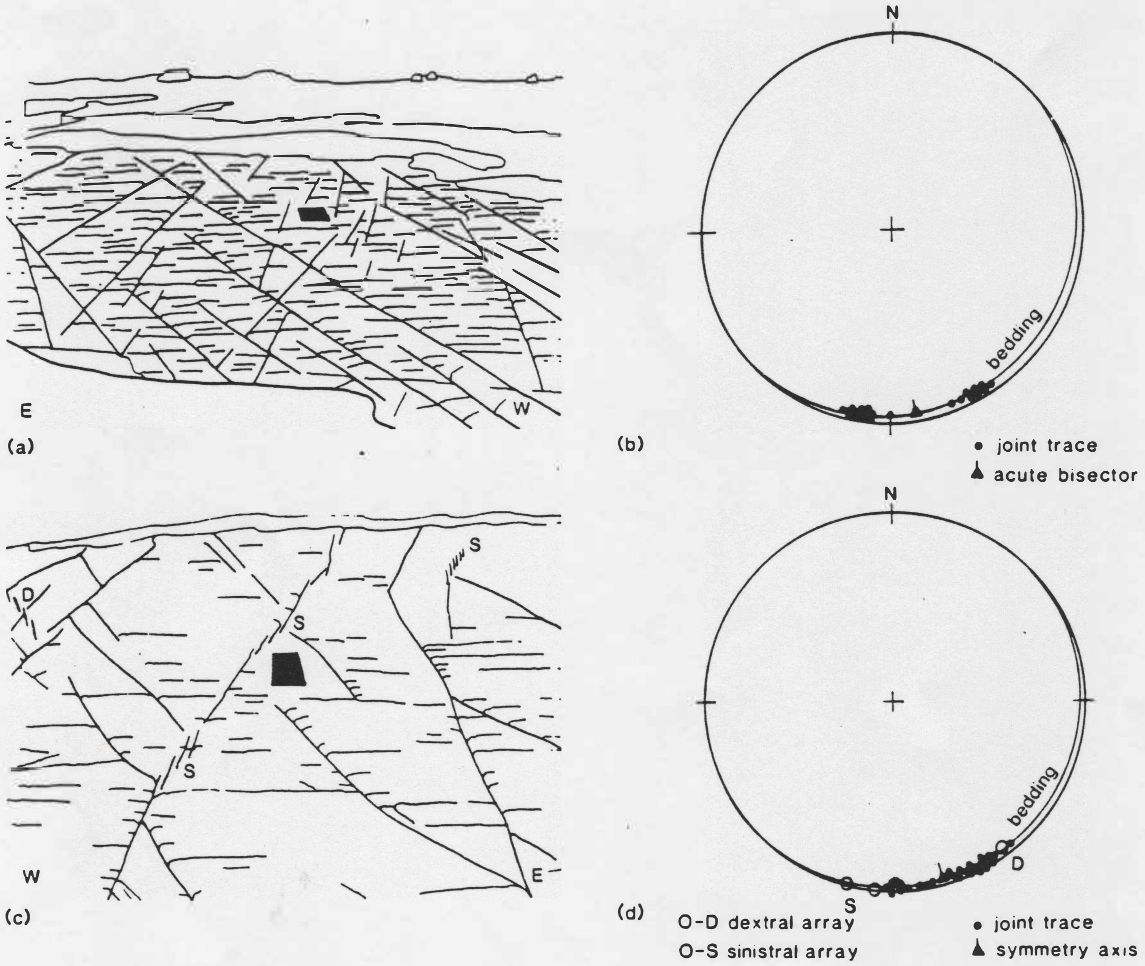

Fig. 4 - Examples of conjugate hybrid joint sets and a partial joint spectrum in a Jurassic dolostone at Kimmeridge Bay, Dorset, England. (*a*) Sketch from a photograph of conjugate hybrid joint traces connected by younger cross-joints. Clip-board (black) is 30 cm long. (*b*) Conjugate joint traces plotted as intersection lineations on a lower-hemisphere, equal-area projection. (*c*) Sketch from a photograph of the traces of joints in a partial spectrum and en échelon cracks belonging to conjugate dextral (D) and sinistral (S) arrays. Clip board (black) is 30 cm long. (*d*) Intersection lineations of the joints in the spectrum and the arrays of en échelon cracks plotted on a lower-hemisphere, equal-area projection. See text for explanation. From HANCOCK (1986a, *fig. 3*).

ment of joint spectra in a uniform rock type is the variation with time of the value of $(\sigma_1'-\sigma_3')$ during a nfailure sequence, but strain-related influences, such as distance from a neutral surface, may be contributing factors. Depending on when jointing occurs during a tectonic cycle (see e.g. ENGELDER 1985) the value of $(\sigma_1'-\sigma_3')$ may be rising or falling, and hence some spectra may comprise early formed extension joints and later-formed hybrid joints, while in other spectra the order is reversed. Field studies to determine which sequence is commoner would be of value.

The occurrence of neighbouring joints at small angles or parallel to each other, both in spectra and sets, demonstrates that the presence of one joint does not necessarily inhibit the initiation and propagation of another in an identically or differently orientated stress field. Because the average separation of parallel and subparallel joints is generally not less than the thickness of the layer containing them it is concluded that the stress field responsible for initiating a joint influences only a small volume of rock, or cohesion is not lost completely across a newly formed joint plane.

FAR-, MID- AND NEAR-FIELD INFLUENCES ON BRITTLE BEHAVIOUR

Assessing whether a suite of brittle mesofractures is a response to a stress field that influenced a region of several thousand square kilometres, an area of several hundred square kilometres or a local tract, restricted to a fold limb or the neighbourhood of a large fault, requires information about the distribution of the suite and the extent to which its members are uniformly orientated. Although analysis of mesofractures of restricted distribution and variable orientation may reveal little about regionally significant stress fields their investigation may yield information critical to understanding the geometry and kinematics of larger structures, especially listric and staircase-trajectory faults. The ideal environment in which to detect the influence of regionally significant far-field stresses is the tectonically quietest; for example those parts of platforms which are distant from major fault or fold zones and within which there have not been large rotations about horizontal or vertical axes.

In order to illustrate styles, orientations and distributions of mesofractures related to far-. mid- and near-field stresses, comparable assemblages related to regional, areal and local extensions of the same age in the same province are discussed. The case-study area is the sedimentary platform bordering the eastern margin of the Arabian shield. With the exceptions of an arcuate late Mesozoic-medial Tertiary fault zone and N-S hydrocarbon-bearing anticlines, the structural style is simple, comprising a crescent of Mesozoic-Tertiary rocks dipping ENE, E and ESE at angles of 1° or less and defining the E-W crest of the central Arabian arch (*fig. 5*)

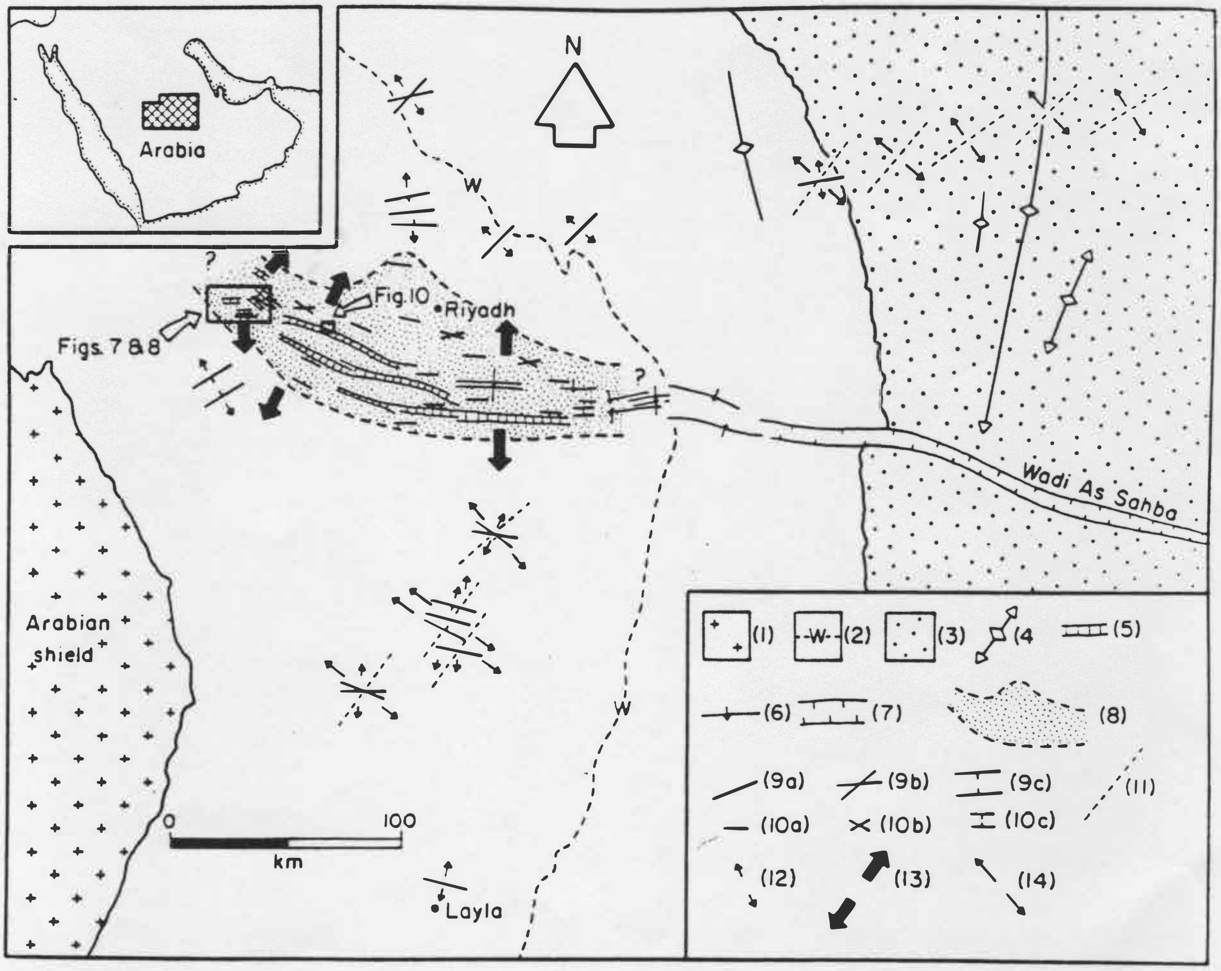

Fig. 5 - Strikes of regionally developed mesofracture sets cutting Mesozoic and Tertiary rocks in the eastern part of the Arabian platform. 1, Precambrian, 2, Permian-Eocene (W-sub-Cenomanian unconformity); 3, Neogene; 4, anticline; 5, graben, 6, monocline; 7, Wadi As Sahba; 8, joint domain of the central Arabian graben system; 9, 10 & 11, strikes of system 1 mesofractures in the arch, graben system and Batin joint domains, respectively (*a*, *b*, & *c* refer to the classes illustrated in (*a*), (*b*) and (*c*) of *fig.* 6; *12, 13, & 14*, generalized horizontal extension axes inferred from mesostructures in the arch, graben system and Batin joint domains, respectively. *After* HANCOCK et al. (1984, *fig.* 4).

(Hancock et al. 1984). The arcuate fault zone (the southern sector of the central Arabian graben and trough system), which is roughly coincident with the crest of the arch, comprises numerous symmetrical grabens and monocline-bounded troughs developed during the late Cretaceous-Palaeogene, at about the same time as amplification of the arch. An eastern cover of Neogene rocks rests uncomformably on those of the arch.

Three regionally developed suites of mesofractures, dominantly comprising joints (and hence referred to as joint domains), are recognizable. The suite comprising the greatest number of sets occurs in a belt up to 80 km wide astride the 560-km-long graben system (*fig. 5*). It defines the graben system joint domain and consists of ten sets divisible into three systems on the basis of geometry and the order in which the oldest fractures in each system were formed. Each system is symmetrically orientated with respect to the strike of the graben-boundary fault or monoclinal flexure closest to the outcrop where the fractures occur (geometric and interpretative details are given in *fig. 6*). Although it is possible to establish that the oldest fractures in system 1 are older than the oldest in system 2, and likewise they are older than the oldest in system 3, cutting and abutting relationships indicate that each system was built up cumulatively and contains some fractures which are older, and some which are younger than those in other systems. In *fig. 5* only system 1 mesofractures are plotted within the graben system joint domain because they are more abundant than those in the other two systems and their geometries are comparable to the dominant mesofractures in the other two domains, which contain joints that are more widely distributed than those in the graben system domain.

Because there is no overlap between structures in the graben system joint domain and those in the arch domain they are probably coeval. The system 1 mesofractures of the arch domain either strike parallel to, or enclose an acute angle about, the direction of dip of rocks in the arch and hence they reflect strike-parallel stretching. System 2 mesofractures in the arch domain are absent or feebly developed as cross-

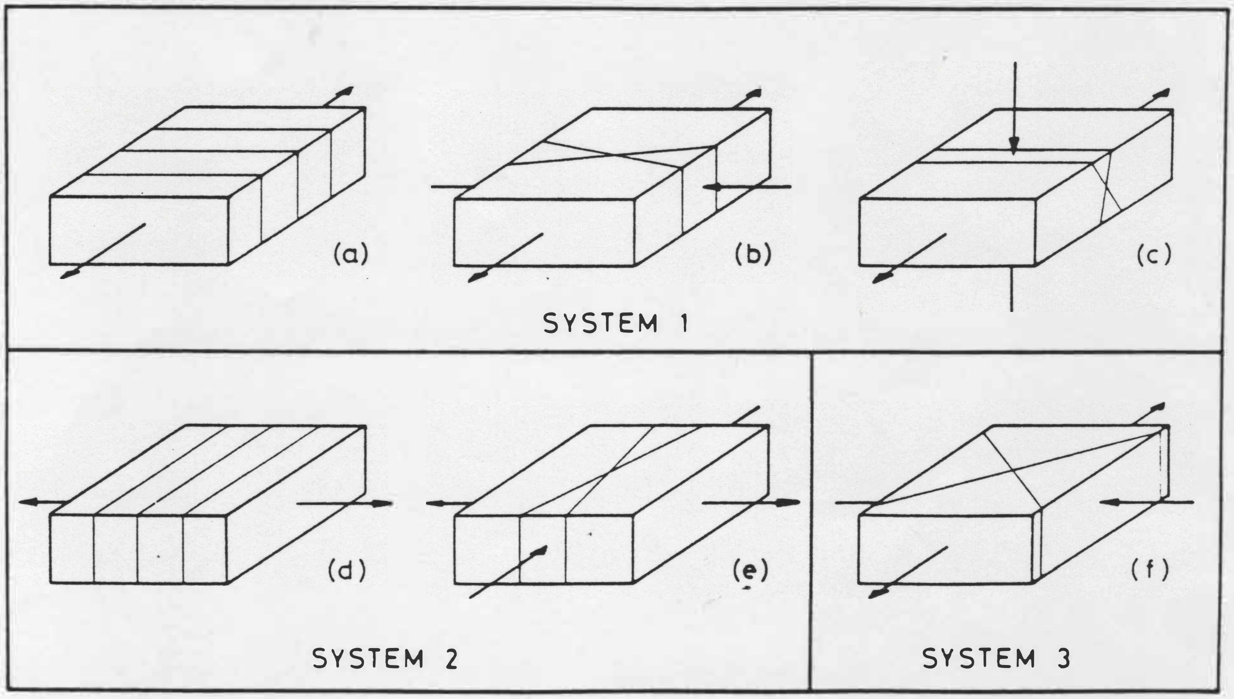

Fig. 6 - Mesofracture sets cutting rocks in the eastern part of the Arabian platform. The front of each block is drawn parallel to the controlling symmetry direction in each joint domain (see *fig. 5*). (*a*) Set J_{1a} extension joints and veins. (*b*) Conjugate sets of J_{1b} and J_{1c} hybrid joints and veins enclosing an average 2θ angle of 28°. (*c*) Conjugate set J_{1d} and J_{1e} hybrid and shear joints and mesofaults (2θ average 36°). (*d*) Set J_{2a} extension joints and veins. (*e*) Conjugate set J_{2b} and J_{2c} hybrid joints and veins enclosing an average 2θ angle of 28°. (*f*) Conjugate set J_{3a} and J_{3b} shear joints enclosing a 2θ angle approaching 90°. System 1 mesofractures characterize all three joint domains but system 2 and 3 mesofractures are absent or feebly developed in the arch and Batin joint domains. Arrows indicate directions of greatest and least stress. After Hancock & Kadhi (1978, *fig. 4*).

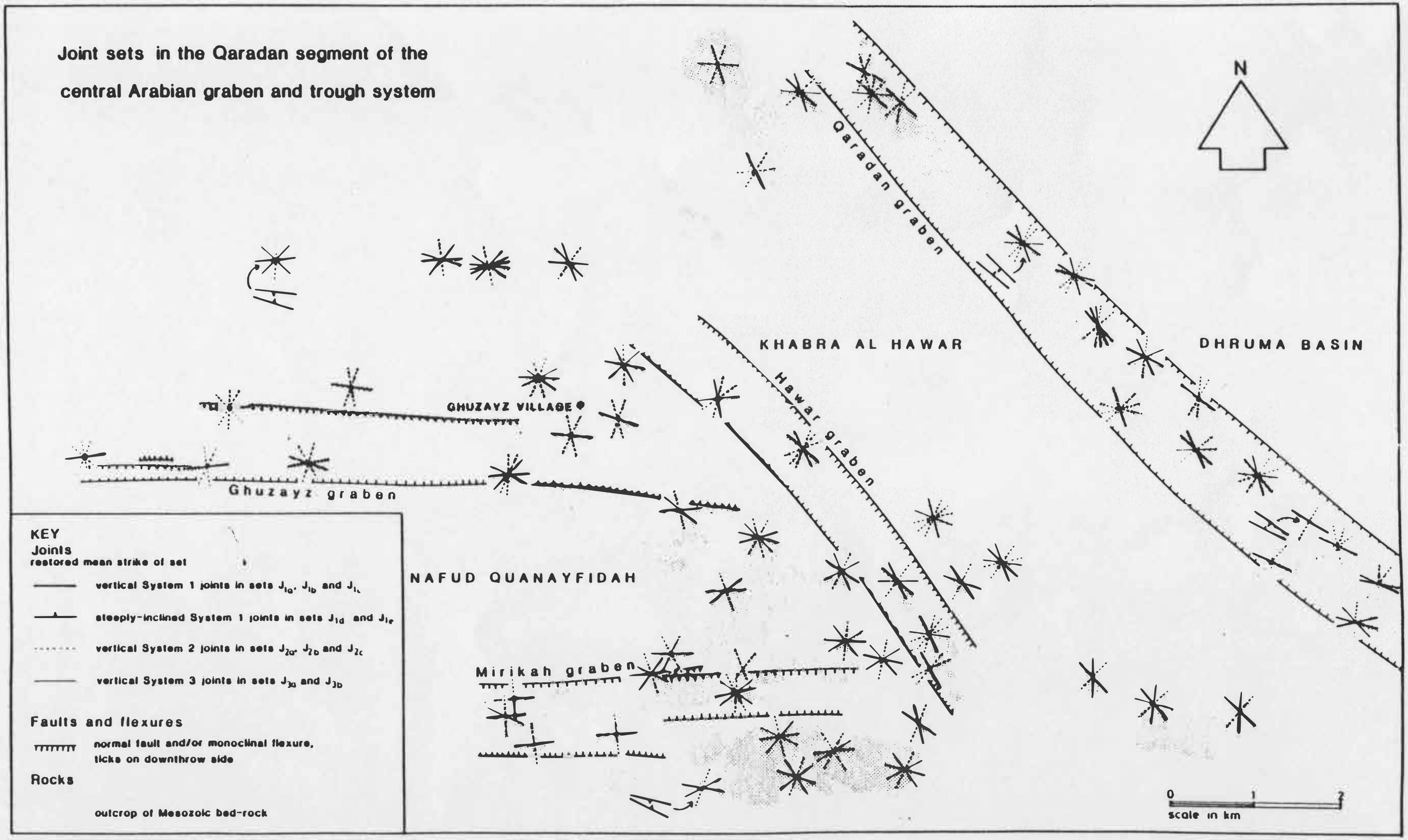

Fig. 7 - Average strikes of mesofracture sets at 64 stations in the Qaradan segment of the central Arabian graben system. For location of study area see *fig.* 5 and for explanation of set nomenclature see *fig.* 6.

joints. Structures in the arch joint domain cut rocks up to the Neogene, whereas those in the third domain, which are the most widespread, cut both the Neogene cover in the east and are superimposed on those of the arch domain. Because they strike parallel or subparallel to Wadi Al Batin, a major 350-km-long NE-trending lineament about 300 km north of the area depicted in *fig. 5*, and are roughly contemporaneous with Neogene faults beneath the wadi, they define the Batin joint domain (HANCOCK et al. 1984). Some of the mesofractures shown in *fig. 5* as belonging to the northern sector of the arch domain may be Batin joint domain structures but the local parallelism of the Batin trend and the direction of dip of rocks in the arch does not enable them to be distinguished.

Initiation of mesofractures in the contemporaneous graben system and arch joint domains probably occurred during regional strike-parallel extension imposed during amplification of the arch. HANCOCK et al. (1984) proposed that amplification might have been an isostatic response to thrust stacking in the Zagros and Oman ranges on the borders of the Arabian subplate. The temporal coincidence of initial thrusting and arching favours this explanation, but from a purely geometrical perspective the elongation of the rocks around the crest of the arch could be related to regional doming of the shield area prior to rifting and separation across the Red Sea. The uniform NW-SE direction of extension which initiated structures in the Batin joint domain has been interpreted by HANCOCK et al. (1984) as a consequence of NE-SW post- collisional shortening in the Zagros ranges. According to HANCOCK & BEVAN (1987) the lateral elongation of forelands is a common response to shortening in neighbouring mountain belts.

Turning to the mid-field scale, *fig. 7* illustrates the arrangement of the 10 sets of graben system domain (*fig. 6*) mesofractures in the Qaradan area where the principal grabens trend NW-SE, but to the south of them there are two E-W trending grabens. Displacements on graben-boundary faults are entirely dip slip throughout the area. At each of the 64 mesofracture stations the symmetry of the sets with respect to nearby faults is clear. The direction of extension inferred from system 1 and 3 sets describes a 50° arc between grabens trending NW-SE and those trending E-W. The smoothness of the arc (*fig. 8*) indicates there was not an

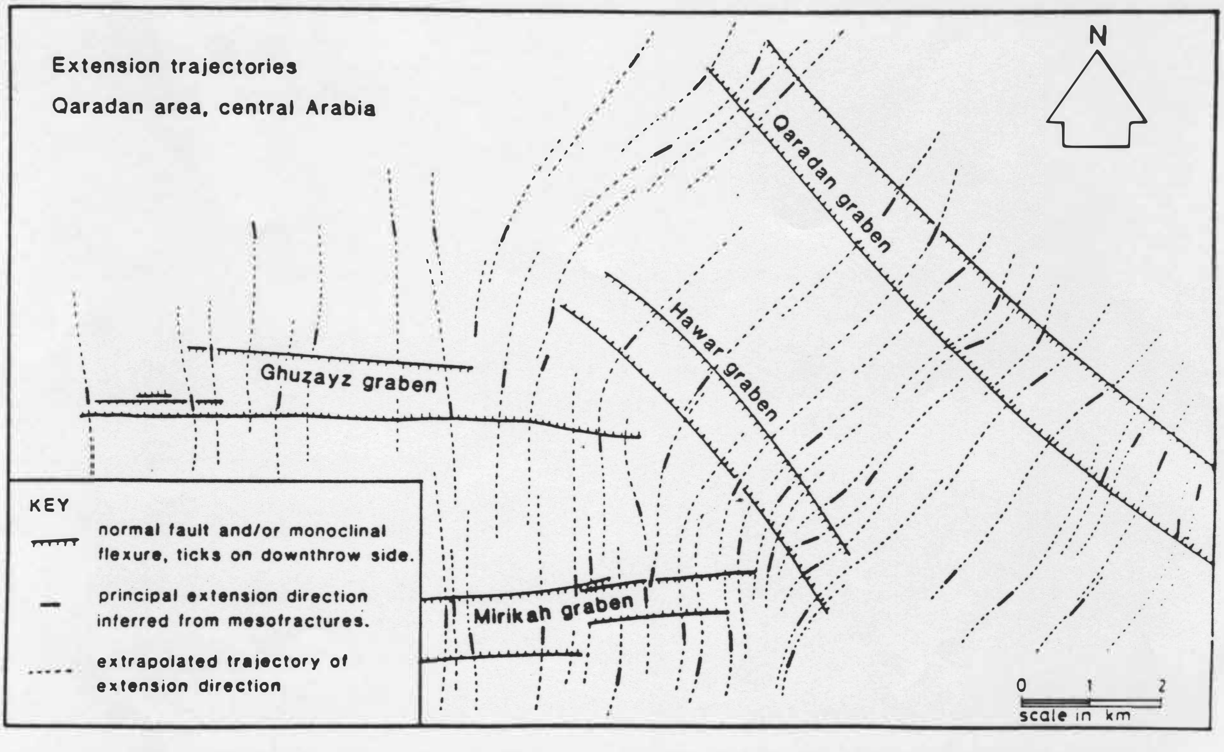

Fig. 8 - Projections of horizontal extension directions inferred or extrapolated from system 1 and 3 mesofractures in the Qaradan segment of the central Arabian graben system illustrated in *fig. 7*. After HANCOCK & KADHI (1985, *fig. 4*)

abrupt stress boundary between the two regimes, and hence grabens of both trends are probably of about the same age.

In order to assess the value of mesofractures that are uniformly oriented only on the scale of an individual outcrop, or cluster of outcrops, it is necessary to focus down again. Folds and second-order faults in extending terrains are commonly products of geometrically imposed accommodation. Such accommodation is commonly consequent on the development of either a precursor (i.e. tip line) roll-forward monoclines formed ahead of an advancing planar fault (slip surface) which later cuts it (*fig. 9a*), or a successor rollover anticline (roll-backward monocline) formed during hangingwall rotation above a listric normal fault (*fig. 9b*). Mesofractures in both settings should reflect layer-parallel stretching and complementary layer-normal attentuation (*fig. 9c*). In tectonically quiet settings, experiencing «background» extension adjacent to fault zones a more modest assemblage of structures will typify the less disturbed strata (*fig. 9d*). Descriptions of second-order structures in the hangingwalls of listric normal faults are given by GIBBS (1983, 1984, 1987) LAUBACH & MARSHAK (1987) & ŞENGÖR (1987) but those accompanying roll-forward monoclines are less well documented. Monoclines accompanying normal faults in the central Arabian graben system are, however, of the type shown in *fig. 9a*. In *fig. 10* some of the structures accompanying the northern boundary of a graben (located in *fig. 5*) whose internal structure is well exposed are illustrated. In the more steeply inclined rocks to the west of the hangingwall cross-fault, itself permitting the differential rotation of longitudinal segments of the roll-forward monocline, there are not only a greater number of subsidiary normal faults at 60-70° to layering, but also former extension fractures, perpendicular to layering, are now normal faults as a result of later shear displacements. Reactivation in shear of preexisting extension fractures is, according to ANGELIER & COLLETTA (1983), a feature of rotated and extended blocks in extensional terrains. In addition, the roll-forward monocline contains a higher frequency of extension joints and veins striking parallel to the faults than the horizontal limestones external to the fault zone.

The most detailed investigation of brittle structures which a field geologist is likely to undertake is a survey of small-scale phenomena

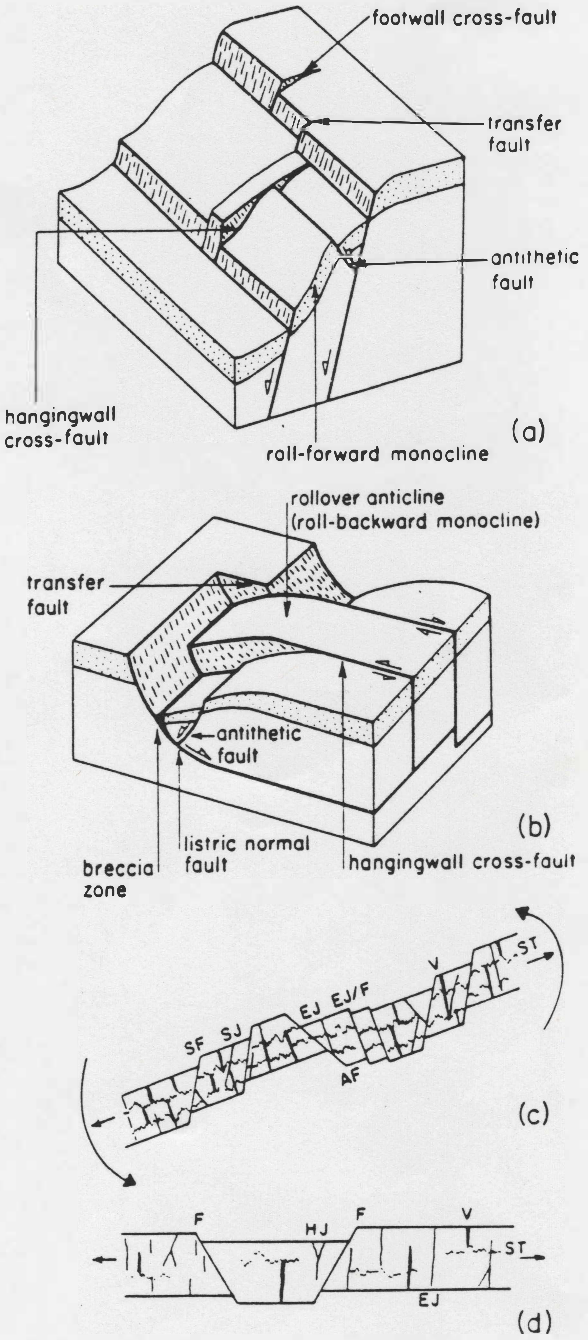

Fig. 9 - Accommodation structures adjacent to normal faults. (*a*) Structures in a precursor roll-forward monocline formed in advance of the tip line of an upward-propagating planar normal fault that later cut the monocline. (*b*) Structures associated with a successor roll-backward monocline (i.e. roll-over anticline) above a listric normal fault (modified after HANCOCK 1986b, *fig. 1c*). (*c*) Mesostructures to be anticipated in a roll-forward or roll- backward monocline accompanying a normal fault. (*d*) Mesostructures to be anticipated in flat-lying rocks adjacent to a major normal fault zone. SF, synthetic fault; AF, antithetic fault; SJ, shear joint; EJ, extension joint; HJ, hybrid joint; V, extensional vein; EJ/F, extension joint transformed into a normal fault; ST, stylolitic solution seam

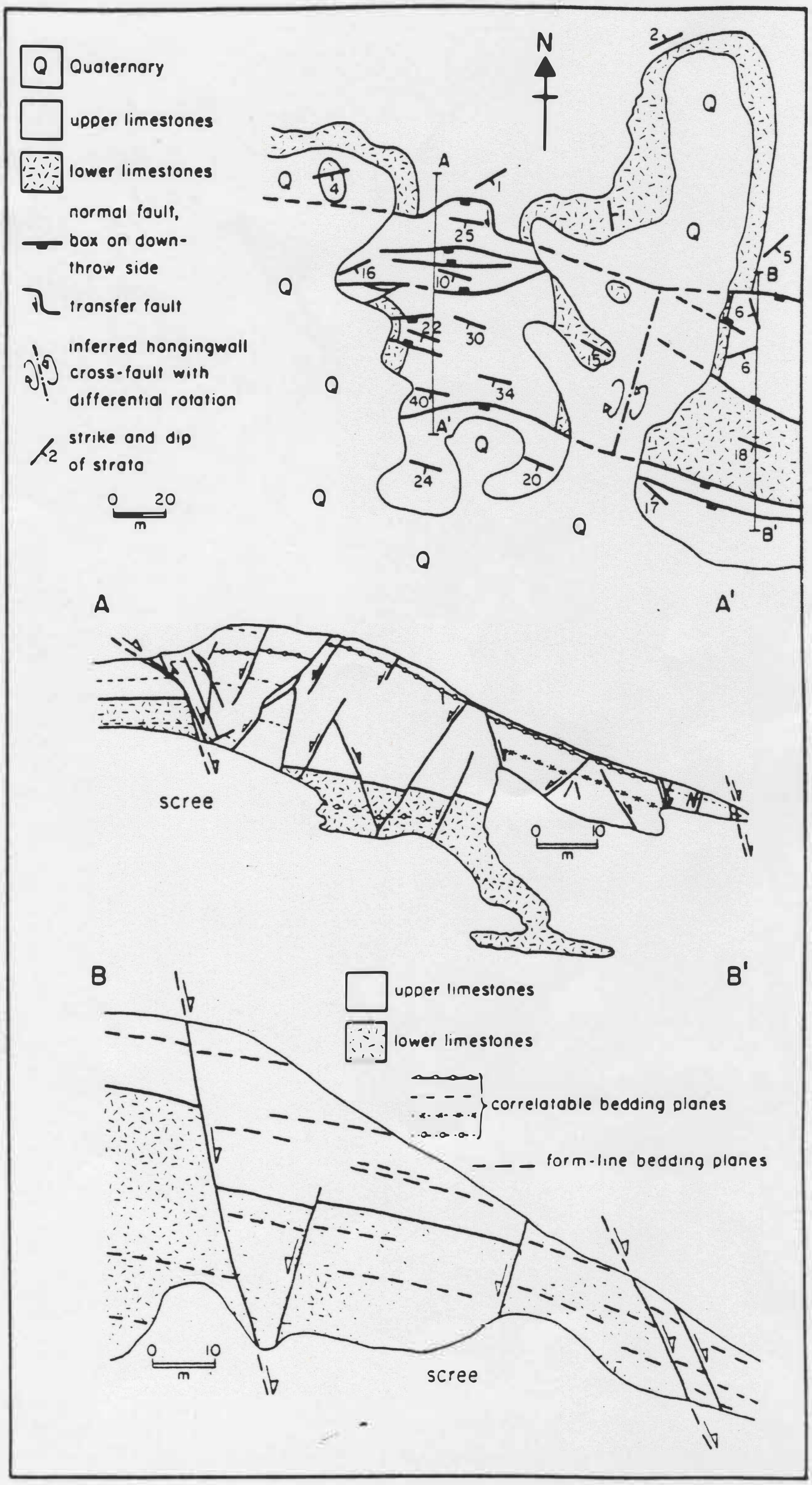

Fig.10 - Sketch map and sections of accommodation structures in a precursor roll-forward monocline in the northern boundary fault zone of the Dhruma graben, central Arabia (see *fig. 5* for location of map and sections).

in an individual fault zone. The employment of frictional-wear striae, accretionary growth fibres, oblique stylolite columns (i.e. slickolites) and asymmetric steps accompanying them is well known (e.g. Hancock 1985). During a survey of a late Quternary normal fault zone at Yavansu, 7 km SE of Kusadasi in the West Anatolian extensional province (Sengör 1987), two neglected categories of slip- parallel lineation were investigated in detail (Hancock

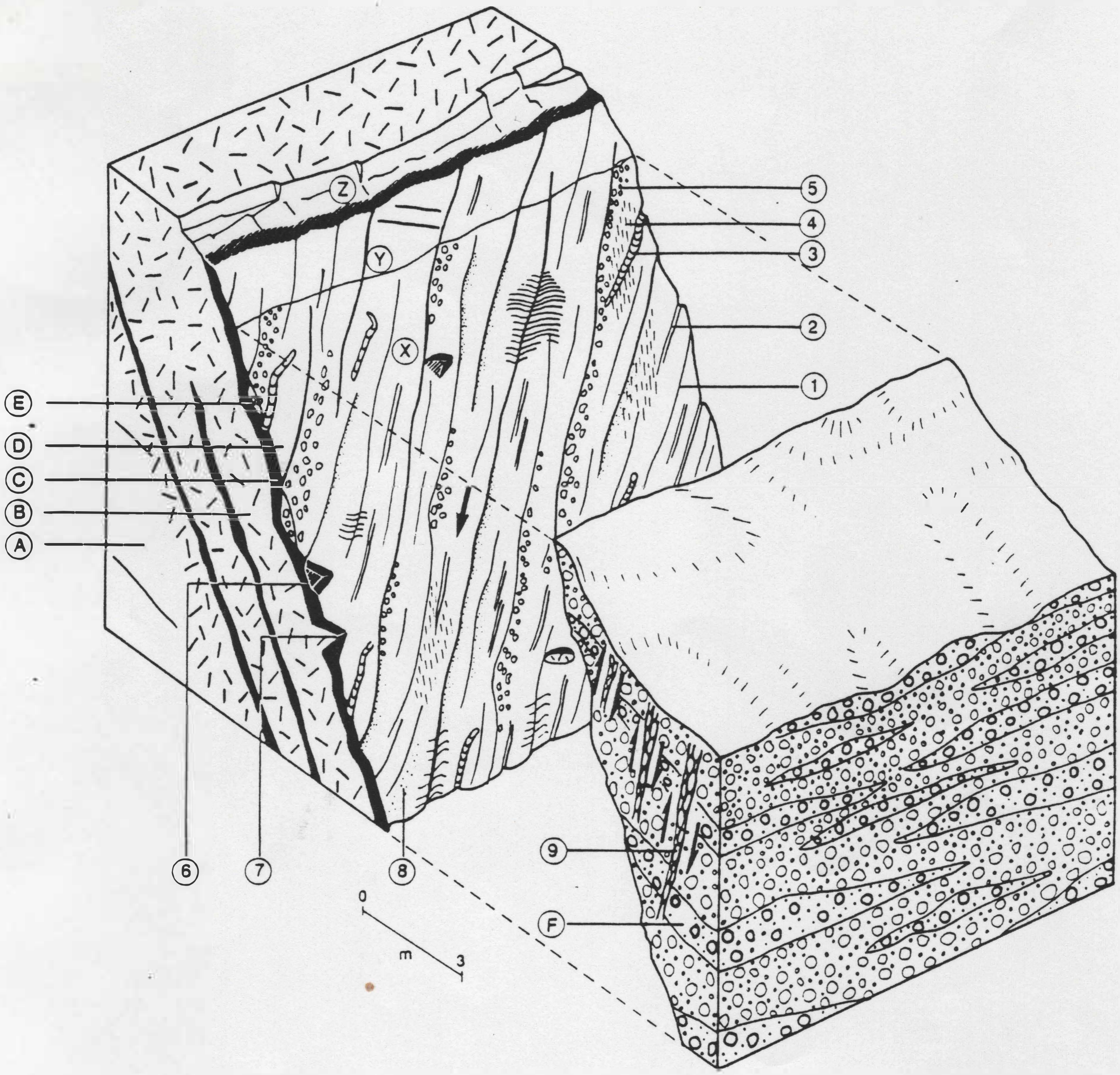

Fig. 11 - Schematic exploded block diagram to illustrate structures exposed in an active normal fault zone at Yavansu, near Kusadasi, Western Turkey. A. unbrecciated bedrock; B. fault-precursor breccia; C. mineralised subslip plane breccia sheet; D. corrugated slip plane; E. brecciated colluvium; F. unbrecciated Quaternary colluvium; X. artificially exhumed slip plane; Y. fresh fault-scarp; Z. degraded fault-scarp; 1. corrugation; 2. gutter; 3. tool track; 4. frictional -wear striae; 5. trail of brecciated colluvium [open symbol] or mud smear [stipple]; 6. spall mark; 7. pluck hole; 8. comb fracture trace; 9. reverse fissure-fault. From Hancock & Barka (1987, *fig. 5*).

&Barka 1987). The two «new» types of lineation exposed on the Yavansu slip planes are corrugations and gutters, both parallel to and accompanying striae and tool tracks, linear structures that are well known elsewhere (*fig. 11*) (Hancock 1985). Corrugation wavelengths, amplitudes and long-axis dimensions are up to 5,1 and 15 m respectively. The largest corrugations affect not only slip planes but also the entire thicknesses of underlying mineralised breccias sheets, which themselves cut coarse, fault-precursor breccias of a type that Vita-Finzi & King (1985) think form in advance of upward-propagating normal-faults. Corrugations on slip planes possibly develop while advancing fault surfaces are seeking undemanding pathways through precursor breccias. Gutters are flat- floored, steep-sided rectilinear channels in the uppermost 1-2 cm of mineralised subslip-plane breccia sheets. Gutters are generally between 2 and 20 cm wide and 1 to 4 m long.

In addition to corrugations and gutters, the subslip-plane breccia sheets at Yavansu also contain irregular fissures and very small faults

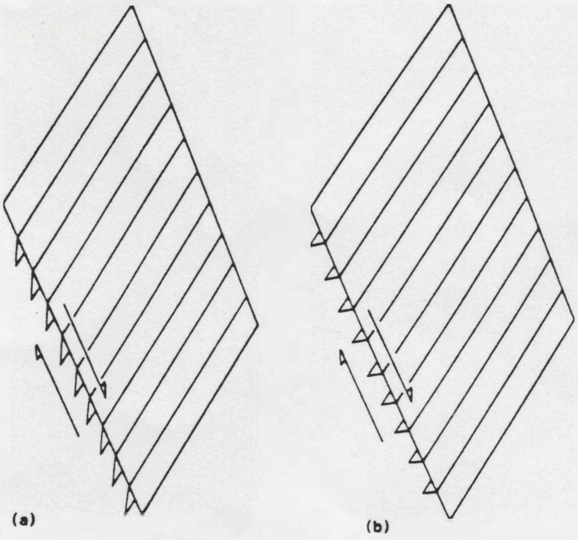

Fig. 12 - Geometry of (*a*) pinnate joints and (*b*) comb fractures in the footwall of a normal fault. From HANCOCK & BARKA (1987, *fig. 8*).

giving rise to crescentic intersection lineations statistically normal to corrugation axes (*fig. 11*). Unlike pinnate joints, which generally subtend angles of about 45° with slip planes (*fig. 12a*), these fractures are nearly normal to slip planes (*fig. 12b*) and hence, because they resemble the teeth of a hand comb, have been called comb fractures (HANCOCK & BARKA 1987).

FRACTURE «GRID-LOCKS»: TECTONIC SIGNIFICANCE OF SEQUENTIAL FAILURE BUILD UPS

The commonest joints in platforms are (a) vertical extension fractures, (b) vertical hybrid fractures ($2\theta < 45°$) and (c) steep hybrid fractures ($2\theta < 45°$) organized in well-ordered sets or partial spectra (e.g. ENGELDER & GEISER 1980; ENGELDER 1985; HANCOCK 1985; SUPPE 1985; BEVAN & HANCOCK 1986; HANCOCK 1986a). Implications following from these generalizations are that during jointing in platforms σ'_3 is horizontal or subhorizontal. σ'_3 and σ'_n are tensile and (σ'_1-σ'_3) is small and frequently less than 5.7T.

Figure 13 illustrates orthogonal sets of extensional joints in Jurassic limestones at the western end of the Mirikah graben, central Arabia (see *fig. 7*). Abutting and cutting relations indi-

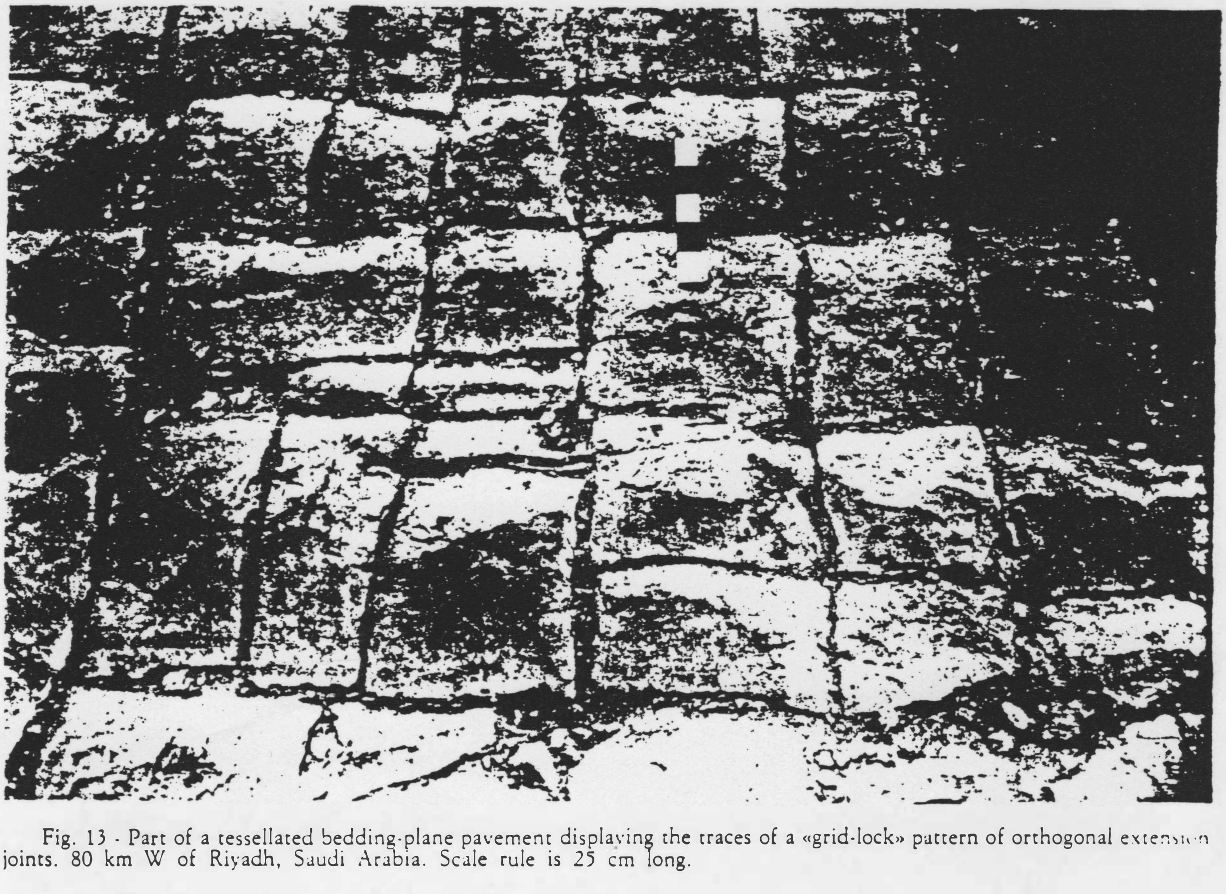

Fig. 13 - Part of a tessellated bedding-plane pavement displaying the traces of a «grid-lock» pattern of orthogonal extension joints. 80 km W of Riyadh, Saudi Arabia. Scale rule is 25 cm long.

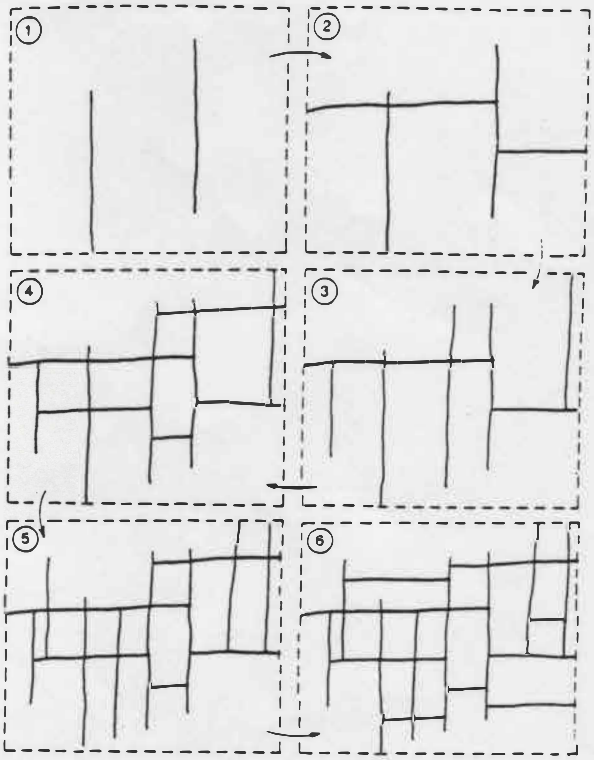

Fig. 14 - Cartoons illustrating in plan how a «grid-lock» pattern of abutting and cutting orthogonal joints might build up in a six-episode failure sequence.

cate that each set comprises some joints older than those in the orthogonal set and some that are younger. The sets appear to have been built up by a sequence of failure events involving alternating episodes of crack development in each set. Some younger joints cut older ones but others abut them where cohesion was lost and a crack could not propagate across the resulting gap. In this respect an older crack acts like a line of traffic blocking the passage of another line travelling on a road at right angles to it. When several lines of traffic at right angles to each other are unable to move the resulting jam is sometimes called a «grid lock» by North American journalists. A six-step cartoon sequence (*fig. 14*) shows how an analogous fracture «grid-lock» might build up.

Orthogonal sets of extension joints comprising fractures that are not precisely contemporaneous but were nevertheless developed in a single generation of failure events are common in many tectonic settings. Roughly simultaneous horizontal elongation along two orthogonal directions is thus likely to be a bulk strain regime favouring their development. This regime is RAMSAY's (1967) two-dimensional strain field 1, within which both λ_1 and λ_2 are greater than unity, and in which chocolate tablet structure forms in more ductile rocks. Its three-dimensional analogue may be the strain regime which RECHES (1983) has proposed for the formation of three or four coeval normal fault sets. The development of approximately contemporaneous sets of orthogonal extension joints implies there are either frequent short-lived 90° switches of σ'_3 axis directions, or extension fractures can form perpendicularly to both σ'_3 and σ'_2 axes. Furthermore σ'_2 and σ'_3 are likely to be nearly equal in settings favouring the development of a fracture grid-lock.

CONCLUSIONS

(*1*) Different genetic classes of brittle structure developed in a uniformly orientated stress field are dynamically compatible but they are not necessarily kinematically compatible.

(*2*) An orientation continuum of coaxial joint planes enclosing a maximum dihedral angle of 60° and defining a joint spectrum could develop when the value of the differential stress in a uniformly orientated field varies between four and eight times the tensile strength of a rock. Complete spectra, comprising extension and shear joints plus a 60° range of hybrid joints, have not been described but partial spectra containing extension joints and a continuum of hybrid joints enclosing a maximum angle of about 45° are not uncommon.

(*3*) Analysing mesofractures in the nearly horizontal rocks of platforms generally permits regionally significant palaeostress directions related to far-field influences to be determined. In less tectonically quiet settings, such as thrust-fold belts, graben fields or transcurrent fault zones, where rocks have been rotated about horizontal or vertical axes, many mesofractures systems are related to mid- or near-field influences affecting only relatively small areas or narrow localised tracts.

(*4*) Even the simplest pattern of orthogonal extension joints commonly displays evidence for having been built up cumulatively as a result of alternating short-lived episodes of elongation along perpendicular directions. The formation of such a grid of extension joints, not precisely contemporaneous with each other but nevertheless belonging to the same generation of events, may be a consequence of either repeated 90°

switches of σ_3' axis directions, or failure having occurred normal to both σ_3' and σ_2' axes.

(5) Because the commonest joints in platforms are vertical extension fractures and steep or vertical hybrid fractures arranged in sets or spectra it is concluded that during jointing σ_3' is generally tensile and horizontal and the value of (σ_1'-σ_3') is generally small, commonly less than about 5.7 times the tensile strength of rocks.

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