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Analogue simulation of natural orthogonal joint set formation in brittle varnish

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Abstract—Two orthogonal joint sets are commonly observed in exposed sedimentary rocks with a wide variety of abutting and cross-cutting relationships.

Brittle varnish analogue models are carried out in conjunction with field studies, in order to classify the different orthogonal fracture patterns and constrain the mechanical basis of orthogonal joint development.

The results suggest that the stress which creates the second joint set can result from: (i) relaxation effects; (ii) slight tension due to warping of the bands defined by the first parallel fractures; and (iii) local and/or regional reversals between σ_2 and σ_3. A 'ladder' pattern, formed by the combination of an initial set of long parallel joints and associated non-cross-cutting joints of the second set, is obtained if the shear strength of the initial joints is low during the development of the second set. A 'grid' pattern, where both sets mutually cross-cut, occurs when the shear strength of the initial joint set is high, possibly the result of a high normal stress or healing and could result from two independent stress events. An intermediate pattern comprising cross-cutting and abutting orthogonal cross-joints can form if the shear strength of the initial joints was intermediate and/or variable during the development of the second set. Mutually abutting joint sets are observed within each pattern and could result from stress reversals or low differential stress during the final stages of joint development.

The classical presentation of joint data using rose diagrams cannot distinguish between the wide variety of orthogonal joint patterns. Maps of fracture intersections should compliment the orientation data. We discuss methods to estimate the joint pattern where intersection data are absent.

INTRODUCTION

THE most commonly observed joint pattern at the surface is two orthogonal sets of joints normal to bedding. Such patterns have been recognized in many field studies and are commonly of regional extent (Nickelsen & Hough 1967, Babcock 1974, Engelder 1982, Lorenz & Finley 1991, Gross 1993). In many foreland areas the orientation of the major joint set is parallel to the regional compression direction and perpendicular to the least principal stress σ_3 (Engelder & Geiser 1980, Hancock & Bevan 1987, Lorenz *et al.* 1991) except where the regional stress field was locally perturbed (Rawnsley *et al.* 1992). The importance of joint geometry for many aspects of rock mass behaviour makes orthogonal patterns of special interest in applied geology.

Different varieties of orthogonal patterns exist (Pollard & Aydin 1988) with different cross-cutting and abutting relationships (Fig. 1). However, neither the classical description by rose diagrams nor the classification scheme of Hodgson (1961) who defines an initial set of long joints (systematic joints) and the second set mainly perpendicular to, and abutting against, the first joints (cross-joints), can account for all these pattern variations.

Within the different patterns the joints of the second set can cross-cut none or several joints of the initial set, which suggests that orthogonal patterns may result from different loading or healing histories, although the specific origin of these patterns remains unclear. In particular, the second set has been interpreted as either the result of: (i) a stress change due to the development of the first set (Simon *et al.* 1988); (ii) tectonic stress reversals (Hancock *et al.* 1987); (iii) a post-tectonic relaxation effect (Nickelsen & Hough 1967); or (iv) a separate stress event.

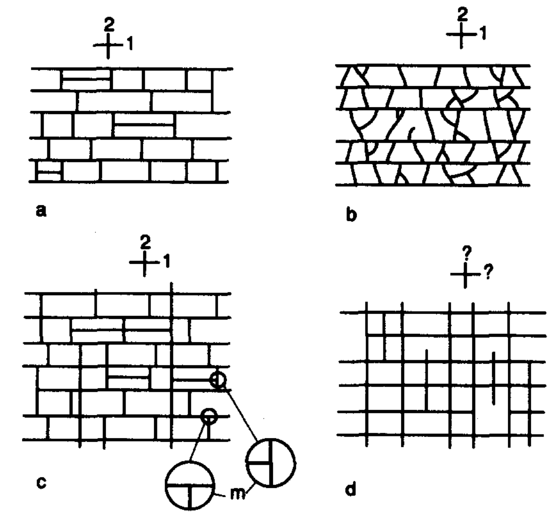

Fig. 1. Types of natural orthogonal joint patterns. (a) Ladder pattern, second joint set (2) does not cross-cut initial joint set (1). (b) Irregular ladder pattern. (c) Intermediate pattern. (d) Grid pattern. Some mutual abutments (m) are present in each pattern.

In order to classify the different orthogonal fracture patterns and to constrain the mechanical basis of orthogonal joint development, we have carried out a series of analogue experiments in conjunction with field studies. Particular attention is given to relaxation phenomena and multi-phase stress events.

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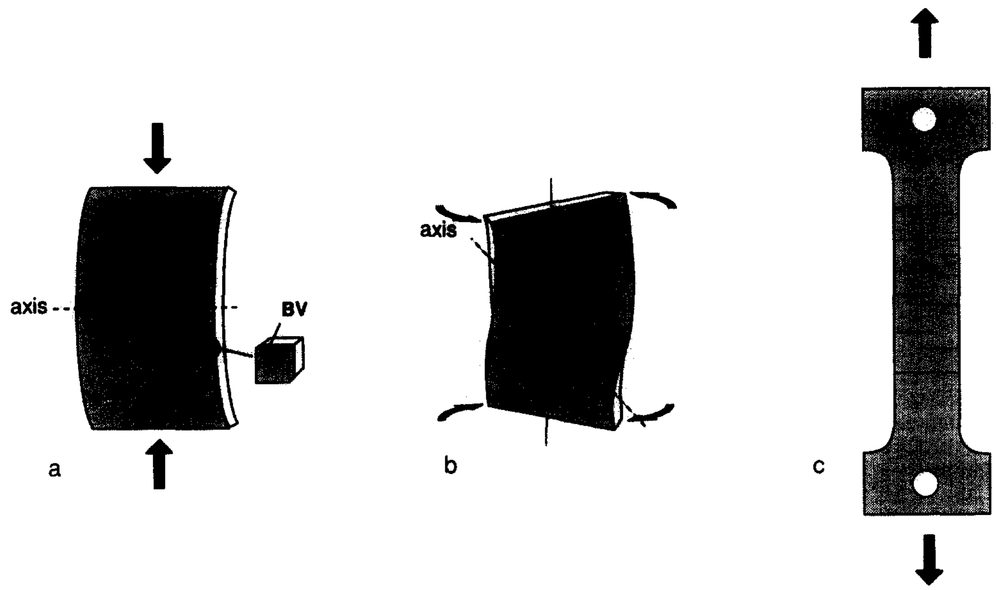

Fig. 2. PVC plates covered with brittle varnish (BV). (a) Cylindrical fold produced by uniaxial loading. (b) Oblique fold induced by torsion. Fold axes are indicated. (c) Extension induced by direct-traction.

PRINCIPLES OF THE BRITTLE VARNISH MODEL

This model consists of a brittle varnish layer bonded to a PVC plate. The plate is submitted to tension which is transmitted to the brittle varnish (Fig. 2). As a result fractures form in the brittle varnish but the opening of the fractures is limited due to the PVC support. This 'stress coating' technique was originally used in industry to determine stress trajectories in machine components, and more recently has been adopted by geologists to model joint development (Rives & Petit 1990a,b, Wu & Pollard 1991, 1992).

An undercoat (VISHAY U-10A) containing aluminium powder is sprayed onto the PVC support. After drying for 30 min the thin undercoat adheres perfectly to the support. The undercoat displays an elastic behaviour and due to the aluminium content, allows light reflection which enhances observation of the fractures in the covering varnish. The brittle varnish (VISHAY TL 500-80 X) is then sprayed onto the undercoat. The presence of bubbles is inherent to the spraying technique. The thickness of the brittle coating is approximately 0.1 mm but cannot be controlled exactly. After the varnish has dried for at least 12 h at room temperature, it develops visible fractures at a very small elongation of about 0.05% (Durelli & Okubo 1954). This very high sensitivity is largely due to shrinkage during drying which induces a residual tensile stress in the varnish which contributes to the low additional strains required for crack propagation. This locked-in stress contributes to the crack driving force (Rives & Petit 1990a). Nevertheless, the additional strain required varies slightly according to temperature, humidity, thickness and drying time, among other factors (Durelli *et al.* 1955, Faure 1966) which does not allow a rigorous quantitative approach.

Tests by folding (Figs. 2a & b), with the brittle varnish on the external part of the curved PVC plate and thus submitted to a tension, are carried out. The samples are deformed rectangular plates (70 × 40 × 1.5 mm). The two short edges of the plates, where the load is applied, are clamped in grooves to prevent sliding of the plates in the jaws. The deformation consists of shortening, which produces a cylindrical fold after buckling (Fig. 2a), and/or axial rotation, which produces a torsion in the plate (Fig. 2b). The slight tension induced by the bending produces a set of parallel, linear, continuous fractures in the brittle varnish. Successive loadings can be applied to represent successive periods of joint development.

Complementary tests on plates (100 × 40 × 1.5 mm) held by metal rods in holes at each end (Fig. 2c) and loaded by direct traction are carried out.

Fractures initiate either from the many small bubbles randomly distributed in the varnish, and concentrate stress, or from the edges of the plate where there is a higher flaw density induced by irregularities and higher stress. They propagate during a few seconds, away from the defects, in a direction normal to the maximum tensile stress.

NATURAL JOINT SET FORMATION AND THE BRITTLE VARNISH MODEL

Because of the properties of the brittle coating, particularly its varying sensitivity, these experiments represent only a qualitative approach. Nevertheless, they can be considered analogous to natural conditions in several aspects.

—The varnish adheres perfectly to the support. Any deformation of the substrate is transmitted to the brittle coating which fractures in tension. But, the substrate which induces tension in the varnish, at the same time, prevents continuous opening of the fractures. The effect of the support is to distribute the tension homogeneously in the varnish. We believe that in this way, the brittle coating experiments could model fracturing in confined layers because in a multilayer, the overlying and underlying beds would prevent continuous opening of the joints.

—The tension in the varnish is generated in the external part of the folded support. Fractures in the brittle varnish model can be linked to folding (Rives & Petit 1990a,b). Also because the substrate distributes the tension to every point of the varnish, these experiments are intended to represent fracturing of a layer in tension, not necessarily in folded strata.

—The initiation of experimental fractures is at defects and the propagation is away from these flaws. Both of these conditions are observed in natural joints (Helgelson & Aydin 1991, Rives *et al.* 1992).

—The fracture sets obtained in the brittle varnish comprise linear, open parallel fractures with regular spacings (Wu & Pollard 1992). If different sets are present, abutment and cross-cutting occurs between the sets. Natural fracture set characteristics are very similar (Rives & Petit 1990a,b, and as shown below).

The brittle coating experiments constitute a promising new technique for understanding fracture network development. It is possible to obtain in an analogue material a set of parallel, open, long, fractures without associated shear structures, which have not been described since Daubrée (1879). To obtain analogous patterns it is important that the fractures are long. The fractures are longer in our experiments (fractures usually cross the total width of the plates), than in those of Wu & Pollard (1992) (fractures are rarely 1 cm long). Wu & Pollard (1992) have shown in their experiments that: (i) the average propagation velocity for longer fractures is generally greater than that for the shorter fractures; (ii) the number of fractures increases quickly during the 10 first load–unload cycles and then remains almost constant; and (iii) as the number of cracks increases, more and more fractures join each other, stopping further propagation. In our more qualitative experiments, there is a wide variety in the size of defects in the varnish and a few first fractures initiate at the largest defects, essentially from the edges of the plates. Fractures often propagate across the width of the plate before other fractures initiate. The probability one fracture joining another increases with increasing strain and the number of fractures. In the experiments of Wu & Pollard the size of defects is almost constant and so many fractures can appear over a short strain interval and have a much greater chance of interaction. As a result, Wu & Pollard have no fractures which traverse their plates. The pattern morphologies we have obtained are closer to the natural joint patterns we have observed than those of Wu & Pollard. The comparison between both techniques suggests that long fractures can develop when fracture initiation is progressive. In our experiments, heterogeneities on the edges of the plates and bubbles, constitute flaws with inhomogenous size distribution which allows progressive fracture initiation. This criterion seems essential in order to obtain long fractures and is probably representative of the real flaw size distributions in rocks; consequently we did not try to prevent bubbles during spraying nor initiation from the edges.

ANALOGUE ORTHOGONAL FRACTURE PATTERNS

Different orthogonal fracture patterns with varying abutting relationships can be produced in the brittle varnish by different loading conditions. In order to clarify the discussion below, we define here the terminology used in this paper. A distinction is made between the relationships (abutment or cross-cutting) between two individual fractures and the complete pattern formed by two joint sets. The classical terminology of Hodgson (1961) can be confusing where the 'cross-joints' of Hodgson may or may not cross-cut an initial joint. We propose to adopt the terms 'ladder pattern' for a set of long parallel fractures and a second set of fractures which systematically abut the initial set forming the 'H-shaped' abutment of Hancock (1985); and 'grid pattern' for two sets of fractures which systematically mutually cross-cut. 'Intermediate patterns' comprise two sets of fractures with coexisting cross-cutting and abutting relationships.

Ladder pattern produced by loading and relaxation

Uniaxial tension is induced in the external part of a fold by buckling the PVC plate. The load is increased regularly until it produces a dense set of fractures parallel to the fold axis. The load is maintained for several hours and then unloaded gradually. Approximately 1 h after unloading, linear fractures begin to form, orthogonal to the initial fractures but do not cross-cut them. The final result is here termed an orthogonal 'ladder' pattern (Fig. 3a). The orthogonal fracture set does not develop in experiments where loading is followed immediately by unloading.

Tests by direct traction show a similar initial set of parallel fractures perpendicular to the tension at approximately 0.2% extension. If the load is maintained for several hours, and then unloaded, new fractures appear perpendicular to the previous ones. These secondary fractures usually do not cross the total width of the bands defined by the first parallel fractures; they are often curved with angular abutments and form an orthogonal 'irregular ladder' pattern (Fig. 3b).

In both of the cases described above each fracture initiates at a point at the surface of the varnish and propagates away from this both horizontally and vertically downwards. The PVC support prevents the fractures from opening further and here the fractures are closed. Intersecting fractures meet first at the surface of the varnish where they are open and not at the bottom of the varnish where they are closed. Because of this, the initial fractures are open at the point of intersection with later fractures. The secondary joints orthogonal to the first are only obtained in long duration experiments which suggests that there is a time-dependent behaviour of the experimental material. The origin of the tension which produces the secondary fractures can be explained by a visco-elastic effect: during the loading, the plate deforms visco-elastically by extension parallel, and shortening perpendicular, to the tension (Fig. 5). In the brittle varnish the visco-elastic deformation and the fractures which release the tension produce a zero stress state in the bands. Unloading the plate induces instantaneous deformation due to elastic release followed by viscous relaxation. The plate eventually returns to its initial form after several hours which produces a tension normal to the first extension. In the varnish the zero stress state is altered by the relaxation in the plate such that a tension is induced parallel to the bands. Orthogonal secondary fractures develop progressively during the relaxation. It is the difference in the visco-elastic responses between the varnish and the PVC support which produces the secondary orthogonal fracture set.

As previously described, the morphologies of the secondary sets in the tension-by-folding tests and in the direct-traction tests are different. In the former case the secondary fractures are linear and generally cross the total width of the bands, suggesting that the tension was greater than that produced in the latter case by the visco-elastic relaxation mechanism alone. In the folding tests, visco-elastic relaxation must remain important but another effect is needed to amplify the orthogonal tension. If an elastic plate of limited width (for example, the PVC plate) is buckled, it will be found that the outer arc of the fold tends to contract along the direction of the fold hinge, while in the inner arc of the fold the material tends to expand along the fold hinge. This gives rise to an additional curvature of the sheet in a direction perpendicular to the main fold axial direction. This curvature is termed an *anti-clastic bending* (Ramsay 1967, p. 402). In the experiment, the unloading is accompanied by unfolding of the PVC plate and disappearance of the anti-clastic curvature which produces an additional tension parallel to the visco-elastic relaxation. This supplementary tension is transmitted to the varnish producing the second fracture set.

Intermediate orthogonal patterns produced by orthogonal loading

A rotation (clockwise 15°) of one jaw of the press produces a torsion of the plate which is maintained for several hours. A fold with an oblique axis is induced in the sample (Fig. 2b). Fractures initiate from the edges of the plate perpendicular to the maximum tension. The result is a set of closely spaced fractures parallel to the fold axis (Rives 1992).

The plate is immediately untwisted by returning the jaws to their original positions, which requires some force to overcome the viscous deformation imposed by the loading. The untwisting is accompanied by the development of fractures orthogonal to the initial ones. This second set shows short linear fractures generally abutting previous ones to form a ladder pattern and some longer fractures cross-cutting a few bands (Fig. 3c).

The initial fracture set is parallel to the fold axis which is close to the diagonal of the plate. The second fracture set develops during the untwisting which induces a new orthogonal tension direction in the varnish. This type of stress inversion, due to the rapid unloading, is well known in visco-elastic materials (Salençon 1983). Untwisting the plate induces a normal stress to the first fractures which closes some of these fractures and some fractures of the second set can cross-cut fractures of the first set.

Intermediate orthogonal patterns induced by sub-orthogonal loading

In another test two rotations, clockwise (15°) then anti-clockwise (−15°) are imposed for a short time (several minutes) to inhibit viscous effects. Each rotation produces a fold with an axis close to each diagonal of the plate, and the angle between the two axes is 70° due to the relative dimensions of the plate. The first rotation generates a set of continuous fractures parallel to the first fold axis. Although the second rotation produces a fold axis oblique to the first, the second set of fractures are orthogonal to the first fractures. The secondary fractures are shorter than the initial ones with generally abutting relationships, but some may cross-cut. In places the second fractures are arranged in stepping arrays which are aligned parallel to the second fold axis (Fig. 3d).

The first set comprises linear, long fractures, parallel to one diagonal of the plate. The second fractures are perpendicular to the pre-existing fractures and abut against them. Ghosh (1988) observes a similar effect in plaster of Paris, where fractures develop oblique to a remote tension, and perpendicular to a set of pre-existing fractures. In our experiments the direction of alignment of the stepping fracture arrays is parallel to the second fold axis and is therefore the potential direction of second fractures in the absence of the first set. As in the previous test the first-formed fractures are partially closed and some second fractures cross-cut the first fractures.

This experiment suggests that two sub-orthogonal loadings can induce an orthogonal fracture pattern. Orthogonal fracture patterns in brittle coatings are only obtained with orthogonal or sub-orthogonal loadings. If the angle between the two loading directions is lower than 70°, second fractures develop oblique to the first ones forming an oblique ladder pattern (Rives & Petit 1990b). This kind of geometry has been described in the field by Dyer (1988).

IMPLICATIONS OF THE ANALOGUE MODELS

Comparison between experimental and natural joint patterns

Orthogonal fracture patterns obtained in the brittle varnish experiments and which result from different

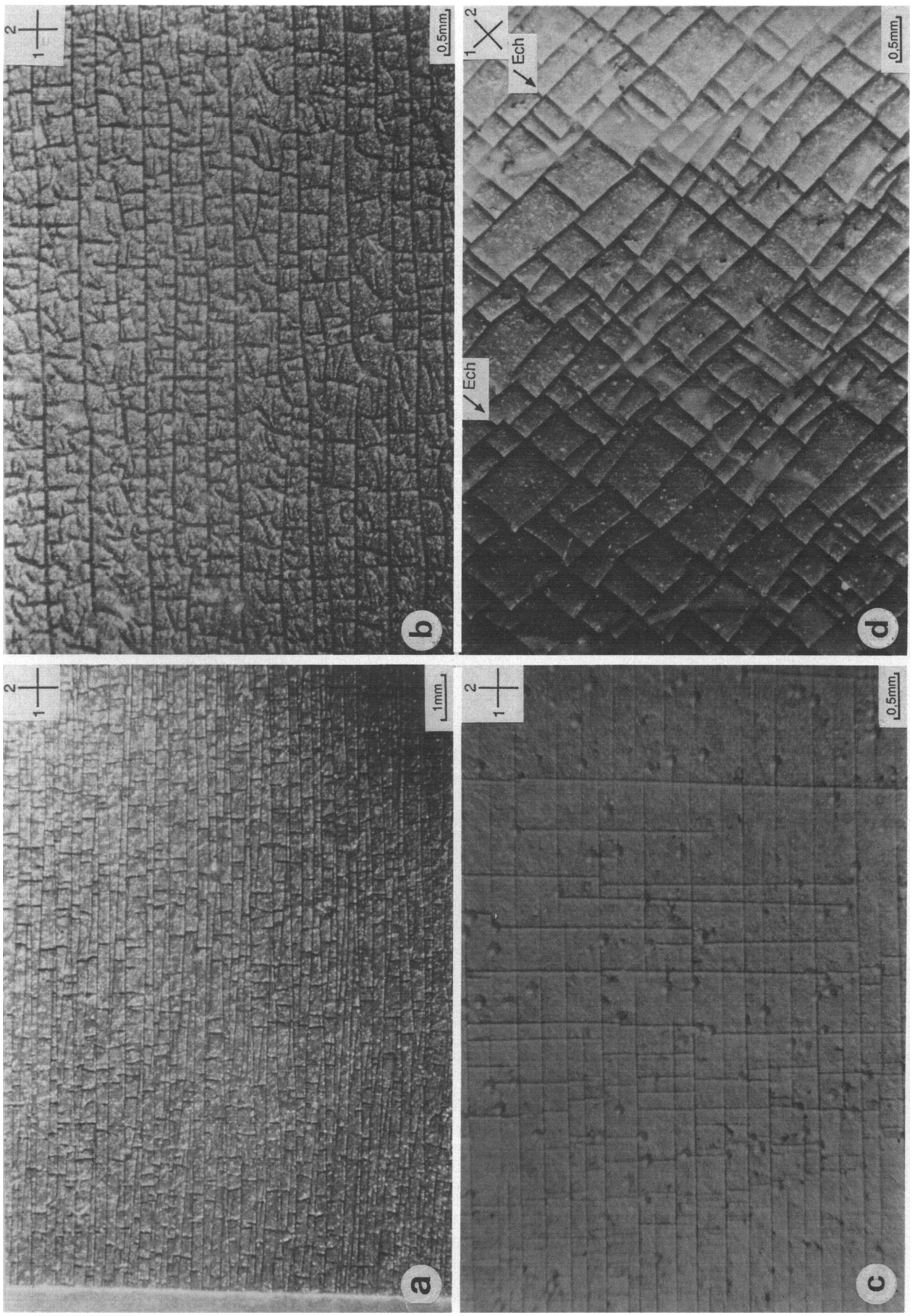

Fig. 3. Orthogonal fracture patterns produced in the brittle varnish analogue models. (a) Ladder pattern; initial set parallel to fold axis in Fig. 2(a). Second set develops during relaxation. (b) Irregular ladder pattern; initial set develops normal to direct traction, second set forms during relaxation. (c) & (d) Intermediate patterns produced by torsion (Fig. 2b). (c) Orthogonal loadings. (d) Sub-orthogonal loadings (70°); second set is orthogonal to the first and can be arranged in stepping arrays which are parallel to the second loading.

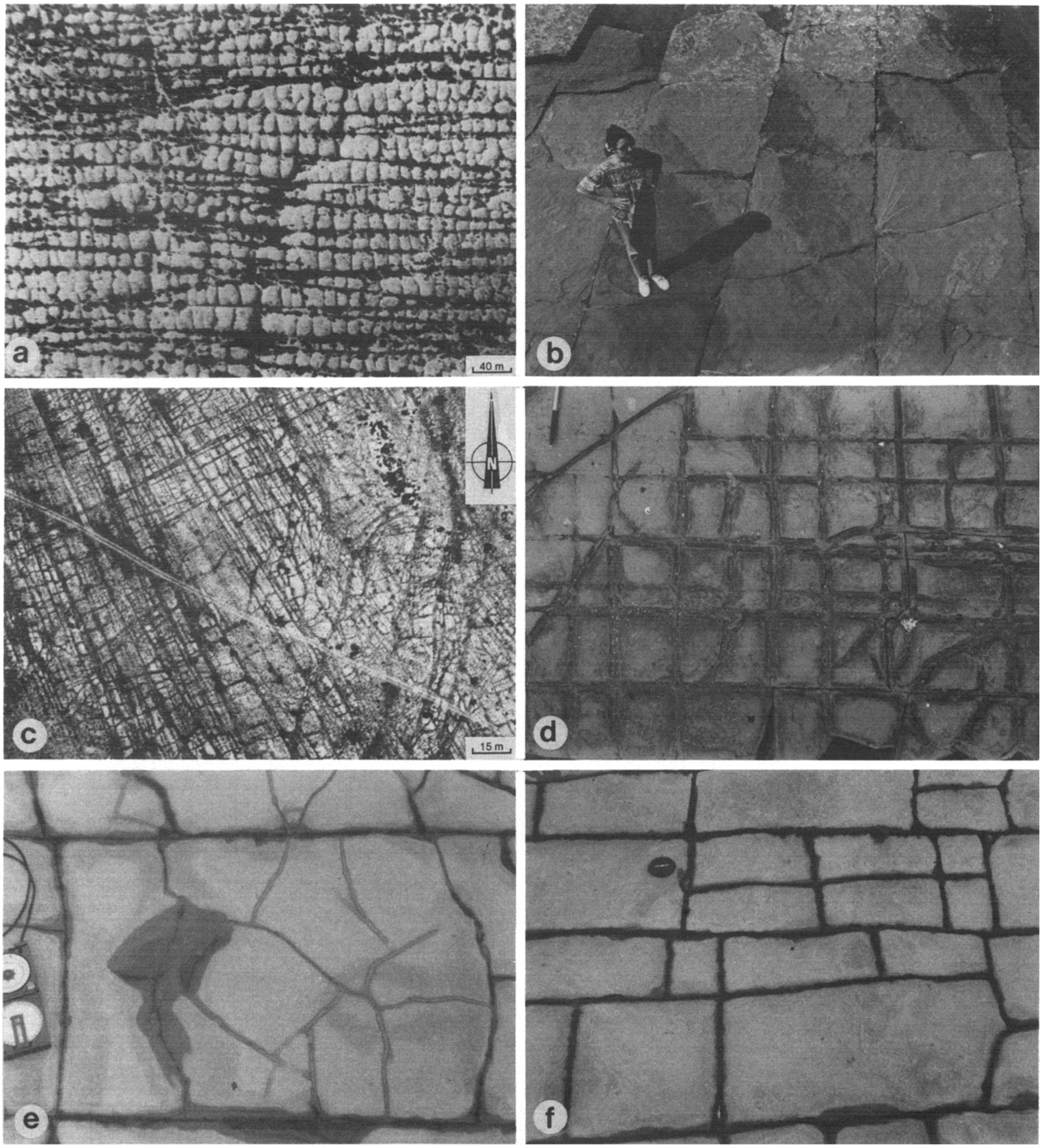

Fig. 4. Natural orthogonal joint patterns. (a) Ladder pattern, Arch National Park, Utah, U.S.A. Aerial view, initial joints striking N120. (b) Ladder pattern in Permian sandstone, Lodève, South France, see also Fig. 8. (c) Intermediate pattern in Jurassic limestone, Causse platform, South France. (d) Grid pattern in Jurassic limestone, Kimmeridge Bay, U.K. (e) Polygonal joints within blocks bordered by orthogonal joints, Jurassic limestone, Lavernock Point, South Wales, U.K. (f) Mutually abutting joints with an intermediate pattern, Jurassic limestone, Lavernock Point, South Wales, U.K.

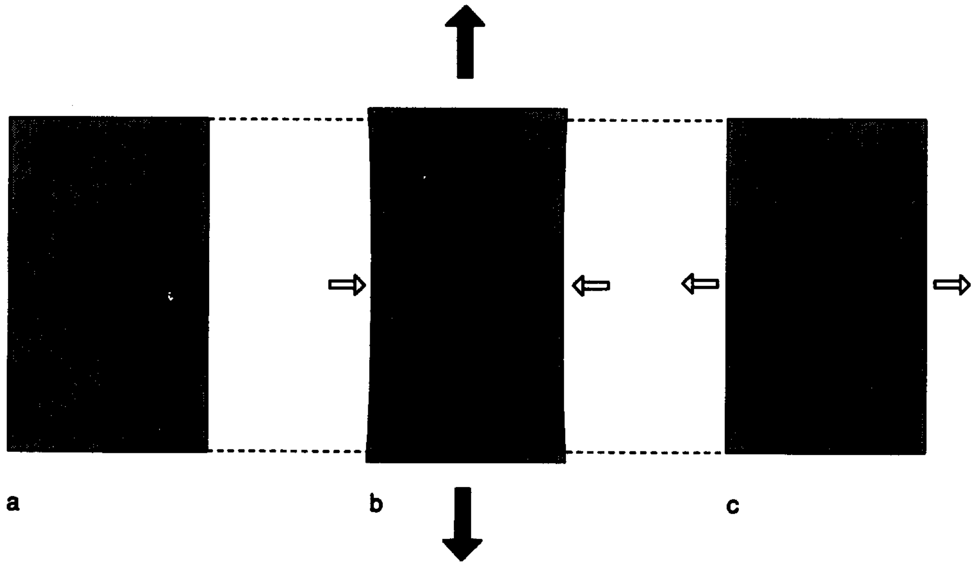

Fig. 5. Visco-elastic effect in a PVC plate. (a) Initial form. (b) Elongation parallel to the traction which induces the initial fracture set and associated perpendicular contraction. (c) The plate recovers its initial form after unloading which induces a traction perpendicular to the initial fractures and produces the orthogonal fracture set.

loading conditions correspond closely to many natural patterns (Figs. 3 and 4). The similarities suggest that in some respects the mechanism of fracturing in the brittle varnish may be analogous to joint formation. However, the brittle varnish models do not reflect the total range and complexity of the geometries observed in natural conditions. In reality most orthogonal joint patterns are intermediate patterns. As the number of cross-cutting joints of the second set decreases the pattern approaches the 'ladder' pattern and as the number of joints cross-cut by the second joint set increases the pattern approaches a 'grid' pattern.

Another discrepancy is that the secondary fractures in the analogue model always abut against the initial joints and never vice versa. In many field examples the chronology of the orthogonal joint sets seems contradictory with joints of both sets abutting against joints of the opposite set (Fig. 4f) (Hancock 1985, Gauthier & Angelier 1986). Mutually abutting relationships may be present in all the natural orthogonal patterns described below.

Origin of the orthogonal stress in natural conditions

The second fracture set in the analogue model forms perpendicular to an orthogonal or sub-orthogonal least principal stress (σ_3) which results from either visco-elastic effects (in the relaxation model) or a second loading. In the relaxation model, the second fracture set results from the different visco-elastic responses between the varnish and its support. In geological conditions visco-elastic relaxation could possibly be invoked where adjacent rock layers have contrasting mechanical properties, for example alternating limestones and shales. Relaxation phenomena in rock and the formation of fractures have been experimentally obtained by Gramberg (1989) in a loading–unloading cycle. The formation of relaxation fractures has also been shown by Engelder & Plumb (1984) in granite by comparing ultrasonic velocities *in situ* and in the same samples cored and relaxed. The corresponding natural joints have been named release joints (Nickelsen & Hough 1967, Engelder 1985). Relaxation in rocks could also result from a release of locked-in stress during uplift and unroofing (Friedman 1972, Rathore *et al.* 1989).

It is also possible that the second joint set may not be created by relaxation. The initial set of parallel open joints cuts the layer into very long and narrow bands that are sensitive to tension. Any warping of the bands, produced for example by inhomogenous settling of the underburden (Granier & Bles 1988) should induce stresses and consequent joints cross-cutting the bands (Hodgson 1961). The joints will normally abut the open initial joints at 90° (Fig. 4b).

In the experiments the second fracture set can form perpendicular to an orthogonal or sub-orthogonal σ_3 produced by a second loading. In geological conditions a second loading can be envisaged in an extensional regime (maximum principal stress σ_1 is vertical) following reversal of the intermediate (σ_2) and the least principal stresses (σ_3). This could result from a regional reversal between σ_2 and σ_3, due to regional fluctuations of the tectonic stresses (Hancock *et al.* 1987, Bahat 1988, Dunne & North 1990). At a smaller scale Simon *et al.* (1988) demonstrate that in a horizontal biaxial tensile stress field the development of a joint set perpendicular to the direction of σ_3 releases the tension in this direction. The stress drop may be sufficient to reverse the directions of σ_2 and σ_3 and so secondary joints could form perpendicular to the initial joints.

The models presented above are not mutually exclusive and the secondary joints in an orthogonal pattern could result from a combination of stress reversal, visco-elastic relaxation and slight warping of the strata. The

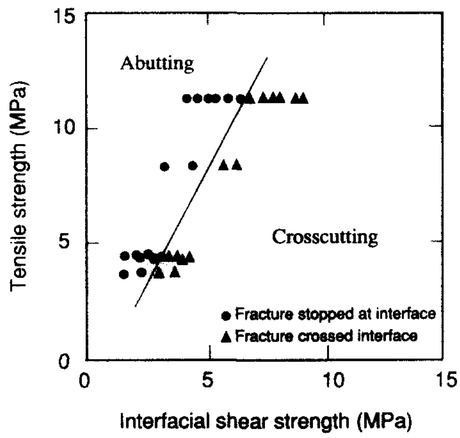

Fig. 6. Relation of interfacial shear strength to tensile strength of monolithologic specimens on the extent of hydraulic fracture propagation. Abutting relationships occur at low interfacial shear strength (modified from Teufel & Clark 1984).

frequency of abutting is controlled by the degree of slippage possible along the pre-existing discontinuity (Loosveld & Franssen 1992).

Cross-cutting mechanisms

In the experiments both abutting and cross-cutting relationships can be created and both relationships are observed in natural joint patterns. Teufel & Clark (1984) suggest that the effect of joints on fracture containment can be divided into two extreme interfacial conditions: perfect bonding (equivalent to no mechanical discontinuity) and the unbonded interface in which there is a complete lack of tensile strength. Compressive stress can be transmitted across an interface but the amount of shear stress transmitted across the interface depends on the shear strength of the interface. The shear strength of a sliding surface has been shown empirically to fit a linear relation:

$$\tau = c + \mu\sigma_n,$$

where τ is the shear strength, c is the cohesion, σ_n is the normal stress and μ is the coefficient of friction (Coulomb criterion, Byerlee 1978). For an unbonded interface the cohesion is close to zero and the coefficient of friction at the initiation of slip has values ranging from 0.4 to 1.0. This variation is related mainly to the surface roughness of the interface.

Teufel & Clark (1984) demonstrate that for each rock type there is a critical interfacial shear strength that has to be exceeded before fracture growth across the interface occurs (Fig. 6). The critical interfacial shear strength is not constant for all rock types but increases with the increasing tensile strength of the rock. Empirically it is shown that the critical interfacial shear strength τ_c and the tensile strength T of the rock can be defined as:

$$\tau_c = 1 + 0.5T.$$

In the experiments of Teufel & Clark (1984) the propagating fracture is a hydraulic fracture. Other types of propagation have not been investigated to the authors knowledge. It is reasonable to assume that τ_c will vary following different propagation mechanisms. In the experiments the second fractures do not cross-cut the initial fractures where they are open ($\tau = 0$). Only where the initial fractures are closed ($\tau > 0$) do the second fractures cross-cut.

Cross-cutting due to healing of the initial set (very high cohesion) has been described in field examples (Dunne & North 1990) but this mechanism was not represented in the experiments.

DEVELOPMENT OF ORTHOGONAL JOINT PATTERNS

Ladder joint pattern

A close analogy exists between the experimental and some natural ladder patterns (Figs. 1a, 3a and 4a). By analogy the initial joint set could form parallel to the maximum horizontal stress ($\sigma_H = \sigma_1$ or σ_2) of a tectonic event and perpendicular to the direction of σ_3. The second joint set could result from a reversal in the horizontal stresses and develop perpendicular to the new direction of σ_3. In a ladder pattern the secondary joints do not cross-cut the initial joints which indicates that the initial joints were not bonded and the normal stress was low ($\tau < \tau_c$). Relaxation or release phenomena and/or the slight warping of the strata are possible mechanisms for the generation of the second set.

In conditions of low stress, for example due to a slight warping of the bands between the initial joints, or viscous relaxation of the rock within each band as in the analogue model, an orthogonal irregular ladder pattern is probable (Figs. 1b and 4b).

Intermediate orthogonal joint patterns

Natural examples of partially cross-cutting joint patterns are frequent (Figs. 1c and 4c) (see, for example, Grillot & Razack 1985) and are similar to the patterns produced in the orthogonal or sub-orthogonal loading experiments (Fig. 3c).

In natural conditions either the orthogonal stress producing the second joint set was high or healing was present and so cross-cutting was possible.

For the same initial joint set and in the absence of healing, the effective stress normal to the initial joints during the formation of the second joint set must be greater than that for a ladder pattern. A regional σ_2/σ_3 stress reversal is the most probable mechanism for generating this relatively high normal stress.

As suggested by the analogue model, partially cross-cutting orthogonal joint patterns could also result from a sub-orthogonal tectonic event (Burg & Harris 1982, Ghosh 1988).

Several field examples of orthogonal joint patterns display two orthogonal sets which almost completely cross-cut each other (Figs. 1d and 4d). Grid patterns are

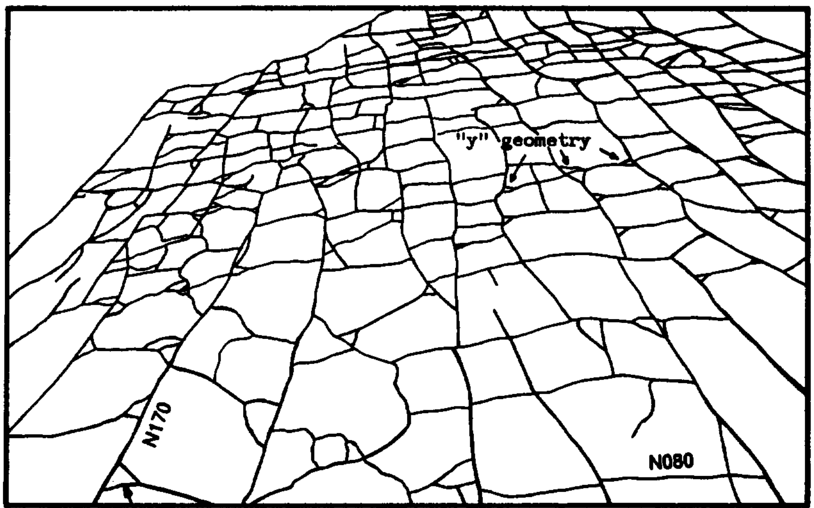

Fig. 7. 'y' geometry within an intermediate orthogonal joint pattern, Liassic calcarous shale Robin Hood's Bay, U.K. Joints of the second set (E–W) display 'y' geometry at intersections with the initial set (N–S). Note also mutual abutments between the two sets (from Rawnsley *et al.* 1992).

more probable if the two loading conditions correspond to separate loading events, where the initial joint set may have healed before the development of the second joint set, and/or the effective normal stress acting across the initial joints may have been higher than that produced by a σ_2/σ_3 reversal.

FINAL STAGE OF JOINT DEVELOPMENT

Orthogonal joints define the edges of orthorhombic blocks within the rock strata. In calcareous beds, these blocks often contain irregular joints which clearly post-date block formation and which form polygonal patterns (Fig. 4e). These polygonal patterns correspond to the final stage of joint development. It is well established that polygonal joint patterns are created in isotropic horizontal stress field (e.g. mudcracks, polygonal joints in basalts). Also the presence of these joints in isolated blocks indicates that they developed without any influence from a remote stress field, but instead are created by an internal tensile stress field. The possible presence of an internal tensile stress influencing late-stage joint development could also explain the commonly observed mutual abutments in orthogonal patterns (Fig. 4f). The joints which originally terminated within the blocks would concentrate the internal tension at their tips and could be reactivated. These could propagate again until they abut a pre-existing joint. The resulting joint pattern could contain mutual abutments. An important implication of the internal tension is that this may not only create the polygonal joints but may also contribute towards the creation of the second orthogonal joints. As described above Simon *et al.* (1988) demonstrate that in a biaxial tensile stress field the presence of an existing set of parallel joints will orientate the principal stresses so that the greatest tension is parallel to the existing joints. Secondary joints will form perpendicular to the first set. The internal tension suggests that late-stage joint development does not necessarily require an increase in the external stress applied to the strata, because it appears that the internal stresses alone are sufficient to create joints. The internal stress may be the result of volume reduction, possibly related to diagenesis (McHugh *et al.* 1993) or thermal changes, or result from the release of residual stresses.

Successive reversals between σ_2 and σ_3, producing mutually perpendicular joints could also produce mutual abutments (Hancock *et al.* 1987).

ORTHOGONAL JOINT DATA FOR PATTERN ANALYSIS

The different orthogonal patterns have varying degrees of connectivity between the two joint sets with subsequent implications for rock mass properties, in particular permeability. Classical presentation of joint data consists of rose diagrams, however orientations alone may not be sufficient to determine which type of orthogonal joint pattern is present. Where possible maps of fracture intersections should compliment the orientation data.

The analysis of the abutting relationships in many joint patterns can be misleading because the abutting relationships may represent only the last phase of joint set development. Where joints cross-cut each other it may be possible to determine the relative chronology if the joints of the second set display a 'y' geometry at the intersection (Fig. 7) (Rawnsley *et al.* 1992).

In many situations, particularly in bore-holes, it may not be possible to observe terminations in which case other methods must be employed.

—A study of the mineralization in the joints may provide some indication of the relative ages of the joints (Fairbairn & Fergusson 1992).

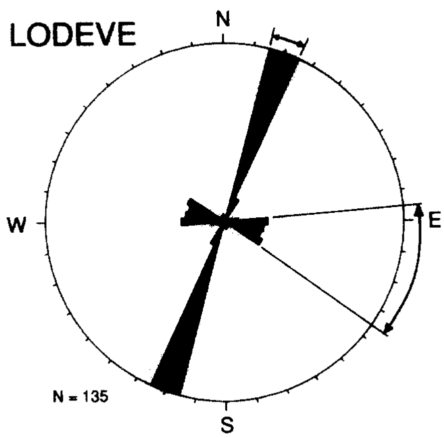

Fig. 8. Rose diagram showing strikes in the irregular ladder pattern of Fig. 4(b), Permian sandstone, Lodève, southern France. The initial set shows a small variation in strike (020° ± 5°). Second set displays a greater range of variation (103° ± 20°).

—In some examples the surface roughness of the through-going joints in a ladder pattern is less than that of the later orthogonal joints (Bouroz 1990).

—As suggested by the analogue model (Fig. 3b) and field observations (Bahat 1988) (Figs. 4b and 8) the direction of the initial joints may display a smaller range of variation than the later perpendicular joints.

CONCLUSIONS

Orthogonal joint sets can be arranged in either ladder, intermediate or grid patterns. Most orthogonal joint sets are organized in intermediate patterns in which some joints of the second set cross-cut joints of the initial set.

The initial joint set can normally be related to tectonic stresses and develops parallel to the compression direction (perpendicular to σ_3). The analogue models suggest that the stress which creates the second fracture set can result from visco-elastic effects or from orthogonal or sub-orthogonal loadings. In rocks the second stress may result from visco-elastic relaxation, release of locked-in stress, slight tension due to warping of the bands, internal tension and local or regional reversals between σ_2 and σ_3.

If the shear strength ($\tau = c + \mu\sigma_n$) of the initial joints is low such that the shear stress transmitted across the joint interface is lower than a critical value (τ_c), a ladder pattern is obtained. If the shear strength of the initial joint is greater an intermediate orthogonal pattern can form. Grid joint sets occur when the initial joint set is perfectly closed or sealed and could result from two independent stress events.

Mutually abutting joint sets are commonly observed in all types of orthogonal patterns and could result from reversals between σ_2 and σ_3 or from conditions of internal tension during the final stages of joint development. The last phase of joint development can be polygonal, showing an internal tension is present in the blocks defined by the orthogonal joints.

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