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The temporal relationship between joints and faults

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Abstract

Examples are presented of three temporal relationships between joints and faults: joints that pre-date faults; joints that are precursors to, or synchronous with, faults; and joints that post-date faults. Emphasis is placed on strike-slip faults in carbonate beds, but other examples are used. General rules are given for identifying the three temporal relationships between joints and faults. Joints that formed before faults can be dilated, sheared or affected by pressure solution during faulting, depending on their orientation in relation to the applied stress system. Faulted joints can preserve some original geometry of a joint pattern, with pinnate joints or veins commonly developing where faulted joints interact. Joints formed synchronously with faults reflect the same stress system that caused the faulting, and tend to increase in frequency toward faults. In contrast, joints that pre- or post-date faults tend not to increase in frequency towards the fault. Joints that post-date a fault may cut across or abut the fault and fault-related veins, without being displaced by the fault. They may also lack dilation near the fault, even if the fault has associated veins. Joints formed either syn- or post-faulting may curve into the fault, indicating stress perturbation around the fault. Different joint patterns may exist across the fault because of mechanical variations. Geometric features may therefore be used in the field to identify the temporal relationships between faults and joints, especially where early joints affect or control fault development, or where the distribution of late joints are influenced by faults. © 2001 Elsevier Science Ltd. All rights reserved.

1. Introduction

The aim of this paper is to present field examples of the temporal relationship between joints and faults, and to use these examples to develop general rules for identifying the relative timing of joint and fault development. A range of field examples is used, along with examples from the literature. So that the field examples are easily comparable, particular emphasis is placed on the relationship between joints and strike-slip faults with displacements of up to several metres occurring in sub-horizontal carbonate beds. Other examples are used, however, to illustrate particular points. The papers referred to give mechanical explanations for features described.

Joints are mode I (dilational) fractures that form normal to σ_3 (e.g. Pollard and Segall, 1987), which occur in almost all rocks exposed at the Earth's surface. In contrast, while faults in the upper crust are fractures, they accommodate wall-parallel displacement. As of yet, little work has been done on the temporal relationship between joints and faults. This situation is especially surprising because of the importance of joints and faults in fluid migration through rock. For example, in their review of the literature on joint development, Pollard and Aydin (1988) showed that faults can develop by the shearing of joints, and suggested that analysis of the relationship between joints and faults would be an attractive future area of research, but they made little other comment on faults.

The relationships discussed in this paper probably only apply to relatively small faults. Large faults with long and complex histories may show more complex relationships with their adjacent joints. For example, intense zones of joints may develop in cover rocks above basement faults that are reactivated (e.g. White et al., 1995).

Various definitions exist for *joints* and *veins*, which are structures used in this paper to identify fracturing sequences. For example, Davis and Reynolds (1996, p. 204) defined a joint as a reasonably continuous and through-going planar fracture with an almost imperceptible extension approximately perpendicular to the walls, while veins were described as joints with precipitated minerals. In this paper, use is made of the differences between joints (mode I, narrow, unfilled cracks) and veins (not necessarily mode I, up to metres wide and filled cracks). Examples of mixed-mode veins are shown by Ramsay and Huber (1983, chapter 13) and by Engelder (1987, fig. 2.10). These differences have particular significance in examining the relationship between joints and faults. For example, whether or not

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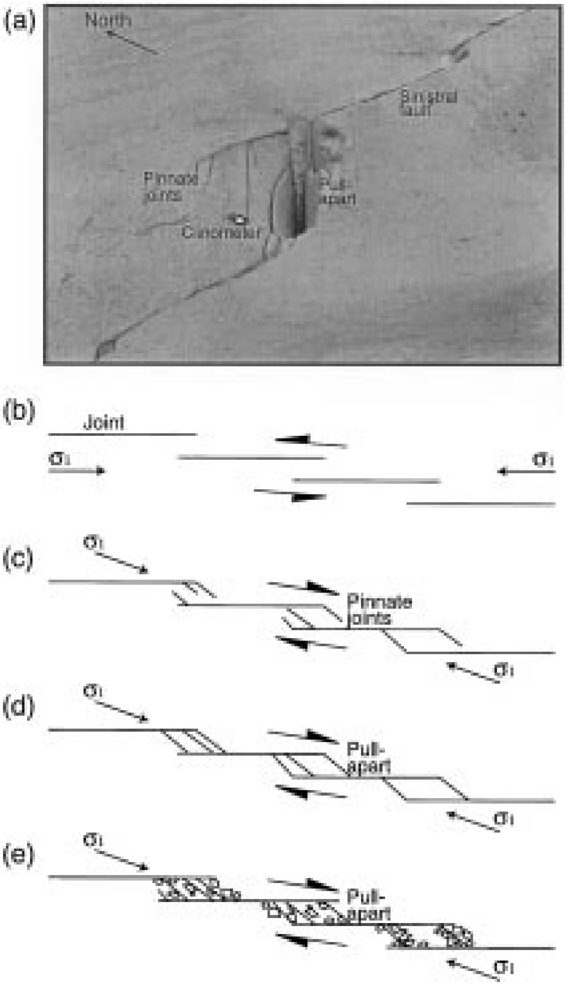

Fig. 1. (a) Photograph of a sinistral strike-slip fault zone that is interpreted as having initiated as overstepping joints, at Marsalforn, Gozo, Maltese Islands. (b–e) Interpretation for the development of the strike-slip faults at Marsalforn. (b) A set of right-stepping joints occurs. (c) The stress system changed, allowing shear on the joints, and causing pinnate joint development in the extensional quadrants of the faults. (d) Pull-aparts developed between faults linked by pinnate joints as displacement increased. (e) A through-going fault developed with brecciation at the pull-aparts.

a fracture is mineralised where it intersects a mineralised fault is significant when interpreting age relationships.

1.1. Previous work on the relationship between joints and faults

Various papers describe the pre-, syn- or post-fault development of joints:

1. Martel et al. (1988), Martel (1990) and Martel and Boger (1998) showed faults developed from shearing along earlier joints with linkage by syn-fault pinnate joints. Dunne and Hancock (1994, fig. 5.18a) showed an example of an older joint offset by a younger fault.
2. Joints can be precursors to, or synchronous with, faults. Mollema and Antonellini (1999) presented excellent examples of joints that are precursors to fault zones. The geometry and mechanics of pinnate joints (or *wing cracks*) around fault tips and that link fault segments were described by Fletcher and Pollard (1981), Martel (1990), Cruikshank et al. (1991), Cruikshank and Aydin (1994), Cooke (1997), Martel and Boger (1998) and Willemse and Pollard (1998). Cruikshank et al. (1991) also showed how faulted joints can pass into a series of smaller en echelon joint segments. Reches and Lockner (1994) presented experimental results and described how faults can develop from the interaction and linkage of swarms of mode I microcracks.
3. Hancock (1967) noted that regional joint systems are commonly younger than the faults to which they are related. Hancock (1985, p. 451) noted that joints and dip-slip faults commonly have the same strike, but usually have different dips, and took this to indicate an age gap between joints and faults.

The results presented in this paper may appear obvious, yet a published comparison identifying temporal relationships between pre-, syn- and post-fault joints does not exist. For example, Hancock (1967, p. 146) gave the impression that earlier papers on the temporal relationship between joints and faults do not present clear data or even a fully developed argument for interpretations.

1.2. Importance of the temporal relationship between joints and faults

The relative ages of joints and faults have several important geological, economic and environmental implications:

- The relationships between these structures are important in determining the tectonic history of a region. Joints may record subtle features of the stress history of a region (e.g. Hancock et al., 1984). For example, Rawnsley et al. (1998) used joint patterns in the Bristol Channel Basin to show that there was an anti-clockwise rotation of stresses during or after the main N–S contraction of the Alpine Orogeny.
- Early joints can influence later fault development (e.g. Martel et al., 1988). Many faults initiate as mode I cracks (e.g. Reches and Lockner, 1994), and it is possible that faults cannot initiate as mode II or mode III cracks (e.g. Petit, 1988). Likewise, early faults can influence subsequent joint development, providing stress concentration points for joint initiation and acting as barriers for joint propagation (e.g. Rawnsley et al., 1992).
- Fractures can act as pathways or barriers for fluid flow, so knowledge of the temporal relationship between joints and faults may give useful information on the history of fluid motion. For example, pre-fault joints may be sealed by mineralisation, while high densities of syn-fault joints may enhance fluid flow. These characteristics have important implications for hydrocarbon migration

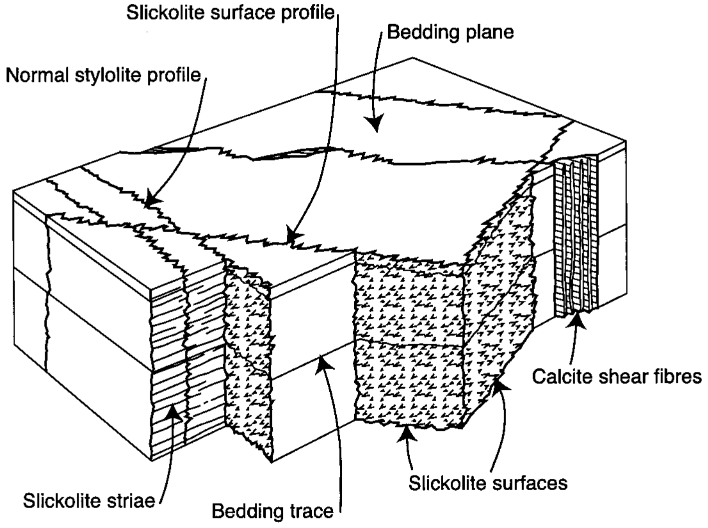

Fig. 2. Schematic block diagram of the structural surfaces at Holderbank limestone quarry, northern Switzerland (Ramsay and Huber, 1987, fig. 27.27). Ramsay and Huber (1987) inferred the stylolites to have initiated as joints, because the oblique teeth show that the surface was not perpendicular to σ_1 during pressure solution. Ramsay and Huber (1987, p. 655) define *slickolites* as stylolites that have cones at an angle to the surface.

(e.g. Dholakia et al., 1998) and for hydrogeology (e.g. Committee on Fracture Characterization and Fluid Flow, 1996).

2. Examples of joints that pre-date faults

Examples are presented of pre-fault joints that have been later sheared, dilated or affected by pressure solution.

2.1. Joints and faults in limestones at Marsalforn, Gozo, Maltese Islands

A set of strike-slip faults are excellently exposed on the beach about 2 km west of Marsalforn (Fig. 1a) (latitude 36°5′N, longitude 14°11′E). The faults are exposed in gently dipping Lower to Middle Miocene-age Lower Globigerina Limestone, which is up to about 40 m thick on Gozo. The unit is a pale cream to yellow, massively bedded packstone that changes upwards into a wackestone (Pedley et al., 1976; Pedley and Bennett, 1985). Gozo has a gentle regional dip to the north-east, and is dominated by normal faults that strike approximately E–W (Pedley et al., 1976, fig. 4). Pedley et al. (1976) interpreted the limited erosion of the fault scarps on Gozo and Malta, and the displacement of the entire Oligocene to Miocene sequence, to suggest relatively recent faulting.

The strike-slip faults at Marsalforn have displacements of up to hundreds of millimetres and are exposed for tens of metres along a raised beach. An impressive feature of these faults is the unfilled pull-aparts up to hundreds of millimetres wide (Fig. 1a). Some calcite mineralisation occurs on the fault planes, but true veins are rare. Some complex fault patterns occur, involving conjugate relationships, block rotation and local brecciation. Because the overlying Tertiary sequence is only about 300 m thick (Pedley et al., 1976), the faults are interpreted to have formed at depths of less than 1 km. They are interpreted to have initiated as a set of distributed joints, some of which were en echelon (Fig. 1b). Some of these joints developed into faults as the stress system rotated, such that the maximum horizontal compressive stress component was orientated 075° (Fig. 1c). Sinistral faults linked through mainly dilational oversteps (pull-aparts), which include pinnate joints and block rotation (Fig. 1d). The importance of these syn-faulting pinnate joints is discussed in Section 3.1. The faults with higher displacements display narrow zones of brecciation (Fig. 1e).

2.2. Joints affected by pressure solution, Holderbank Quarry, Switzerland

Ramsay and Huber (1987) described the relationship between faults and pre-existing joints in the Holderbank limestone quarry, northern Switzerland (Fig. 2). For photographs of these structures, see Ramsay and Huber (1987, figs. 27.23 to 27.26, and 27.28). Some joints are faulted and some are affected by pressure solution, while other joints are affected by a combination of faulting and pressure solution to form *slickolites*. Ramsay and Huber (1987, p. 655) used the term *slickolites* for oblique stylolites, which have cones at an angle to the surface. Oblique stylolites imply combined shear and pressure solution, and indicate that the original joint was not orientated perpendicular to the maximum principle stress axis during pressure solution. This example illustrates that early joints can be reactivated as stylolites or slickolites during faulting.

2.3. Faulting along pre-existing joints in granite

Martel et al. (1988) and Martel (1990) described joints and faults in granites of the Mount Abbot quadrangle,

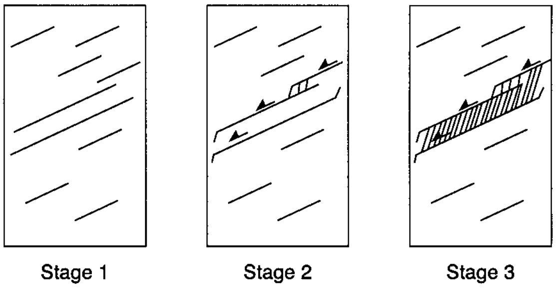

Fig. 3. Development of "simple" fault zones in granite (from Martel et al., 1988, fig. 11b; also see Martel, 1990, fig. 2). Faults develop from pre-existing joints (stage 1), with progressive linkage by pinnate joints as shear increases (stages 2 and 3).

California (latitude 37°20′N, longitude 118°50′W). ENE-striking faults developed along pre-existing sub-vertical, sub-parallel joints. The joints were filled by epidote and chlorite less than 10 mm wide during a phase of hydrothermal activity prior to faulting. These fractures were then faulted, with up to 2 m of sinistral slip. The magnitude of slip on the faults is marked by displaced dykes (e.g. Martel et al., 1988, fig. 4). Linkage by pinnate joints (the *splay joints* of Martel et al., 1988) between some of these slipped joints (see Section 3.1) allowed the development of fault zones with up to about 10 m displacement. An interpretation of the development of these faults is shown in Fig. 3 (also see Pollard and Aydin, 1988, fig. 19b). Granier (1985) described a similar origin of faults from joints in granite.

2.4. Cooling joints and tectonic cracks around the Koae fault system, Hawaii

The Koae Fault System (latitude 19°22′N, longitude 155°17′) is a zone of active normal faults about 20 km long and 2 km wide perpendicular to strike, linking the East Rift Zone with the South West Rift Zone of Kilauea volcano, Hawaii. The dominant downthrow direction is to the north. Duffield (1975) measured the extension along two approximately 2 km long cross-sections through the eastern part of the Koae Fault System as 18.69 m and 32.55 m. The Koae Faults have greater displacements at depth because they are growth faults that are periodically covered by lava. The displacement at the surface only represents displacement since the last resurfacing event, 500 to 2500 years ago (Duffield, 1975).

A map of a relay ramp and of the cracks that link the two overstepping faults is illustrated in Fig. 4. The relay ramp is about 400 m across, with the faults underlapping by about 300 m. The faults that bound the relay ramp have >20 m throw down to the north. Partial linkage between the two bounding faults is represented by right-stepping en echelon cracks. The faults, and the cracks around the faults, have zigzag surface traces, with irregular pathways and sharp bends (Fig. 5). These bends appear to become less sharp downwards. Such zigzag surface traces, decreasing in sharpness downwards, are characteristic of the polygonal cooling joints that are ubiquitous in the lavas of Kilauea Volcano and elsewhere (e.g. Pollard and Aydin, 1988, fig. 14d). This geometry indicates that the fault and cracks initiated as cooling joints that opened during faulting. The cooling joints formed shortly after basalt extrusion and they must have existed during faulting. Although the number of joints does not increase close to the faults, the joints close to the faults are more dilated, which is interpreted to have occurred during faulting.

3. Examples of joints formed synchronously with faults

3.1. Pinnate joints that link faulted joint segments

The examples of strike-slip faults at Marsalforn

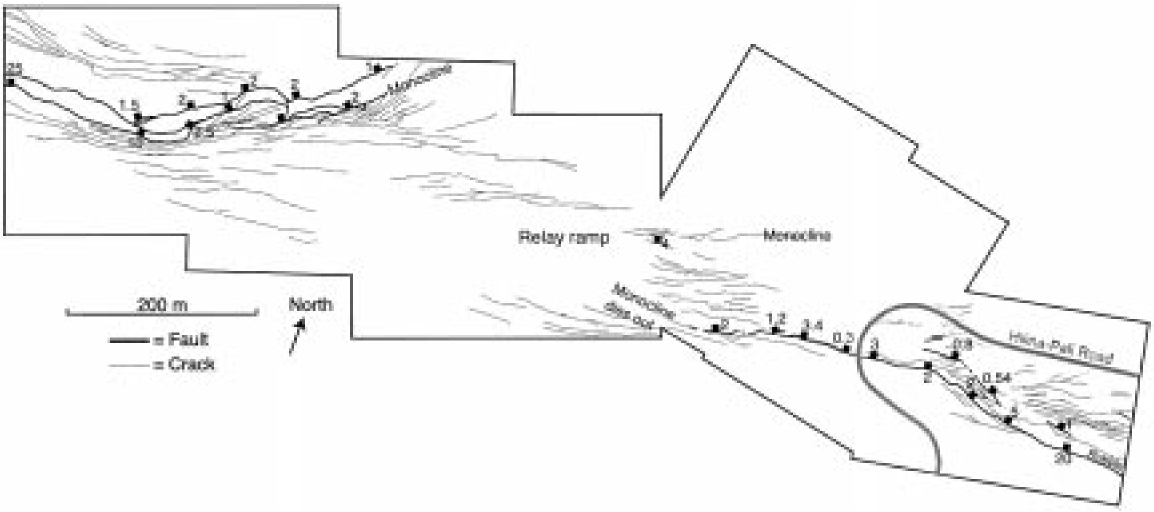

Fig. 4. Map of part of the Koae Fault System. Structures were mapped onto aerial photographs taken at heights of about 300 m. Ticks are shown on the downthrow sides of faults, with throws in metres. All of the cracks and faults shown appear to be reactivated cooling joints. See Parfitt and Peacock (2000).

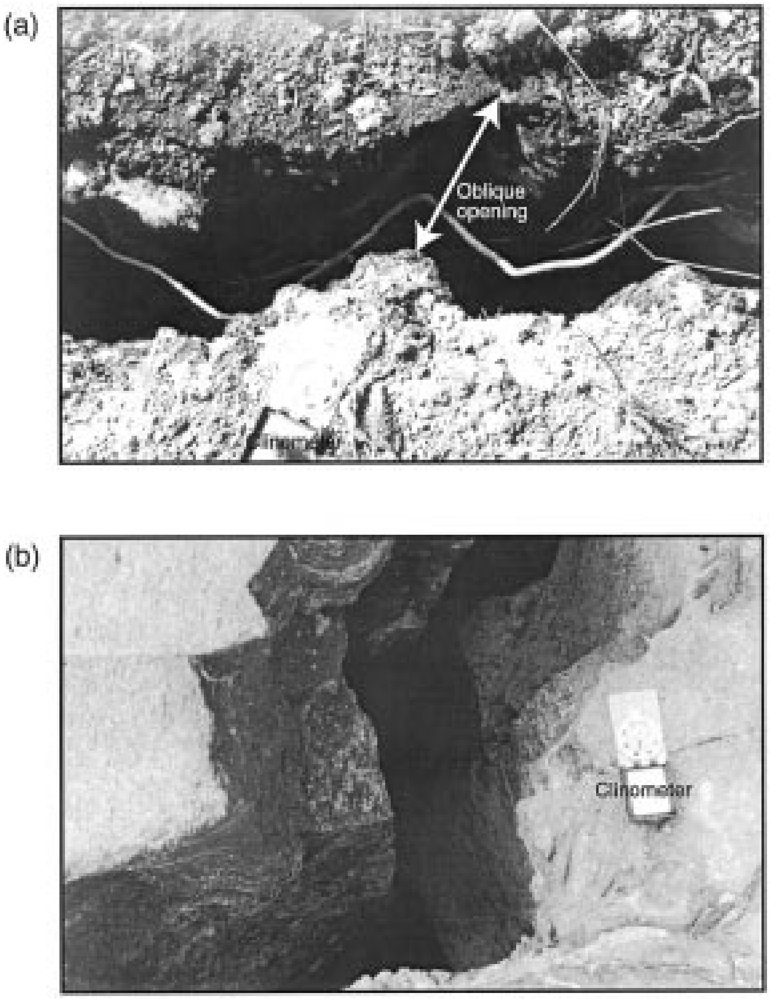

Fig. 5. Photographs of polygonal cooling joints opened up as irregular, approximately E–W striking cracks adjacent to the Koae fault system. Even though the joints and faults are approximately straight at the scale of the map in Fig. 4, they are more irregular when observed in detail. The example in (a) opened obliquely.

(discussed in Section 2.1), and of fault zones in granite (Section 2.3), initiated as joints that were then faulted. Fault development was aided by linkage between the first set of joints by a second set of joints that are syn-faulting pinnate joints. Pinnate joints (or *wing cracks*) typically develop in extensional quadrants at the tips of faulted joints to accommodate variations in displacement along the fault (e.g. Hancock, 1985, fig. 8; Martel, 1990; Cruikshank and Aydin, 1994; Cooke, 1997; Willemse and Pollard, 1998; also see Section 5.2). Where pinnate joints connect between two faulted joints (Fig. 3), they typically produce extensional bends (pull-aparts) that allowed the faults to link, increase in length, and thereby increase in displacement.

3.2. Faults in the Sella Group, northern Italy

Mollema and Antonellini (1999) described strike-slip fault zones (Fig. 6) in the dolomites of the Sella Group of northern Italy (latitude 46°31′N, longitude 11°51′E). These dolomitised reef carbonates are in the central part of the Dolomites, and were deformed during the Alpine Orogeny. Mollema and Antonellini (1999) suggested that these structures formed at depths of less than 1 km. The fault zones initiated from distributed joints that formed parallel to σ_1. The joint pattern developed locally intense concentrations, where cross-joints formed and linked the older joints. Some of these concentrations evolved into faults that are marked by zones of brecciation. This sequence of development is illustrated by Mollema and Antonellini (1999, fig. 15). My interpretation of the cross-joints is that they were caused by local reorientation of principal stress directions within the joint zone due to the original intensely developed joints. Linkage by cross-joints allowed shear to develop along the zones. The joint zones were therefore incipient fault zones, formed during a single progressive deformation event.

Joint frequency greatly increases into the fault zone (Fig. 6), reflecting the localisation of deformation. It appears, therefore, that an increase in joint frequency is an important characteristic for distinguishing syn-fault joints. A good

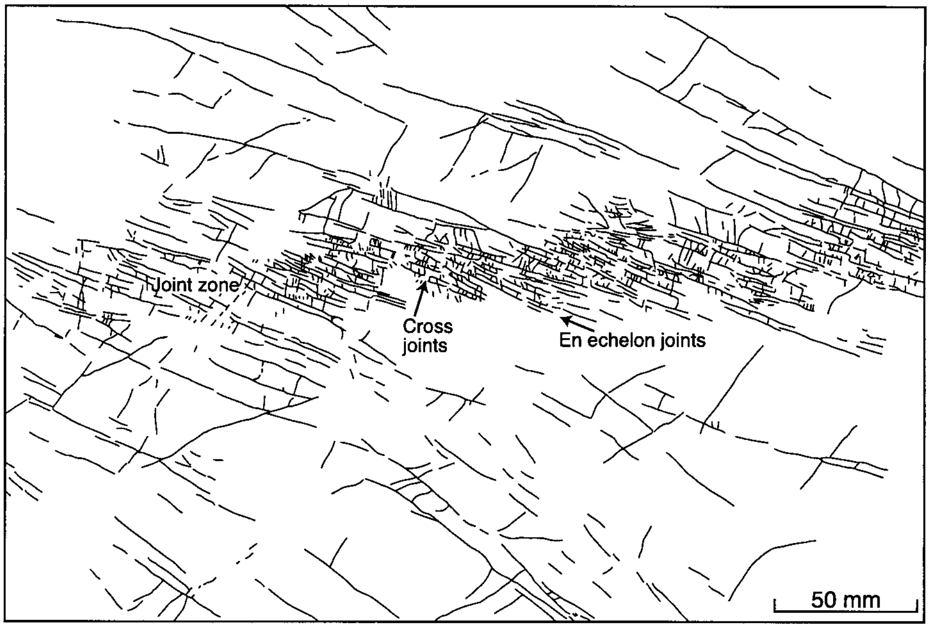

Fig. 6. Map of a zone of en echelon and cross-joints formed in dextral shear in the Sella dolomites of northern Italy (from Mollema and Antonellini, 1999, fig. 4, who did not include a north arrow).

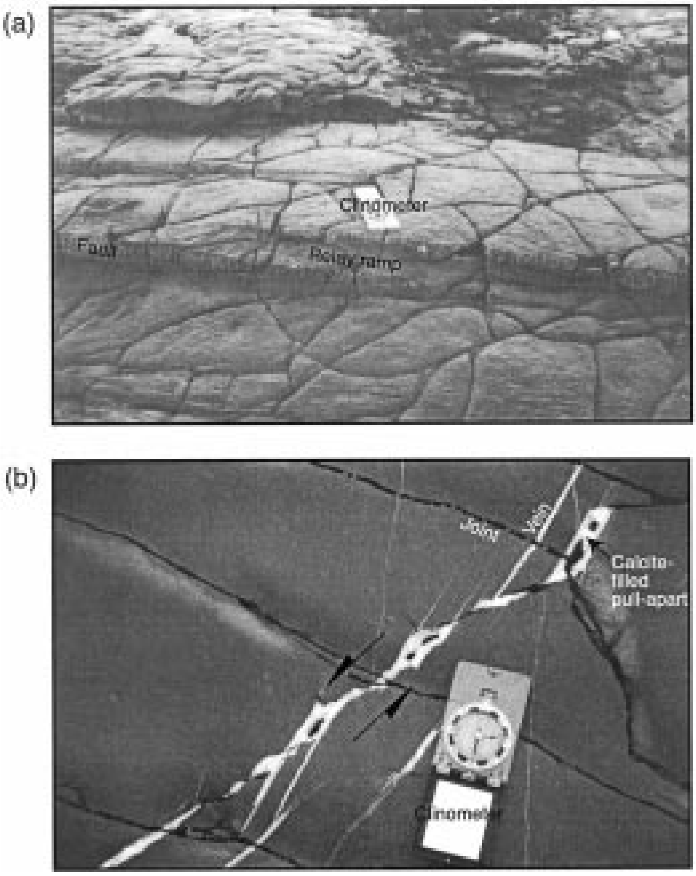

Fig. 7. Photographs of: (a) joints cutting an E-W normal fault and associated calcite veins at East Quantoxhead, and (b) joints a cutting a small strike-slip fault at Blue Ben (Peacock and Sanderson, 1995a).

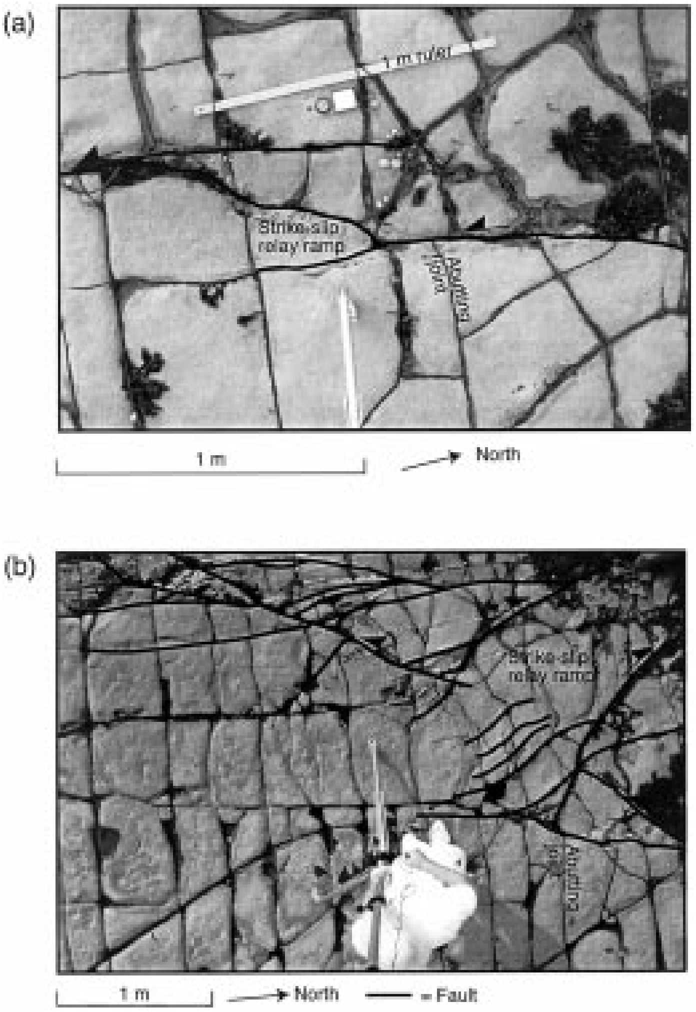

Fig. 8. Photographs of joints that abut a segmented strike-slip fault zone, but that are not displaced by the faults.

example of syn-fault joints increasing in frequency towards a fault in the Aegean region of Greece was shown by Stewart and Hancock (1990) and by Dunne and Hancock (1994, fig. 5.28a), who showed grid patterns of joints locally developed near the Earth's surface around a neotectonic fault.

4. Joints that post-date faults: the Liassic rocks at East Quantoxhead, Somerset

The approximately 18 km long outcrop of Mesozoic sedimentary rocks along the coast between Hinkley Point and Blue Anchor Bay, Somerset, SW England, contains exceptional exposures of a wide range of structures. The large tidal range has produced a wide wave-cut platform, with rapid erosion of the relatively soft rocks maintaining fresh exposure. The rocks consist of Triassic marls and sandstones, and of Liassic limestones and mudrocks, deposited on the south side of the Bristol Channel Basin. Whittaker and Green (1983) gave an account of the stratigraphy and larger tectonic structures, while Peacock and Sanderson (1992, 1999) and Dart et al. (1995) described the deformation history of the coast. The development of joints in the Liassic limestones at Lilstock, about 3 km to the east of East Quantoxhead, is described by Rawnsley et al. (1992, 1998) and by Engelder and Peacock (2000). East Quantoxhead (latitude 51°11′N, longitude 3°15′W) shows excellent exposures of normal and strike-slip faults, with extensive limestone bedding planes allowing joints to be analysed.

The Triassic and Liassic sedimentary rocks record three tectonic events between Kilve and Watchet, including East Quantoxhead (Peacock and Sanderson, 1992, 1999; Dart et al., 1995; Kelly et al., 1999). The first event was an approximate north-south extension during the Mesozoic, indicated by 095°-striking normal faults and calcite veins. East–west striking gentle folds occur in the faults blocks, are parallel to the faults, and are interpreted as coeval with the normal faults.

The second event was approximate north–south contraction, indicated by:

1. widely-developed strike-slip faults conjugate about a

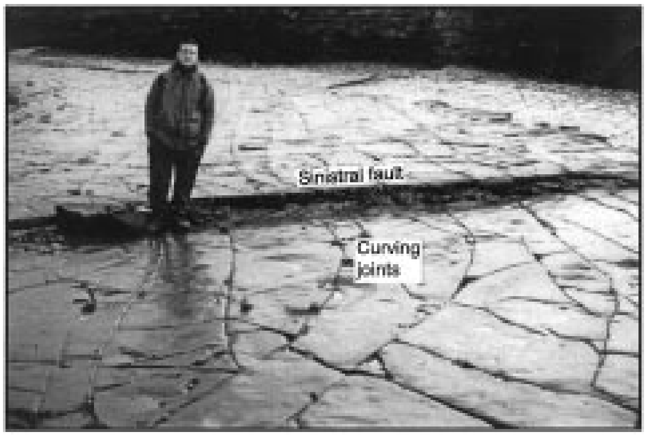

Fig. 9. Photograph of joints curving into a NNE-trending sinistral strike-slip fault zone that has tens of millimetres displacement at East Quantoxhead. Beds have a separation across the fault zone because the slip vector is slightly oblique to the gently dipping beds.

north–south trend (described by Peacock and Sanderson, 1995b),
2. north–south striking calcite veins,
3. less commonly developed east–west striking thrusts,
4. east–west striking folds (possibly tightened folds between the normal faults) with crenulation cleavage, and
5. thrusts and tight folds in the wall-rocks of the larger 095°-striking normal faults, indicating reverse-reactivation (Kelly et al., 1999).

These contractional structures consistently cut and displace the 095°-striking normal faults and calcite veins. This north–south directed contractional deformation is related to compression during the Alpine Orogeny (e.g. Dart et al., 1995).

Jointing was the third major tectonic event. Hancock (1967) noted that regional joint systems are commonly younger than the faults in a region. NW–SE striking joints dominate in the Mesozoic and Tertiary rocks of southern England and NW France, and reflect the current regional stress system (e.g. Hancock and Engelder, 1989, fig. 2). The joints at East Quantoxhead are interpreted to post-date the normal and strike-slip faults. Evidence for this interpretation includes:

1. Normal faults and associated calcite veins consistently strike E–W, while E–W striking joints are only locally developed. The dominant (earliest and longest) joint set in the area strikes approximately NW–SE. Later sets are shorter because they abut the earlier joints (e.g. Rawnsley et al., 1998). This suggests that there was no consistent set of E–W striking joints before the development of the E–W striking normal faults and calcite veins, or before development of the NW–SE striking joints.
2. The joints consistently abut the E–W striking normal faults that separate beds, and cut the smaller normal faults and the associated calcite veins (Fig. 7a). The normal faults and all associated fractures are mineralised, implying that all open fractures were affected by a phase of mineralisation. The joints are not mineralised, suggesting they post-date the mineralisation and therefore the normal faults. Some 095°-striking joints run along and extend from the tips of some of the normal faults. It could be argued that these faults followed pre-existing joints (C. Townsend, personal communication), but while all normal faults die out along strike into calcite veins (e.g.

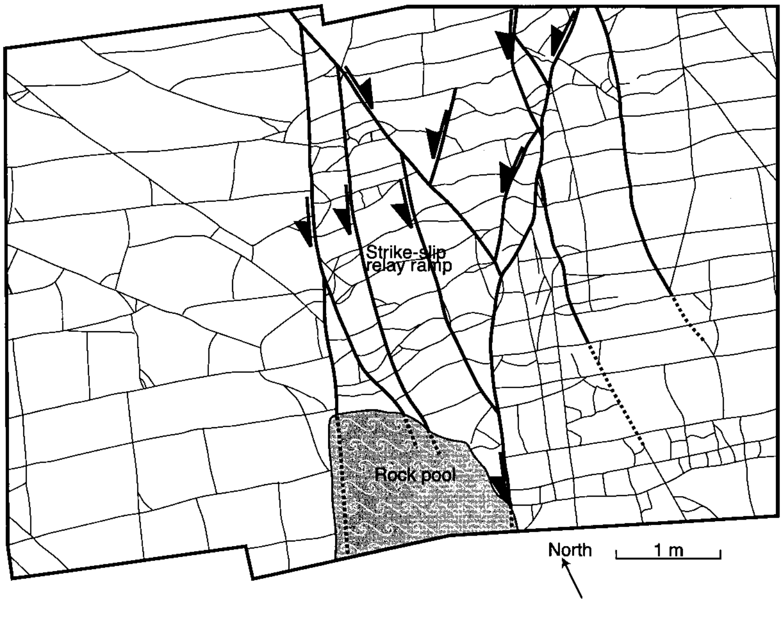

Fig. 10. Map showing different joint patterns in the same bed across a strike-slip fault zone at East Quantoxhead.

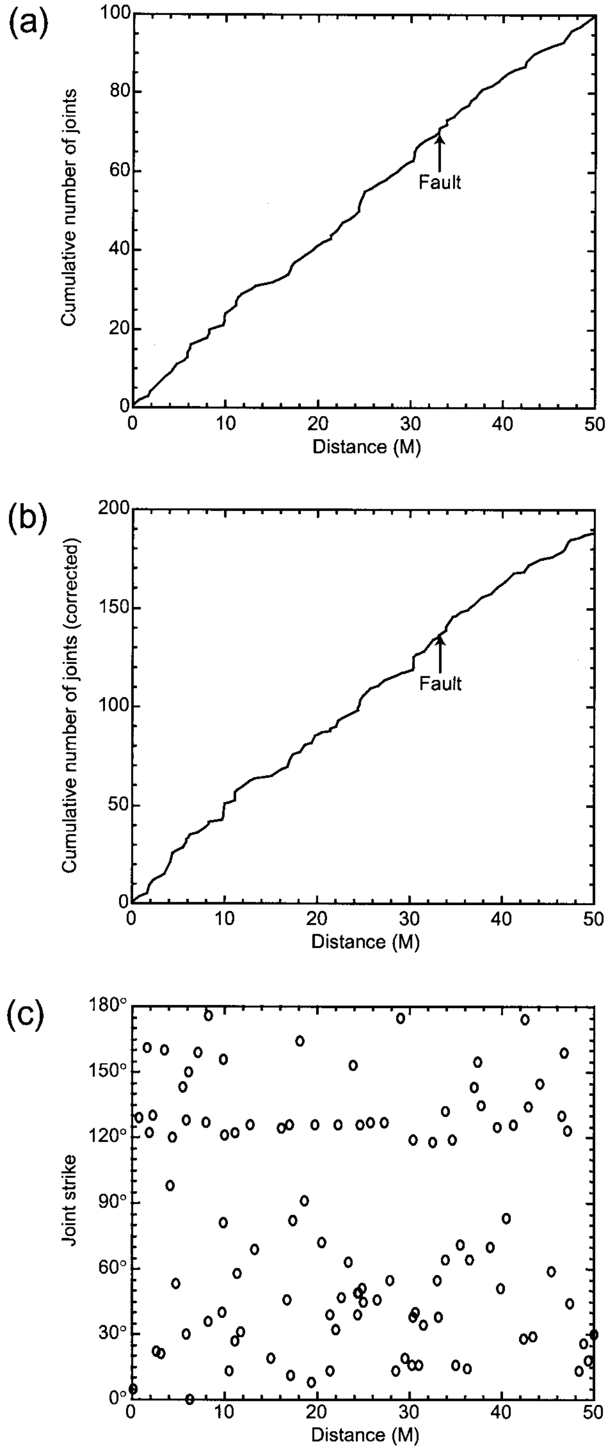

Fig. 11. (a) Graph of cumulative number of joints against distance across a sinistral strike-slip fault zone with a displacement of less than 1 m at East Quantoxhead (scan-line along a 288° trend). Joint frequency does not increase around the fault, indicating that the joints did not form at the same time as the fault. (b) Graph of corrected cumulative number of joints against distance for the scan-line shown in Fig. 11(a). The strikes of each joint are "corrected" such that $F = |1/\sin(\theta\text{-}\gamma)|$, where F = corrected frequency, θ = orientation of scan-line, and γ = joint strike (e.g. Terzhagi, 1965). (c) Graph of joint strike against distance along the scan-line, showing no evidence for variations in joint patterns or frequency around the fault.

Peacock and Sanderson, 1991, 1992), not all normal faults pass into joints.

3. Joints commonly cross smaller strike-slip faults and are not displaced by them (Fig. 7b). Many joints probably cross the smaller strike-slip faults because these faults do not separate beds, so joint propagation lacks a lithological barrier. Joints consistently abut larger strike-slip faults (Fig. 8), which were therefore barriers to joint propagation. This geometry is probably because the strike-slip faults with larger displacements tend to separate beds, causing lithological barriers to joint propagation. Joints of all sets cross or abut the strike-slip faults, but the relationship is most obvious in joints that strike at a high angle to the faults. The strike-slip faults consistently offset the normal faults, so the joints must post-date the normal faults.
4. Joints commonly curve into the strike-slip faults (Fig. 9), indicating that stresses were perturbed around the strike-slip faults. The earliest joints abut the strike-slip faults at about 90°, indicating that the strike-slip faults were traction-free surfaces at the time of jointing, so the principle axes of stress were parallel and perpendicular to the faults (Engelder and Gross, 1993). Rawnsley et al. (1992, 1998) showed joints curving into points along strike-slip faults at Lilstock and elsewhere in the Bristol Channel Basin. It is possible that such a curving pattern of joints could form in a diffuse zone of shearing either as a precursor to or during the strike-slip faulting. Evidence against this, however, includes that the fault-related calcite veins do not follow this curved trajectory, but consistently striking approximately north–south.
5. Some strike-slip faults have different patterns of joints on either side of the fault zone (Fig. 10). This geometry is interpreted to mean that the strike-slip faults compartmentalised the stress field during joint formation, so the joints are either syn- or post-faulting.
6. Joint frequency does not increase along scan-lines where the lines cross the strike-slip faults (Fig. 11a). To test that this observation is not a sampling effect, the strike of each joint was used to "correct" frequency of joints (Terzhagi, 1965). Again, joint frequency and orientations do not change systematically around strike-slip faults (Fig. 11b).

This interpretation of post-fault joints is consistent with the suggestion of Rawnsley et al. (1998) that the joints in the Mesozoic sedimentary rocks of the Bristol Channel Basin resulted from relaxation of stresses after the Alpine faulting and folding, during uplift and erosion.

5. Identification and mechanical implications of the relationship between joints and faults

This section summarises how the temporal relationship between joints and faults may be identified in the field, and discusses the implications for the mechanics of jointing and faulting. Also, the field interpretations presented in this paper are supported by results from published experiments and models.

5.1. Pre-fault joints

Pre-existing joints may be sheared (e.g. Marsalforn), affected by pressure solution (e.g. Holderbank Quarry), or dilated (e.g. the Koae fault system). Pre-fault joints may be identified by their incorporation into a fault zone, with increased veining, shear or solution of the joint set. If joints pre-date faulting, they will tend to act as heterogeneities that influence fault development, controlling fault geometry and evolution. Cruikshank et al. (1991) discussed the mechanics of the reactivation of joint as faults.

5.2. Syn-fault joints

Syn-fault joints show a close kinematic and dynamic relationship to the faults. For example, the en echelon joint set in the fault zones described by Mollema and Antonellini (1999) are parallel to the far-field σ_1. These zones contain pinnate or cross-joints orientated with respect to locally perturbed principal stress directions. These cross-joints create linkages with other fractures that facilitate shear across the zone, eventually leading to a fault zone. Linkage between faulted earlier joints by later pinnate or cross-joints allows the faults to increase in length and thereby to increase in displacement (e.g. the faults at Marsalforn. See Section 2.1 and below). The increase in joint density towards such zones is an important characteristic of joints that are precursors to, or synchronous with, faults. Such damage around faults (Stewart and Hancock, 1990) indicates stress and strain localisation. Pohn (1981) contoured intensities of joints in the Appalachian foreland of New York and Pennsylvania, and suggested that zones of increased joint frequency indicate the presence of poorly-exposed faults. Similarly, Wheeler and Dixon (1980) showed that joint frequency increases in “lineament zones”, but did not speculate on the origin of these lineaments.

Petit (1988) presented experimental data that showed that joints are unlikely to form as mode II cracks, but form from pre-existing extension fractures. Similarly, Reches and Lockner (1994) carried out rock deformation tests and found that faults form and propagate as zones of intense microcracking.

When joints are syn-faulting or post-date faulting, the faults can locally modify the mechanical conditions and therefore control jointing. Hancock (1985), for example, noted that faults can be boundaries between different joint domains, with different patterns or frequencies on either side of a fault. Rawnsley et al. (1992) showed that joint formation can be affected by pore fluid pressure, mechanical properties of the rock, bed thickness, residual stress and stress-strain magnitudes, so different patterns of joints can develop if any of these factors vary across a fault. Joints may curve out from points of stress concentrations along faults (Rives et al., 1992), or joints may curve to abut faults at 90° if the faults are open so have no resolved shear stress (e.g. Engelder and Gross, 1993).

Pinnate joints (or *wing cracks*) have been produced experimentally by Adams and Sines (1978), Ingraffea (1981), Horii and Nemat-Nasser (1985), Cox and Scholz (1988) and Germanovich et al. (1994). Cruikshank et al. (1991) presented fracture mechanics interpretations of pinnate joints around the tips of faulted joints. They showed that a pinnate joint that is clockwise of the main joint indicates dextral shear on the main joint. Numerical models for the development of pinnate joints around faults and faulted joints have also given by Fletcher and Pollard (1981), Martel (1990), Cruikshank and Aydin (1994), Cooke (1997), Martel and Boger (1998), and Willemse and Pollard (1998).

5.3. Post-fault joints

If faults separate beds, or if they were traction-free surfaces, they can act as barriers to later joints. For example, Rawnsley et al. (1992) presented the results of photoelastic modelling that showed the perturbation of stresses, and therefore of joints, around a pre-existing fault. Later joints may cut faults that do not separate beds and that were sealed by minerals. Renshaw and Pollard (1995) presented experimental and modelling results on joints that cross-cut earlier interfaces, and suggested that cross-cutting is allowed by high normal stresses acting on the earlier interfaces.

6. Application of these results

The results of this analysis have applications in the hydrocarbon industry. For example, Formation MicroImager (FMI) and core data may be used to determine the variations in joint frequency around a fault, and this may be used to indicate the relative chronology. Increases in joint frequency near faults may indicate synchronous development, while variations in joint pattern towards, or on either side of, a fault indicates the joints were syn- or post-faulting. Pohn (1981) proposed that increases in joint abundance might even be used to locate poorly-exposed fault zones. Care is needed, however, as the results presented here suggest that a fault may not be marked by an increase in joint frequency. These relationships have important implications for fluid flow. For example, the synchronous development of joints around faults represents damage that may enhance fluid flow. Such information may give valuable insights into the history of fracturing, and therefore into fluid migration across and along joints and faults.

7. Conclusions

Characteristic features for determining the relative ages

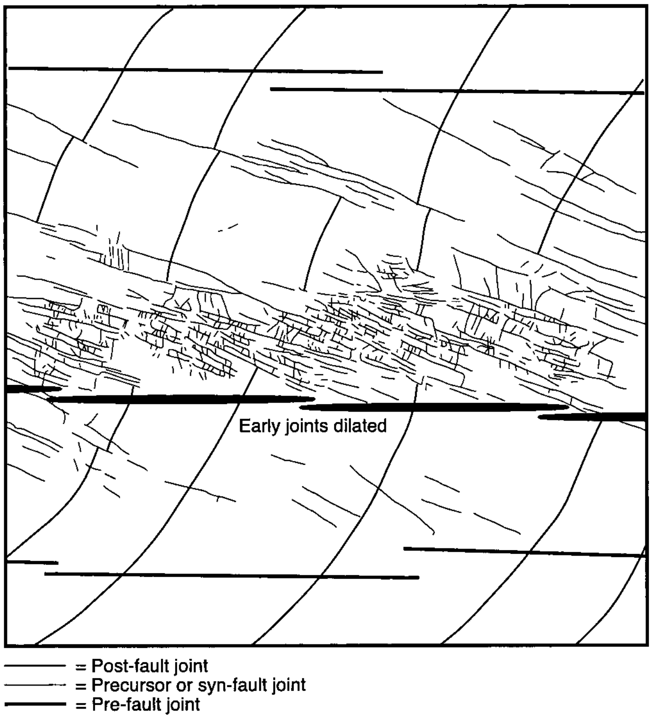

Fig. 12. Schematic diagram of the temporal relationships between joints and faults. Possible patterns of pre-, syn- and post-fault joints are shown. Pre- and post-fault joints tend not to increase in frequency towards the fault zone, while syn-fault joints tend to increase greatly in frequency near the fault. Pre-fault joints will be modified into the fault zone, e.g. opened to form veins. Syn- and post-fault joints can be perturbed around, and show different frequencies and patterns on either side of, the fault.

of joints and faults (Fig. 12) include:

1. Joints may show a geometric or kinematic relationship with faults, indicating they formed in the same stress system (e.g. the en echelon joints described by Mollema and Antonellini, 1999). Alternatively, the joints may have different orientations and formed in different stress systems than the faults (e.g. the first set of joints at Marsalforn).
2. Joints formed before or during faulting may show dilation around the fault zone. These dilated joints may remain as open cracks (e.g. around the Koae fault system), or may be mineralised to become veins. Similarly, early joints may be sheared (e.g. Marsalforn) or affected by pressure solution. Joints formed after the faulting are commonly un-mineralised (e.g. Somerset).
3. The joints may cross-cut or abut faults, indicating they post-date the faults (e.g. Somerset).
4. Joints may curve to abut the faults at about 90°. This indicates the joints formed in a stress system that was perturbed into an open fault zone either during or after faulting (e.g. Somerset; Rawnsley et al., 1992).
5. Different patterns or frequencies may occur on either side of a fault, indicating that mechanics varied across the fault, e.g. the fault may have acted as a stress barrier (e.g. Somerset). These changes indicate that the joints formed during or after faulting.
6. Joint frequency may increase towards a fault zone, indicating that the joints are related to the faulting. Joints formed either before or after faults are not characterised by increased frequency towards the fault.

It is recommended that care is taken in interpreting the relative ages of joints and faults because individual geometric features may not uniquely determine the relationship. For example, it is possible that joints that curve into a fault zone are related to distributed shear precursor to faulting, while joints that curve to abut a fault at 90° indicate that the fault was a traction-free surface during syn- or post-fault joint formation.

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