PERGAMON

Journal of Structural Geology 21 (1999) 1199–1207

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.nl/locate/jstrugeo

'Crack–seal', slip: a new fault valve mechanism?

Jean-Pierre Petit*, Christopher A.J. Wibberley, Geoffrey Ruiz

Laboratoire de Géophysique et Tectonique, Case 060, Université Montpellier II, Place E. Bataillon, 34095 Montpellier, France

Received 10 April 1998; accepted 31 October 1998

Abstract

This paper presents a new model of fault development in carbonate rocks involving a crack–seal–slip sequence. The structures of sheared calcite veins from the Les Matelles outcrop, Languedoc (S. France), and the observations used to construct this new model which integrates aspects of 'crack–seal' evolution of calcite-filled veins with concepts of fault valve behaviour are described. In our model, hydraulic mode I reopening of an oblique pre-existing vein in an overall strike-slip stress regime is accompanied by precipitation of calcite, but significant fault slip cannot occur initially despite this obliquity because the ends of the pre-existing structure limit further reopening propagation beyond the tips. The rate of aligned calcite precipitation keeps pace with the rate of dilation of the structure, so that calcite cement essentially seals the system. Stress concentrations at the tips are allowed to rise with reopening until failure of the tip zone results in branch crack formation, triggering both slip along the vein and hydraulic pressure drop. This is followed by sealing within the branch cracks. Such a crack–seal–slip cycle may be repeated several times, as evidenced by fault-perpendicular calcite vein growth interlayered with calc-mylonite lamellae within these structures. Later cycles will become less pronounced because strength recovery of the sealed branch cracks does not regain the initial strength of the intact rock. This model could apply at various scales, and could be a mechanism for triggering earthquakes. © 1999 Published by Elsevier Science Ltd. All rights reserved.

1. Introduction

The purpose of this paper is to present a new model for the mechanical development and stick-slip behaviour of faults. This model is distinct from previous basic models dealing with discontinuous displacement in carbonate rocks in that it involves the mechanical relationships between fault zone fluid pressures, calcite vein cement, slip zones, and fault tip zone deformation features (branch cracks). The work uses previous ideas on the involvement of calcite precipitation processes in mode I and mode II deformation, and is based on a detailed study of brittle structures associated with strike-slip faulting of Languedoc Jurassic limestone during foreland Pyrenean deformation (40 Ma).

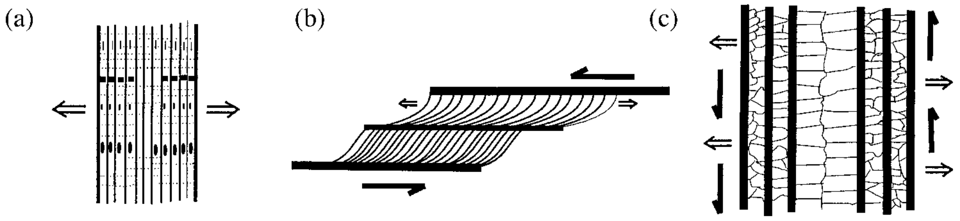
Most outcrop studies of brittle fault structures in carbonate rocks focus on the geometrical and kinematical aspects of the structures in the system (e.g. Peacock and Sanderson, 1991; Davison, 1995; McCrath and Davison, 1995; Petit and Mattauer, 1995; Willemse et al., 1997). However, the mechanics of their development are less well understood: in particular the relationship between rupture and the governing local and far field stress fields; the possible mechanical contribution of fluid pressure, in particular the role of fluid pressure fluctuations in the rupture cycle and associated carbonate cementation, have not yet been fully assessed from a point of view of field based studies.

Two basic models describe the conditions of fault slip in carbonate rocks: *the small fault model* given by Rispoli (1981) in which the slip is accommodated by fault tip structures (stylolites as contractional structures and branch cracks as extensional structures) predicted by the orientations and intensities of the local principal stress at opposite sides of a fault tip; and *the crack–seal model of calcite cement in dilational jogs* (or 'pull-aparts') given by Gaviglio (1986) and Labaume et al. (1991) who explored the origin of zoned calcites curving asymmetrically and their relationship with the

---

* Corresponding author.
E-mail address: petit@dstu.univ-montp2.fr (J.-P. Petit)

PII: S0191-8141(99)00038-3



	Crack, then Seal	Crack+Slip, then Seal	Crack+Seal, then Slip
Scale	Cm to dm	Cm to dm	Cm upwards
Feature	Veins	Pull-aparts	Slip-reactivated veins
Kinematics	1 - Crack 2 - Seal	1 - Slip+oblique crack 2 - Sealing oblique to slip direction	1 - Crack+seal 2 - Slip parallel to fault
Fluid pressure	Overpressure not necessary	Overpressure likely	Overpressure necessary
Fluid transfer	Vein-parallel	Perpendicular to fault displacement	Fault parallel towards the tip
Structure evolution	Vein widening	Pull-apart widening	Fault widening and branching

Fig. 1. A comparison of previous models (a, b) implying crack and seal evolution (with slip in certain cases) for discontinuous deformation of carbonates with the model proposed in this paper (c).

local stress field, perturbed around the fault surface. Such calcite zones were considered to have been generated in a 'crack–seal' mechanism, as originally proposed by Ramsay (1980) to explain multiple precipitation and re-cracking episodes in purely mode I veins cutting oolitic limestones and sandstones with antitaxial fibre growth (Fig. 1a). Similar concepts of calcite crack–seal episodes in dilational jogs of faults have been discussed by Davison (1995) to infer specific slip history patterns on faults segmented by pull-aparts. In these models of crack–seal in dilational jogs, the *crack* periodically reopens as a consequence of *slip* along the pre-existing fault segments. This slip phase may correspond to an increase in fluid pressures and/or deviatoric stress up to a given threshold. The crack event corresponds to a relatively fast dilational jog opening at the calcite–wall rock interface (or within the wall rock very close to the jog) into which calcite precipitation occurs (seal), typically forming increments in a 'pull-apart' zone. Presumably as a consequence of sealing, fluid pressures and/or deviatoric stress will rise until a new crack failure and slip episode occurs. In this way, these faults would be behaving in a stick-slip manner (Davison, 1995). These models may hence be referred to as 'crack–slip, then seal' (Fig. 1b). In all these cases, the term 'seal' is used to refer to vein or fault mineralised infilling drastically reducing the overall open fracture volume, but has no connotation of supporting a hydraulic pressure difference across the fault as is often meant nowadays by the term 'sealing fault' in literature on reservoir compartmentalisation.

The purpose of this article is to briefly present information on calcite-filled, strike-slip faults which present some common aspects with the features presented above, and to propose an alternative cyclic model termed 'crack–seal, then slip', or the simpler term: 'crack–seal, slip'. We present mechanical arguments for a new fault valve model in terms of likely cyclic fluid pressure and local stress evolutions through time. This is deduced from field and microscopic observations of a well identified small fault system.

2. The problem of fault propagation at Matelles

The Matelles exposure is a suitable site for the study of meso-scale brittle tectonics in limestones. Initial studies of structures from the exposure (Rispoli, 1981) demonstrated the importance of stress perturbations around faults on the genesis of stylolites and branch cracks at the tips of reactivated segments of pre-exist-

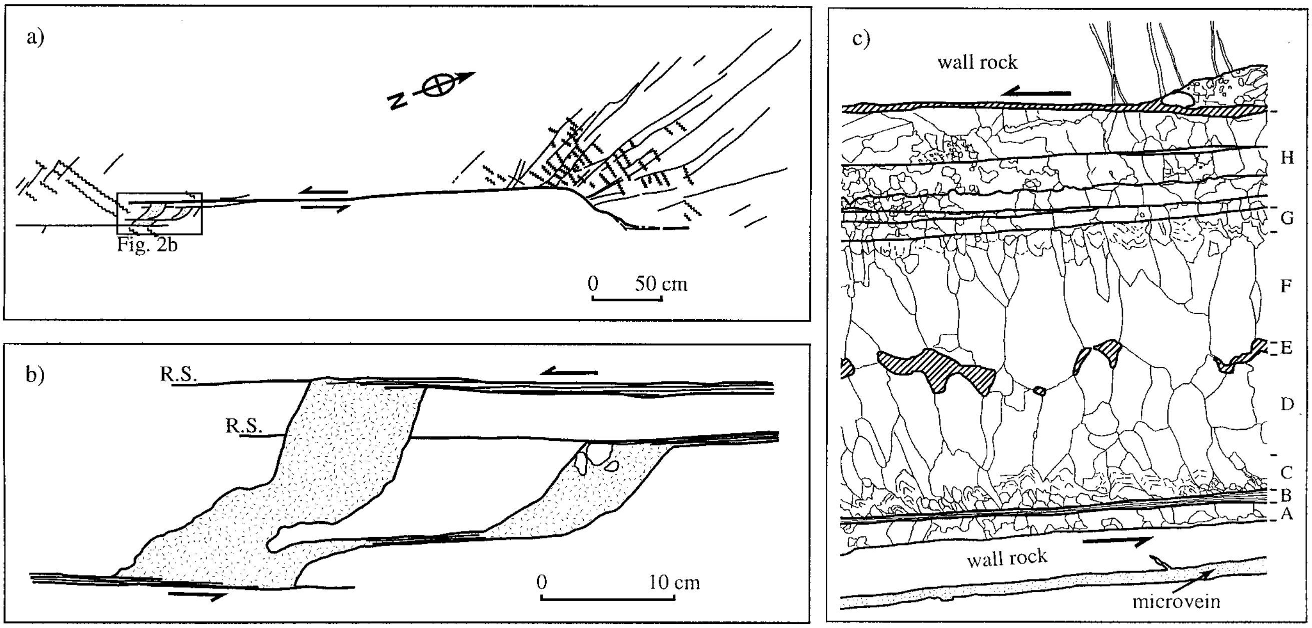


Fig. 2. An example of a slip-reactivated vein at Matelles. (a) An entire example, drawn from photographs. (b) Details of a linkage zone, originating from branch cracking and evolving into a pull-apart, drawn from photographs. (c) Drawing of a thin section view of a typical example of slip-reactivated vein [same orientation as the views in (a) and (b)], with a width of 10 mm.

ing stylolite seams within brittle kink bands (Rispoli, 1981). A more recent, fuller meso-scale analysis by Petit and Mattauer (1995) gives a complete description of the high density of calcite-filled veins, calcite-filled faults and stylolites observed at the exposure. These structures allow an interpretation in terms of palaeostress trajectories, showing that at least two distinct Pyrenean deformation episodes (each related to specific phases of movement on the neighbouring Lirou Fault) were experienced in order to explain the complicated spatial and orientation arrangement of features (Petit and Mattauer, 1995). Although it appears now as an essentially normal fault, the Lirou Fault operated during the Pyrenean as a minor strike-slip fault, branching from the left-lateral Matelles Fault north of Montpellier. At that time, the exposed Upper Jurassic strata were covered with an approximately 1000 m thick series formed of Lower Cretaceous argillaceous marls passing into massive bioclastic limestones, and by Eocene lacustrine limestone and continental conglomerates.

The exposure exhibits a dense pattern of veins, stylolites and small-scale conjugate strike-slip faults which formed with the help of fluids in decimetre thick, very low-porosity micritic limestone layers alternating with thin argillaceous bands. The absence of fluid inclusions prevents an accurate determination of pressure and temperature.

We concentrate on the mechanical origin of the strike-slip faults. The fault pattern consists of two conjugate sets: a N020° left-lateral set, and a N140° right-lateral set. These faults are expressed as rectilinear traces of sheared calcite veins whose lengths are in the order of metres to tens of metres, with calcite infillings typically of a few millimetres to centimetres in total thickness. Laterally, these faults are vertically persistent but a shape ratio cannot be established. Shear displacements along faults (having displacements of a few centimetres to tens of centimetres) are marked by contractional jogs with stylolites (e.g. Peacock and Sanderson, 1995a; Willemse et al., 1997), dilational jogs with calcite infilling (e.g. Gamond, 1983; Gaviglio, 1986; Davison, 1995; Peacock and Sanderson, 1995a, b), and some branch cracks when the tip of the fault can be observed. These faults are interpreted as reactivated veins for the following reasons (Petit and Mattauer, 1995):

1. The deformation is only located at oversteps and fault tips [i.e. in zones where stress concentrations are located in the case of reactivated fractures (Rispoli, 1981; Pollard and Segall, 1987)], whereas the fault walls are sharp and rectilinear (excluding remains of arrays of veins and stylolites which characterise shear neo-rupture).
2. Outcrops further away from the Lirou Fault display non-reactivated mode I veins of the same orientation (N020°) as these faults. This indicates that reactivation was triggered by stress concentrations in the vicinity of the Lirou Fault. This suggests that the veins were widespread and that their reactivation occurred to accommodate localised strains created by slip phases on the Lirou Fault.

3. As shown in Fig. 2(a and b), non-reactivated segments of the initial mode I veins are still preserved beyond the extent of the pull-apart connected fault segments. The model discussed in this paper stems from the observation that the calcite-filled fault segments are at least ten times wider than these preserved (non-reactivated) vein terminations (Fig. 2b). We investigate possible explanations for why these initially thin veins can result in significantly thicker structures when reactivated in a shear context.

This article tackles the problem of how the mechanics of oblique crack propagation work in the context of reactivated veins using data from the Matelles outcrop.

3. Data

3.1. Field observations

Figure 2(a) shows an example of a N020° fault with one of its tips located at locality f on the detailed mesostructural outcrop map of fig. 3 in Petit and Mattauer (1995). Displacement deduced from pull-apart opening widths is 150 mm. Both pull-aparts signifying dilational connection of overlapping segments, and a restraining bend originating from a curving vein termination with widely developed (mode I) branch veins, are present. These pull-aparts are also illustrated in Fig. 2(b) and show that some larger pull-aparts cross-cut redundant tips of earlier veins. An example of the contrast in thickness between the slip-reactivated and the non-reactivated parts of the veins is shown in Fig. 2(b). Here, the main calcite-filled fault segments are at least 10 mm wide, whereas the redundant tip portions are typically about 0.5 mm. Furthermore, the pull-aparts within the zone of overlapping segments occur before the ends of the earlier veins, suggesting that the location of the pull-apart is controlled by local stress perturbations between overlapping fault segments (Segall and Pollard, 1983; Pollard and Segall, 1987). Finally, a certain asymmetry in the pull-apart geometry suggests that the original wall rock failure mechanism was by branch crack failure at one of the two originally isolated fault tips in the overlap zone [with branch crack curvature being dictated by the stress perturbations around the fault tip (Petit and Barquins, 1988)], and was then reactivated as a pull-apart as slip displacement later occurred on both reactivated veins. The curved northern fault termination could be due to the influence of another pre-existing fracture (now hidden underneath a small scarp) which could have affected the initial (mode I) propagation of the crack by stress perturbations towards this free surface (as described by Thomas and Pollard, 1993). The branch cracks at the zone of fault tip curvature are mode I veins, making an angle of 30° to the main fault orientation, with a diverging tendency of ±20°. This divergence may be due to a Herzian contact type indentation of the ‘inner’ fault wall on the ‘outer’ wall during slip on this fault surface. These branch fractures indicate an important localised tension around the curved fault tip surface. In this region, stylolite seams are also present, indicating localised compression perpendicular to this tension. Absence of curvature on branches and the large development of these branches as tensile fractures enables us to consider their orientation as that of the remote main principal stress σ_1. The angle between this σ_1 and the fault is about 30°, hence the fault has an Andersonian attitude in a strike-slip regime.

3.2. Microtextural observations

Several samples were cored from the main calcite-filled N020° faults such as the fault illustrated in Fig. 2(a). Figure 2(c) shows a line drawing of a thin section traverse across a 10 mm wide example. The following salient points are highlighted:

1. Several relatively planar slip zones are present (zones B and H on Fig. 2c) within generally coarse-grained calcite vein material.
2. The wider (up to 0.5 mm) slip zones (zone B) visibly consist of fine-grained calc-mylonite. The narrower ones (in zone H) occasionally branch and in one case, reactivation as a stylolitic feature due to later compression has occurred.
3. The coarsest calcite material is in the central zone (zones C–G) in between the regions of slip zones, which are concentrated at the sides of the structure (zones B and H). These calcite crystals are generally elongate suggesting calcite growth towards the centre of the structure where occasional, isolated voids are present (zone E).
4. Earliest formed calcite in the central zone, in contact with the adjacent slip zones, is generally finer grained (zones C and G). Here, calcite crystals and growth zones (defined by variation in impurity content and verified by unpublished cathodoluminescence work) are orientated with a slight obliquity to the fault-normal growth direction indicated by the larger crystals in the rest of the central zone (zones D and F). This suggests that the earliest calcite grew in combined opening/left-lateral displacement of the structure walls.
5. Calcite crystals in the outer zones are generally finer grained, but still with a vein origin. The growth directions are harder to discern because of the finer nature of the material and the truncations of the crystals by the slip zones, but a hint of obliquity is apparent in the external part of zone H.
6. The region of slip zones on one side of the structure

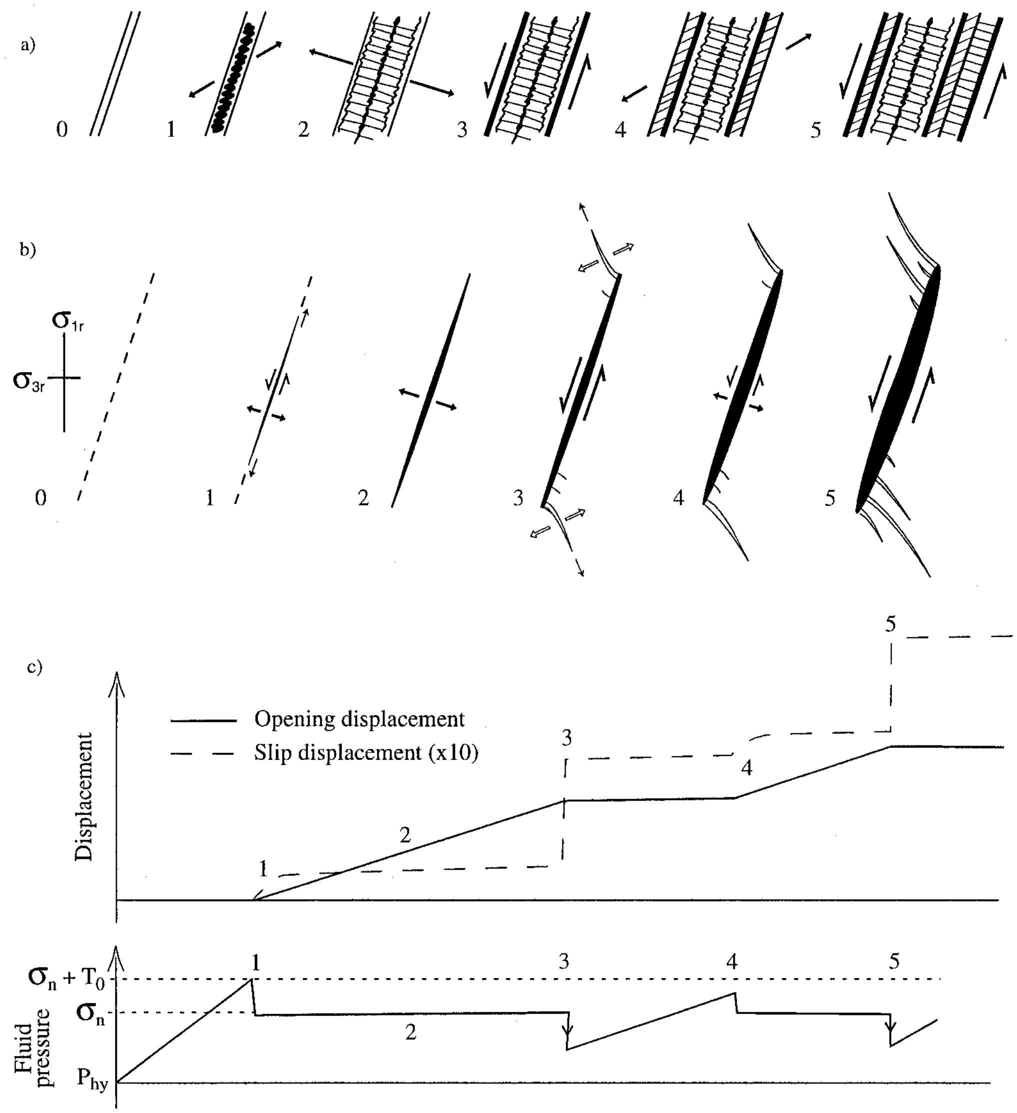


Fig. 3. Proposed evolution of the slip-reactivated veins at Matelles in a crack–seal–slip model. (a) Schematic evolution of the calcite crystal growth phases in relation to the opening and slip events. Thick straight lines indicate calc-mylonite slip zones; oblique thin lines indicate the direction of oblique crystal growth linked to minor shear displacement during the initial part of the reopening phase; crack-perpendicular thin lines indicate crystal growth during opening without shear displacement. (b) Schematic chronology of opening and slip events on an entire slip-reactivated vein in the crack–seal–slip sequence (σ_{1r} denotes maximum remote compressive stress, σ_{3r} denotes minimum remote compressive stress). (c) Graphs sketching the evolution of (i) opening and slip displacements, and (ii) fluid pressure (σ_n = normal stress; T_0 = tensile strength of the sealed pre-existing crack; phy = hydrostatic pressure), with time and in relation to the evolution of the structure shown in (b).

is defined by four relatively narrow slip planes, and a crack zone at the wall rock/calcite fault contact. On the other side of the structure, only one main slip structure is visible, defined as a wider (0.5 mm thick) calc-mylonite zone. A narrower zone of very fine grained material at the wall rock/calcite fault contact may also be a slip zone.

7. A 0.5 mm wide non-reactivated calcite vein is present in the wall rock of the main structure (left hand side of Fig. 2c). Its microstructure is considered analogous to that of the redundant vein tip zones to the main calcite-filled faults, beyond the pull-aparts.

Thus it appears that the internal structure of the calcite-filled faults has been acquired by successive opening events and slip events, with a first major opening event initially accompanied by a small left-lateral shear component.

4. A crack–seal–slip valve model

This section will describe the new crack–seal–slip model that we propose, involving the observations described above (Fig. 2). This model aims to solve the basic question of how a very thin pre-existing mode I

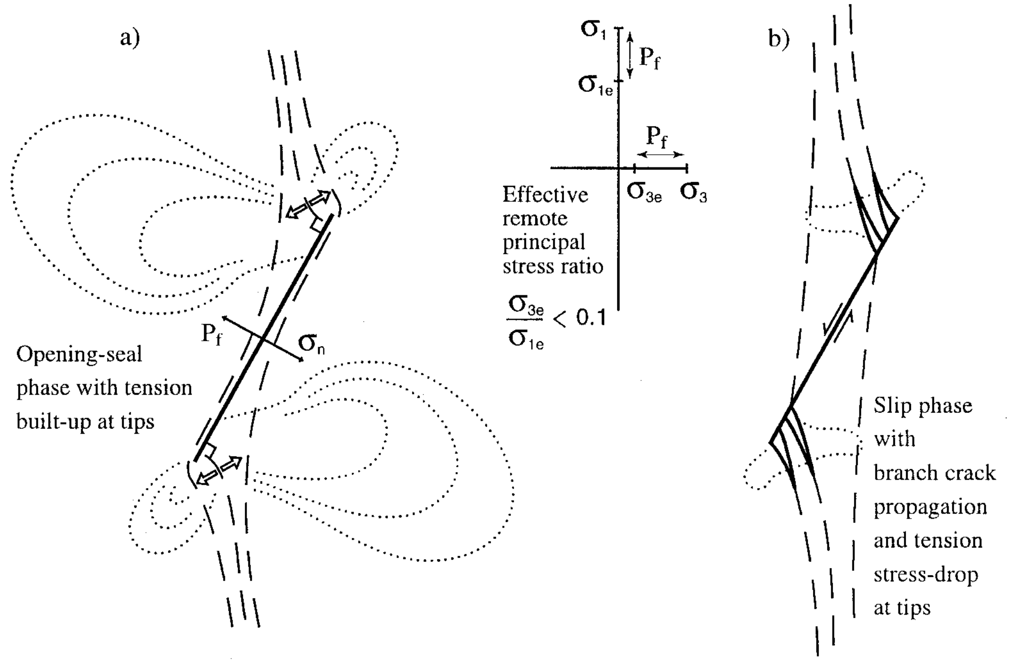


Fig. 4. Geometry of a stress field around the pre-existing planar defect, deduced from analytical and experimental (photoelastic) models (e.g. Petit and Barquins, 1990). Dashed lines represent local σ_1 trajectories, and dotted lines represent contours of $(-)\sigma_3$ values. (a) Pre-slip state. Note that maximum tension is located adjacent to the fault tips. (b) Post-slip state with branch crack formation, stress drop, and reorientation of the stress trajectories.

vein could evolve towards a fault several tens of times thicker. From a kinematic point of view, examination of the internal structures has revealed that reactivation involved a succession of distinct alternating opening (explaining the thickening) and slip displacements. In constructing our model, we pose the question: what mechanical conditions could lead to these successive events? The prerequisites of the model are that earlier formed extension fractures are oblique to a later, independent stress field with a maximum compressive stress oriented oblique to the fracture (step 0 in Fig. 3a and b) together with a fluid pressure build-up in a low porosity rock. Figure 3 synthesises the model, and shows how the microstructural observations can be linked to its various sequences. Steps are first described generally, and then justified mechanically in further detail.

4.1. Step 1—crack

A rising fluid pressure permitting the recracking of the oblique pre-existing fracture is considered the only way to explain an essentially mode I reopening. This implies a suprahydrostatic pressure build-up within the fracture porosity. During step 1, the fluid pressure (Fig. 3c) is assumed to be constant during the progressive opening of the initial 'recrack' before significant fracture opening (step 2). This is analogous to the pressure evolution during fracture reopening tests (HTPF method, Cornet and Valette, 1984) when a fluid is injected at constant rate into a randomly oriented fracture. At this stage, it can be assumed that the fluid pressure matches the stress component normal to the fracture surface plus either the tensile strength of the initial calcite, or a lower resistance if some stress corrosion is involved in the reopening fracture tip. The oblique orientation of early calcite growth structures at the edges of the central zone (step 1 in Fig. 3a and b) may be due at least partly to an initial elastic shear deformation, pinned by the ends of the pre-existing vein.

4.2. Step 2—opening-seal—the rising fluid pressure permits the essentially mode I opening with associated seal

Step 2 begins when the reopening tip-line reaches the tip-line of the pre-existing fracture. However, slip is still blocked as the strong resistance of the wall rock prevents crack tip propagation. Thus the pressure build-up (stage 2 in Fig. 3a) induces an essentially mode I opening (stage 2 in Fig. 3a and b) taking place slowly, allowing precipitation of elongate aligned calcite in the fracture perpendicular to the structure walls. The aligned crystallisation keeps pace with the rate of opening displacement so that calcite cementation is effectively acting as a seal.

4.3. Step 3—slip with associated branch rupture and self-sealing

Due to stress concentration at the fracture tips which creates a metastable situation, rock failure occurs by branch cracking around the tip zone (step 3 in Fig. 3a and b). Propagation may be triggered by internal pressure, slight change in the far-field stress regime, or development of microcracks linked to elastic deformation at the crack tip during opening. The newly formed volume creates a fluid sink and therefore causes a drop in fault zone fluid pressure (Fig. 3c). This pressure drop favours rapid mineralisation within the branches, leading to partial healing.

At step 3, the failure around the tip zone occurs because the fracture is oriented favourably for shear displacement. The branching character of this rupture is linked to the difficulty of promoting mode II rupture (Segall and Pollard, 1983; Petit and Barquins, 1988). But it also suggests the presence of suprahydrostatic fluid pressure. Indeed, experiments suggest that branching with respect to an oblique defect is only possible at a very low (less than 1/10) σ_1/σ_3 stress ratio. Such a situation is seldom found in the Earth's crust on the whole, but it can be easily obtained locally by a decrease in the effective principal stress with fluid pressure increase. In this case, tensile stress concentrations at fault tips would be particularly strong (Fig. 4a). The effect of this failure mechanism is two-fold: (1) slip occurs, probably at the wall rock/vein calcite contact but will cause a certain amount of deformation within the vein calcite, resulting in relatively narrow calc-mylonite slip zones (observed in Fig. 2c); (2) because the slip can be extremely fast (at least in relation to the other processes operating), calcite precipitation which may now occur in the open branch cracks will not keep pace with the rate of branch crack opening. The apparent sparitic sealing in branches is not in contradiction with this idea. The slip magnitude and dynamics of rupture is an instability problem in which slip and branch crack propagation are related. This will be discussed below.

4.4. Steps 4 and 5—repetition of the crack–seal–slip cycle, with a changing character as the structure evolves

Another rise in fluid pressure will again cause hydraulic fracturing, with crack reopening occurring at one or both of the wall rock–calcite contacts (step 4 in Fig. 3a and b) in an outward progressing growth succession. Again, an opening displacement and calcite cementation ('seal') is facilitated by the high fluid pressure, whilst slip is prohibited by the crack tip's strength due to self-sealing (and consequent strength recovery) of the branch fractures. Again, a drop in fluid pressure will accompany the slip/branch crack reopening, and another cycle will then start, as branch crack calcite refilling and a rise in fluid pressure leads to a third hydraulic fracturing episode. In step 5, because the tip zone strength is unlikely to be anywhere as high as the tensile strength of the intact rock (because the healing effect, and consequent strength recovery, will be less than complete), the rise in fluid pressure does not need to be so high in the second or later cycles than for initial branch crack formation (stage 5 in Fig. 3c). Hence the stress concentration build-up at the tips will be less for the later cycles, so that the associated slip could be less and the phase of calcite cementation in the faults may not be as long as in the first cycle, explaining why the central zone is much wider than the other zones of calcite fill in Fig. 2(c).

Dilational jog formation is essential in the studied case as this will increase the fault length by linkage. At an early step, tip zones on overlapping adjacent fault segments may have been sufficiently close for branch cracks to connect these faults, forming dilational jogs to larger faults. Once calcite-filled, these pull-aparts will have a finite cohesion [or tensile strength, often expressed as 'healing' or strength recovery (e.g. Main et al., 1994)] so that they too can support certain fault segment tip stresses after hydraulic fracture *crack* generation. This allows a certain build-up of segment tip stress concentration during the calcite cement *seal* phase of later cycles before pull-apart refailure occurs with consequent *slip*.

5. Discussion and conclusions

The model presented here combines several previously described mechanisms or concepts: the idea of fault nucleation by reactivation of pre-existing mechanical discontinuities is classical although not frequently demonstrated from field examples. This is the case for the reactivation of mineral-filled joints described by Segall and Pollard (1983) in granite where propagation is accommodated by branching and relays, excluding in-plane (mode II) propagation which is difficult (Petit and Barquins, 1988).

Two previously published models present similarities with our model in that they relate fault dynamics to hydraulic fracturing. Phillips (1972) studied in general terms the interplay between pore water pressure, pressure of hydrothermal solution and differential stress at the tip of normal faults and its consequences on upwards fault extension by brecciation with mineralisation. Sibson (1990) in his fault valve behaviour model discussed the cyclic and seismogenic character of rupture with special emphasis on the role of fault orientation on rupture. The common points between Sibson's model and our model are: (i) a low permeability barrier; (ii) a suprahydrostatic fluid pressure build-up which implies a more or less constant flux from a remote deep source; and (iii) a self-healing phase. Unlike in Phillips' and Sibson's models, the case examined here implies a regional pressure build-up beneath an overlying shallow barrier, i.e. Lower Cretaceous clayey marls acting as a barrier above the Upper Jurassic limestone. As in Phillips' model, the fracture tip-line itself (i.e. the peripheral contact where the vein terminates in the wall rock) acts as a local permeability barrier. Dealing with stress, contrary to both Phillips' and Sibson's models, rupture is presented in association with a description of a strong local stress field reorganisation around the fault, resulting from fluid-induced recracking. This local stress field instability may contribute to trigger further slip-branching events in surrounding faults which are in metastable situations.

Sibson's model (Sibson, 1990) also states that the valve effect should be more likely for unfavourably oriented faults, this being accompanied by the formation of arrays of pre-failure mode I veins in intact rock away from the fault. This is not the case here where the orientation of the pre-existing plane of weakness is mostly favourable to shear rupture. Hence for our case, the effective stress level would not be allowed to rise sufficiently for mode I vein formation away from the zones of tensile stress concentration (and indeed, this was seldom observed in the field).

Our model also integrates some aspects of crack seal in pull-aparts, in that the crystallisation is incremental, opening of the crack occurs at the calcite–wall rock interface, and the stick-slip behaviour corresponds to a repeated dissipation of energy linked to a permanent fluid pressure and/or deviatoric stress build-up. However, this situation leads to the repetition of a great number of events of the same magnitude, whereas in our model, a relatively small number of relatively important events (in proportion to the fault length) is invoked. The kinematics are also different in that pull-apart seal post-dates and is a passive consequence of the crack–slip (crack–slip, then seal sequence) in models such as those by Gaviglio (1986) and Davison (1995), whereas in our case the pressurised seal phase within the fault preceeds and prepares the slip phase (crack–seal, then slip sequence).

Finally, as it may imply metastable situations, the crack–seal–slip model provides a conceptual basis for seismic triggering, in the same manner as Sibson's fault valve model (Sibson, 1990). The corresponding seismic instability should be discussed in terms of fracture mechanics. It has been shown (Barquins and Petit, 1992) that in the case of an open oblique defect under constant applied stress and internal (fluid) pressure, the propagation speed of the branch crack can evolve from subcritical (promoting short branch crack associated with creep type slip) to catastrophic (promoting long branch cracks associated with seismic type slip along the fault). This depends on the presence, size and location of microdefects at the crack tip (Barquins et al., 1992), on absolute and relative values of applied stress, especially when an internal (fluid) pressure is involved, and on material toughness. In these conditions the occurrence of catastrophic behaviour during step 3 and step 5 cannot be demonstrated. However, the classical common build-up of both fluid pressure and remote stresses could provide very favourable conditions for unstable seismic rupture. It is proposed that this mechanism could exist in much deeper conditions on much larger faults. In particular this model is fully compatible with the in situ stress data made along the San Andreas Fault showing local maximum horizontal stress near perpendicular to the fault (e.g. Zoback et al., 1987) as for certain zones around the fault in Fig. 4(a). This corresponds to a pre-rupture situation as in the slip phase, determining fault-oblique stress trajectories (Fig. 4b). Moreover, a branched distribution of aftershocks has been described on the Imperial Fault in a geometry similar to that of the branching fracture (Johnson and Hutton, 1982). At the small scale of the example described here, a similar unstable behaviour can be envisaged just after a late slip phase at the fault tip. Our example is much smaller and simpler than the larger fault zones typical of seismic faults, which generally have complicated internal structures, such as the San Gabriel Fault (Chester et al., 1993). However, our model is compatible with the mechanical principles invoked in such works on the internal structures of larger faults, and has the advantage of being able to describe a complete, albeit small, system (that is to say, to describe the evolution of interaction between the whole fault and its tip zones).

In conclusion, our model invokes a particular type of valve behaviour, comparable in various aspects to Phillips' hydraulic fracturing model (Phillips, 1972) and Sibson's fault valve model (Sibson, 1990). However, this paper proposes a more comprehensive model for the cyclic evolution of fracturing, cementation, and opening and strike-slip displacements on reactivated veins, based on simple field and microscopic observations of mesoscale examples. It presents a coherent scenario which helps to link far and local stress, fluid overpressure, shear and opening mode rupture and mineralisation. The model uses concepts of fluid pressure evolution, related to reopening phases of the reactivated vein and rupturing at the tips to generate branch cracks. It suggests that slip is allowed only when the tension at the tip reaches a critical value in the tensile stress concentration zone allowing tip zone failure and branch cracking. It shows how tensile stress concentration is made possible by the hydraulic reopening of an oblique fracture which is itself the result of pressured fluid flow at the calcite–wall rock or calcite–calcite interface. In reality, a change in stress field may also contribute to a rise (and then to branching and slip) in the tip zone tension, provided the oblique fracture is already reopened. This could occur especially when the stress field around a metastable reopened oblique fracture is modified by rupture on nearby faults. Despite the fact that the faults observed at the Matelles exposure cannot evolve into larger faults without losing the characteristics described here, the work is nevertheless important in understanding the birth and early behaviour of larger faults before these structures are destroyed.

Acknowledgements

This work was undertaken when the second author was in receipt of an Elf Aquitaine post-doctoral grant. Anne Delplanque is thanked for the graphics, and Juan Watterson made some useful reviewing comments. François Cornet is thanked for his comments on hydraulic pressure evolution.

References

Barquins, M., Petit, J.-P., 1992. Kinetic instabilities during the propagation of a branch crack: effects of loading conditions and internal pressure. Journal of Structural Geology 14, 893–903.

Barquins, M., Petit, J.-P., Maugis, D., Ghalayini, K., 1992. Path and kinetics of branching from defects under uniaxial and biaxial compressive loading. International Journal of Fracture 54, 139–163.

Chester, F.M., Evans, J.P., Biegel, R.L., 1993. Internal structure and weakening mechanisms of the San Andreas Fault. Journal of Geophysical Research 98, 771–786.

Cornet, F.H., Valette, B., 1984. In situ stress determination from injection test data. Journal of Geophysical Research 89, 11829–11849.

Davison, I., 1995. Fault slip evolution determined from crack–seal veins in pull-aparts and their implications for general slip models. Journal of Structural Geology 17, 1025–1034.

Gamond, J.F., 1983. Displacement features associated with fault zones: a comparison between observed examples and experimental models. Journal of Structural Geology 5, 33–45.

Gaviglio, P., 1986. Crack–seal mechanism in a limestone: a factor of deformation in strike-slip faulting. Tectonophysics 131, 247–255.

Johnson, S., Hutton, L., 1982. Aftershocks and pre-earthquake seismicity. In: The Imperial Valley Earthquake of October 15, 1979. U.S. Geological Survey Professional Paper 1254, pp. 59–76.

Labaume, P., Berty, C., Laurent, P., 1991. Syn-diagenetic evolution of shear structures in superficial nappes: an example from the Northern Appenines (NW Italy). Journal of Structural Geology 13, 385–398.

Main, I.G., Hutcheon, R., Meredith, P.G., Crawford, B.R., Smart, B.G.D., 1994. Characteristic size effects during self-sealing brittle deformation. In abstracts to: Tectonic Studies Group conference ‘Fault Populations’, Edinburgh, U.K., pp. 75–78.

McGrath, A.G., Davison, I., 1995. Damage zone geometry around fault tips. Journal of Structural Geology 17, 1011–1024.

Peacock, D.C.P., Sanderson, D.J., 1991. Displacements, segment linkage and relay ramps in normal fault zones. Journal of Structural Geology 13, 721–733.

Peacock, D.C.P., Sanderson, D.J., 1995a. Pull-aparts, shear fractures and pressure solution. Tectonophysics 241, 1–13.

Peacock, D.C.P., Sanderson, D.J., 1995b. Strike-slip relay ramps. Journal of Structural Geology 17, 1351–1360.

Petit, J.-P., Barquins, M., 1988. Can natural faults propagate under mode II conditions? Tectonics 7, 1243–1256.

Petit, J.-P., Barquins, M., 1990. Fault propagation in mode II conditions: Comparison between experimental and mathematical models, applications to natural features. In: Rossmanith, H.P (Ed.), Mechanics of Jointed and Faulted Rock. A.A. Balkama, Rotterdam, pp. 213–220.

Petit, J.-P., Mattauer, M., 1995. Palaeostress superimposition deduced from mesoscale structures in limestone: the Matelles exposure, Languedoc, France. Journal of Structural Geology 17, 245–256.

Phillips, W.H., 1972. Hydraulic fracturing and mineralisation. Journal of the Geological Society of London 128, 337–359.

Pollard, D.D., Segall, P., 1987. Theoretical displacements and stresses near fractures in rock: with applications to faults, joints, veins, dikes, and solution surfaces. In: Atkinson, B.K (Ed.), Fracture Mechanics of Rock. Academic Press, London, pp. 277–349.

Ramsay, J.G., 1980. The crack–seal mechanism of rock deformation. Nature 284, 135–139.

Rispoli, R., 1981. Stress fields about strike–slip faults inferred from stylolites and tension gashes. Tectonophysics 75, T29–T36.

Segall, P., Pollard, D.D., 1983. Nucleation and growth of strike-slip faults in granite. Journal of Geophysical Research 88, 555–568.

Sibson, R.H., 1990. Conditions for fault-valve behaviour. In: Knipe, R.J, Rutter, E.H (Eds.), Deformation Mechanisms, Rheology and Tectonics, 54. Geological Society of London Special Publication, pp. 15–28.

Thomas, A.L., Pollard, D.D., 1993. The geometry of échelon fractures in rock: implications from laboratory and numerical experiments. Journal of Structural Geology 15, 323–334.

Willemse, E.J.M., Peacock, D.C.P., Aydin, A., 1997. Nucleation and growth of strike-slip faults in limestones from Somerset, U.K. Journal of Structural Geology 19, 1461–1477.

Zoback, M.D., Zoback, M.L., Mount, V.S., Suppe, J., Eaton, J.P., Healy, J.H., Oppenheimer, D., Reasenberg, P., Jones, L., Raleigh, C.B., Wong, I.G., Scotti, O., Wentworth, C., 1987. New evidence on the state of stress on the San Andreas Fault system. Science 238, 1105–1111.