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The evolution of faults formed by shearing across joint zones in sandstone

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Abstract

The evolution of strike-slip and normal faults formed by slip along joint zones is documented by detailed field studies in the Jurassic Aztec Sandstone in the Valley of Fire State Park, Nevada, USA. Zones of closely spaced planar sub-parallel joints arranged en échelon are sheared, forming faults. Fracturing occurs as a result of shearing, forming new joints. Later shearing along these joints leads to successively formed small faults and newer joints. This process is repeated through many generations of fracturing with increasing fault slip producing a hierarchical array of structures. Strain localization produced by shearing of joint zones at irregularities in joint traces, fracture intersections, and in the span between adjacent sheared joints results in progressive fragmentation of the weakened sandstone, which leads to the formation of gouge along the fault zone. The length and continuity of the gouge and associated slip surfaces is related to the slip magnitude and fault geometry with slip ranging from several millimeters to about 150 m. Distributed damage in a zone surrounding the gouge core is related to the original joint zone configuration (step sense, individual sheared joint overlaps and separation), shear sense, and slip magnitude. Our evolutionary model of fault development helps to explain some outstanding issues concerning complexities in faulting such as, the variability in development of fault rock and fault related fractures, and the failure processes in faults.

Keywords: Faults; Joint zones; Fragmentation; Gouge; Damage zone

1. Introduction

Several different kinds of mechanisms for fault growth and development have been documented by experimental and field studies in instances where initial conditions are well constrained and material property effects are known or minimized. In particular, several studies document a faulting mechanism involving shearing of pre-existing joints. Cruikshank and Aydin (1994) document arrays of secondary joints formed near the ends of single or two interacting sheared joints. Segall and Pollard (1983) and Martel et al. (1988) documented the formation of small strike-slip faults formed from pre-existing joint sets in granites of the Sierra Nevada; they describe a faulting sequence that begins with jointing, followed by slip on individual joints forming small faults, and evolving into simple fault zones with boundary faults. Martel (1990) later extended this progression to include complex zones produced through linkage of simple faults. The formation of tail cracks as a result of shear on joints is the basic mechanism of fault development proposed by these previous studies.

An important finding from these and other field studies is that those faulting mechanisms that are shown to involve earlier formed discontinuities are greatly influenced by these discontinuities. In particular, shearing of pre-existing joints is shown to result in formation of secondary joints along the sheared joint periphery in regions of high tensile stress (Segall and Pollard, 1980). These joints are referred to collectively as secondary fractures, horsetail fractures (Granier, 1985), pinnate fractures (Engelder, 1987), splay cracks (Martel et al., 1988), splay fractures (Martel, 1990), kink fractures (Cruikshank et al., 1991a), bridge fractures and tail fractures (Cruikshank and Aydin, 1994). We use the term splay fractures to describe these joints in the context of this study.

It is these subsidiary splay fractures that most convincingly differentiate sheared joints as a deformational structure distinctly different from deformation bands that lack these secondary opening mode fractures. Deformation

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mechanisms identified through rock fracture experiments are in good agreement with results from the field-based analyses. Changes in porosity and localization of grain crushing occur in experimental deformation of pristine sandstones (Fredrich et al., 1995; Menendez et al., 1996; Wong et al., 1997). Experiments that explicitly include macroscopic joints subject to shear deformation verify that new shear related fractures are formed in the joint periphery (Brace and Bombolakis, 1963) and that strain is localized between adjacent joints in en échelon arrangements (Peng and Logan, 1991).

In this study we expand the knowledge of fault growth and development in sandstone by considering faults produced by shearing along well developed joint zones with a range of different joint zone starting geometries. Previous work describing the initial stages of faulting across simple joint structures in sandstone has been limited to faults with a few centimeters to at most a few meters slip (Cruikshank et al., 1991b; Zhao and Johnson, 1992); whereas we describe the evolution of fault architecture related to slip amount over a range of four orders of magnitude (centimeters to hundreds of meters). We document the evolution of fault zone architecture through detailed outcrop mapping of faults with progressively greater net slip. This provides insight into the macroscopic deformation mechanisms by allowing direct observation of various stages in fault evolution, as preserved in outcrop, related to the amount of accrued slip. We derive conceptual models of fault zone growth based on the outcrop observations and aided by knowledge of initial conditions (zones of joints with various configurations) and boundary conditions (deformation history related to regional orogenic events and the sense and amount of shearing). The scale of deformation that we address is typically of interest for aquifer and reservoir characterization where knowledge of the fault failure process and architecture is relevant but is difficult to obtain.

2. Geologic setting

Field examples of faults developed from joint zones in sandstone are found in the Northern Muddy Mountain range of southeastern Nevada, USA. The faults are in the Jurassic age Aztec Sandstone, which outcrops extensively in the Valley of Fire State Park, located about 60 km northeast of the city of Las Vegas (Fig. 1). The Aztec Sandstone is an eolian deposit estimated to be between 1 and 2 km thick in the study area (Bohannon, 1977, 1979; Marzolf, 1983). Principal bedding surfaces are formed by dune boundaries with spacing that varies from 1 to more than 10 m (Marzolf, 1983). Many of the dunes contain cross-beds with a wide range of orientations. The sandstone is poorly cemented and relatively homogeneous except for occasional clay/silt interdune deposits, which are discontinuous and of limited areal extent. Average porosities range from approximately 18 to 24%.

The rocks in the Valley of Fire park were deformed during Sevier age contraction due to overthrusting by approximately 2–5 km of silici-clastic rocks (Bohannon, 1979, 1983; Carpenter and Carpenter, 1994). Since the Late Tertiary the area has undergone high angle normal and strike-slip faulting, inferred to result from Basin and Range extension, probably in Oligocene–Miocene time, though possibly as recent as Pliocene (Longwell, 1960; Anderson, 1973; Bohannon, 1983). The high angle faults are the focus of this study.

There are two dominant steeply dipping fault sets present in the park; one is N-trending and offsets the shallowly dipping bedding in an apparent left-lateral sense; the other is NW-trending and has apparent right-lateral offsets (Fig. 2). Each set of faults contains examples of predominantly normal and predominantly lateral slip and are mutually cross-cutting, though in parts of the central Valley of Fire the N-trending faults postdate the NW set. In many instances neighboring faults that may intersect have contrasting pure dip-slip and pure strike-slip slickenlines, respectively. In so far as the most recent motions are essentially contemporaneous, the contrasts in slip sense suggest that these faults probably do not form a simple conjugate system. The kinematics are consistent with scenarios of slip partitioning within an interacting network of faults documented in other parts of the basin and range (Oldow, 1992) and in other locations on a tectonic scale (Jackson, 1993).

Outcrop scale structural features include: isolated joints, smaller scale faults with millimeters to centimeters of slip, which are deformation bands, sheared joints, and slipped bedding planes, and larger scale high angle faults with 10's of centimeters to meters of slip that feature multiple slip surfaces, joints associated with shearing, and fault rock development. There are at least two generations of deformation bands; thick deformation bands (1–2 cm) predate thin bands (1–2 mm) wherever both are present in an outcrop. Hill (1989) has tentatively linked the thin deformation bands to Sevier age contraction. Regional jointing postdates deformation band formation. Shearing along these regional joints and along bedding planes produces a younger generation of joints that form either as splay fractures to individual sheared joints or as arrays of fractures at step-overs between faults.

3. Methodology

The high fault density within the Valley of Fire State Park results in intersecting and anastamosing fault zones, which effectively prevents studying a single isolated fault along its entire length. Instead, a conceptual model of fault zone evolution is developed through compilation of outcrop maps of portions of faults with increasing net slip magnitudes. This compilation is then used as a proxy for

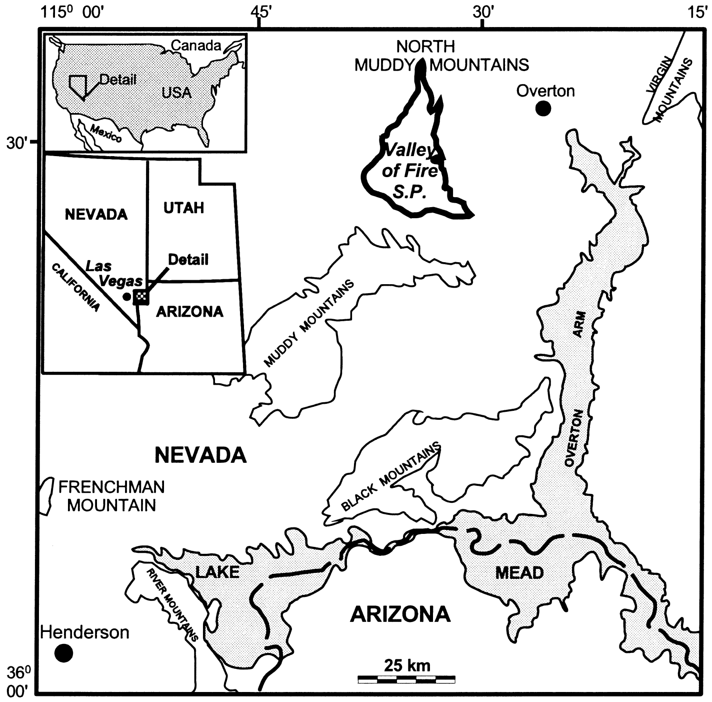


Fig. 1. The location of the study area, Valley of Fire State Park, southern Nevada, USA.

evolution of an idealized fault with increasing slip. The locations of mapped faults shown in later figures are noted in Fig. 2.

We use kinematic indicators (i.e. slickenlines), piercing point solutions, and the orientation of secondary structures within the fault to determine net slip. Some of the faults contain contradictory slip indicators. In this sub-population, slickenline orientations from primary slip surfaces lie at a high angle (40°–90° rake) while piercing point solutions show low angle (0°–14° rake) slip vectors. The orientation of secondary structures produced by shearing within these faults is consistent with the piercing point derived slip vectors. These relationships suggest that the slickenlines represent either recent minor events, or were formed in a locally heterogeneous stress field associated with individual slip events along a patch of a fault (Pollard et al., 1993), or interaction among neighboring faults as proposed by Cashman and Ellis (1994).

The detailed fault maps used to document fault zone evolution are produced in the field by mapping onto high resolution photographs taken from a low altitude balloon. The photographs are digitally compiled and orthorectified using ground control points to remove distortions produced by the camera lens and topographic relief. The resulting fault maps are nominally accurate to sub-centimeter scale.

4. Joint zone characteristics

Joint zones in the Aztec sandstone occur as clusters of closely spaced planar opening mode fractures. The geometry of joints in a zone ranges from distinctly en échelon to nearly completely overlapping sub-parallel joint arrangements (Fig. 3). The en échelon geometry occurs as right-stepping or left-stepping parallel joints with small overlaps. The sub-parallel arrangements show a continuum of variation in spacing and overlap of joints within a zone, though the joints tend to have a consistent co-planar orientation, similar to joint zones in other locations (Hodgson, 1961; Dyer, 1983; Laubach, 1991, 1992; Cruikshank and Aydin, 1995).

Many of the joint zones that consist of sub-parallel joints with large overlaps typically originate in the Valley of Fire as splay fracture arrays emanating from slipped bedding planes or larger scale faults. Joint clusters formed by this process in the Navajo Sandstone in Utah have been documented by others (Cruikshank and Aydin, 1994). This mechanism probably does not explain all the different joint zone geometries in the field area. Some proposed causes of joint clustering at other locations include mode I/III joint breakdown, or segmentation, of a parent joint (Pollard et al., 1982; Cruikshank et al., 1991a), variations in stresses around joints during their formation (Du and Aydin, 1991) or during later loading (Olson and Pollard, 1991). Explanations that do not depend upon shearing, such as variations in sub-critical joint propagation velocity (Olson, 1993) and elevation of fracture driving stresses in the near tip region (Dyer, 1983) have been proposed to explain zones of sub-parallel joints with large overlaps.

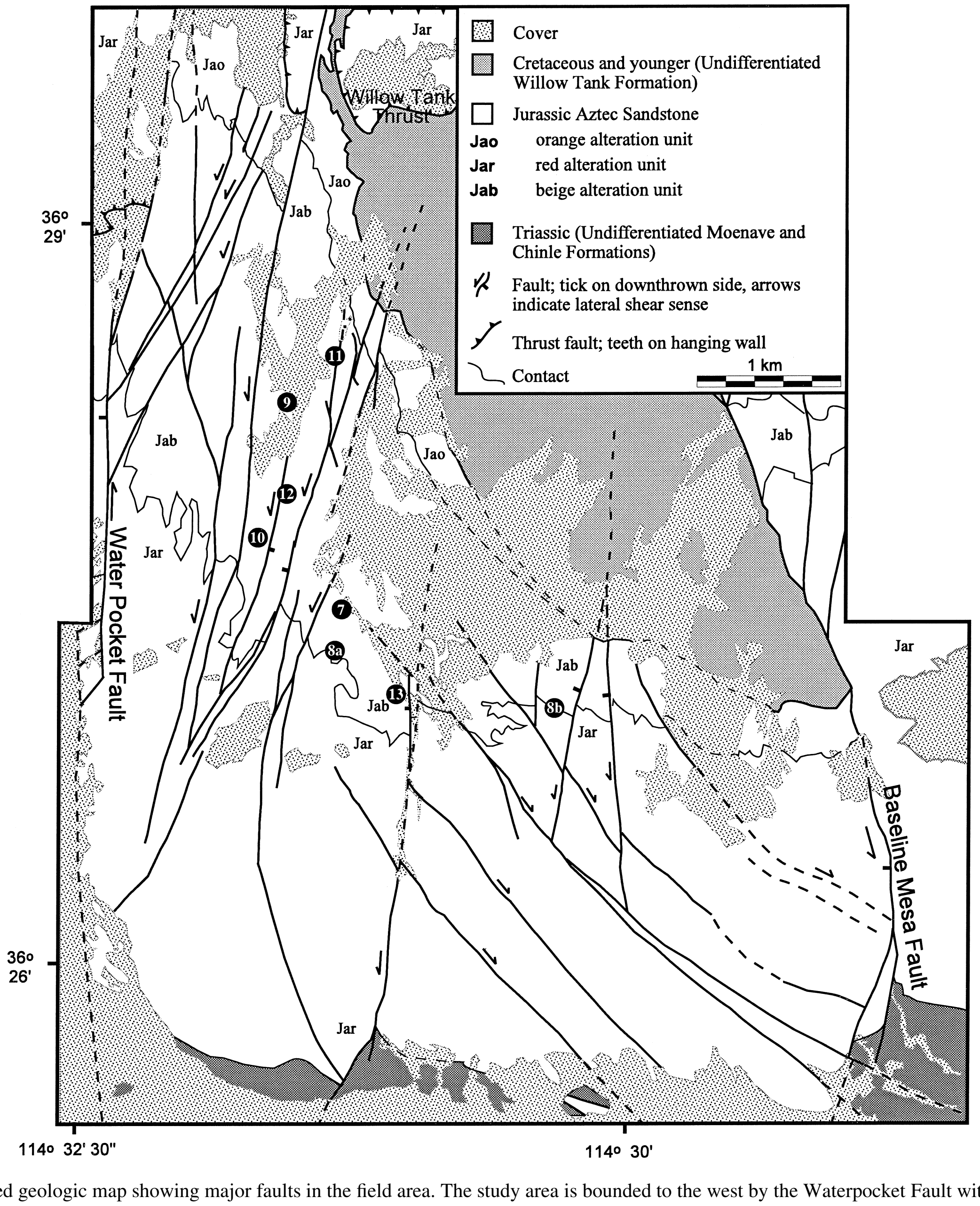


Fig. 2. Generalized geologic map showing major faults in the field area. The study area is bounded to the west by the Waterpocket Fault with ~1 km normal slip and undetermined amount of left lateral slip, and to the east by the Baseline Mesa Fault which has ~800 m of normal slip with inferred minor left lateral slip. Smaller faults occur in two sets; a N-trending set and a NW-trending set which is frequently cut by the N-trending set. Black circles are locations of outcrops shown in later figures.

5. Shearing across joint zones

5.1. Evidence for jointing preceding shearing

In a practical sense a unique interpretation of previous deformation states for a particular fault is impossible. However the simplest explanation is usually preferred and in some cases the original states can be confidently inferred based on compelling indirect evidence, such as fault zone geometry. If faults formed from joint zones, they will inherit the characteristic zone geometry. The many fault zones with small offset observed in the Valley of Fire are remarkably similar to the joint zones with no shear offset. Examples of these early shear stages are described in detail in subsequent sections. This is perhaps the most convincing evidence that the faults developed from joint zones. In rare instances, small faults are observed to terminate in zones of joints. This is a more direct indication of the deformation state immediately preceding shearing. It is possible that the joint zones and fault zones evolved simultaneously through different mechanisms resulting in similar final geometry. Simultaneous formation of both opening model and shearing model fractures with identical orientations is mechanically inconsistent. The simpler and mechanically

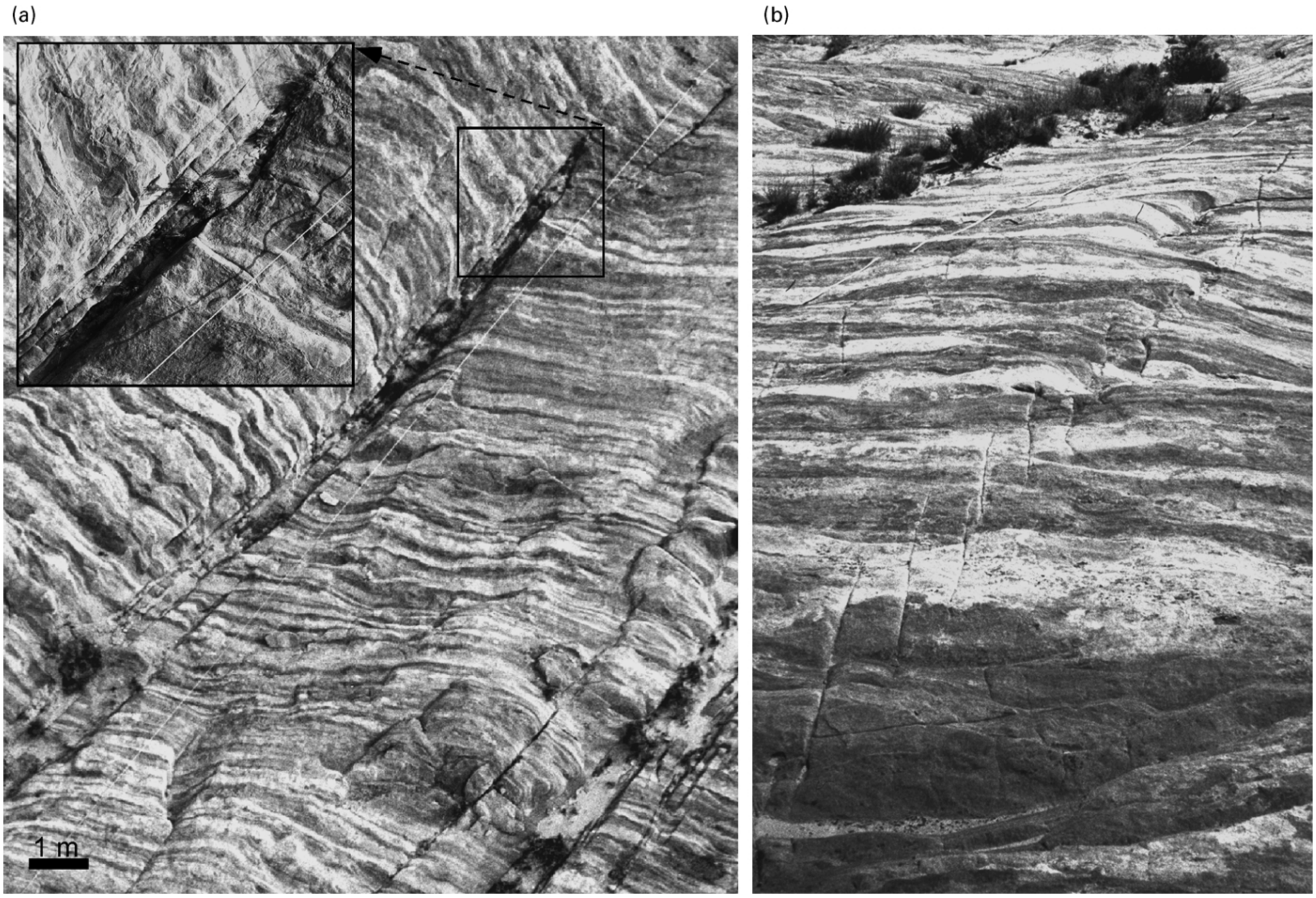


Fig. 3. (a) Low altitude photograph showing zones of sub-parallel joints. The zone near the middle of the photo terminates to the north (inset). Part of another sub-parallel zone can be seen in the lower right corner of the photo. (b) Oblique view of a right stepping en échelon joint zone. Joints are approximately 1 m long.

consistent interpretation is that the faults formed along existing zones of weakness when the rock mass was subjected to shearing subsequent to jointing.

Though rare, some direct evidence within small offset faults shows that the displacement discontinuity began as a joint. Examples include remnants of joint surface features such as plumose structures, arrest lines, or hackle fringe fractures. These characteristic features are occasionally preserved on primary surfaces within faults zones with up to tens of centimeters slip (Fig. 4). Other direct evidence, though more difficult to find, is the presence of carbonate mineralization originally deposited in joints and later sheared. An example is shown in Fig. 5. Microscopic analysis shows the fill is an altered carbonate precipitate with entrained quartz grains. It forms micro-boudins of discrete calcite packets containing shattered crystals indicating that the calcite was present prior to shearing (visible in crossed polars at high magnification); entrained quartz grains are relatively fracture free and form spiral and linear grain trails, indicating they were mixed with the carbonate precipitate during shearing. These features document that shearing occurred after opening and infilling of the fracture. Lack of cataclastic textures within quartz grain assemblages trapped within the sheared precipitated material, specifically a range of quartz grain sizes usually associated with cataclasis, suggests that no shearing occurred prior to infilling. In Fig. 5 gouge formation occurred in parts of the sheared joint where it was not propped open by the carbonate precipitate. Therefore, jointing and subsequent mineralization pre-dates the shear deformation in this sample.

5.2. Fault zone classification

The variability in joint zones can be characterized by the predominant geometry of the component joints. These geometries are right stepping en échelon joints, left-stepping en échelon joints, and sub-parallel joints with large overlaps. Shearing of right-stepping joints in a left sense (RS/LL), or left-stepping joints in a right sense (LS/RL), produces fault zones with contractional configurations. Shearing of left-stepping/left lateral (LS/LL) or right-stepping/right lateral joints (RS/RL) produces dilational configurations (Fig. 6). Shearing of parallel zones results in deformation controlled by individual joint geometries and

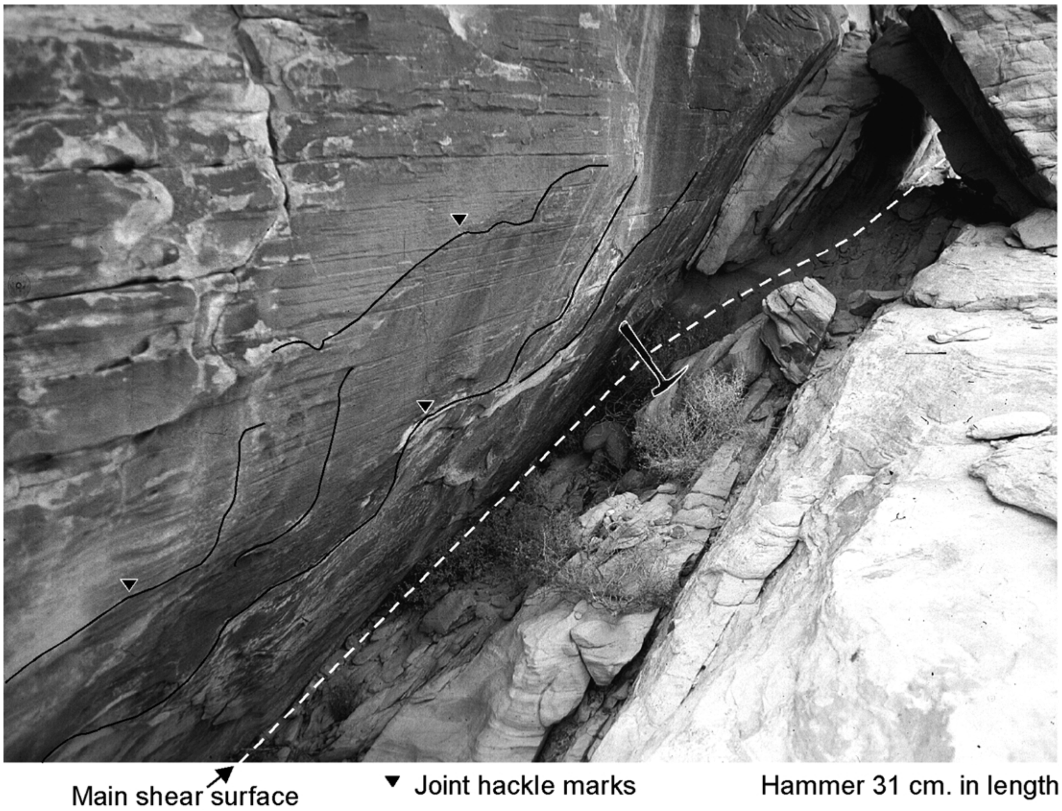


Fig. 4. Joint surface features are preserved along some small magnitude slip faults. The photograph shows remnant fringe hackle located on the margin of a strike slip fault with 0.75 m slip. The majority of slip is accommodated along a marginal sheared joint, with other joints in the zone that lie parallel to the main shear surface being visible in the photograph.

overlap sense, and may promote localized contractional and/or dilational domains.

Larger scale rock volume or principal stress re-orientations can produce shear loading of joints in a zone, though this is not a requirement for sheared joint zones with the contractional configuration. In this case the joints form a zone of discontinuity whose overall orientation is such that the principle stresses responsible for jointing may cause shearing across the zone (Fig. 6). The resultant shear zone is analogous to shear failure in crystalline rock which occurs through interaction of initial opening mode fractures and eventually results in formation of a through-going fault (Peng and Johnson, 1972; Cox and Scholz, 1988a,b; Lockner et al., 1992; Reches and Lockner, 1994). Dilational configurations form a fault with a step/offset sense that requires stress and/or material rotations. This requirement is direct evidence that there was a hiatus between joint zone formation and later shearing. Rotations are necessary to

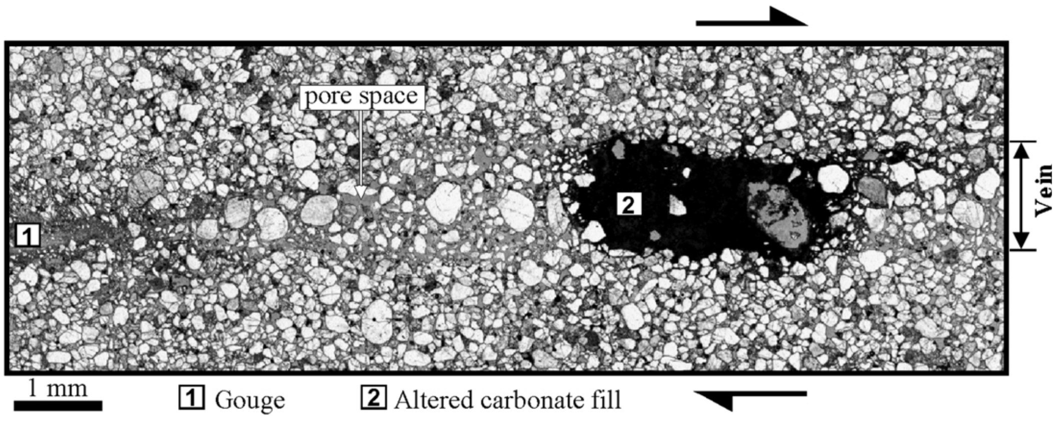


Fig. 5. Plane light photomicrograph of sheared and altered calcite joint fill from a sheared joint with 4 mm right slip. The micrograph shows encapsulated grains of undeformed host rock, sparse small quartz grain size fraction in the sheared material, and sheared fabric within the calcite fill (circular grain trail). Fine-grained gouge is only produced where the sheared joint is not propped open by the joint fill. These features indicate that the structure initiated as an opening mode fracture, was at least partially filled with cement and was later sheared.

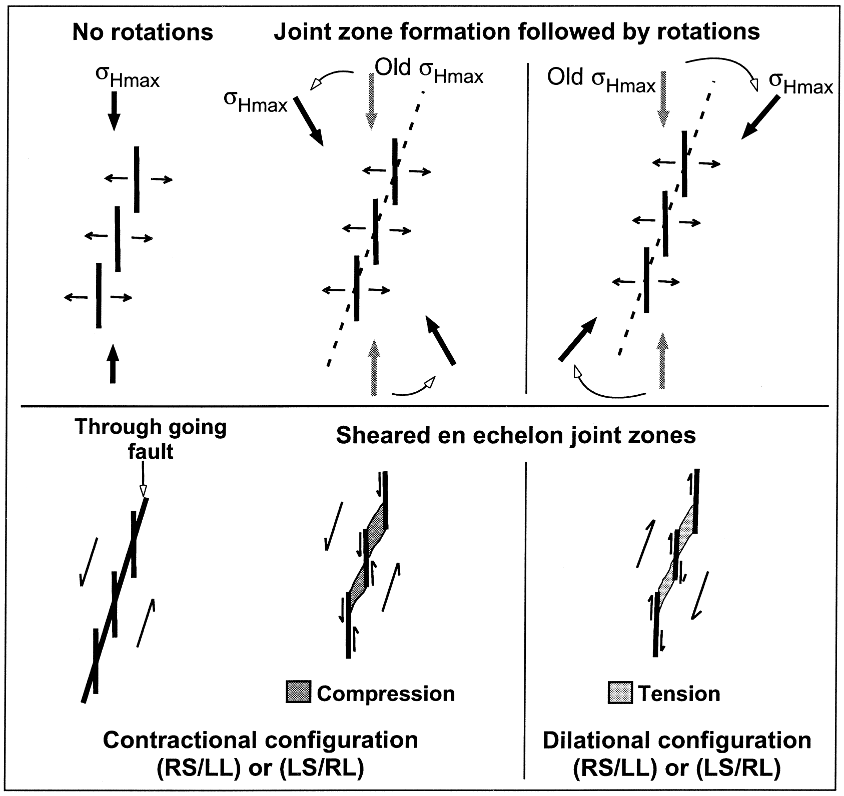


Fig. 6. Comparison of idealized sheared joint zones. Initial joint formation may be followed by later stress and/or material rotations. Shear zones formed with no rotation of principal stresses are analogous to microscopic shear failure in crystalline rocks. Small rotations may produce contractional sheared joint zones where the shear sense and step sense are opposite (right stepping/left lateral or left stepping/right lateral). In these cases joint step/shear sense are identical to the case of no rotations. Rotations in the opposite direction may produce dilational sheared joint zones from en échelon joint zones where the shear sense and step sense are the same (right stepping/right lateral or left stepping/left lateral).

impart shear traction along the joints in sub-parallel joint zones and either rotation sense results in similar fault evolution. Thus the presence of faults with dilational or sub-parallel configurations supports the interpretation that these faults formed from pre-existing joint zones. Examples of faults formed from shearing of en échelon or sub-parallel joint zones, at various strain levels, are described in the following sections.

6. Fault zone evolution through increasing slip

6.1. Fault map elements

The mapping and field observations indicate that the fundamental structural components of the faults formed from joint zones located in the Valley of Fire are joints, sheared joints, fragmentation zones, and slip surfaces. Where possible these components are carefully differentiated in field mapping because their distribution and cross-cutting relationships are crucial for deciphering the faulting process. The structural relationships of the fundamental components provide a framework for characterization of the fault zone architecture developed from different initial conditions and at various strain levels.

Fragments, as used in this study, are mechanically detached portions of rock that are bounded on all visible surfaces by displacement discontinuities (faults or joints). The macroscopic fragmentation occurs simultaneously with formation of a thin frictional wear gouge along the surfaces of individual sheared joints. These small faults are similar to a single thin deformation band, which is a tabular zone of porosity and grain size reduction due to cataclasis (Aydin, 1978). The larger scale mapped faults contain well-defined high strain zones composed of fine-grained fault rock. Thin-sectioned samples indicate this material is a non-cohesive fine-grained cataclastic fault gouge (Sibson, 1977). The thin section gouge corresponds to a readily distinguishable lithology that can be mapped at outcrop scales. Well-developed gouge zones formed in faults with larger slip contain slip surfaces, which are planar discontinuities.

6.2. Small-scale faults

6.2.1. Dilational configuration

The fault zones with slip less than approximately 0.5 m strongly resemble observed joint zones without shear. Fig. 7 shows a fault zone that has approximately 10 mm cumulative apparent right lateral slip across a zone of right-stepping en échelon joints, and is an example of a dilational configuration at the initial stages of shearing. The original joint zone is composed of primary joints, splay fractures result from shearing along primary joints and are formed predominantly near joint terminations. These splay fractures represent a secondary fracture network produced by shearing. In dilational configurations the splays often terminate against adjacent fractures and rarely if ever propagate into the host rock away from the outermost sheared joint in the network. The splay fracture geometry is identical to that reported for faults formed from joints in granites (Segall and Pollard, 1980, 1983; Granier, 1985; Martel, 1990; Burgmann and Pollard, 1994). This characteristic geometry is controlled by localization of tensile stresses in the span separating adjacent primary joints.

The bridging of sheared primary joints by secondary joints forms a distinctive fragmentation style that consists of roughly rhomboidal blocks. These fragment zones are distributed along the trend of the fault zone. Where shear strains are relatively small, as in the fault zone in Fig. 7, the discrete fragment zones (shaded regions in Fig. 7) are confined to regions near the tips of individual sheared joints or along the central portion of the fault zone.

6.2.2. Contractional configurations

Contractional configurations differ from the dilational case in two important ways. First, in these sheared joint zones, many of the splay fractures produced from shearing of primary joints propagate into the host rock, away from the joint zone margins. These fractures form a network in the fault zone periphery. Second, a larger proportion of earlier formed splay fractures are sheared, which generally results in another generation of splays and an increase in fracture density and fragmentation.

Fig. 8a shows an en échelon joint array with contractional steps (RS/LL) at initial stages of slip (0.24 m net oblique slip). The map shows a portion of the fault that is exposed along a nearly horizontal surface. The original right stepping geometry of the primary joints is readily apparent. Secondary fractures terminate on primary sheared joints at angles characteristic of splay fractures and some of these fractures remain unsheared, indicating their origin as opening mode splays. The splays propagate both between primary sheared joints and outwards from the original joint zone into pristine rock adjacent to the fault zone. Within the span between primary sheared joints some splay fractures have themselves sheared (in a right sense), producing a second generation of splay fractures. The marker bed shown in Fig. 8a is offset in a right sense by sheared splay fractures, and left sense by shearing along the primary joints that form

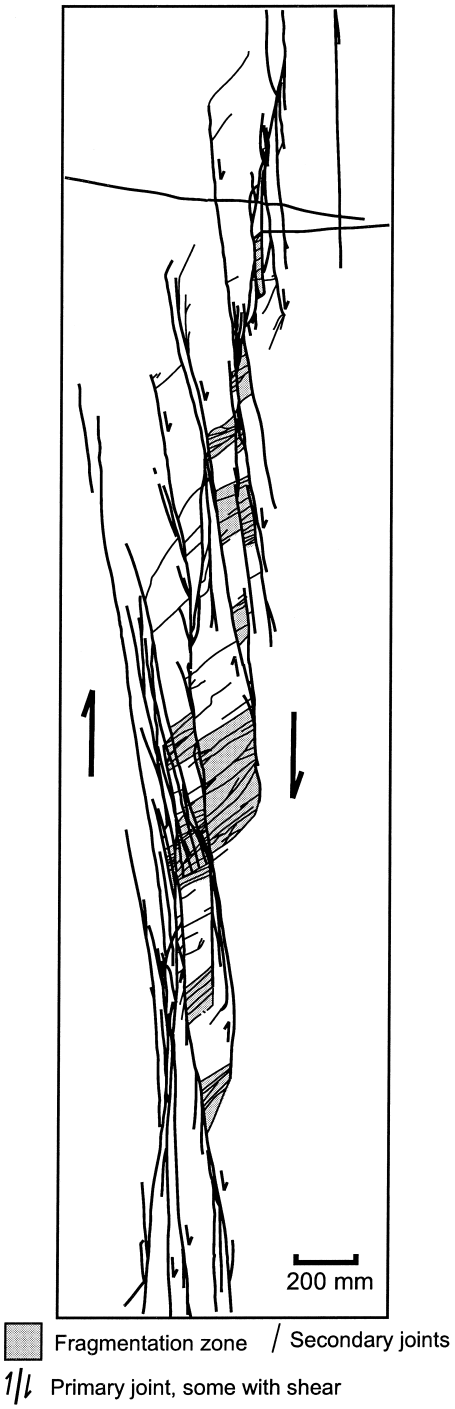
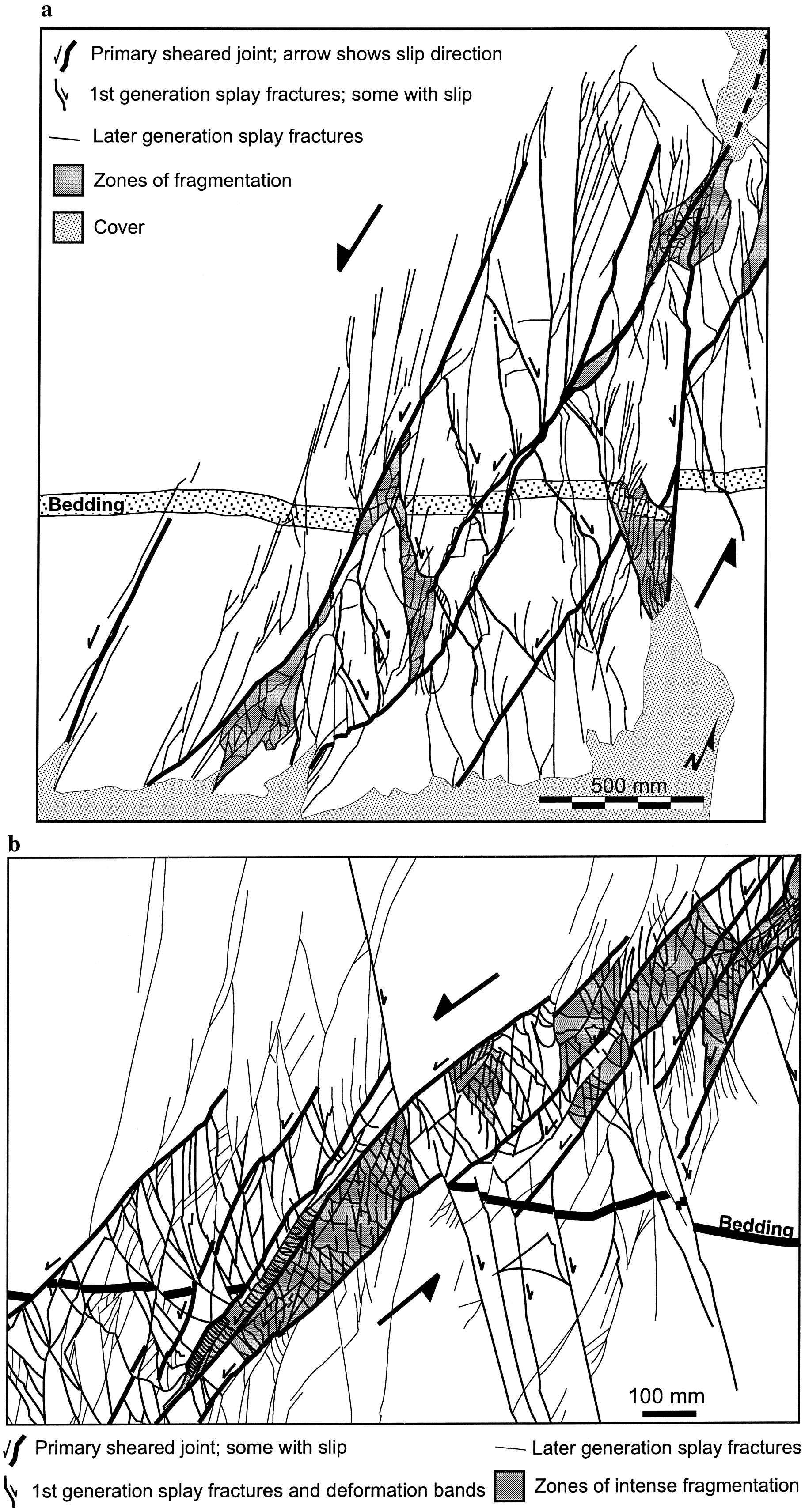


Fig. 7. A small fault (~ 1 cm slip) formed from right-stepping joints which have been sheared in a right lateral sense. The fault map shows the initial breakdown of rock spans between adjacent sheared joints by inward directed splay fractures that result from tensile failure.

Fig. 8. (a) A fault with 24 cm left slip on a right stepping zone of sheared joints. Shaded regions are zones of intense fragmentation that occur at sheared joint intersections, between adjacent sheared joints, and at irregularities in sheared joint traces. (b) Cross-section map of a normal fault with 75 cm of slip. The fault zone formed from shear along a right-stepping en échelon joint zone sheared in a top-to-left (normal) sense. Numerous splay fractures project outwards into the fault margins while deformation bands and sheared splay fractures form between adjacent sheared joints. Several splay fractures in the fault periphery have sheared and produced a second generation of joints.


a
Primary sheared joint; arrow shows slip direction
1st generation splay fractures; some with slip
Later generation splay fractures
Zones of fragmentation
Cover
Bedding
500 mm
b
Bedding
100 mm
Primary sheared joint; some with slip
Later generation splay fractures
1st generation splay fractures and deformation bands
Zones of intense fragmentation

the original joint zone. The result is a heterogeneous strain distribution within the fault zone resulting from differences in joint orientation, and shear sense. In this figure the overall fault zone is relatively wide, especially when compared with the fault in Fig. 7. The width contrast in this case is the result of differences in inherited joint zone geometry.

In contractional configurations strain localization results in evolution of a fault zone that can be differentiated into two parts; a fragmented zone where the main displacement occurs that forms a central fault core and a peripheral fracture network located outside the margins of the main displacement zone. In Fig. 8a the fragmented core is in the initial stages of formation and consists of fine grained wear gouge developed along individual shear planes plus macro-scale fragmented material that retains its original sedimentary textures. Localized gouge is particularly well developed at irregularities in the sheared joint traces. The normal fault zone with 0.75 m net slip shown in cross-section in Fig. 8b is more clearly differentiated into a central highly fragmented core zone and an associated fracture network. Joints in the periphery are clearly splay fractures related to shearing along individual joints in the original right-stepping joint zone. The zones of fragmentation form an irregular right-stepping en échelon geometry that reflects strain localization at contractional stepovers due to the RS/LL configuration.

6.2.3. Sub-parallel joint overlap

A third fault type, different from en échelon geometries, forms from shearing of zones of joints wherein individual sub-parallel joints overlap for most of their length. Faults formed from this joint zone configuration typically contain both contractional and dilational steps between adjacent sheared joints.

The fault map in Fig. 9 shows a sheared sub-parallel joint zone with 80 mm of right slip with a small normal component. Most slip occurs along the two sheared joint surfaces that form the fault zone margins, though virtually all primary joints in the zone have slipped to some degree. The secondary splay fractures produced by shearing are concentrated around the termination of several sheared joints at the northern end of the fault zone. The splay fracturing is preferentially along one margin and creates a pronounced asymmetry in the fault damage. The locally high fracture density outside the main displacement zone of the fault corresponds to locations where shear fractures within the fault zone terminate near the margins of the fault zone. Fault slip is less than 10 mm near the splay fracture zone, and increases to 80 mm at the offset bedding marker. South of the bedding marker slip is unchanged over the mapped fault extent. The region of highest slip gradient is coincident with the area of highest density of secondary joint formation within the fault core. This is also the region of highest shear strain since the fault zone width is essentially constant while slip increases by a factor of eight. The splay fractures are almost completely confined within the joint zone along the trend of the fault and their density decreases away from the termination zone. Variations in primary joint strike and dip are characteristic of the sub-parallel zones (Fig. 9). The differences in orientation result in low angle conjugate slip surfaces within the fault.

The joint zone grew in the vicinity of another joint zone against which it terminates at a steep angle (visible in the upper left corner of Fig. 9). Similar curvature of single joints due to mechanical interaction with nearby joints has been documented in the field (Dyer, 1983), and experimentally (Thomas and Pollard, 1993). In this case the entire zone appears to have curved in response to variations in stress around the earlier formed joint zone in a geometry consistent with interactions between two solitary joints.

6.2.4. Fragmentation zones

As faults slip increases, better developed and more continuous fragment zones form between adjacent sheared joints. Within these zones there is an increase in the number of fragments and a decrease in fragment size. Cross-cutting fracture relationships suggest that the fragment zones break down by addition of successive splay fractures. A more advanced stage of fragmentation produced through this process is shown in Fig. 10.

The fault in Fig. 10 has 0.65 m right slip along a zone of right stepping joints, forming a dilatant configuration. Tertiary splay fractures formed by shear along secondary joints can be seen within the central portion of the fault. Fragment zones formed between primary sheared joints contain clasts with bounding surfaces that have a geometry consistent with splay fracturing (Fig. 10b). The fragment zones form a discontinuous and anastamosing damaged core; remnant bedding in fragments indicates they rotated independently during shearing. The peripheral fracture network consists of remnants of original joints that are connected by splay fractures resulting from shearing. In this outcrop, faulting of the joint zone results in increased joint density, but the overall width of the damage zone has not increased beyond the perimeter of the primary sheared joints. This condition results from the mechanics of jointing in the dilational configurations where failure is controlled by high tensile stresses concentrated within the damaged core.

6.3. Large-scale faults

Larger slip magnitude faults (>1.0 m) are typically more complex than the smaller scale faults, though they are composed of the same principal structural elements. The original joint zone configurations can often be recognized by characteristic geometrical relationships. These relationships are documented in detailed fault zone maps, and are described below.

6.3.1. Contractional configuration

The fault shown in Fig. 11 has 14 m left-oblique normal net slip, the slip vector rakes approximately 12°. Individual

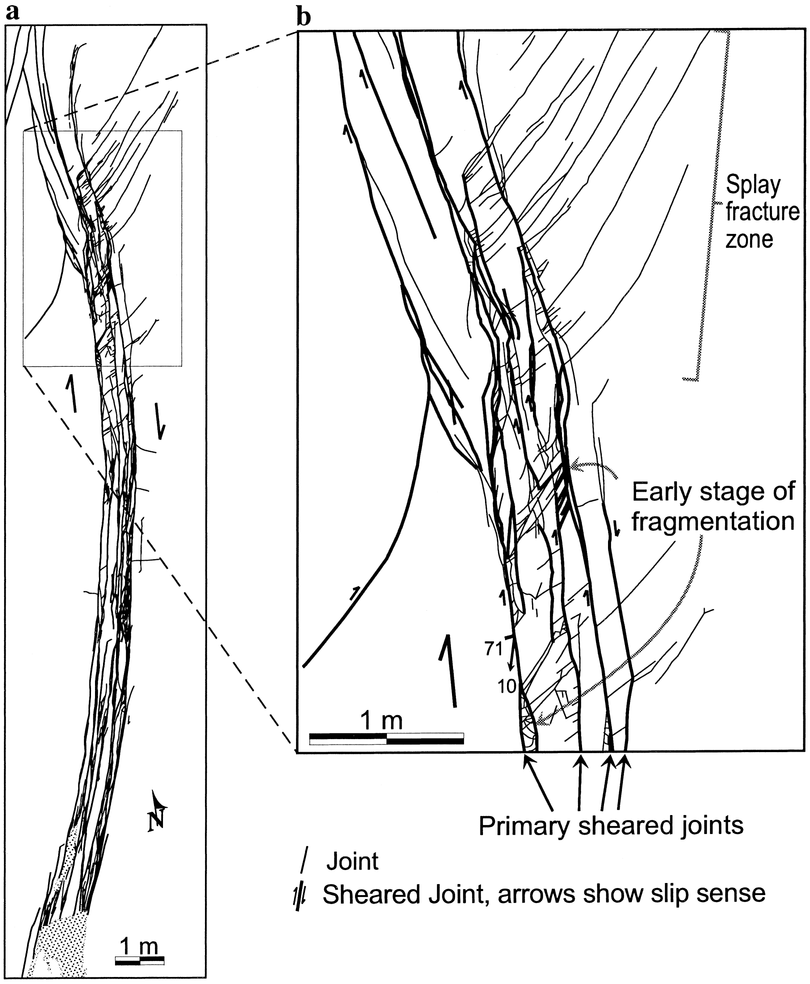


Fig. 9. (a) A right-lateral fault with a sub-parallel configuration with 80 mm of slip. Nearly every original joint in the zone has sheared, but splay fracturing only occurs near the fault tip where individual shear fractures within the fault zone terminate near the margins of the fault zone. Curvature of the fault trace is interpreted to be an inherited feature of the original joint zone, which formed at an angle to an adjacent sheared joint zone. (b) Close-up of the zone of splay fractures produced near the fault tip due to termination of individual component sheared joints in the zone.

highly fragmented zones form gouge zones that are linked forming a central gouge core continuous over the 50 m of exposed fault. The densely fractured portion of the peripheral fracture network extends for 1–2 m from the fault margins. Small left-lateral faults with centimeter scale slip in the periphery are right stepping and are usually truncated by the central gouge zone, although some merge with the major slip surfaces at the gouge boundary. The truncations indicate that these structures either existed prior to the gouge zone formation, or were formed early in the localization history. The angular relationship between these small faults and the through-going gouge zone is consistent with their initiation as an early generation of splay fractures or the remnants of right stepping primary joints.

The fracture hierarchy in the periphery is well developed. It is formed from right stepping joints, sheared in a left sense, producing associated first order splay fractures. Some of the first order splay fractures were later sheared in a right sense and produced a second generation of splays. The angle between splay fractures and the sheared joints along which they form can be used as slip sense indicators, and are consistent with offset bedding markers. The hierarchy and cross-cutting relationships are consistent with this fault forming from an original right stepping joint zone sheared in a left sense (i.e. contractional configuration).

Faults observed throughout the field area exhibit large variations in gouge zone thickness. Key observations imply a genetic relation between progressive increases in fracture density, gouge formation, and fault interactions. In faults with minor slip thinner fragmentation zones occur where primary sheared joints are particularly closely spaced (i.e. central portion of fault in Fig. 7). The fault shown in Fig. 11 has an undulatory gouge core that varies from approximately 1.8 m at the south end to as little as 20 cm (1.5 m south of the inset box in Fig. 11a). The variations occur periodically over distances of 10–20 m depending upon spacing of the shear surfaces which bound the gouge zone. These undulations probably result from spacing variations inherited from the original joint zone. This is clearly the case in smaller slip faults where fragmentation zones

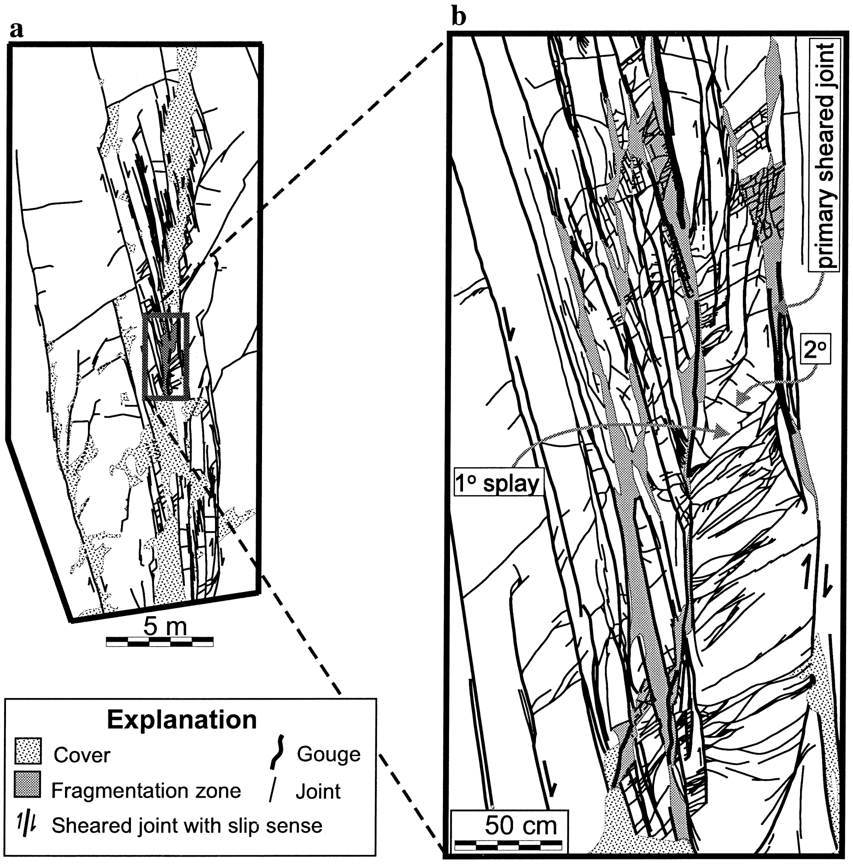


Fig. 10. (a) A fault with 60 cm of right slip along a right stepping en échelon joint array. (b) The core of the fault contains localized fragmentation zones and isolated gouge. The peripheral fracture network consists of the remnants of the original joint zone (primary sheared joints). Splay fractures have formed but are directed inwards and thus do not contribute to widening of the fracture network; however, they do substantially increase fracture connectivity by joining together primary sub-parallel joints (1° are first order splay fractures, 2° are second order splay fractures).

develop earliest between more closely spaced sheared joints and are wider where adjacent sheared joints are spaced further apart (Figs. 7–9). In the fault in Fig. 11 thicker gouge packages correspond to the location of high density fracture zones in the fault periphery and the intersection of small right lateral faults with the main fault. In these regions the dense fracture network defines regions of macro-scale fragmentation. If continued slip results in progressive fragmentation of these regions then the wider zones of highest fracture density represent likely future locations of anomalously wide gouge.

Within the fracture network adjacent to the gouge zone are lenticular packages of sheared joints and deformation bands that are bounded by small right-stepping left-lateral faults (Fig. 11b). Strain localization in the rock bounded by these small faults occurs by progressively increasing density of secondary sheared joints and deformation bands. The deformation bands are thin ($\sim 1-2$ mm) and accommodate slip up to a few centimeters. They are restricted to the highly damaged portions of the fault within and immediately adjacent to the gouge zone, and are localized within compressional steps (Fig. 11). Cross-cutting relationships in the lenticular packages indicate the following deformational sequence. (1) Left slip on early formed joints producing secondary joints (splay fractures). (2) Right slip on the secondary joints. (3) Formation of deformation bands with right slip sense that offsets secondary sheared joints at a low angle. Note that this marks the introduction of a different deformation mechanism into the system. (4) Continued slip on primary sheared joints offsetting the deformation bands and formation of additional deformation bands (in parts of the damaged core, sheared joints and deformation bands are mutually cross-cutting). (5) Formation of new splay fractures at certain regions within the fragmentation zones. An identical sequence of events was observed within all faults formed from contractional sheared joint zone configurations.

Within the fault zone there is a gradational contact between sandstone with discrete deformation structures (bands and sheared joints) and fault gouge. Though the margins of the central gouge core are typically well-defined slip surfaces, the gradational deformation in fragment zones can produce an irregular gouge distribution. Principal slip surfaces exist within the gouge at a low angle to the fault trend. They are arranged in a right stepping fashion; consistent with the original joint zone step sense. Typically the principal surfaces cross from one side of the central damaged core to the other and the majority of slip occurs

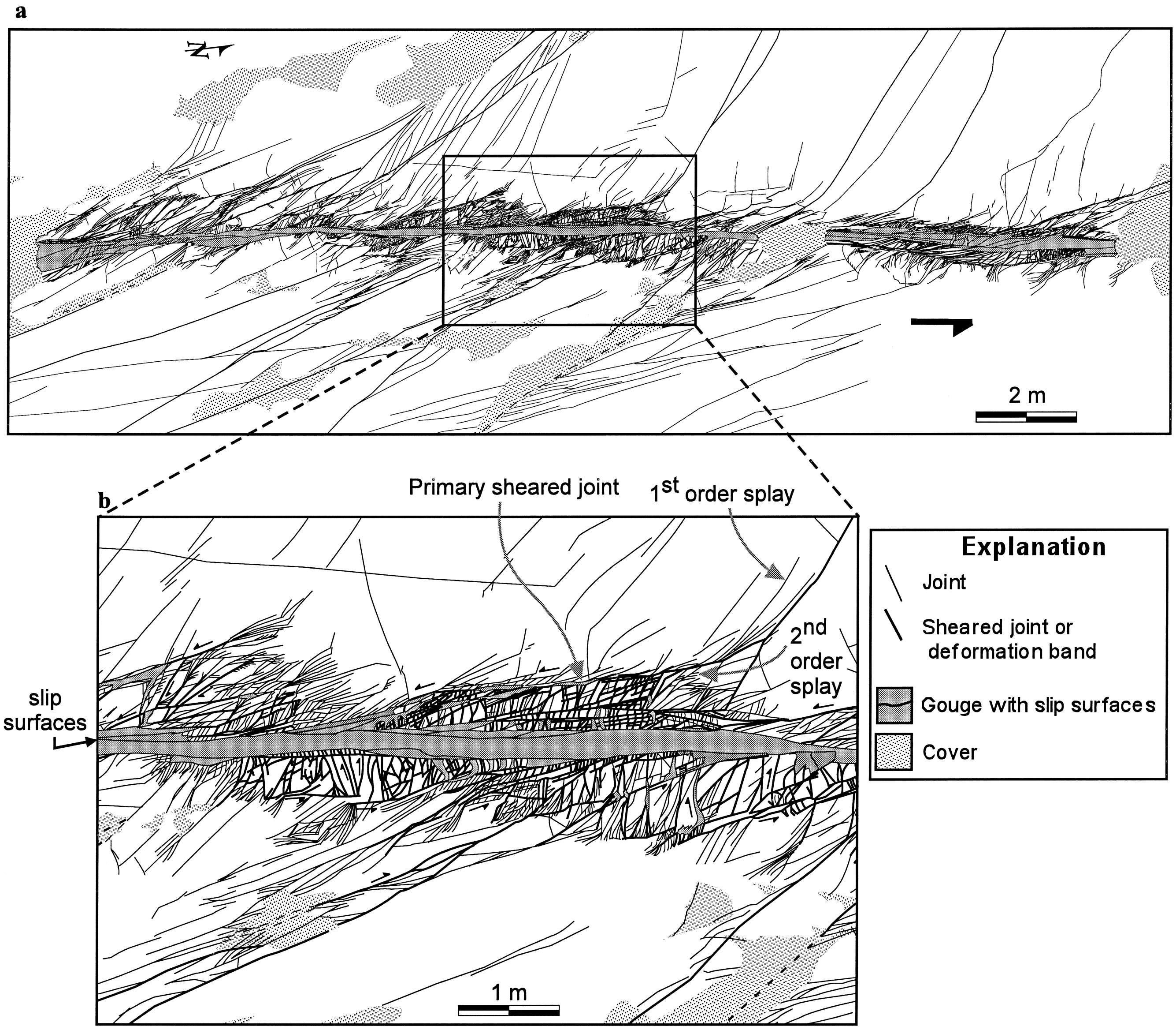


Fig. 11. (a) Left-lateral fault with 14 m net slip. Remnants of original joint zone segments in the fault periphery, orientation and shear sense of subsequent splay fractures, and orientation of en échelon gouge zones indicate this fault initiated in a contractional configuration. The undulatory gouge zone can be explained by original joint step and overlap geometry where fault rock forms first along individual sheared joints and in the overlapping step between closely spaced sheared joints. (b) The peripheral fracture network shows second and third order tail fractures. Remnants of the original sheared joint zones can be seen in the fault margins immediately adjacent to the gouge zone in the detailed map.

preferentially along these surfaces. The key observation is that the central gouge zone is not a localized zone of simple shearing, rather it is an amalgamation of stepping fragmentation zones bounded by slip surfaces.

6.3.2. Dilational and sub-parallel configurations

Larger scale faults formed from dilational and sub-parallel configurations have a much different morphology than the contractional case described above. Their characteristics are illustrated with a left-lateral oblique slip fault with approximately 24 m of net slip (Fig. 12). The fault terminates within 200 m of the mapped extent to the north, but continues southward with little change in net slip. The relatively high slip gradient towards the northern termination is coincident with greatly increased internal fracture density, similar to the smaller sub-parallel example (Fig. 9). Along the western margin 3–4 m of slip occurs across a cluster of sub-parallel sheared joints (Fig. 12b). The net shear strain across the cluster is low ($\gamma \sim 2$–2.7) and results in a heterogeneous fragmentation zone. Most of the slip (approximately 19 m) is accommodated along the eastern fault margin where the best developed gouge occurs (Fig. 12b). This is also the region of highest shear strain ($\gamma \sim 19$–12.6) in the portion of the fault mapped in detail. The remaining slip is partitioned into discrete sheared joints or smaller clusters within the fault zone (Fig. 12b). Overall fault morphology and slip partitioning along the

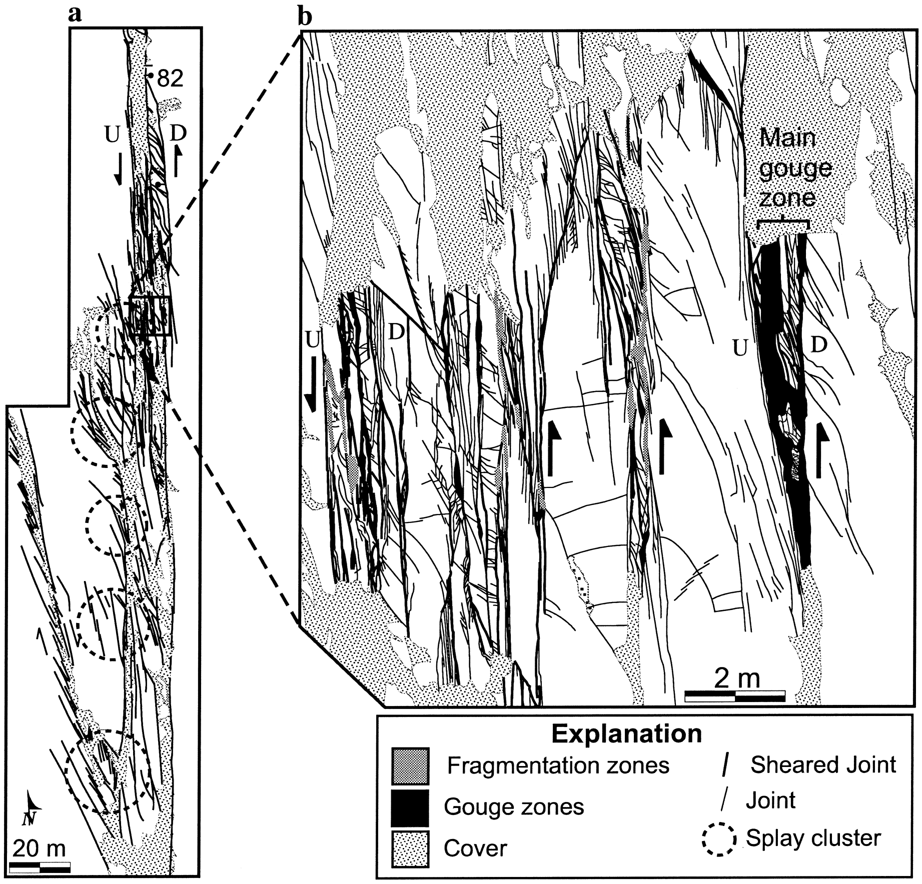


Fig. 12. (a) Meadows Dome Fault, a left oblique normal fault of sub-parallel configuration with approximately 24 m of slip. Areas of locally high fracture density outside the main displacement zone of the fault correspond to locations where sheared joints within the fault zone terminate at the fault margins (dashed circles). The uniform spacing along the strike of the fault zone is controlled by the length and overlap of the primary sheared joints. Increased fracture density within the zone occurs to the north as fault slip dramatically decreases to zero within 200 m of the mapped extent. (b) A well-developed gouge zone is localized between fault parallel surfaces along the east and west margins of the fault zone. Discrete zones of fragmentation associated with single sheared joints, or small clusters of sheared joints, occur within the fault as shown in the detail map.

fault margins is very similar to the small-scale sub-parallel fault zones.

Although this fault accommodates greater overall slip than the previous example it lacks the well-developed peripheral fracture network (Fig. 11). The few fractures formed in the fault periphery are the result of interaction with adjacent faults outside the mapped area, or sparse clusters of splays where sheared joints along the fault margins terminate. Where developed these splay fractures lack the fracture hierarchy seen in the contractional case, which is consistent with the interpretation that the fault originated from a different initial joint zone configuration.

In some faults with 10's of meters offset en échelon slip surfaces are observed within the gouge zones that have the same step sense as the overall fault shear sense (i.e. LS/LL or RS/RL). These are not the expected orientations based on notions of strain localization in simple shear zones. A mechanically consistent explanation is that the slip surfaces are inherited from an original sheared joint zone with dilational configuration. These faults also show only periodic splay fracturing in the periphery, and where present such fracturing can be attributed to interactions with adjacent faults.

6.3.3. Rainbow Vista Fault

Rainbow Vista Fault is the largest slip magnitude fault mapped in detail for this study (Fig. 13). Slickenline measurements along the main slip surfaces indicate it is an oblique normal/left-lateral fault. The slip magnitude is approximately 150 m and is constrained by offset of a planar beige/red oxidation front, which is sub-parallel to bedding in this locality (Fig. 13c). At this stage of slip the contacts between the highly strained gouge zone and the fracture clusters in the fault margins is sharp. A through-going gouge zone varies in width from 1.5 to 5 m; however, the fault is not exposed sufficiently for estimation of the periodicity of the undulations. The gouge is not homogeneous, as it encompasses several lenticular bodies where fragmentation is less well developed. This is most noticeable near the intersections of the larger faults where the gouge zone is widest (Fig. 13a). The original joint zone is obliterated; however, the main slip surfaces within the gouge are right stepping. The fragmentation envelope around the central gouge zone is variable in width and damage density (variable clast size), but generally is well developed compared with faults with less slip. Clasts are bounded by

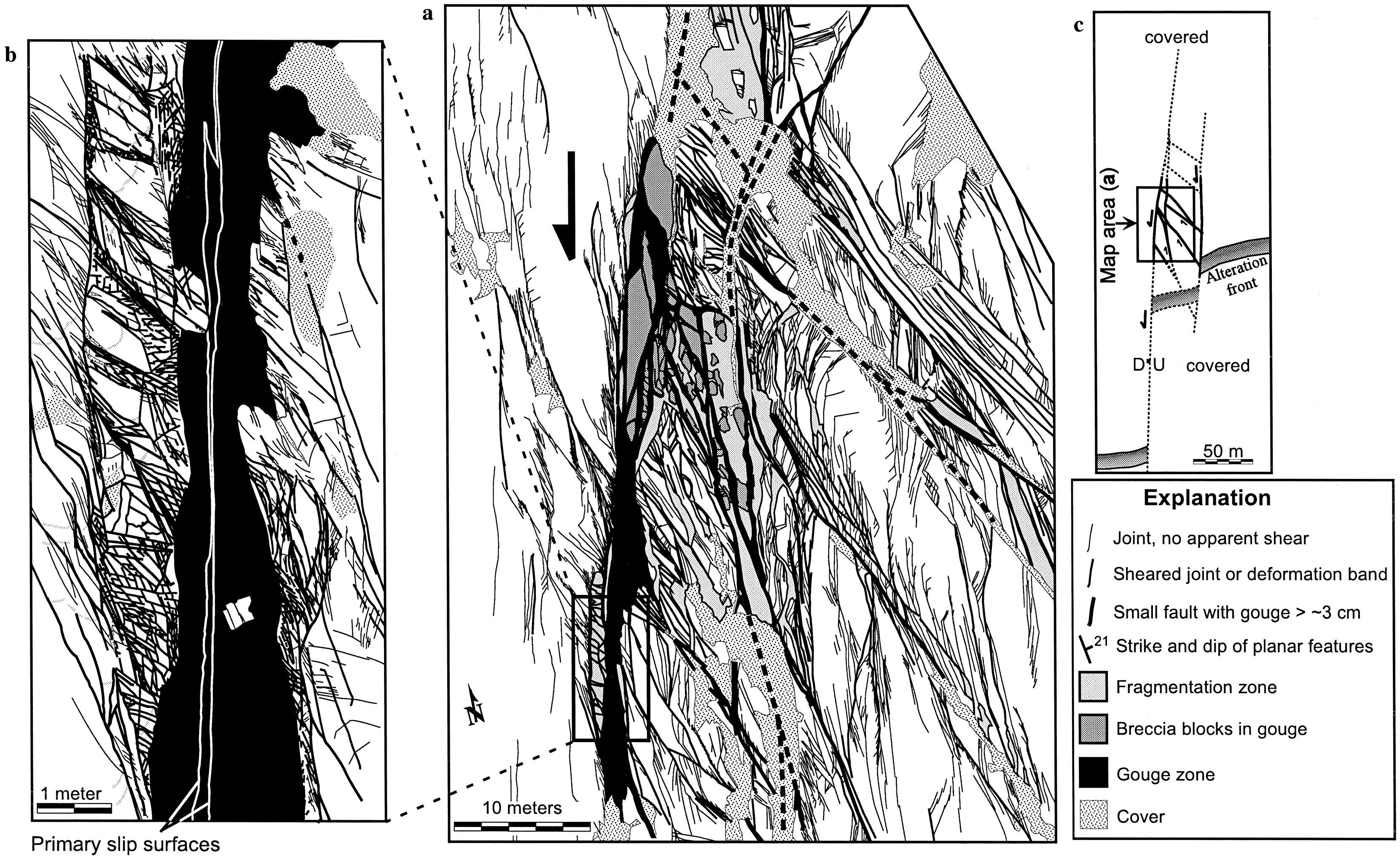


Fig. 13. (a) Rainbow Vista Fault, a left-later/normal oblique fault with 150 m of net slip. The original joints in the array are interpreted to have been right-stepping from the degree of fracturing in the fault periphery and by right stepping slip surfaces in the gouge zone and along the western gouge margin. (b) Detail map showing the development of fragmented material immediately adjacent to the gouge core and the continuous peripheral fracture network. These damage zones consist of joints, sheared joints and deformation bands (undifferentiated on map), and fault rock developed to varying degree. (c) The wide zone of deformation and increased fracture densities to the east are attributed to the location of this outcrop in a relay zone linking the exposed fault to a covered segment in a large right-step.

sheared joints and have rotated up to 40° (counter-clockwise). The clasts may host simple joints and deformation bands that typically do not extend past the host block margins (Fig. 13b). Deformation within blocks closely resembles deformation bands and sheared joints that occur in lenticular packages adjacent to gouge zones in faults with less slip (Fig. 11).

A fracture network formed by successive slip on splay fractures is well developed in the fault periphery and extends for several meters into the host rock. The network is best developed in the east margin of the fault shown in Fig. 13; this asymmetry is due to the presence of an adjacent left lateral fault located about 100 m to the east of this outcrop. The small magnitude right lateral faults connect the two larger faults forming a relay zone within which damage is enhanced (Fig. 13c).

7. Discussion

7.1. Fracture hierarchies

Shearing across joint zones represents a change in deformation from dominantly tensile failure to dominantly shear failure. Joints and sheared joints in this system are formed through stages of shearing starting from slip along primary pre-existing joints, which produces first generation splay fractures at moderate to high angles to the bounding sheared joints. The splays are opening mode features that form along principal planes. Second generation splay fractures are created when the first generation splays are sheared (Fig. 14). This iterative process forms a fracture hierarchy that may continue for multiple generations. Field mapping suggests that the iterations of fracturing are related to the magnitude of shearing along individual faults. Some faults can contain up to three generations of fracturing variably developed along different parts of the faults (Figs. 10–12). This represents a minimum sequence of fracturing in these larger slip faults since earlier formed splays are obliterated by fragmentation processes. Shearing along a single joint resulting in formation of splay fractures in the dilational quadrants at joint terminations is a well-documented phenomenon (Segall and Pollard, 1980, 1983). Splay fractures may also form between two overlapping sheared joints due to stress inhomogeneities that result from oppositely verging slip patches on parallel sheared joints (Martel and Pollard, 1989), and from stress localizations due to changes in traction and slip gradients along parallel sheared joint faces (Erickson and Wiltschko, 1991; Cooke, 1997; Ohlmacher and Aydin, 1997; Willemse and Pollard, 1998). We propose a different mechanism based on stress localization due to geometric irregularities in joint surface topography. Joints commonly have a specific, often complicated, surface morphology consisting of multiple arrest lines and plumose structures, and may contain many subsidiary fractures in the hackle zone (see Pollard and Aydin (1988) for a review). These irregularities may serve as stress concentrators when subjected to shear and splay fractures may initiate at these locations rather than strictly at fault terminations.

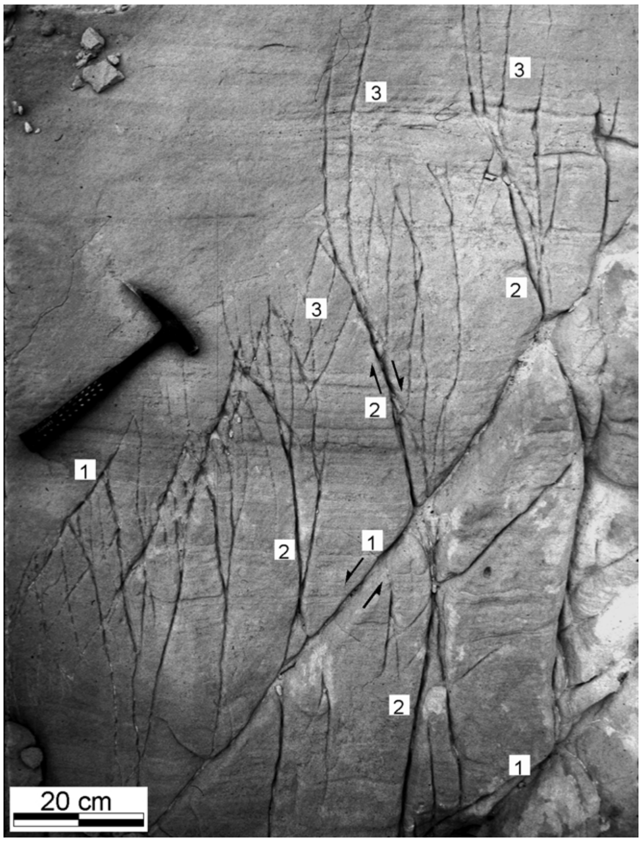


Fig. 14. Outcrop photograph of multiple generations of splay cracks that form a fracture hierarchy adjacent to a set of sheared sub-parallel joints. Slip on joints labeled 1 produced the second set of splay fractures labeled 2 on the photograph. Shearing of the splay fractures resulted in formation of new splay fractures labeled 3 on the photograph. The identical hierarchy is developed to varying degrees in all faults formed from shearing along joint zones.

To resolve shear on joints loading conditions must be different than when they formed. This is most easily accomplished through material or stress-field rotations. Though both stress field and material rotation are possible causes for the successive shearing of multiple generations of splay fractures, material rotations are more likely to produce a self-consistent set of cross-cutting relationships as observed in the faults formed from joint zones in the Valley of Fire. An analogous system occurs in the development of small faults in limestone where secondary structures are solution seams which grow as anti-mode I principal surfaces and are later subjected to shearing which initiates growth of new solution seams (Willemse et al., 1997).

7.2. Fault zone evolution

An idealized fault zone evolution model is presented in Fig. 15. The scale of these models is dictated by the length

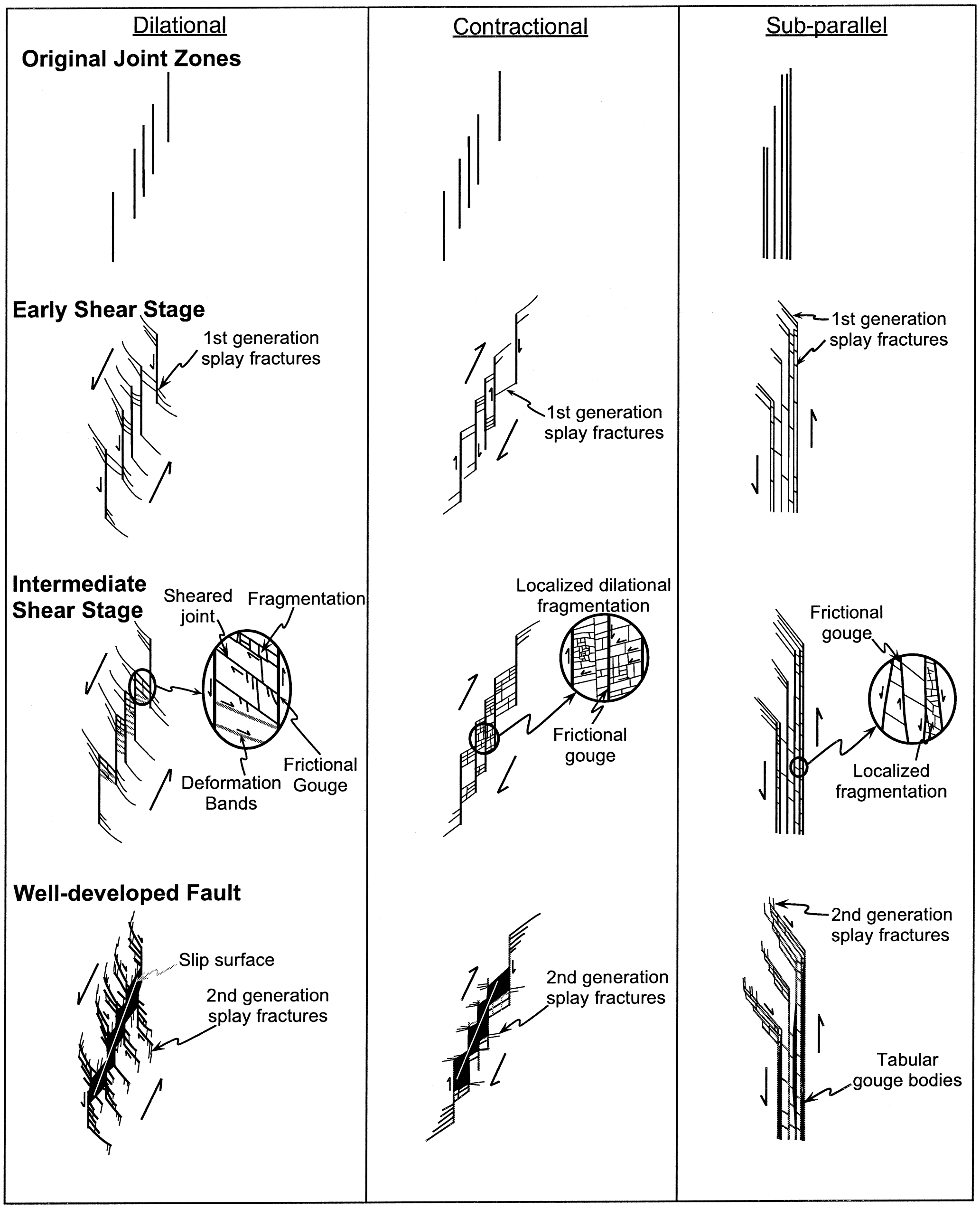


Fig. 15. Schematic fault zone evolution for three types of fault geometry and loading configurations. All fault types evolve a damaged core accompanied by varying degrees of fracturing in the fault periphery as slip increases. The architecture of well-developed faults varies dramatically with different initial conditions, yet all faults consist of the same fundamental structural elements: joints, sheared joints, fragmentation zones, and slip surfaces.

and spacing of the component joints. The models apply to dip-slip faults in cross-section or strike-slip faults in map view. The faults initiate as zones of échelon or sub-parallel joints and are subsequently sheared. The early stage is marked by shearing of primary joints producing splay fractures not present in the initial joint zones. Zones with contractional configurations develop splay fractures in the fault zone periphery. Faults with dilational configurations develop splays that project towards adjacent sheared joints. Shearing across sub-parallel joint zones results in irregular splay fracturing in the fault periphery, usually near terminations of individual sheared joints.

At intermediate shear stages (Fig. 15b and c) the developing fault zones contain one or more well-defined fragmentation zones. The fault core in contractional configurations consists of both sheared joints and deformation bands. These small-scale structures interact to form a complex fragmentation zone with characteristic micro-fault geometries (Fig. 15, inset). Variations in the degree of development of these elements are due to the nature of the loading and material properties of the sandstone.

In dilational configurations shearing induced splay fractures are confined to the regions between existing joints. Localized fragmentation zones bounded by primary sheared joints at the margins are produced through the hierarchical fracturing process. Up to the intermediate stages the fragmentation zones are predominantly dilational features and shear localization occurs primarily along the marginal sheared joints (Fig. 14; intermediate shear stage). The intermediate shear stage of sub-parallel configurations is marked by localized fragmentation in the portion of the fault where primary joints have large overlaps. Local steps between sheared joints may fail in a manner consistent with either dilational or contractional configurations, depending upon the local step sense.

In all sheared joint configurations the magnitude of fault normal stress is expected to influence the rate of damage zone expansion. In particular high mean stress will probably enhance deformation band localization within steps while inhibiting dilational effects such as clast rotation and joint formation.

At slip magnitudes generally between 0.5 and 1.0 m, depending upon original joint zone spacing and step sense, isolated gouge bodies may develop within the fragmentation zones. These bodies are discontinuous on the outcrop scale, though they are connected by microfaults with thin frictional wear gouge. In contractional configurations peripheral fracture density may increase due to formation of higher order splay fractures. Deformation band density typically increases between primary sheared joints with decreasing distance to the fault core. In dilational configurations inward projecting splay fractures intersect sheared joints causing fragmentation that reduces the effective rock strength immediately adjacent to the central fault core. Undulations in the central gouge zone appear to form in part through incorporation of previously fragmented materials. The peripheral fracture network is relatively undeveloped in dilational configurations. In sub-parallel configurations isolated gouge bodies usually occur along the fault zone margins. These gouge zones are typically more tabular than gouge zones within échelon systems that tend to be irregular and anastamosing.

A well-developed fault zone consisting of through-going gouge zones with discrete slip surfaces characterizes late stages of shearing. Faults with contractional configurations have densely fractured damage zone halos consisting of multiple fracture hierarchies. The fault zone can expand outward by exploiting the relatively weaker rock in the fault periphery, which has been pervasively fractured. This results in an undulatory or en échelon gouge zone with segmented slip surfaces. These slip surface and gouge zone irregularities form kinematic asperities that may cause stress concentrations during slip events. Particular splay fractures that emanate outwards from the fault core and/or slip surface terminations may result from stress localizations produced by these rupture barriers. Faults formed from dilational configurations have non- to poorly-developed peripheral fractures and the central gouge zone is relatively narrow. In sub-parallel configurations several gouge zones may form rather than a single central zone, and the peripheral fracture network is irregularly developed, and often asymmetric. In all configurations the principal slip surfaces are located within the gouge zone (well-developed fault; Fig. 15) and may have a subtle en échelon arrangement.

8. Conclusions

We describe the evolution of a new class of faults formed in porous sandstone, which is different from deformation bands (Aydin and Johnson, 1978; Antonellini et al., 1994), and previously documented fault zone growth in granite (Segall and Pollard, 1983; Granier, 1985; Martel and Pollard, 1989) and limestone (Gamond, 1987; Willemse et al., 1997). These faults formed from slip on zones of joints with various configurations and are characterized by the presence of fragmentation and fracturing at every stage of evolution.

The geometry of fault zones formed from pre-existing zones of joints evolves in a predictable fashion, which is the result of basic mechanics of brittle fracture in an otherwise relatively homogenous medium. The fault zones are composed of sheared joints, splay fractures, and fragmentation zones. The accumulation of strain results in hierarchical succession of these structures. This hierarchy is defined by first order splay fracturing produced by shear along initial joint surfaces followed by shear of the first order fractures producing a second order splay joint which in turn may be sheared producing a third fracture, and so on. This process of recurring opening mode fracturing followed by shearing is the basis of the conceptual models proposed here.

Fragmentation initially occurs at discrete loci associated with intersecting fractures, irregular joint geometry, or strain localization by contraction or dilation at step-overs; it is also related to the spacing of original échelon joint segments. Fragment zone growth occurs primarily within sheared joint steps that have been weakened by splay fracturing. Continued localization results in gouge formation the width and continuity of which is dependent upon fault width and the amount of slip (i.e. directly related to shear strain magnitude).

We treat a spectrum of possible sheared joint zone geometries by considering three end-members: en échelon joint zones with contractional configurations, en échelon zones with dilational configurations, and sub-parallel joint zones. Though a simplification of actual joint zone configurations this division allows us to constrain the fault evolution between end members. Inherited joint zone geometry influences fault evolution and some generalizations can be made for each system.

Contractional configurations show a gradual widening of the fault peripheral fracture network, accompanied by increased fracture density, and development of a thicker and laterally continuous gouge zone though large variations in gouge thickness are common. Dilational systems evolve through rapid localization of deformation into a damaged core at the center of the zone. Shear strain is well defined along a relatively narrow gouge zone. The peripheral fracture network is repressed except at later stages where mechanical interaction between adjacent faults may produce a highly fractured relay zone. Sub-parallel systems typically show strain localized within discrete highly fragmented zones oriented parallel to the fault trace. Splay fractures projecting outside the fault margins are sparse and occur episodically related to the length of individual joint segments. Splay fractures within the fault zone show an increase in density with increasing slip gradient.

An understanding of the inter-relationship between damage zone evolution and peripheral fracture growth, under different initial conditions, allows one to interpret incomplete data sets, for example from the subsurface, and to make predictions about fault zone architecture if the process of faulting is known or can be inferred.

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