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Faults with asymmetric damage zones in sandstone, Valley of Fire State Park, southern Nevada

Eric Flodin*, Atilla Aydin

Rock Fracture Project, Department of Geological and Environmental Sciences, Stanford University, Stanford, CA 94305-2115, USA

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Abstract

Models for the evolution of faults formed by shearing along joint zones in Aztec sandstone, Valley of Fire, Nevada predict damage zones either localized within the fault core or symmetrically distributed about the core or a slip surface therein. We expand these models by presenting two examples of faults with asymmetric damage zones from the same field locality. Asymmetric damage is attributed to the inherited geometry of a parent joint with a peripheral joint breakdown fringe. One example is of a fault formed along a parent joint with continuous breakdown fringe. The other example is of a fault formed in part along a parent joint with abrupt breakdown fringe. When compared with the symmetric examples, the damage in the asymmetric cases is minimized due to the presence of an already through-going surface.

Keywords: Asymmetric damage zone; Sheared joint; Slip surface; Faults; Aztec sandstone

1. Introduction

Numerous examples of faults that form along preexisting weaknesses (e.g. joints, veins, bedding surfaces) in rock have been described in granites (e.g. Segall and Pollard, 1983), carbonates (e.g. Willemse et al., 1997), shales (e.g. Engelder et al., 2001), sandstones (e.g. Myers and Aydin, 2004), and layered clastic sequences (e.g. Kim et al., 2001). In this paper, we focus on faults with asymmetric damage zones that formed by shearing along joint zones in sandstone.

Myers and Aydin (2004) describe a hierarchical model for faults that form by shearing along joint zones in sandstone, and propose that initial joint zone configuration bears a strong influence on the final outcome of damage distribution on faults with small to moderate offsets (0.01–150 m). For each initial joint geometry that they describe, fault related damage is more or less symmetrically distributed with respect to a centrally located fault core and associated slip surface (i.e. damage occurs on both sides). We present a companion model to that of Myers and Aydin to explain new observations of asymmetric damage with respect to the fault core and associated slip surfaces along small offset faults. In this paper, we present examples of asymmetric joint breakdown fringe and fault architectures with asymmetric damage zones in the Aztec sandstone, Valley of Fire, Nevada (Fig. 1). We conclude with the presentation of our conceptual model that relates faults with asymmetric damage zones to preexisting joint breakdown geometry. The reader is referred to Myers and Aydin (2004) for a detailed description of the geologic setting and lithology.

2. Field observations

The architecture of faults that form along preexisting joint zones is influenced by the spatial arrangement of the preexisting joints. In order to understand fault zone architectures with asymmetric damage zones, we first examine the breakdown fringe patterns of unsheared joint zones.

* Corresponding author. Now at and correspondence address: ChevronTexaco Exploration and Production Technology Company, 6001 Bollinger Canyon Road, San Ramon, CA 94583, USA. Tel.: +1-925-842-0131; fax: +1-925-842-2061.

E-mail address: eflodin@chevrontexaco.com (E. Flodin).

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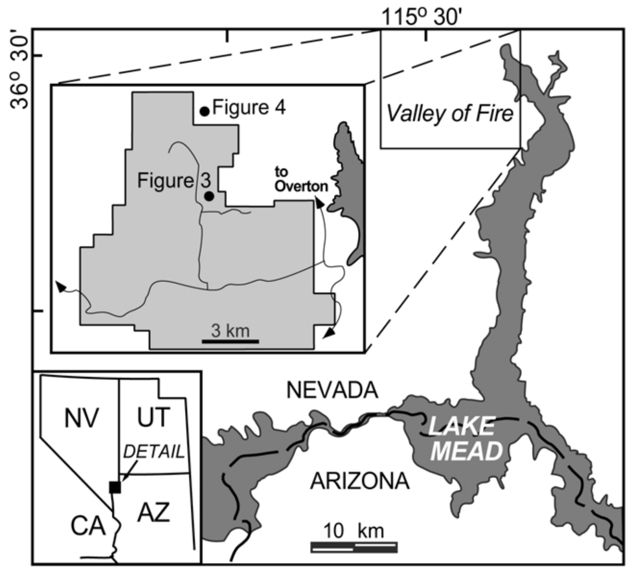


Fig. 1. Map of the study area: Valley of Fire State Park, southern Nevada, USA (after Myers, 1999). Note the approximate locations for Figs. 3 and 4.

2.1. Joints with asymmetric breakdown fringe

Previous studies have described the formation of a breakdown fringe along the perimeter of opening mode (mode I) fractures (Hodgson, 1961; Pollard and Aydin, 1988; Younes and Engelder, 1999) Breakdown fringes are caused either by spatially or temporally varying stress about a mode I fracture (Pollard et al., 1982). Continuous breakdown where the fringe joints share a surface with the parent joint is generally attributed to spatial variations in stress. Abrupt breakdown where the parent and fringe joints do not share a common surface is generally attributed to temporal variations in stress (Pollard and Aydin, 1988; Younes and Engelder, 1999).

We present two different examples of joint breakdown patterns that are asymmetrically distributed with respect to a through-going parent joint (Fig. 2). In both cases, the parent joint surfaces have preserved features diagnostic of opening mode displacement discontinuity (e.g. rib marks and hackle) and lack noticeable shear displacement discontinuity. The first (Fig. 2a and b) is an example of continuous breakdown. Each joint in the breakdown zone forms a continuous surface with the parent joint below. In map view (i.e. looking down on the fracture trace in a horizontal outcrop), these fringe joints show a slightly curving geometry in a direction concave away from the parent joint. Measured away from the parent joint, the fringe joints form angles between 8 and 13° with respect to the parent joint. The second example (Fig. 2c and d) is that of abrupt breakdown: no continuous surface exists between the parent joint and the fringe joints. In this example, angles between the fringe joints and the parent joint range from 33 to 37°. Most of the fringe joints are confined to one side of the parent joint. However, some of the fringe joints locally extend to the other side of the parent joint tipline (arrow, Fig. 2c and d). In outcrop, the abrupt breakdown joints generally have a straight trace (Fig. 2c).

2.2. Faults with asymmetric damage zones

We present two field examples of faults with asymmetric damage zones. The first example shows a slip surface with secondary fractures that have a smooth, continuous connection to the through-going slip surface (Fig. 3). The second example is a slip surface with a set of secondary fractures that have a sharp, discontinuous connection to the through-going slip surface (Fig. 4).

2.2.1. Slip surface with curved peripheral fractures

The fault shown in Fig. 3 shows a maximum left-lateral offset of approximately 1 cm. Two general observations are made about this fault. First, damage is localized along one side of the fault. Second, compared with faults formed along en échelon joint zones with similar offset magnitude (Myers and Aydin, 2004), damage is less intense. Slip along this fault is localized along a slightly undulating and through-going slip surface. At first glance, all of the joints emanating from the through-going slip surface might be interpreted as splay fractures formed in response to shearing across a planar discontinuity (e.g. Segall and Pollard, 1983). However upon closer examination of the fracture intersections, many of the abutting relationships are atypical of those normally found between splay fractures and parent sheared joints (e.g. inset a, Fig. 3) (e.g. Martel and Boger, 1998). Splay fractures are generally found to truncate against the parent sheared surface (e.g. inset b, Fig. 3), whereas here most of the peripheral fractures are continuous with the through-going fractures. Away from the through-going slip surface, the peripheral joints follow a curved trace. Close to the slip surface, the average angle between the parent sheared joint and peripheral joints is 9° (±3°), while the angle between the last increment of the peripheral joint tip and that of the parent joint is 21° (±7°).

2.2.2. Slip surface with primarily straight peripheral fractures

The fault shown in Fig. 4 has a maximum apparent left-lateral offset (with a minor normal-slip component) of 85 cm that occurs near the center of the fault and decreases approximately linearly toward both ends. When viewed along its entire length, this fault shows considerable variability with respect to peripheral damage. The northern half of the fault (north of the midsection of inset b, Fig. 4a) is characterized by approximately symmetrically distributed peripheral fractures about a complicated network of subparallel and branching slip surfaces. The peripheral joints in this section of the fault form acute angles with slip surfaces that open in a direction opposite to the slip sense. These peripheral joints might also be viewed as right-stepping. These observations contrast with observations of the southern portion of the fault where the peripheral joints are localized

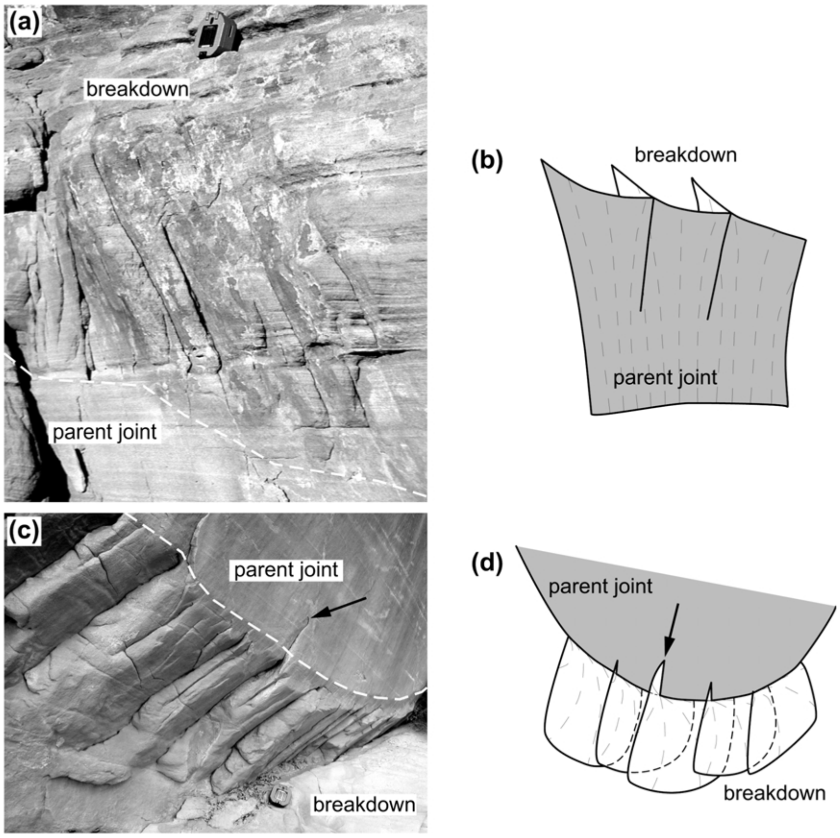


Fig. 2. Asymmetric joint breakdown fringe in sandstone. (a) Field example of continuous joint breakdown fringe. (b) Schematic drawing of continuous joint breakdown. (c) Field example of abrupt joint breakdown fringe. (d) Schematic drawing of abrupt joint breakdown. In (a) and (c), the white dashed line demarcates the approximate boundary between the parent joint and the breakdown zone. A Brunton compass is shown in both pictures for scale.

along the eastern periphery of the fault with respect to the through-going slip surface (Fig. 4c–e). The peripheral joints in the southern section form an acute angle with the through-going slip surface, which opens in the same direction as the slip sense. These peripheral joints are also viewed as left-stepping. The angle of intersection between the left-stepping joints and the through-going slip surface is 33° (±9°), while for the right-stepping joints the angle is 25° (±7°).

Three fracture sets are identified in the mapped area shown in Fig. 4 (Fig. 5). The mean dip of all measured fractures (joints, sheared joints, and slip surfaces) is 78° (±5°). Most Set 1 fractures are joints that, based on crosscutting relationships, appear to be some of the oldest features of the fault. Some Set 1 joints are sheared (filled circles, Fig. 5) as evidenced by the recognition of both offset markers and attendant splay fractures. Set 2 fractures include joints, sheared joints, and through-going slip surfaces. Joints and sheared joints in Set 2 orientations are generally confined to the fault core. Set 3 fractures consist entirely of joints and appear to be some of the youngest features of the fault zone based on crosscutting relationships.

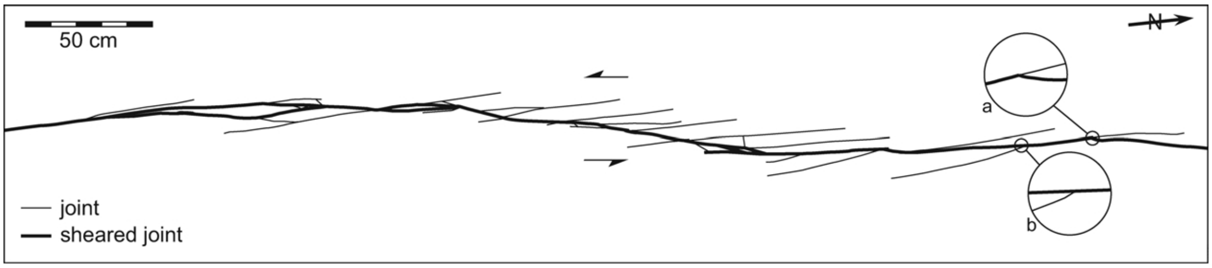
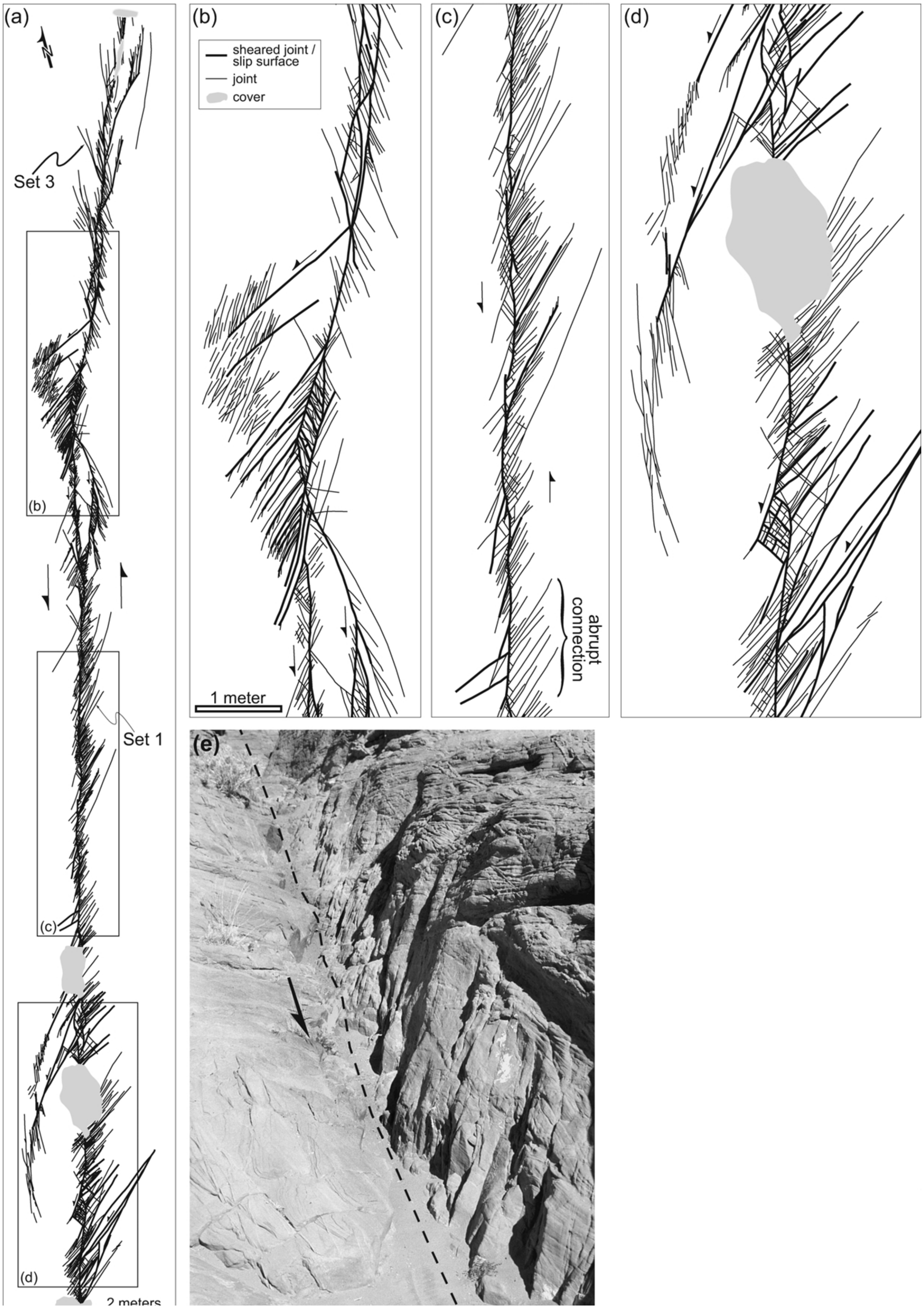


Fig. 3. Strike-slip fault with 1 cm maximum left-lateral offset that is characterized by curved secondary fractures localized primarily on one side of a through-going slip surface. (a) Detail of the intersection between a peripheral fracture and the through-going slip surface. (b) Detail of the intersection between a peripheral fracture and the through-going slip surface.


(a)
Set 3
(b)
(c)
Set 1
(d)
2 meters
(b)
sheared joint / slip surface
joint
cover
1 meter
(c)
abrupt connection
(d)
(e)

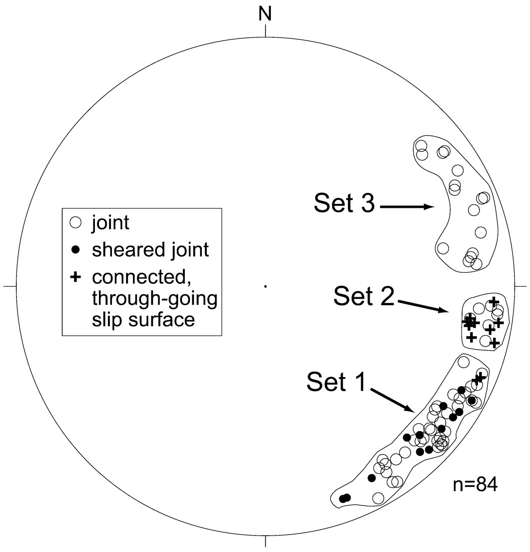


Fig. 5. Equal-area lower hemisphere stereonet plot of a representative number of fractures from the map shown in Fig. 4. Three separate groups of joints are identified. Set 1: a preexisting joint breakdown set that has a left-stepping configuration. Set 2: fault related joints localized near the fault core and between closely spaced primary joints. Set 3: fault related splay fractures in the fault periphery associated with left-lateral slip that have a right-stepping configuration. Sheared fracture orientations (sheared joints and slip surfaces) coincide only with Set 1 and 2 orientations.

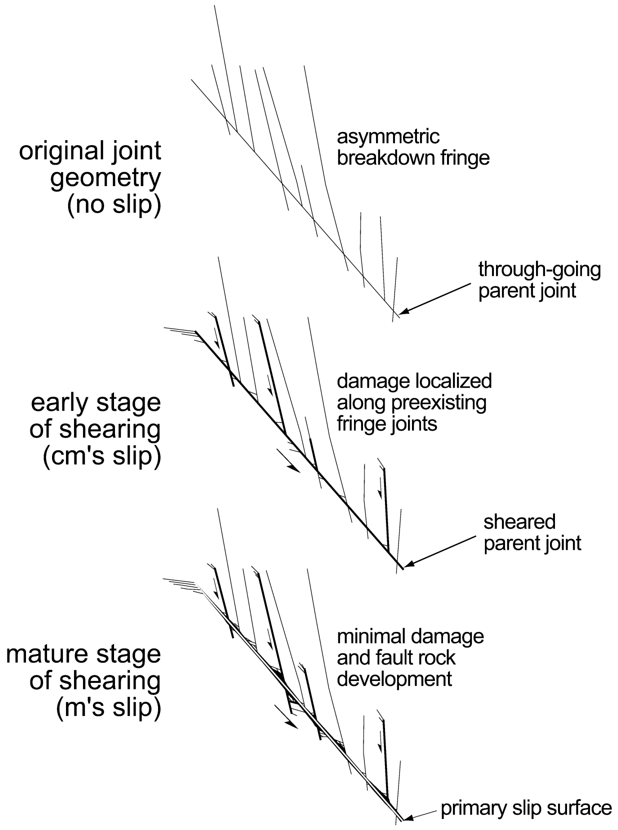


Fig. 6. Conceptual model for the development of an asymmetric damage zone about a fault formed along preexisting joints with breakdown fringe (format after Myers and Aydin, 2004). The conceptual model we show is of a left-stepping asymmetric abrupt breakdown fringe subjected to left-lateral shear, but a right-stepping breakdown fringe subjected to left-lateral shear is also possible.

3. Conceptual model

We present a conceptual model (Fig. 6) that is complementary to models presented by Myers and Aydin (2004) for fault zone development along preexisting joints. In our model, the breakdown geometry of the original joint plays an important role in architectural evolution of the fault. In contrast to the previous models, damage is preferentially localized to one side of the through-going slip surface where off-fault (damage zone) strain is accommodated along preexisting weaknesses in the joint breakdown fringe zone.

We propose that the fault shown in Fig. 3 formed along a joint zone with dominantly asymmetric continuous breakdown fringe. The overall configuration and angular relationships between the through-going and peripheral fractures are nearly identical between the unsheared and sheared examples (Figs. 2a and 3, respectively). However, the terminal orientations of the peripheral fractures in the sheared example are at a higher angle of intersection compared with the unsheared case ($\sim 21°$ compared with $\sim 10°$).

The fault shown in Fig. 4 is proposed to have formed at least in part (Fig. 4c and d) along a joint zone with an abrupt breakdown fringe. Peripheral fractures along the fault shown in Fig. 4 have two general orientations with respect to the through-going slip surface. We attribute the formation of the right-stepping peripheral joints along this fault to be splay fractures related to left-lateral shear strain accommodation where the apex of the acute angle between the splay fractures and the parent sliding fracture points in the direction of slip (Engelder, 1987; Cruikshank et al., 1991). However, the left-stepping joints along this fault do not have the typical angular relationship found between splay fractures and sheared parent fractures with a left-lateral

Fig. 4. Strike-slip fault with 85 cm maximum left-lateral offset. (a) Field map of a left-lateral fault showing varying styles of damage (note the map legend in detail (b)). Along the southern portion of the fault (details (c) and (d)), most of the damage is localized on the eastern margin of the fault. An example area of peripheral fractures that have abrupt connections with the parent fracture is highlighted by the curly-bracket in detail (c). Around the middle of the fault (detail (b)), the slip is divided between two slip surfaces separated by undeformed host rock. North of this section (detail (b)), the general trend of the fault changes direction by 10°. This portion of the fault is characterized by a more or less symmetric distribution of damage. (e) Field photo of the area mapped in part (c) of this figure (view north). Note the greater abundance of structures on the right side of the main fault trace. Most of the shear offset has been accommodated along a primary slip surface on the left side of the fault (shown schematically as a dashed line). However, some of the fractures in the fault periphery have been reactivated in shear.

sense. Thus, we interpret the left-stepping joints in the southern region of the fault (Fig. 4c and d) to have formed prior to the faulting and attribute their origin to joint breakdown fringe.

4. Discussion

The strike-slip faults we describe are part of the same family of faults described by Myers and Aydin (2004). In many cases, different fault architectures implying different evolutionary paths occur along the same fault. For example, the architecture of the northern part of the fault shown in Fig. 3 implies an initial joint configuration similar to dilational-stepping (en échelon) joint zones described by Myers and Aydin (2004), whereas the southern portion implies an initial configuration similar to an abrupt joint breakdown fringe. In this case, we suggest that the differing fault architectures along the same fault are related either to the current depth of outcrop exposure or to the slip tendency of the parent joint and the fringe joints. The latter factor is controlled by the orientation of the principal stresses with respect to the parent and fringe joints, whereas the former is just a matter of chance. The northern exposure of this fault is more than a meter higher in elevation. The geometries we describe where both parent joint and breakdown joints are exposed at the same outcrop level must be of limited extent given that the initiation points for the breakdown joints are localized along the parent joint tipline and that the extent of their overlap is generally small (see Fig. 2). Thus, the dilational-stepping joints along the northern portion of the fault are likely the upward extension of the breakdown fringe joints along the southern portion.

5. Conclusions

We present an intriguing fault architecture in which damage is localized along one side of a slip surface and interpret this pattern in terms of the initial joint breakdown fringe geometry. This provides a complementary model to that of Myers and Aydin (2004) for damage zone geometry around faults formed by shearing across preexisting joints. In contrast to previously developed models, fault damage is minimized due to the nearby presence of an already through-going parent fracture surface. Fragmentation and fault rock along the through-going slip surface is minimized, as the primary slip surface develops along the already through-going parent joint surface without breaking the bridges of intact rock between en échelon segments. These conclusions suggest that care should be taken in interpreting the sense of slip from apparent splay fractures in the damage zone of a fault.

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