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Sequential and incremental formation of conjugate sets of faults

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Abstract—The evolution of a system of strike-slip faults in porous Entrada Sandstone of Arches National Park, Utah, is investigated here. The area includes domains of parallel faults, oriented either N30E or N60E, and domains of conjugate sets. The age relations indicate that conjugate faults do not form simultaneously, but that a few members of one set form and then are offset by a few members of a second set. Then, new members of the first set form and offset some members of the second set. In this way, a conjugate pattern is built up.

Cross-cutting relations also indicate that individual faults do not form simultaneously along their lengths. The traces of individual faults are segmented, with individual segments ranging from 10 cm to 60 m. The cross-cutting age relations indicate that the individual faults form sequentially by longitudinal growth and coalescence of segments. In an area of two sets of conjugate faults, segments in the sets form alternately, so a segment in one set is older than some segments and younger than other segments in the other set.

The field observations of temporal and geometrical relations among conjugate faults in porous sandstone are consistent with experimental observations of growing faults in clay. Domains of a single set of faults, the sequential growth of fault segments, and the alternating growth of two sets all have been observed in carefully controlled experiments by Reches. Members of one set of conjugate faults interfering with members of another set, recognized by Oertel, is reflected in multiple fault splays in the vicinity of intersecting faults. The similarity between the field and experimental observations suggests that the processes controlling these relations are not restricted to faulting in porous rocks.

INTRODUCTION

THIS paper describes the evolution of a system of strike-slip faults in sandstone. We mapped in detail 1.5 km^2 of perfectly exposed Entrada Sandstone, located in the Garden Area of the SW limb of the Salt Valley anticline, near Arches National Park, Utah (Fig. 1). The purpose of this paper is to compare the sequence of formation of the conjugate pattern, as documented in the field, with the way conjugate faults form in theory and in clay experiments.

It is common knowledge in structural geology that conjugate strike-slip faults form when rocks are subjected to horizontal maximum and minimum principal stresses and to vertical intermediate principal stress, provided that the rock properties favor fracturing by faulting. While the orientation of the faults relative to the direction of maximum compression can be inferred from Mohr's diagram (e.g. Billings 1954, Suppe 1985), the diagram provides no information about the sequence of events in faulting (e.g. Johnson 1970, Chap. 9). Experimentation with rocks (e.g. Paterson 1978) and with clay (Oertel 1965, Reches 1988) has verified some of the common knowledge, in addition to providing considerable information about how different members of conjugate fault sets initiate, interact, and evolve into complex patterns.

The experimental studies of faulting by Oertel (1965) and Reches (1988) are particularly informative. Oertel (1965) showed that, in three-dimensional deformations, more than two (typically four) sets of faults form to accommodate the deformation. Reches (1988) showed that strike-slip faults in two-dimensional strain grow by coalescence of segments, and that different members of the two sets form at different times. Oertel (1965) deduced that the two sets such as we observe in conjugate faulting form under plane-strain deformation and that, in vertical strike-slip faulting, the direction of zero

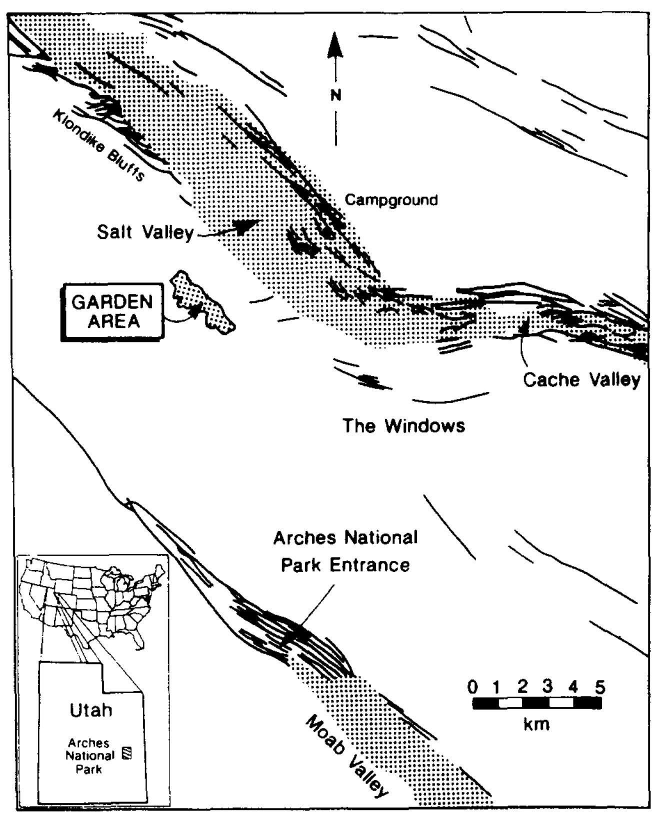

Fig. 1. Location of Garden Area that exposes Entrada Sandstone on the SW limb of the Salt Valley anticline. Only larger faults (from Doelling 1985) are shown. Stippled areas are approximate areas underlain by salt. The Garden Area is in relatively undeformed rocks between the Salt Valley anticline and the Moab Valley fault zone.

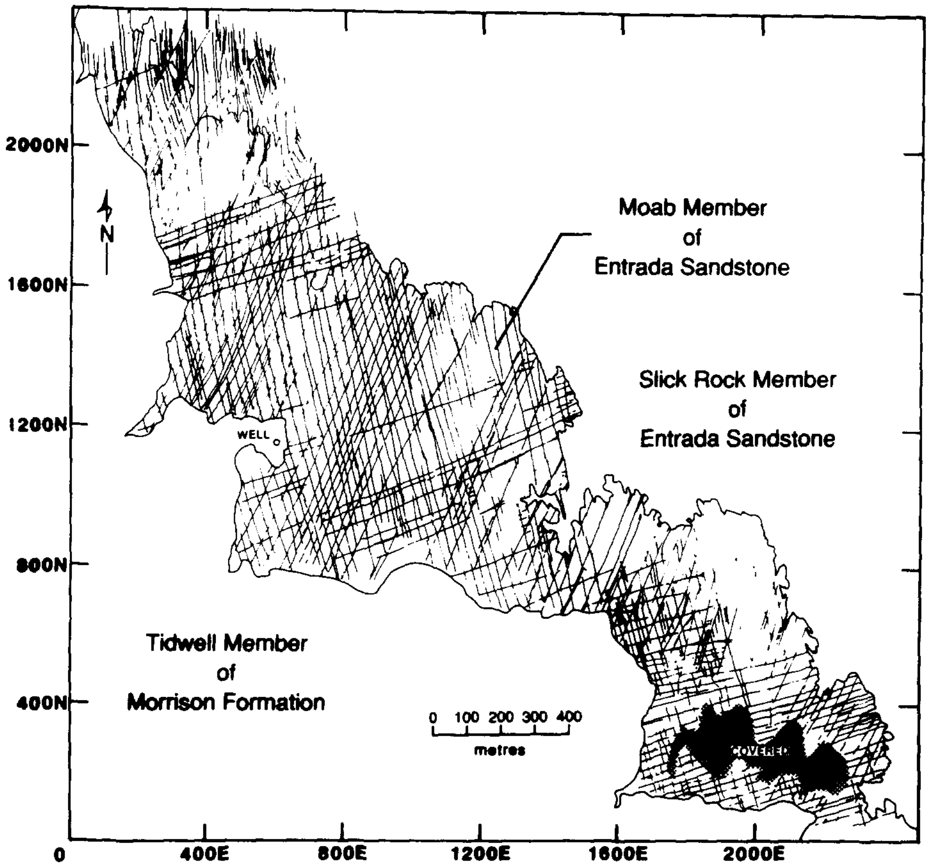

Fig. 2. Traces of systematic faults, joints and faulted joints in the Garden Area. All the faults are strike-slip. There are at least three sets, but the set with traces trending about N5W is invariably younger than the sets trending N30E and N60E. Also, the set trending N5W is a faulted joint and the sets trending N30E and N60E are band faults.

strain is vertical. He suggested that interference due to crossing of members of different sets would influence the orientation of the faults.

Reches (1988) studied the formation of strike-slip faults in clay, by examining fault traces exposed at the clay's surface. He observed that short segments of fault traces form at certain locations on the surface of the clay, either as conjugate sets or as arrays of parallel faults of one set, and that the faults lengthen by propagation of segments and by coalescence of nearly-collinear neighboring segments. His experiments show that segments tend to be oriented such that segments step left in right-lateral faults, and step right in left-lateral faults.

During lengthening, the segments of fault traces remain in the original pattern of either conjugate or parallel. The parallel arrays enlarge through addition of new fault segments beside older ones. The conjugate arrays enlarge as new fault segments appear, cross-cutting the earlier ones. Thus, the fault arrays result from sequential rather than simultaneous formation of individual fault segments. Ultimately, a single fault, or a small number of faults, accommodates most of the further deformation and dominates the fault pattern in the clay.

Reches (1988) also described the growth of individual faults that ultimately traversed nearly the full width of clay bodies used in the experiment. Individual faults, he indicated, are composed of coalesced fault segments. Individual segments start at lengths smaller than about 1 mm and lengthen by propagation, in line with the fault trace, to about 5–20 mm. Individual segments form along the alignment of the fault and coalesce to form the trace of the through-going fault.

Our study of intersecting faults in Entrada Sandstone near Moab, Utah, indicates that we can recognize, if not deduce, many of the features of faulting observed by Oertel and Reches in strike-slip faulting of clay.

Faults of the Garden Area

The rocks within the Garden Area (Fig. 1) are only mildly deformed (shearing strain accommodated by the faults is on the order of 0.1%), yet the rocks contain several types of fractures: pristine joints and faults, joints that have become faults, and faults that have become joints. The traces of all the large, systematic fractures are shown in Fig. 2, which shows a complex pattern of at least three fracture sets. Although all are strike-slip faults (Dyer 1983, Zhao & Johnson in review), there are two distinct types. One is the *band fault*, described in porous sandstones by Aydin and others (e.g. Dunn *et al.* 1973, Aydin 1977, 1978, Aydin & Johnson 1978, 1983, Smith 1983). The other is the *faulted joint*, described by Segall, Pollard and others (e.g. Dyer 1979, 1983, 1988, Segall & Pollard 1983a,b, Davies & Pollard 1986, Martel *et al.* 1988, Cruikshank *et al.* 1991). We focus here on the band faults, traces of which are shown in Fig. 3.

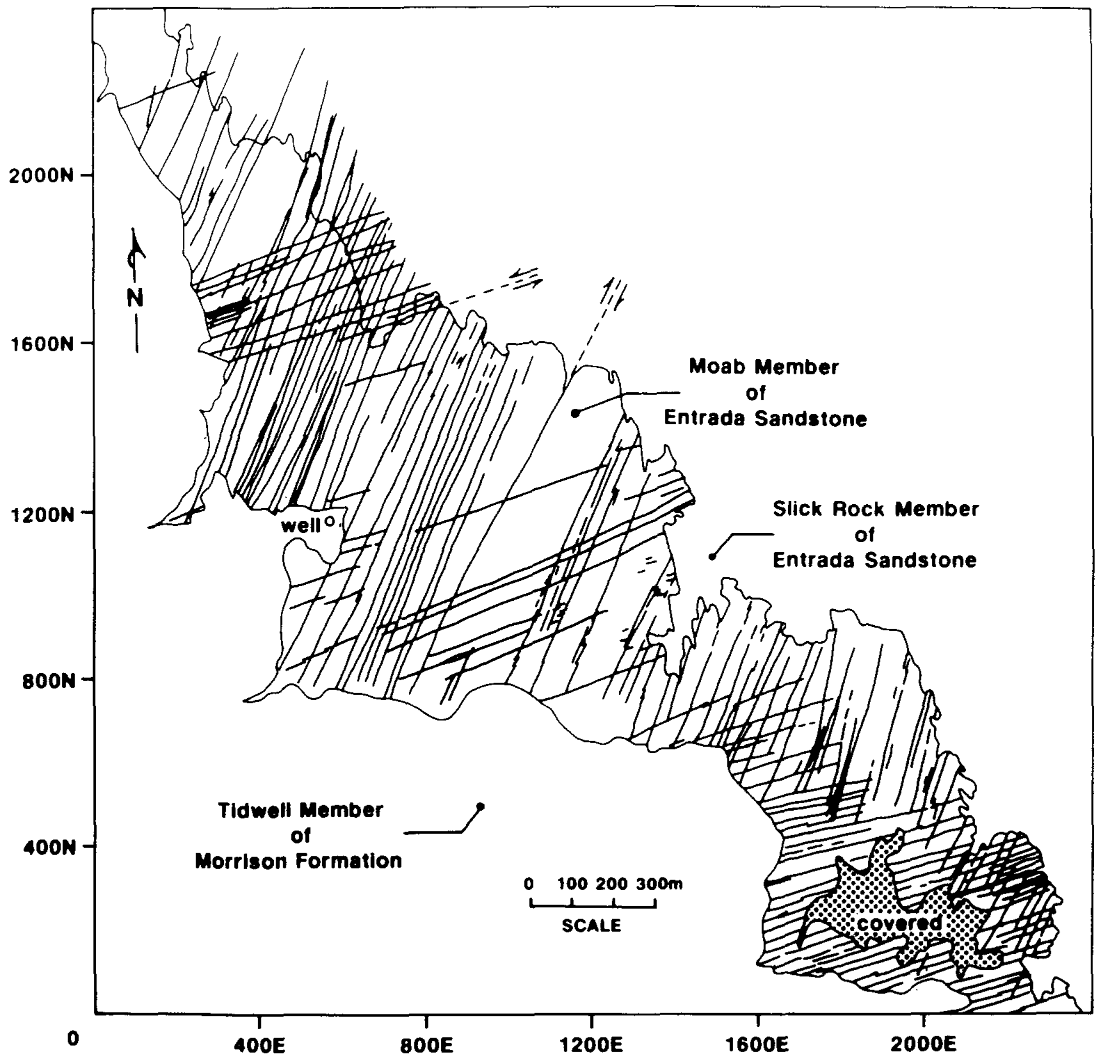

Fig. 3. Traces of zones of band faults in the Garden Area. The band faults trending N30E are invariably left-lateral, and those trending N60E are invariably right-lateral in the area. In the northernmost part of the area, centered at co-ordinate 2000N–200E, the faults occur in a domain of parallel faults trending N30E. This domain is terminated in the south, near co-ordinate 1800N–300E, by a swarm of faults trending N60E, although the traces of most of the faults trending N30E pass through the traces of the faults trending N60E. This is the area where we have made a detailed study of cross-cutting relations.

Type of fault

The Garden Area faults are of the band-fault variety, a type of porous rock faulting first described by Aydin in sandstones near San Rafael Swell, Utah (Aydin 1977, 1978), in the middle 1970s. The deformation bands are about 1 mm thick, with lengths from a few meters to many tens of meters. Within the bands, pores have collapsed, sand grains have fractured, and shearing offsets of a few mm to 1 cm have occurred. A zone of deformation bands is formed by two or more adjacent deformation bands sharing the same strike and dip, with the zone becoming thicker through the addition of new bands, side by side (Aydin 1977). Specifically, in the Garden Area we have deformation bands and zones of deformation bands, but no slip surfaces. Aligned segments of zones of deformation bands are spaced by a few tens of meters, and extend for distances up to about 1 km (Fig. 3).

Closer views of a deformation band and two narrow zones are shown in Fig. 4(a), which is a photograph of the trace of a zone trending N30E offset about 3.6 cm in a left-lateral sense by an intersecting zone whose trace trends N60E. Geometric analysis of offset cross-bedding with different orientations indicates that both the faults shown in Fig. 4(a) are strike-slip faults, and that one is left-lateral and the other is right-lateral. At the intersection of the faults shown in Fig. 4(a) is a single, white, deformation band that diverges away from the N30E zone, crosses the N60E zone, and coalesces again with the continuation of the N30E zone. A map of the intersection is shown in Fig. 4(b). The offset is too small to determine whether the band offsets the N60E zone.

The band faults and zones of band faults in the Garden Area are small, generally having accommodated less than a few cm of slip. The typical width of zones in the Garden Area is about 5 mm. Although the widths and amount of slip across the faults are small, the traces of the faults extend for great distances, as shown in Figs. 3 and 5(a).

Fault patterns

The band faults in the Garden Area form a remarkably simple regional pattern (Fig. 3), with traces of one set trending about N30E and traces of the other set trending N60E. Without exception, the faults in the N30E set are right-lateral and the faults in the N60E set are left-lateral. (We will call these the 30E faults and the 60E faults, respectively.)

The 30E faults dominate the pattern in the northern three-quarters of the Garden Area, and the 60E faults dominate in the southern quarter. In the northernmost part of the area, the faults occur in a domain of parallel, 30E faults (Fig. 3). This domain is terminated in the south by a swarm of 60E faults, although the traces of most of the 30E faults pass through the traces of the 60E faults. It is in this area that we made a detailed study of cross-cutting relations.

AGE RELATIONS OF FAULTS

We have established age relations of the members of conjugate sets by studying fault intersections and determining the order of offset. The intersections of members of the conjugate sets appear much as shown in Fig. 4. Most of the bands in one zone of deformation bands are offset and are, therefore, older than the bands in the other zone. In our maps, we report the relative age of only the largest slip episodes. However, we wish to emphasize that the age relations can be different for different bands within the zone of deformation bands. For example, Fig. 4(b) shows that all but one of the deformation bands in the 30E zone are offset and are, therefore, older than the bands in the 60E zone. We thus report in our map, Fig. 6, that at the intersection of trace I with trace B, slip occurred first on the 30E zone, then along the 60E zone. (The arrows indicating relative slip near an intersection are placed on the younger fault in the maps.) One band within the 30E zone, however, is continuous across the 60E zone, indicating that minor slip occurred along the 30E zone after the 60E zone had formed. We have ignored such minor slip in our maps.

By examining all intersections, and constructing a matrix of age relations, we can reconstruct the major stages in the evolution of the fault pattern in the area. Intersections between five faults of the 30E set (labeled *I*, *II*, *III*, *IV* and *V*), and four faults of the 60E set (labeled *A*, *B*, *C* and *D*), are shown in Fig. 6 (some details are shown in Figs. 7a & b). The exposure at several intersections was inadequate to determine the predominant offset, so we show the intersection as covered in Fig. 6. Where the offset could be determined, the amount of slip is given in cm and the sense of slip is indicated by a pair of arrows placed along the younger fault. For example, at the intersection of faults *I* and *A*, the amount of offset is 0.5 cm and fault *A* is younger than fault *I*. At the intersection of faults *III* and *B*, the exposure was inadequate to determine offset. Table 1 shows the relative ages determined by examination of Figs. 6 and 7.

Table 1. Relative ages of fault segments. The oldest segments are on the left, and the youngest segments on the right

30E	60E	30E	60E	30E
I	*A*			*III, IV, V*
I, II	*B*			*V*
I'	C'			
II, IV'	*C*			*V*
II, IV'	*C*	I''	C''	
		I'''	*D*	*III*, IV'', *V*
		I'''	*E, F*	*III*

The table and the maps in Figs. 6 and 7 show that age relations can vary among the different segments of a fault, whether the segments are splays (as in the case of *C*, Fig. 7a), or stepped (as in the case of fault *IV*, Fig. 6). Fault *C* consists of three splayed segments (identified as *C*, C' and C''), and fault *I* consists of three stepped segments (identified as *I*, I' and I'' in Fig. 7a). Segment I'' is younger than the part of *C* in its vicinity, but older than C''. Segment C'' diverges from, then rejoins *C* on both sides of the intersection between *C* and I''. In this case, we infer that some of the bands in *C* slipped, followed by bands in segment I'' , and then other bands within *C*, including those within segment C''; the slip on *C* appears to be both younger and older than slip on I''.

The patterns of fault segments at several stages in the development of the conjugate faults are shown in Fig. 8. The only special assumption used in the construction (and in Table 1) is that segment I''', like I'', formed later than fault segment *C*. The cross-cutting relations show that faults *D*, *E* and *F* formed later than segment I'''.

CONCLUSIONS

The patterns of traces of strike-slip faults in the sandstone of the Garden Area on the SE flank of the Salt Valley anticline closely resemble, in most respects, patterns of faults in the early stages of plane strain deformation of clay (Reches 1988).

(1) The small angle between the traces of faults in clay was bisected, roughly, by the axis of maximum compression. In the Entrada Sandstone, the small angle is about 30°, and the sense of slip on the faults indicates that the direction of regional compression was contained within the small angle (Fig. 3). The small angle may have been bisected by the regional compression, and oriented roughly N45E, at the time of faulting. The axis of the Salt Valley anticline is oriented about N45W (Fig. 1), so the axis of compression would have been normal to the fold axis.

(2) The traces of faults form parallel domains in some places and conjugate sets in others, both in the clay (Reches 1988) and in the sandstone (Fig. 3).

(3) The traces of faults are segmented both in the clay and in the sandstone. Individual bands and zones of deformation bands occur in segments. Some of the larger segments are visible in the map of the Garden

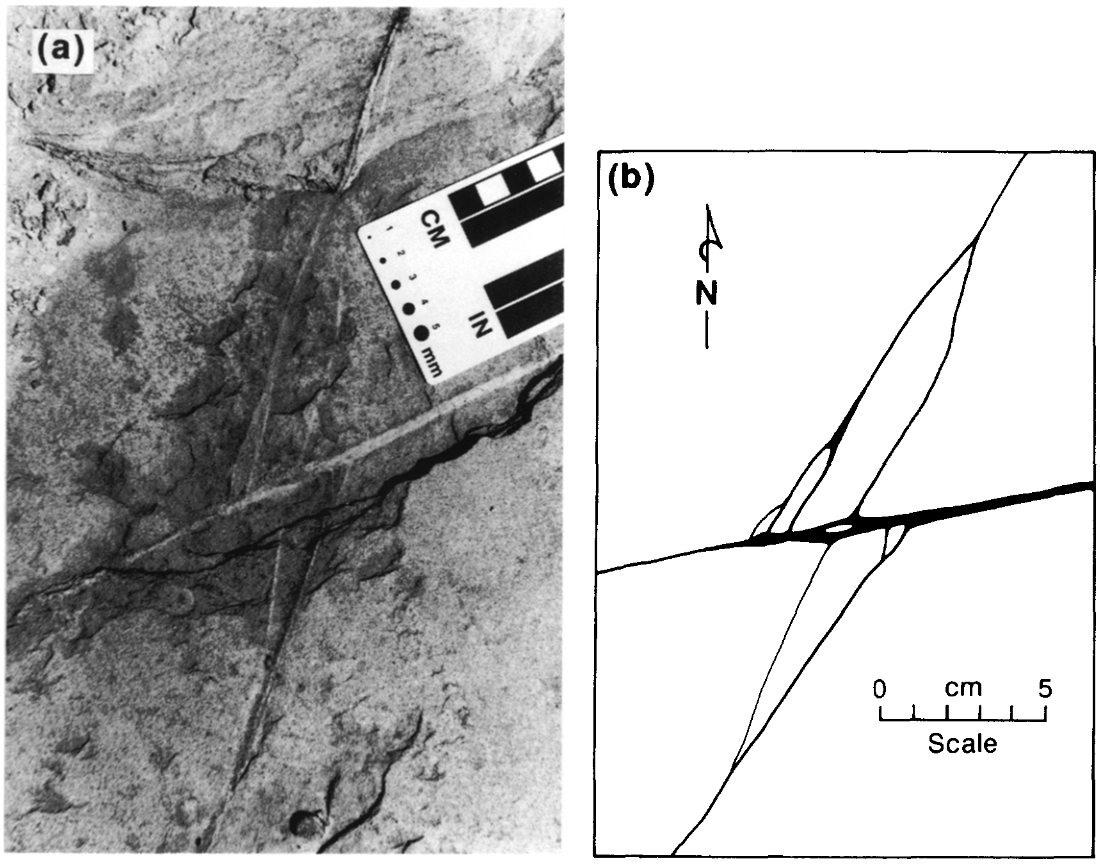

Fig. 4. Photograph and map of intersection between a zone of N30E (right-lateral) band faults and a zone of N60E (left-lateral) band faults, at intersection of trace *I* and trace *B* in Fig. 6. The age relations can be different for different bands within a zone. All but one of the deformation bands in the N30E zone are offset and are, therefore, older than the bands in the N60E zone. One band within the N30E zone, however, is continuous across the N60E zone, so minor slip occurred along the N30E zone after the N60E zone had formed. In our maps, we have ignored such minor slip.

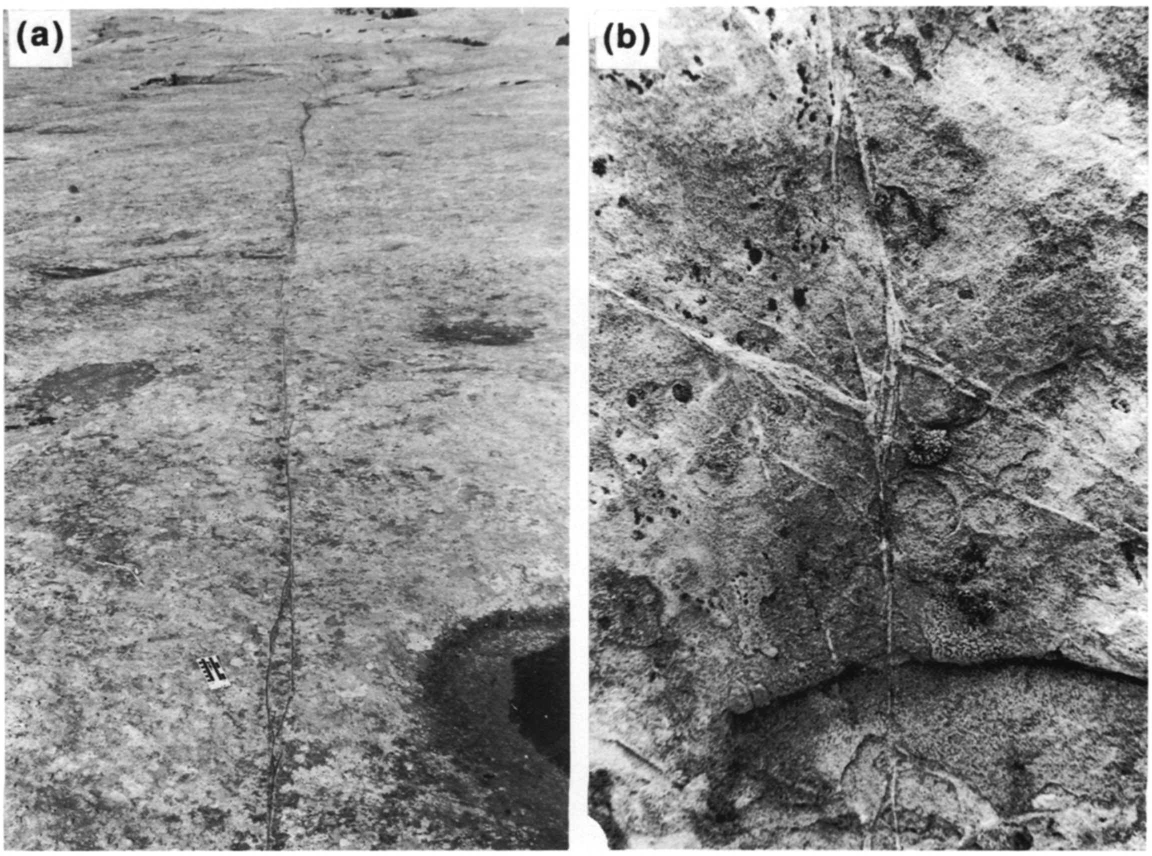

Fig. 5. (a) Right-lateral zone of deformation bands trending about N30E and extending for tens of meters across the bare outcrop of white Moab Member of Entrada Sandstone in the Garden Area. (b) Multiple fault splays in the vicinity of intersecting band faults. The intersection consists of tens of splays from each of the intersecting narrow zones, apparently reflecting many episodes of slip on each of the intersecting faults.

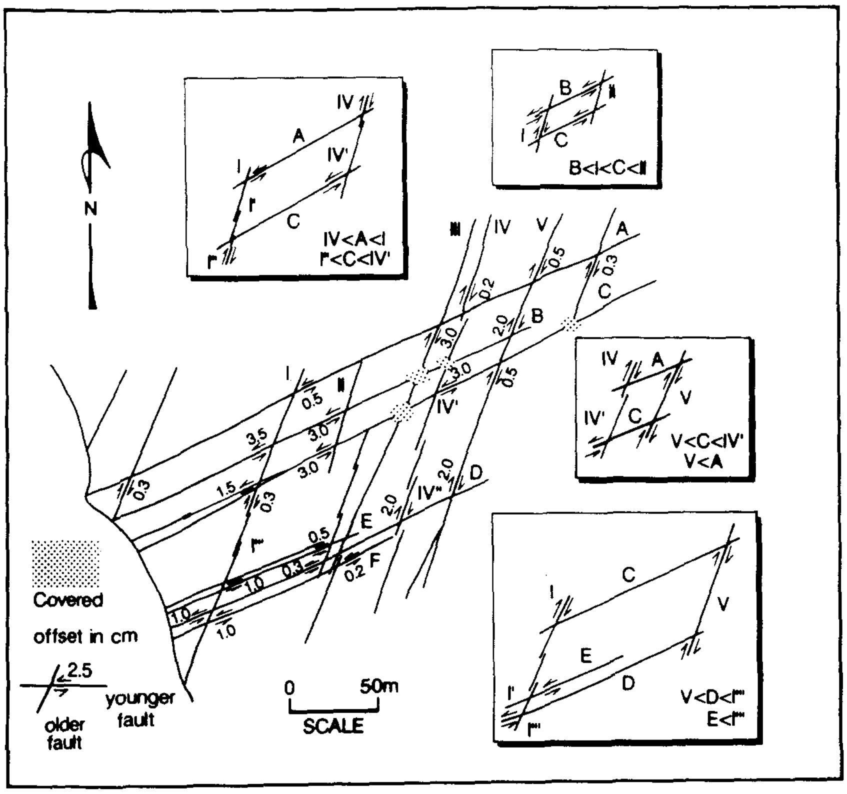

Fig. 6. Traces of several zones of deformation bands trending N30E or N60E in part of the Garden Area centered at coordinate 1650N 400E (Fig. 3). Intersections are shown between five faults of the 30E set (labeled *I*, *II*, *III*, *IV* and *V*) and four faults of the 60E set (labeled *A*, *B*, *C* and *D*), except where obscured by cover. Sense of slip is shown by a pair of arrows placed along the younger fault and the amount of slip is shown in cm. Four inset figures show fault parallelograms, in which one can make a complete circuit and determine relative ages of members of each fault set. Relative ages are indicated by inequalities, as defined in Table 1.

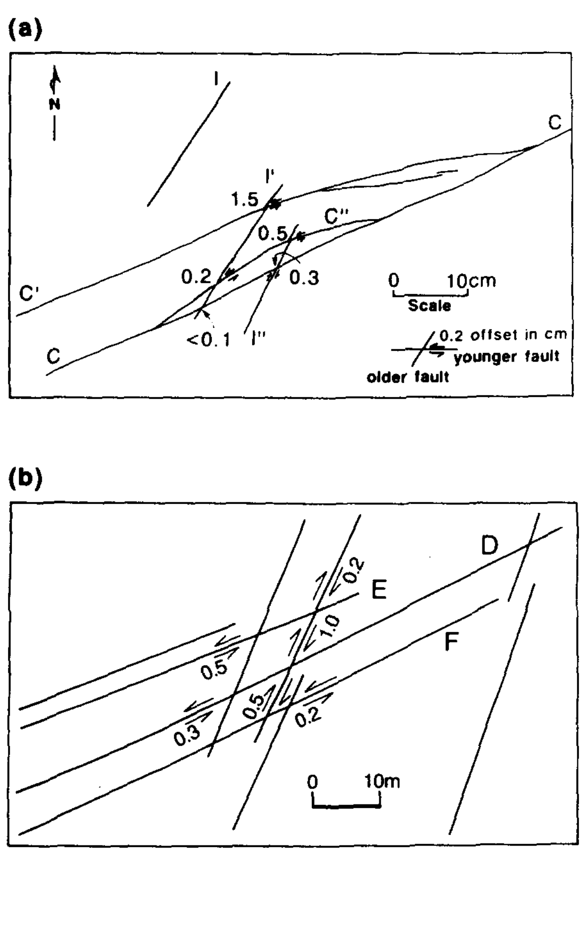

Fig. 7. More details of intersections of fault segments in the vicinity of the intersection of faults *I* and *C* shown in Fig. 6. Age relations can be different for different splays of a fault. Fault *C* consists of three splayed segments, identified as *C*, *C'* and *C''*, and fault *I* consists of three stepped segments, identified as *I*, *I'* and *I''*. Segment *I''* is younger than the part of *C* in its vicinity, but older than *C''*, which diverges from and then rejoins *C* on either side of the intersection between *C* and *I''*. In this case, we infer that some of the bands in *C* slipped, then the bands in segment *I''* slipped, and then other bands within *C*, including those within segment *C''*, slipped. Slip on *C* appears to be both younger and older than slip on *I''*.

Area (Fig. 3), but many smaller ones are visible only in more detailed maps. For example, a map of faults in the area of conjugate faulting in the northern part of the area shows lengths of segments ranging from 5 m to perhaps 60 m (Fig. 6). A map of faults near the intersection of faults *C* and *I* shows segments of fault *I* that are 10–20 cm in length (Fig. 7).

(4) The faults form sequentially by coalescence of segments. In an area of conjugate faulting, segments in the sets form alternately, so a segment in one set is older than some segments and younger than other segments in the other set.

(5) Segments of band faults tend to step right in left-lateral faults and step left in right-lateral faults. This is the same tendency reported in the experimental faults in

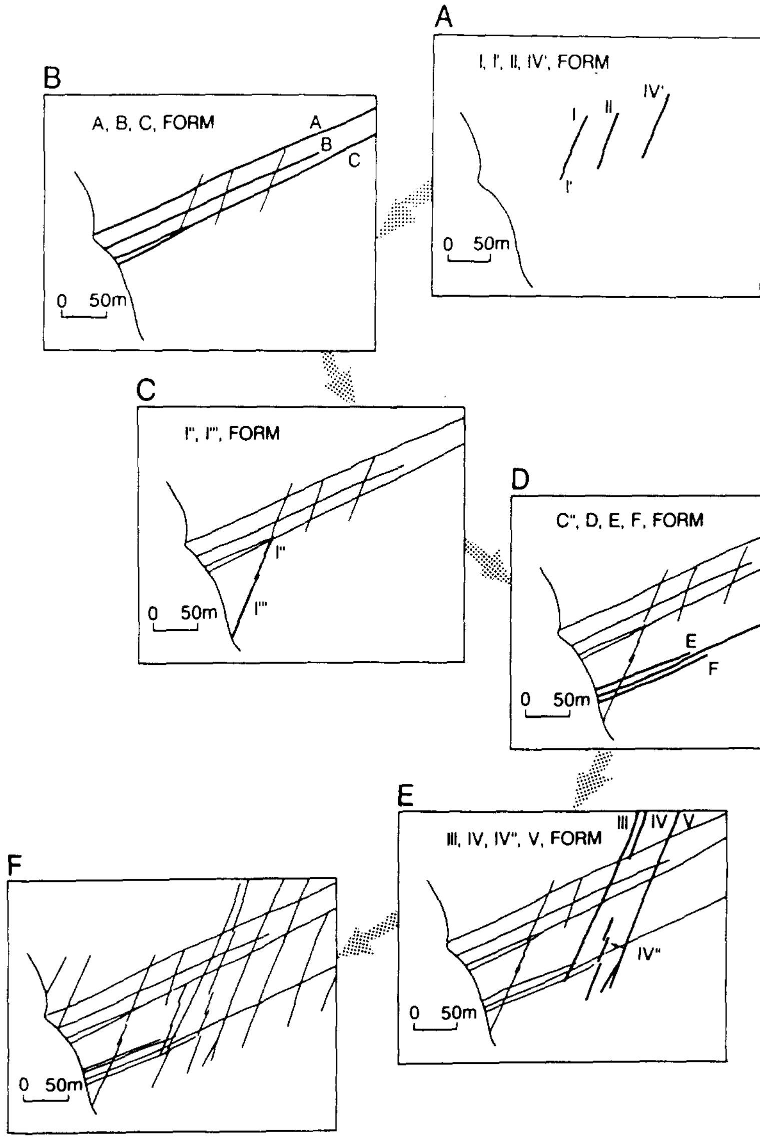

Fig. 8. Scenario of development of fault segments in the area of detailed study. (a) Some right-lateral faults formed. Two segments of fault *I*, one segment of fault *IV'*, and fault *II* formed early. (b) These were subsequently offset by three left-lateral faults, *A*, *B* and *C* (note that heavy lines indicate faults that are currently active in a snapshot). (c) Two other right-lateral segments, *I''* and *I'''*, formed (we assume simultaneously). (d) Then two other left-lateral faults, *D* and *E* formed. (e) Finally, a different segment of right-lateral fault *IV* and faults *III* and *V* formed, cross-cutting many of the left-lateral faults. (f) This scenario accounts for many of the faults in the area of detailed study.

clay by Reches (1988) and in faults bounding landslide blocks by Fleming & Johnson (1989).

(6) Members of one set of faults interfering with members of the other set, recognized by Oertel (1965), is reflected in multiple fault splays in the vicinity of intersecting faults. In some places the pattern is simple, as in Fig. 4, where only one band fault splayed from the narrow zone to straighten out the trace at the intersection. In others, the pattern is complex and the intersection consists of tens of splays from each of the intersecting narrow zones, apparently reflecting many episodes of slip on each of the intersecting faults (Fig. 5b).

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REFERENCES

Aydin, A. 1977. Faulting in sandstone. Unpublished Ph.D. dissertation, Stanford University, California.

Aydin, A. 1978. Small faults formed as deformation bands in sandstone. *Pure & Appl. Geophys.* **116**, 913–930.

Aydin, A. & Johnson, A. M. 1978. Development of faults as zones of deformation bands and as slip surfaces in sandstone. *Pure & Appl. Geophys.* **116**, 931–942.

Aydin, A. & Johnson, A. M. 1983. Analysis of faulting in porous sandstones. *J. Struct. Geol.* **5**, 19–31.

Billings, M. P. 1954. *Structural Geology* (2nd edn). Prentice-Hall, Englewood Cliffs, New Jersey.

Cruikshank, K. M., Zhao, G. & Johnson, A. M. 1991. Analysis of minor fractures associated with joints and faulted joints. *J. Struct. Geol.* **13**, 865–886.

Davies, R. K. & Pollard, D. D. 1986. Relations between left-lateral strike-slip faults and right-lateral monoclinal kink bands in granodiorite, Mt. Abbott Quadrangle, Sierra Nevada, California. *Pure & Appl. Geophys.* **124**, 177–201.

Doelling, H. H. 1985. Geologic Map of Arches National Park and vicinity, Grand County, Utah. Utah Geological and Mineral Survey Map 74 accompanying text.

Dunn, D. E., LaFontain, L. J. & Jackson, R. E. 1973. Porosity dependence and mechanism of brittle fracture in sandstones. *J. geophys. Res.* **78,** 2403–2417.

Dyer, J. R. 1979. A 3-D elastic bending-plate model for joint formation. *EOS* **60,** 944.

Dyer, J. R. 1983. Jointing in sandstones, Arches National Park, Utah. Unpublished Ph.D. dissertation, Stanford University, California.

Dyer, J. R. 1988. Using joint interactions to estimate paleostress ratios. *J. Struct. Geol.* **10,** 685–699.

Fleming, R. W. & Johnson, A.M. 1989. Structures associated with strike-slip faults that bound landslide elements. *Engng Geol.* **27,** 39–114.

Johnson, A. M. 1970. *Physical Processes in Geology.* Freeman, Cooper & Co., San Francisco.

Martel, S. J., Pollard, D. D. & Segall, P. 1988. Development of simple strike-slip fault zones, Mount Abbot Quadrangle, Sierra Nevada, California. *Bull. geol. Soc. Am.* **100,** 1451–1465.

Paterson, M. S., 1978. *Experimental Rock Deformation: The Brittle Field.* Springer, Berlin.

Oertel, G. 1965. The mechanism of faulting in clay experiments. *Tectonophysics* **2,** 343–393.

Reches, Z. 1988. Evolution of fault patterns in clay experiments. *Tectonophysics* **145,** 141–156.

Segall, P. & Pollard, D. D. 1983a. Joint formation in granitic rocks of the Sierra Nevada. *Bull. geol. Soc. Am.* **94,** 563–575.

Segall, P. & Pollard, D. D. 1983b. Nucleation and growth of strike-slip faults in granite. *J. geophy. Res.* **88,** 555–568.

Smith, G. A. 1983. Porosity dependence of deformation bands in the Entrada Sandstone, La Plata County, Colorado. *Mountain Geol.* **20,** 82–85.

Suppe, J. 1985. *Principles of Structural Geology.* Prentice-Hall, Englewood Cliffs, New Jersey.

Zhao, G. & Johnson, A. M. In review. Sequence of deformations recorded in jointed-faults and faulted-joints, Arches National Park, Utah. *J. Struct. Geol.*