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Sequence of deformations recorded in joints and faults, Arches National Park, Utah

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Abstract—Faults and joints in an area of essentially undeformed rocks on a limb of a salt anticline in Utah record a surprisingly complex deformational history. Most of the faults started as widely-spaced zones of deformation bands accommodating a few cm of strike-slip. Some were subsequently opened as joints, then were sheared with a sense opposite that of the original faults. Other faults in the Garden Area are fractures that started as joints, then were subsequently sheared. The sense of shear changes across the area, however, and the pattern of shearing is the pattern that would be produced by bending of joint-bounded slabs about a vertical axis. Slip on the faults and joints produced a total regional strain of about 0.15%.

Examination of relations among the structures indicates the following deformational history: first were conjugate, strike-slip faults oriented N30°E or N60°E, reflecting zero vertical strain (and presumably vertical intermediate compression), maximum compression in the NE direction (normal to the axis of Salt Valley), and maximum extension in the SE direction. The faults are of the deformation-band variety and so, presumably formed when the rocks were several kilometers deep. Deformation bands never again formed in these rocks. Subsequent fracturing was mode I, tension cracking.

Second, tension in the SE direction (or minimum compression in the SE direction and pore-water pressure exceeding the minimum compression), parallel to the long axis of the Salt Valley anticline, opened joints along some of the weak deformation-band faults, causing them to become jointed faults. The orientation of minimum compression was unchanged, but the orientations of the maximum and intermediate principal stresses are unknown and may have changed.

Third, systematic zones of joints formed, cutting across the band faults without deviating in trend throughout most of the Garden Area, but interacting with the open jointed faults locally. The direction of tension (or minimum compression) at this time was about N75°E to N90°E, indicating that the direction of principal extension had rotated about 45–60° clockwise, oblique to the axis of Salt Valley anticline. At the same time, short joint segments formed along the jointed-faults. The jointed faults slipped to become faulted-jointed-faults. Although the amount of slip was less than that on the original deformation bands, the sense of slip was reversed.

Finally, the rock slabs bounded by the zones of joints were subjected to flexural slip with different centers of curvature in different parts of the area, converting most of the joints into faulted-joints, with three or four domains of different senses of slip.

INTRODUCTION

NEARLY undeformed rocks on the SW limb of the Salt Valley anticline in eastern Utah (Fig. 1) have been subjected to a remarkably varied loading history. The rocks contain many types of fractures: pristine joints and faults, joints that have become faults, and faults that have become joints. The traces of the fractures define at least three sets of essentially vertical fractures (Fig. 2). Although all the faults are strike-slip faults (Dyer 1983, Zhao & Johnson 1991), there are two distinct types. One type is the band fault described in porous sandstones by Aydin and others, (e.g. Dunn *et al.* 1973, Aydin 1978, Aydin & Johnson 1978, 1983, Smith 1983). The other is the faulted joint, described by Segall, Pollard and others (e.g. Segall & Pollard 1983b, Dyer 1979, 1983, 1988, Davies & Pollard 1986, Martel *et al.* 1988, Cruikshank *et al.* 1991a). Furthermore, individual fractures may be faults or joints as they change behavior during different stages of the deformational history, much as demonstrated by Fleming & Johnson (1989) in landslides in Utah.

We use the term fracture in a general sense, to include cracks, joints and faults. We use the terms *crack* and *joint* for fractures that formed by mode I (as in Pollard & Aydin 1988), and we use the term fault for a fracture that formed primarily in mode II or mode III (see Lawn & Wilshaw 1975 for a discussion of modes I, II and III fracturing). With this terminology, we form compound terms such as *jointed fault*—a fracture that formed in mode II or III and subsequently opened in mode I—or *faulted joint*, a fracture that formed in mode I and subsequently slipped in mode II or III.

The Salt Valley anticline is the northwesternmost salt-cored anticline of the Paradox fold and fault belt in western Colorado and eastern Utah (Dane 1935, Elston *et al.* 1962, Cater & Craig 1970, Doelling 1985). Our study focuses on the Garden Area, on the SW limb of the Salt Valley anticline, where the rocks dip about 7° towards the SW (Fig. 1). The area is largely within Arches National Park, and about mid-distance between the Salt Valley anticline to the northeast and the Moab fault zone to the southwest.

The Garden Area provides excellent exposures of fractures that were arrested in different stages of development. The fractures occur within about 10 m of white sandstone, the Moab Member of the Entrada Sandstone. Underlying the white sandstone, according to Dyer (1988), are 70–95 m of red, cross-bedded sandstone of the Slickrock Member of the Entrada Sand-

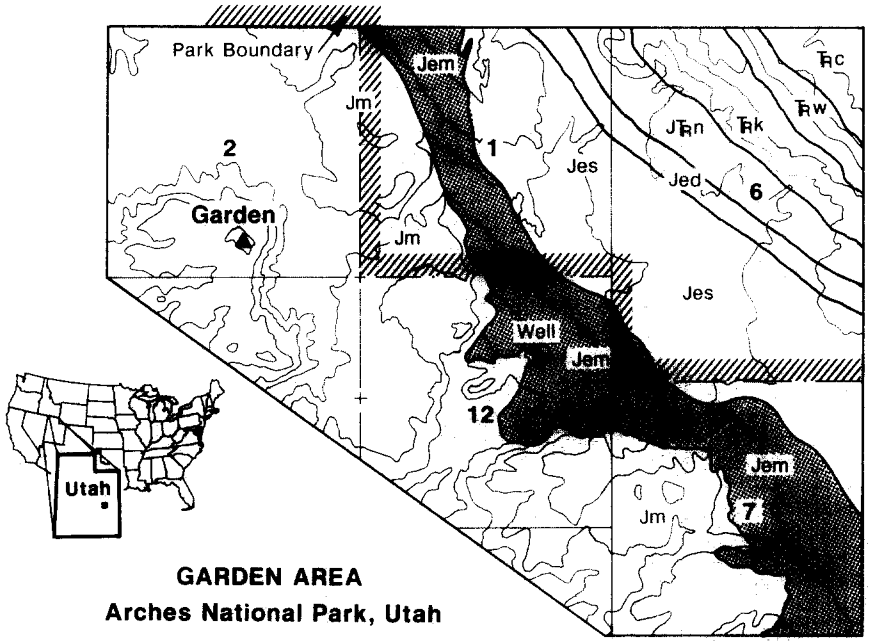

Fig. 1. Geologic map of Garden Area in southeastern Utah. Garden Area is stippled area underlain by Moab Member of the Entrada Sandstone (Jem). Jm is Morrison Formation and Jes is Slippery Rock Member of the Entrada Sandstone. Each section (numbered) is nominally 1 mile square.

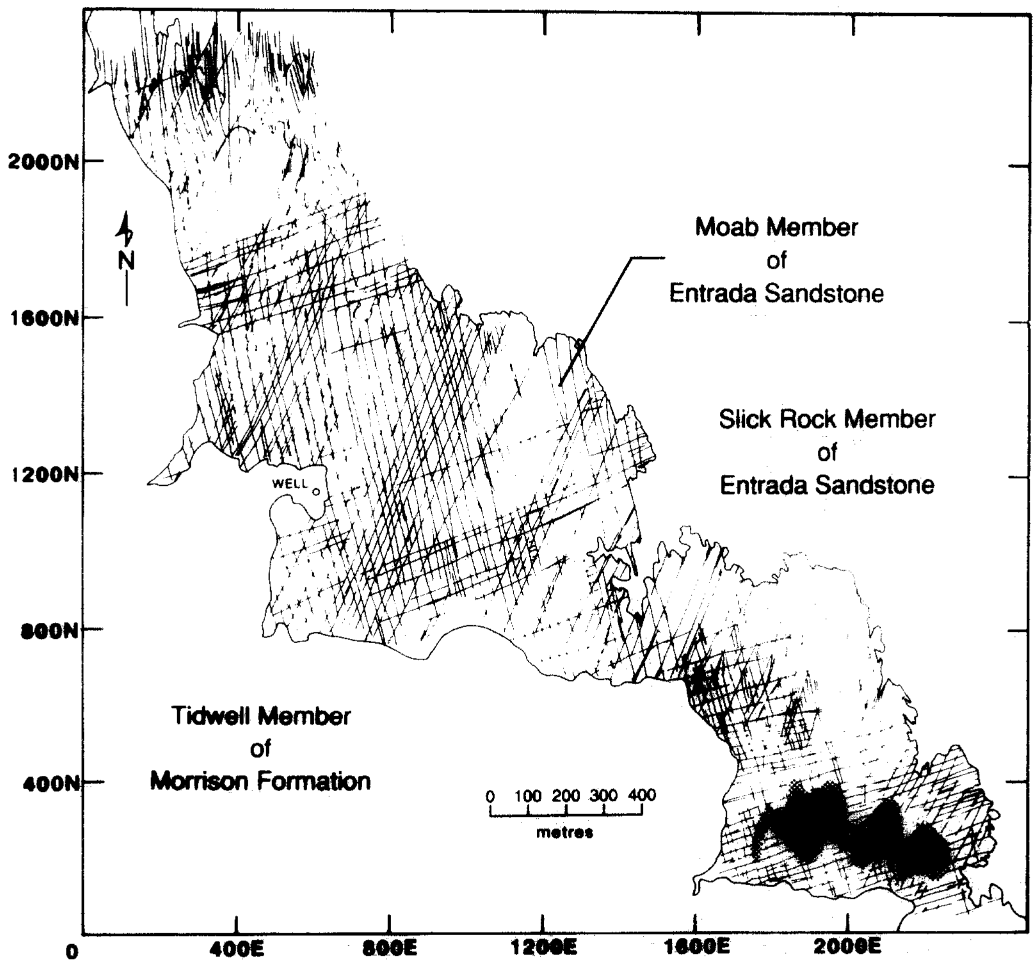

Fig. 2. Traces of systematic fractures, including faults, joints and faulted joints, in the Garden Area. All the faults are strike-slip faults. Slip arrows are representative. Faults trending N60°E are left-lateral and faults trending N30°E are right-lateral.

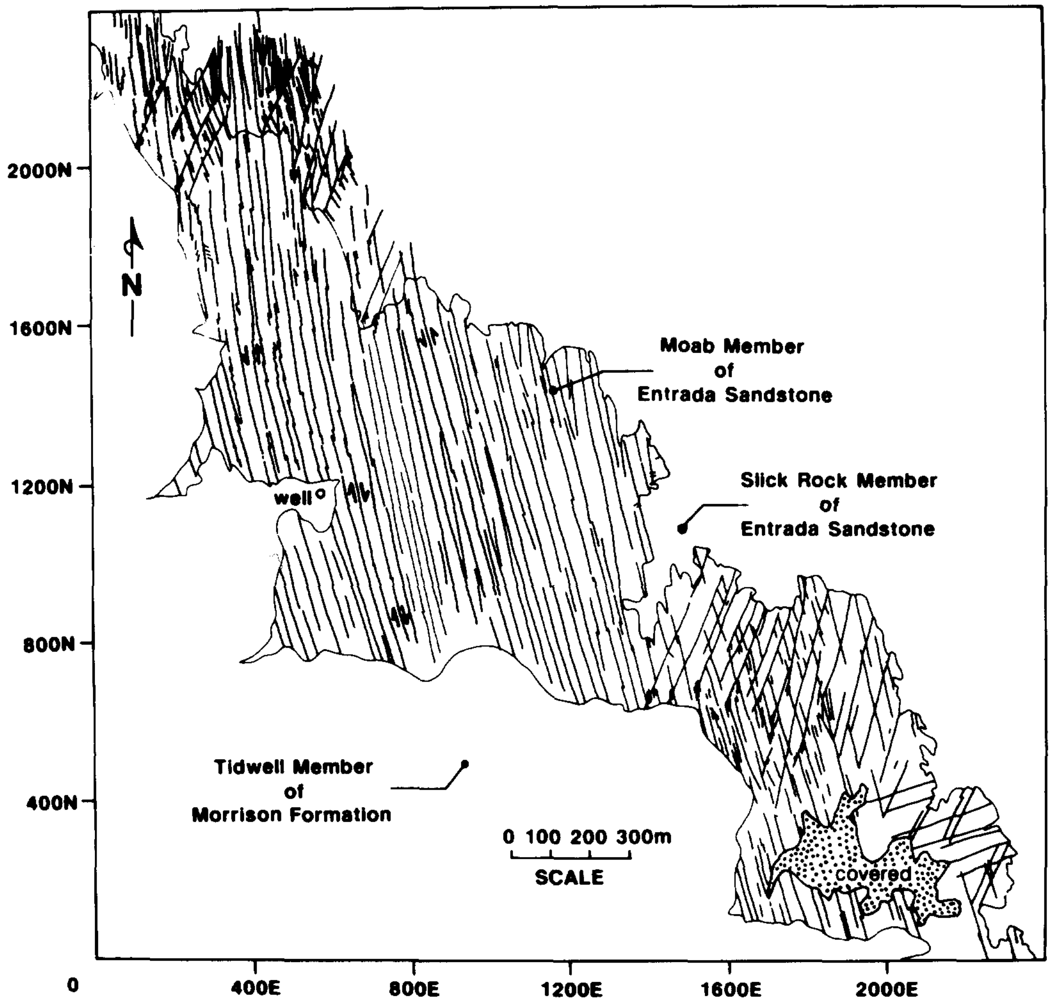

Fig. 3. Traces of joints, faulted joints and jointed faults in the Garden Area. All are nearly vertical and are open, mode I fractures. Joints of Dyer's J-3 set trend about N10°W and occur throughout the area. Sense of strike-slip along J-3 indicated by arrows in a few areas.

stone and overlying are about 12 m of thinly-interbedded claystone, sandstone and limestone of the lower part of the Morrison Formation (Cater & Craig 1970, Dyer 1988).

The purposes of our study are to describe the fractures, particularly their regional patterns, and to interpret the fracture patterns in terms of regional and local deformations accommodated by the formation and subsequent development of the fractures. We address the development of individual structures through detailed study of their forms and by mechanical analysis, then deduce the regional evolution of the structures.

JOINTS AND FAULTS

The primary fractures in the Garden Area are *small faults*, defined by narrow bands or zones of bands containing crushed sand grains and across which slip of a few mm or cm has occurred, and *joints* or *zones of joints*, across which the rock has opened.

Joints

Dyer (1983) recognized three sets of fractures in the Garden Area. He called them 'joints' and termed them J-1, J-2 and J-3, with J-3 being the youngest. Dyer's terminology is confusing because J-1, J-2 and J-3 actually refer to sets of fractures, and not to sets of joints. Fractures J-1 and J-2 are actually band faults and many of the J-3 fractures originated as joints, but have subsequently slipped as faults, and so are faulted joints. We use the notation J-1, J-2 and J-3 only in this section, where we review the contribution of Dyer. Dyer's J-1 fractures trend about N60°E and occur only in the southern part of the area. His J-2 fractures trend about N30°E and occur in both the northern and southern parts of the area (Fig. 3). Traces of J-3 fractures trend about N10°W throughout the Garden Area and dip vertically or steeply eastward (Figs. 3 and 4a). The J-3 fractures are of the type Dyer (1983, 1988) called 'zoned joint', a group of subparallel systematic joints in which individual joint segments are confined to a narrow zone, but are not coplanar (Segall & Pollard 1983a, b). The zoned nature is characteristic of both plan and cross-section views of the joints (Dyer 1983, 1988). The zones are confined to the Moab Member and degenerate into fringe fractures near the upper and lower contacts of this unit in the Garden Area. Typically, joints are stepped with smooth faces although faint hackle may be present (Fig. 4). Individual joints within a zone typically have traces a few meters to a few tens of meters long and spacing between zones generally is 20–45 m (Fig. 2), which means that the maximum dimensions of individual joints and the spacing between adjacent zones are of the order of the thickness of the Moab Member (Dyer 1983).

Although the average trend is about N10°W for J-3 fractures, the traces are broadly curved, concave toward the east, with a trend of N15°W in the south and about N5°W in the north (Figs. 3 and 4a). We assume that the J-3 fractures formed under regional, mode I loading, with the minimum compression (or tension, if water pressure in the joints was low) oriented about N80°E. This is supported by detailed examination of the J-3 fractures which indicates that most complexities in their forms can be explained in terms of interactions between adjacent fractures that behave as mode I fractures, such as joints and cracks (Cruikshank *et al.* 1991a).

Band faults

The primary faults in the Garden Area are band faults, which occur in two sets striking N30°E or N60°E (Fig. 6). Band-faults (Fig. 5a) were first described by Aydin in sandstones near San Rafael Swell, Utah (Aydin 1977, 1978), where they occur mainly as normal- and oblique-slip varieties, and in a few places as reverse and strike-slip faults. In the Garden Area, we have deformation bands and zones of deformation bands (Aydin & Johnson 1978, 1983). The deformation bands in medium-grained sandstone are about 1 mm thick (Fig. 5a) and their traces are a few meters to many tens of meters long (they are thinner in finer-grained sandstone). Within the bands, pores have collapsed, sand grains have fractured, and shearing offsets of a few millimeters to 1 cm have occurred.

The deformation bands occur in segments (Fig. 5b), with short connecting faults, most of which have coalesced, as in the foreground of Fig. 5(b). Individual fault segments within a zone are a few decimeters to a few meters in length, but zones of deformation bands are much more extensive. Zones have spacings of a few tens of meters and extend for distances up to about 1 km in the Garden Area (Fig. 6). The ways that deformation bands interact suggest that they are predominantly mode II or III fractures (Zhao *et al.* submitted).

The primary faults in the Garden Area are strike-slip faults, according to measurements of offset of bedding and cross-bedding. Measurement of offset bedding in several places indicates that the net slip plunges toward the SW at 5–12°, subparallel to the dip of bedding (which is about 7°), and that the net slip is 2–30 mm. Offsets of many single vertical markers also indicate the same slip sense and magnitude parallel to bedding. The minimum slip amount of the faults is indicated by their offset of older faults, as shown in a detailed map of part of the Garden Area (Fig. 7).

The band faults in the Garden Area form a remarkably simple regional pattern (Fig. 6). Traces of a right-lateral set trend about N30°E, and traces of a left-lateral set trend N60°E. There are three remarkable features of the band faults. First, narrow zones of band faults extend through the entire thickness of the Moab Member, about 10 m, and extend laterally for hundreds or thousands of meters, yet they have an average width of perhaps only 5 mm. The only exception is a zone of band faults with an average width of about 100 mm, which trends N60°E near the northern edge of the inkblot-shaped, covered area (Fig. 6) in the southern part of the Garden Area, and which accommodated strike slip of several decimeters.

Another remarkable feature of the band faults is their coalescence along trend in both plan and cross-section. The segments of narrow band faults step laterally with respect to adjacent segments. The left-lateral, strike-slip fault segments generally step right, and the right-lateral fault segments generally step left, although we have seen several examples where the opposite occurs. Where the bands coalesce by stepping, a duplex structure forms, as we have demonstrated elsewhere (Cruikshank *et al.* 1991b). The duplex structures along strike-slip faults are rhomboidal shapes in plan view, a few centimeters to a few decimeters long and a few centimeters wide. There is a series of short, parallel bands between the stepping fault segments connecting the overlapping bands at an angle of about 5–20°.

The third remarkable feature of the band faults is their growth sequence. The two sets of faults transect each other to form a conjugate strike-slip rhomboidal network (Fig. 7). Cross-cutting relations indicate that the faults in each set formed incrementally and sequentially so that the band faults in the two sets have developed roughly simultaneously (Zhao & Johnson 1991), where the swarm of one set of faults cross-cuts members of the other set (Fig. 7). Members of one set offset members of the other, and vice versa, even in an area of a few hundred square meters. Examination of cross-cutting relations also indicates that segments comprising a single band fault develop at different times. For example, Fig. 8 shows the formation sequence of the faults in the area shown in Fig. 7. Four fault segments of the N30°E set formed first (Fig. 8a) and were offset by four longer segments of the N60°E set (Fig. 8b). This process was repeated (Figs. 8c & d), and then two long segments and one short segment of the N30°E set formed (Fig. 8e). The final pattern shown in Fig. 8(f) presumably represents several more alternations of N30°E faulting and N60°E faulting.

FAULTED JOINTS

Throughout the Garden Area, the J-3 fractures of Dyer, striking about N10°W, have slipped. According to

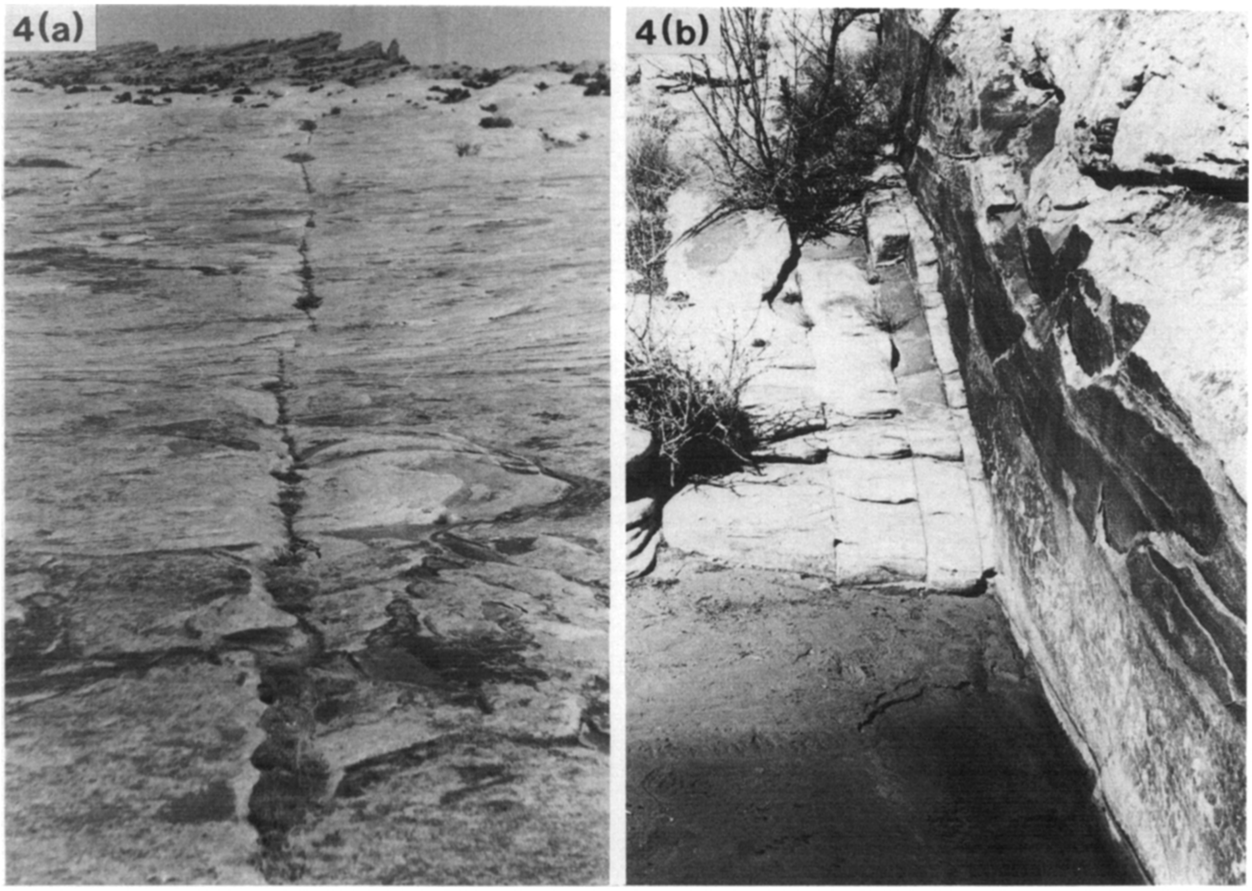

Fig. 4. (a) View of one of the zones of joints that trends about N15°W showing the typical stepped and segmented nature. Most segments step right and are misaligned in a counterclockwise sense. (b) Surfaces of individual joints within a zone typically have smooth faces, although faint hackle marks are present.

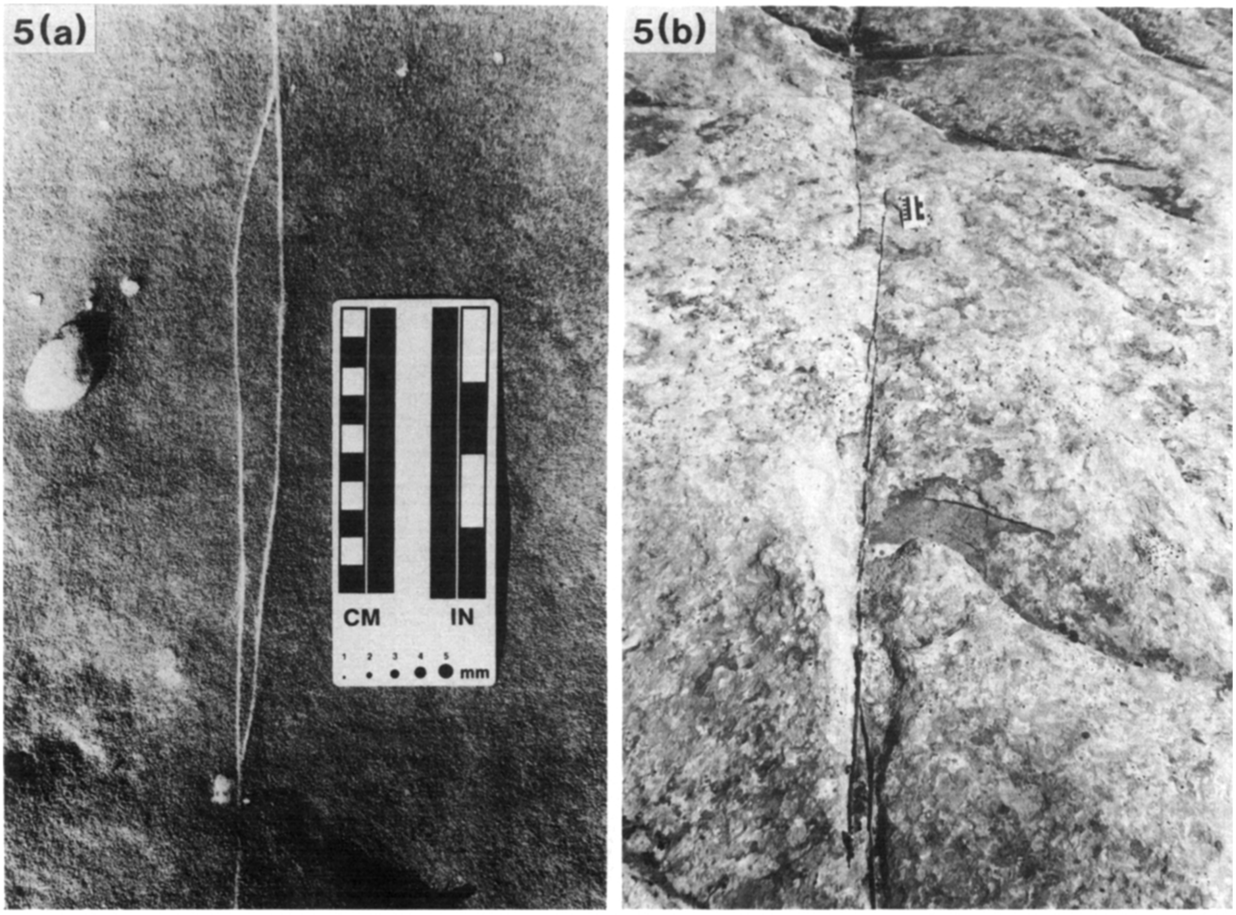

Fig. 5. (a) Vertical view of two left-lateral strike-slip deformation band faults (light traces) in medium-grained sandstone containing concretions. (b) Four segments of a band fault. The three segments in the foreground have coalesced, with short connecting faults, while the two in the background overlap but remain separate (next to the scale).

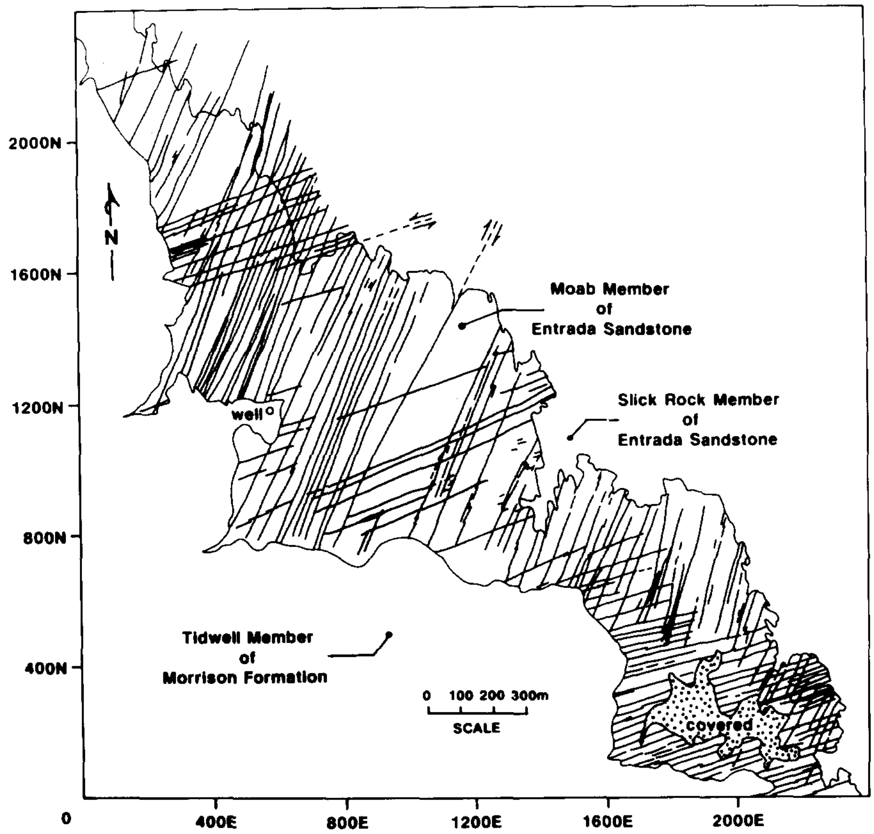

Fig. 6. Traces of band faults in the Garden Area. The band faults trending N30°E are invariably left-lateral and those trending N60°E are invariably right-lateral in the area.

Dyer (1983), the slip along the J-3 fractures has been roughly horizontal, so the fractures are joints that have reactivated as strike-slip faults. The amount of slip along the faulted joints differs across the locality, but is a few millimeters to a few centimeters. One faulted joint in the eastern central part of the area has a slip of 9 cm.

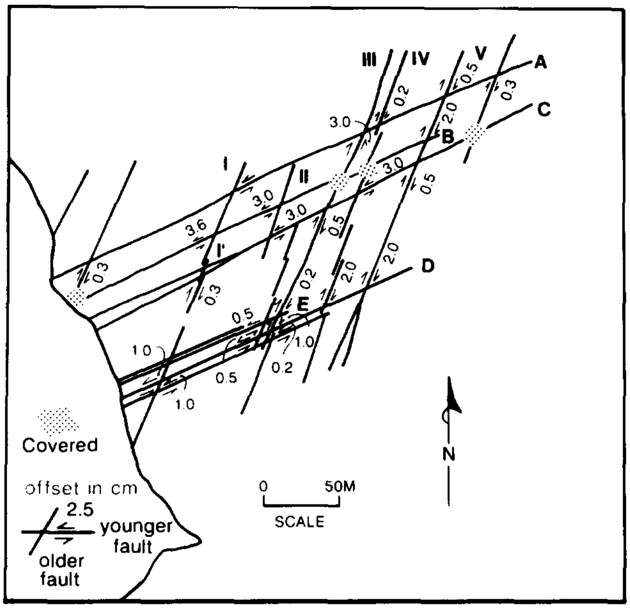

Fig. 7. Traces of several zones of deformation bands trending N30°E or N60°E in part of Garden Area centered at co-ordinate 1650N 400E (Fig. 6). Intersections shown between five faults of the N30°E set (labeled I, II, III, IV and V) and four faults of the N60°E set (labeled A, B, C and D) except where obscured by cover. Sense of slip shown by a pair of arrows at each intersection is placed along the younger fault and the amount of slip is in cm. Thus, at the intersection of faults I and A, the amount of offset is 5 mm and fault A is younger than fault I.

The slip increases with length of a faulted joint or a zone of faulted joints. We measured slip along four composite faulted joints, which we judged to be behaving as single fractures, and obtained the results in the first three columns in Table 1. The faulted joints were close together near the well (Fig. 2). They range in length from about 13 to 42 m, a factor of more than 3, and all except the shortest one are composed of several echelon segments connected, or nearly connected, by secondary cracks. The longest one, 42 m long, contains at least nine segments.

The results in the last column in Table 1 were computed from an equation that relates the shearing displacement across a fault, ΔU, to the dimensional parameters of the fault and to the shear stress in excess of the strength $(\sigma_{xy} - \tau)$, applied to the rock containing the fault (Pollard & Segall 1987, p. 300):

$$\frac{\Delta U}{a} = 2\left(\frac{\sigma_{xy} - \tau}{\mu}\right)(1 - \nu)\sqrt{1 - \left(\frac{x^*}{a}\right)^2}.$$

where a is the half-length of the crack. The numbers in the last column are

$$2\left(\frac{\sigma_{xy} - \tau}{\mu}\right)(1 - \nu) = \frac{\left(\frac{\Delta U}{a}\right)}{\sqrt{1 - \left(\frac{x^*}{a}\right)^2}}.$$

Here ν is Poisson's ratio and μ is shear modulus.

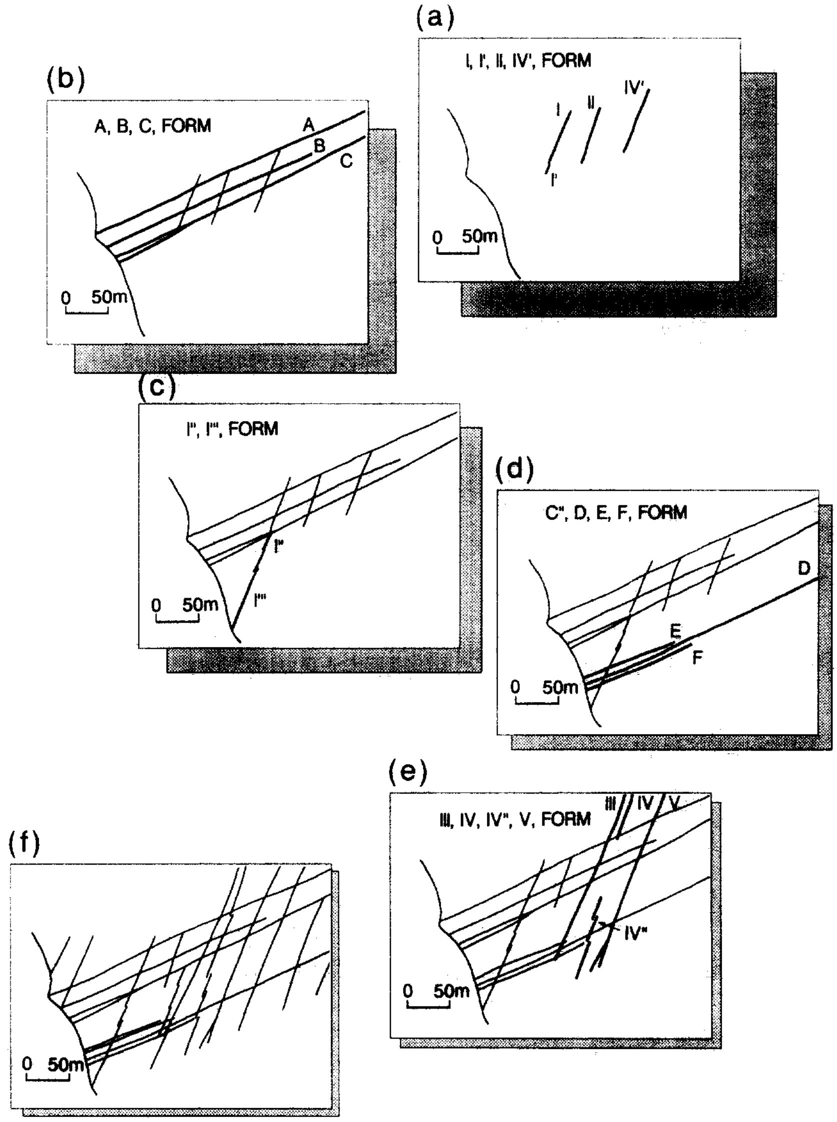

Fig. 8. Scenario of development of fault segments in the area of Fig. 7. Heavy lines indicate faults that are currently active in a snapshot. (a) Three right-lateral faults formed. (b) They were subsequently offset by three left-lateral faults, A, B and C. (c) Two other right-lateral segments, I″ and I‴, formed. (d) Two new 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 left-lateral faults. (f) This sequence accounts for the development of many faults in the area of Fig. 7.

The results are remarkably consistent, suggesting that the far-field stress state was roughly uniform for the faulting of the joints in this small area.

The sense of slip is different in different parts of the Garden Area, as shown in Fig. 3. Opposite senses of slip along faulted joints in different parts of the area reflect inhomogeneous deformation, but there is a definite pattern. Within the northern third of the area, the sense of slip is consistently left-lateral. In a narrow band trending NW–SE, about 200 m north of the well (coordinate 1400N 400E, Fig. 3), the left-lateral slip reduces to zero and the slip changes to right-lateral. The sparse data for the southern part of the area suggests that the slip reverses, to again become left-lateral, and may reverse farther south to become right-lateral. Because the sense of slip reverses over short length scales, it is probably not a result of regional shearing. The shearing distribution may result from flexural slip of rock plates that were bounded by vertical zones of joints about a vertical axis of flexuring.

Table 1. Slip measured on composite joints judged to be behaving as single fractures

Half length (a, cm)	Slip (ΔU, cm)	Distance from midlength (x^*, cm)	$2\left(\frac{\sigma_{xy}-\tau}{\mu}(1-\nu)\right)$
1250	1.0	−140	0.0008
2100	1.2	−1800	0.0011
2100	1.7	−45	0.0008
2100	1.4	60	0.0007
640	0.45	220	0.0007
640	0.4	270	0.0007
1400	1.0	−38	0.0007

JOINTED FAULTS

In both the northern and southern parts of the Garden Area, deep grooves or slots have been eroded along or

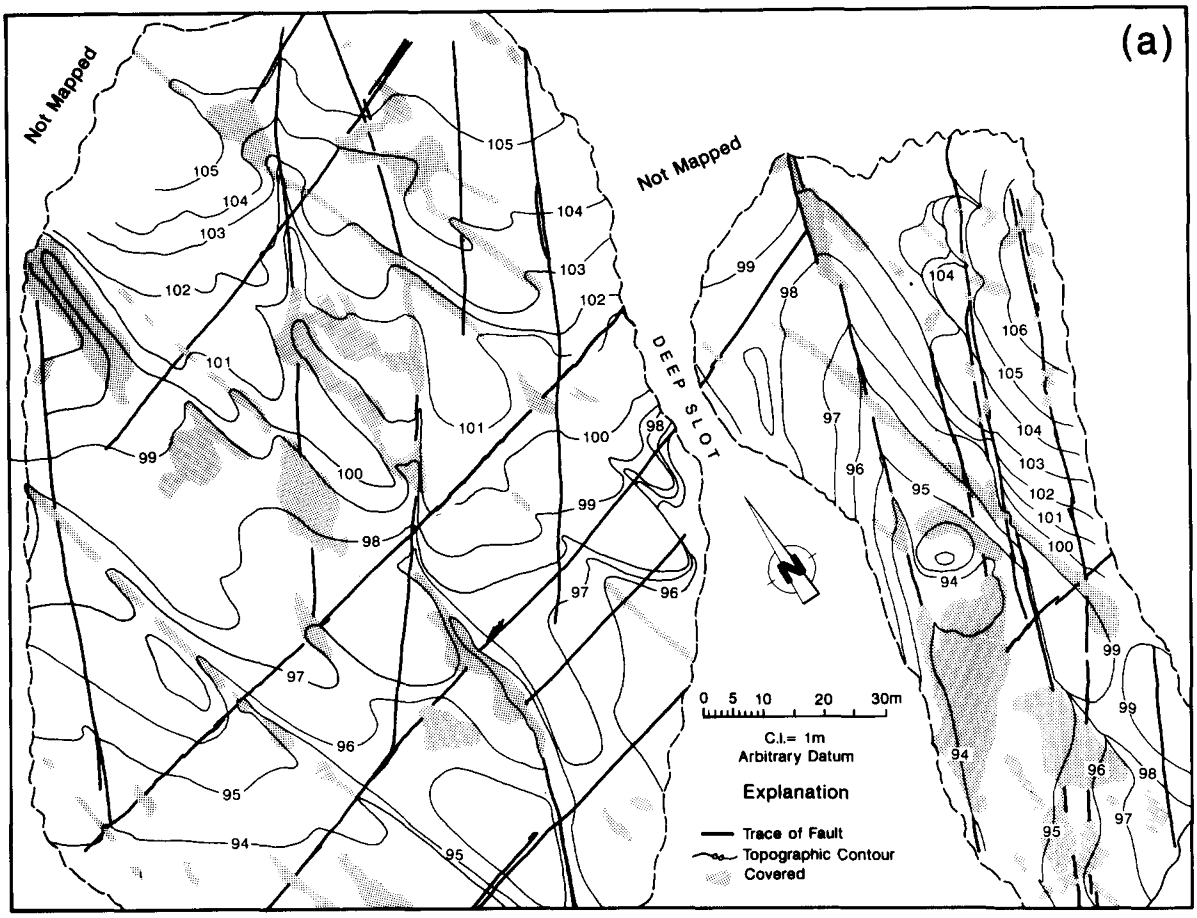

Fig. 9. (a) Plane-table map of the topography and the traces of the band faults in the southern part of the Garden Area (co-ordinates 700N 1600E, Fig. 2).

near the traces of some band faults, particularly those trending N30°E. The grooves are similar to those that have been eroded along the J-3 fractures throughout the Garden Area. Within the grooves are both band faults and joints, indicating that the faults apparently reactivated as weak zones for jointing. Subsequently, weathering and erosion were concentrated along the jointed faults just as they were along the joints and faulted joints trending N10°W.

In general, the northern parts of the band faults became jointed faults. The other parts were not activated. Also, unjointed zones of deformation bands are parallel and adjacent to jointed faults, presumably indicating that some zones of band faults were weaker than others during jointing. The jointed faults in the northern part of the Garden Area trend N30–35°E. In the southern part, they trend either N30–35°E or N65–70°E, the same as the conjugate band faults, as shown in Fig. 6.

Figure 9(a) is a plane-table map of the topography and the traces of the band faults in the southern part of the Garden Area. The contours and elongated sand-covered patches show topographic slots, trending about N15°W and N30°E. The slots trending N15°W are parallel to the J-3 fractures (Fig. 9b). The slots trending N30°E are along only parts of band faults, trending N30°E. The map shows that many of the band faults trending N30°E, and all the band faults trending N60°E, cut across the topographic surface, having no effect on the erosion pattern. A slot trending N30°E (Fig. 9b) has short joints on either side that extend a few meters away. The same kind of short fractures occur predominantly on the eastern sides of the two joints and band faults trending N30°E through the center of the map area (Fig. 9b). The first 12 m of the western band fault (Figs. 9b and 10a) has no topographic expression. The last 12 m of the structure are band-fault segments and joint segments in a topographic slot (Fig. 10a). Parts of the joint are exposed and there are gaps a few millimeters wide at, or near, the base of the topographic groove. Thus erosion has been able to exploit the band faults where they are reactivated by jointing.

Branching off the joint segments, almost exclusively on the eastern side, are short joints that curve toward parallelism with the main joint, but generally trend about N15°W (Fig. 10a). Only where the fracture segments are open joints does one find the branching joints on either side of the structure. Where the fracture segments are band faults, the joints extend through the fracture segments without disruption.

The northeastern end of the deeply-incised fracture cuts across and offsets, by 50 mm right-lateral, a band fault trending N70°E (Fig. 10a). This is the typical sense of displacement across band faults trending N30°E throughout the Garden Area. Further, the band fault

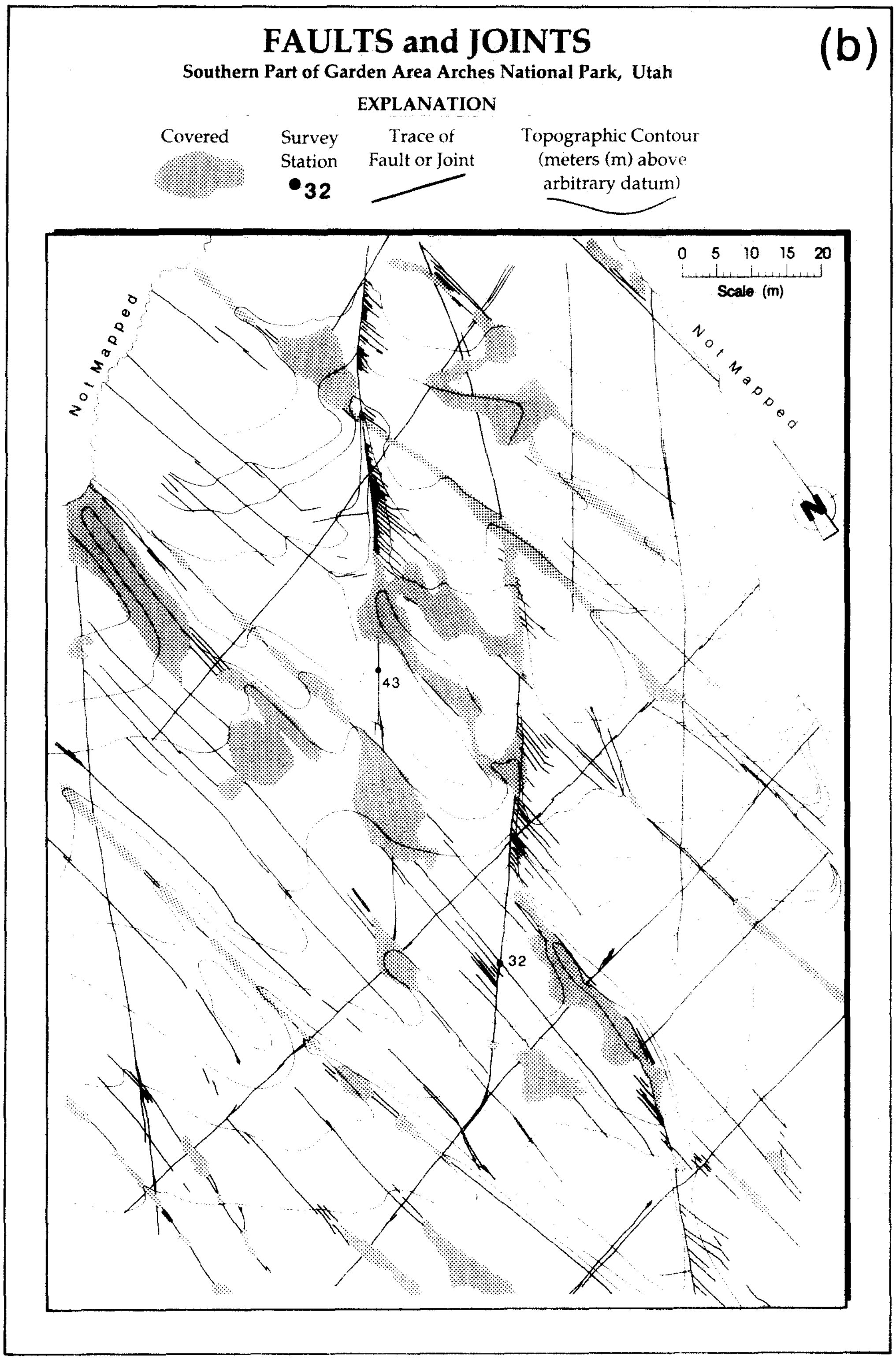

Fig. 9. (b) More detailed map of the western side of the area shown in Fig. 10(a), showing traces of band faults and joints.

trending N70°E offsets a band fault trending N30°E about 10 mm in a left-lateral sense.

The structure shown in Fig. 10(b) extends about 20 m from near station 32 (Fig. 9b) toward the northeast. The structure is a typical band fault, except that it appears as an open joint near station 32, where short fractures branch off to the northwest. A few meters northeast of where it passes through a deep slot, the structure offsets a band fault trending about N60°E 20 mm in a right-lateral sense (Fig. 10a). Beyond that point the structure appears as an open joint and branching joints coalesce with it from the southeast (Fig. 10b).

The trend of the branching fractures possibly reflects left-lateral shear on the band faults that opened as joints, trending N30°E, which is opposite to the right-lateral shear measured on the band faults that did not open as joints. Thus, the sense of shear reversed along the N30°E zones defined by a combination of band faults and

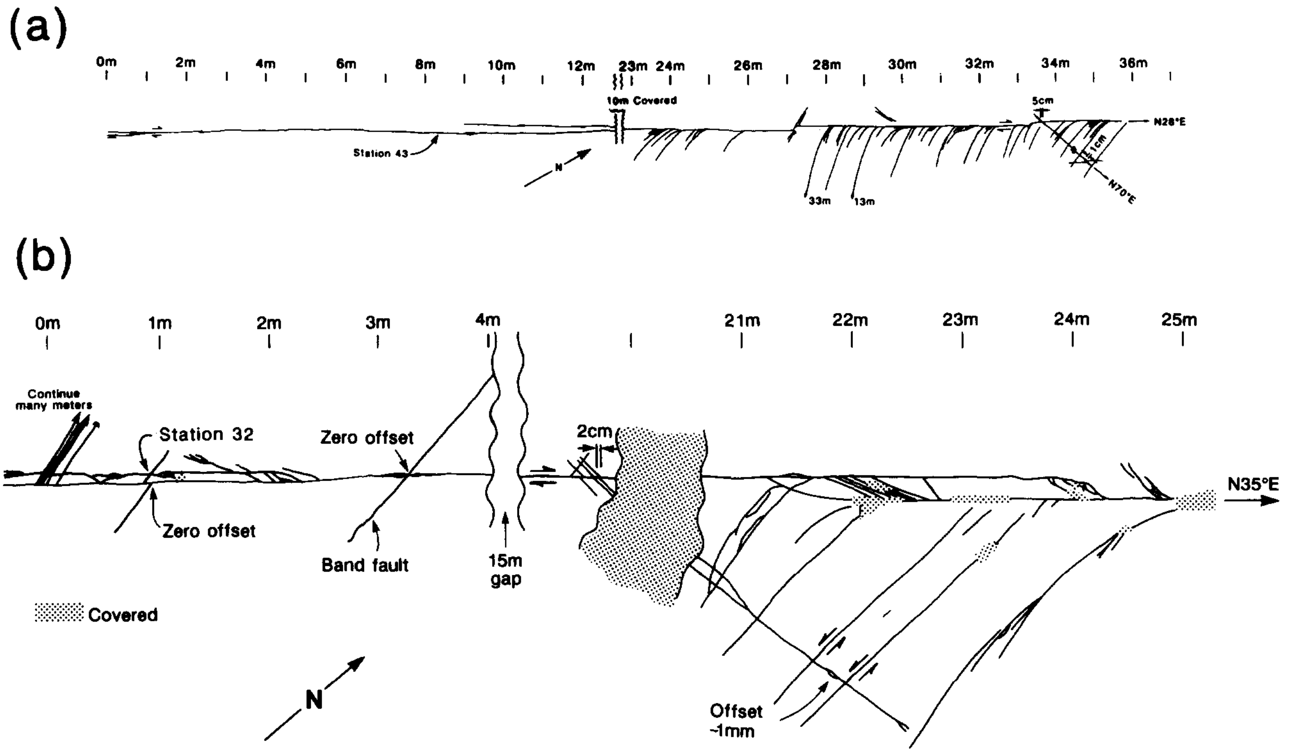

Fig. 10. (a) Detailed map of about 25 m of the trace of a jointed fault near station 43 in Fig. 9(b). (b) Jointed fault in the southern part of the Garden Area. It extends about 20 m from near station 32 (Fig. 9b) toward the northeast.

faulted joints. At the time of band faulting, there was right-lateral shear and at the time of faulting on joints, there was left-lateral shear.

SCENARIO

The intersections of different structures in the Garden Area provide an opportunity to determine their age relations. Faults and joints cut or intersected each other at different stages of evolution and in different places to form a complex net of fractures in the Garden Area (Fig. 2). The simplest deformation sequence is as follows.

(1) After the Entrada Sandstone was consolidated and buried to a depth of a few kilometers, the Garden Area was subjected to compression in the direction N45°E and to extension in the direction N45°W. The vertical strain was zero and the area deformed via strike-slip faults oriented N30°E and N60°E. The deformation was rotational in most areas because the faults generally occur in domains containing single sets.

(2) Subsequent tension in the SE direction, or a combination of extension in the SE direction and high pore-water pressure in fractures, localized mode I fractures along some of the weak band faults and formed the jointed faults in the northern and southern parts of the Garden Area. The orientations of principal stresses need not have changed, because the band faults provided the rock with fracture anisotropy. These jointed faults have eroded to form deep slots (Fig. 9a).

(3) The third recorded event was the formation of systematic zones of joints in most places in the Garden Area, trending N15°W to N5°W. At that time, the minimum compression was reoriented to about N80°E, so the principal horizontal stresses had rotated about 45–60°. The cover presumably was shallow, or the pore-water pressure was high, because there is no evidence for normal faulting in the Garden Area. At the same time, the short joint segments formed along the jointed faults, and the sense of slip on the jointed faults was opposite to that on the original band faults. That is, the slip on the original N30°E band faults was right-lateral whereas the slip on the subsequent N30°E jointed faults was left-lateral.

(4) The final deformation was slip along joints trending about N10°W. The rock slabs bounded by the zones of joints were subjected to flexural slip, converting most of the joints into faulted-joints, with different senses of slip in different parts of the Garden Area. The bending was essentially a local, not a regional, phenomenon.

Thus, our study indicates that the area was subjected to two mild regional deformations: First, compression normal to the axis of the Salt Valley anticline, about N45°E, and extension parallel to the axis; the vertical deformation was negligible. The amount of horizontal strain was of the order of 0.1%. Second, N–S compression at a high angle to the axis of the anticline, and E–W tension or extension. The amount of strain accommodated by the opening of joints was about 0.05%.

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