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Duplex structures connecting fault segments in Entrada Sandstone

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Abstract—All stages in the development of a duplex structure—from isolated, stepped fault segments, to segments joined by a single ramp, to segments joined by tens of ramps—are preserved along strike-slip and normal faults in Entrada Sandstone in Arches National Park, Utah. Bedding is either absent or at a high angle to the duplex-like structures in Entrada Sandstone, thus it had no significant role in constraining their geometry.

We can reproduce the essential features of a duplex structure along a normal fault with mechanical and kinematic models previously used to simulate duplex structures along thrust faults. However the models do not account for the amount of observed thickening at the step where the structure forms. This suggests that the geometry of duplex-like structures along these strike-slip faults may be a result of interaction between the fault segments.

INTRODUCTION

A HOST of intriguing structures are formed in transfer zones where strike-slip faults overlap and interact within an area of mildly-deformed Entrada Sandstone in the Garden Area of Arches National Park, Utah (Fig. 1). Some of the faults are fractures that originated as joints and subsequently slipped as faults (e.g. Segall & Pollard 1980), and others are fractures that originated as band faults (e.g. Aydin 1978). Both types of faults are zones composed of numerous parallel fault segments. The zones of faults extend for hundreds of metres, but the fault segments are a few metres or tens of metres long (Zhao & Johnson 1991, in press). Slip throughout a zone of faults occurs along individual segments and is continued to adjacent segments through transfer zones. The transfer zones accommodate the deformation where the fault segments step left or right.

The structures within the transfer zones are quite different depending on whether the faults are band faults or faulted joints (Zhao & Johnson in press). In right-lateral shear, the transfer zones between segments of faulted joints in Entrada Sandstone are bridged by tension cracks if the step is right (Fig. 2b), whereas they are unbridged if the step is left (Fig. 2a). In contrast, transfer zones between segments of band faults are bridged by short ramp faults whether the segments step to the right (Fig. 2d) or left (Fig. 2c).

Many of the transfer-zone structures between segments of band faults within the Garden Area contain ramp faults and thus have the fault pattern of duplex structures; they are duplex-like structures. We will show that the structures not only look like duplex structures, but that their internal kinematics are those of the classic duplex structure described along thrust faults (e.g. Boyer & Elliott 1982, Cruikshank *et al.* 1989, Johnson & Berger 1989). Although these structures have the same geometry and sense of slip as duplex structures described along thrust faults, we use the term 'duplex-like' to describe them because it is unclear if duplex and duplex-like structures were formed by the same mechanism.

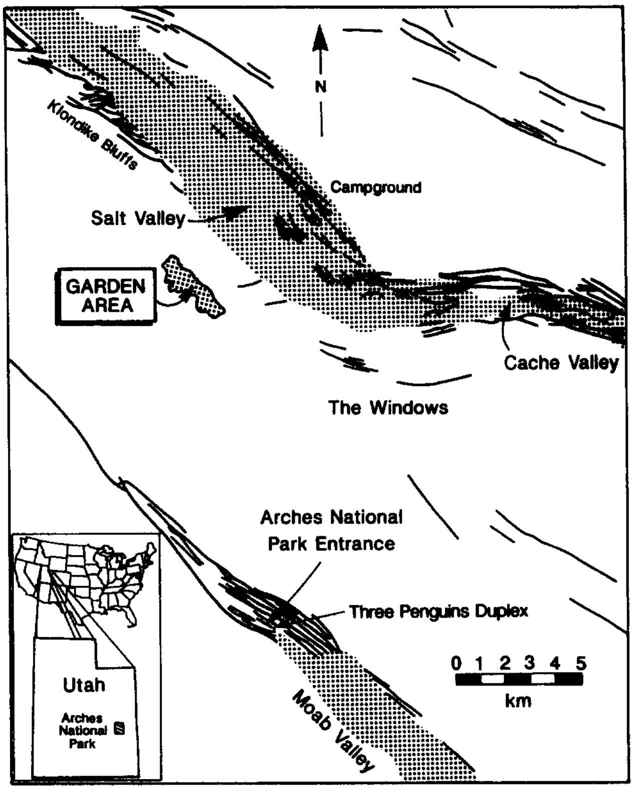

Fig. 1. Location map for Garden and Three Penguins areas of Arches National Park, near Moab, Utah. Area is underlain by Entrada Sandstone exposed on the SW limb of the Salt Valley anticline, one of the Salt structures (indicated by stippled pattern) within the Paradox basin of western Colorado and eastern Utah. The Garden Area is in relatively undeformed rocks between Salt Valley anticline and Moab Valley fault zone. The Three Penguins Area, which is near the Park entrance, is close to the Moab Valley fault zone. Only larger faults (from Doelling 1985) are shown.

Duplex-like structures have previously been de-

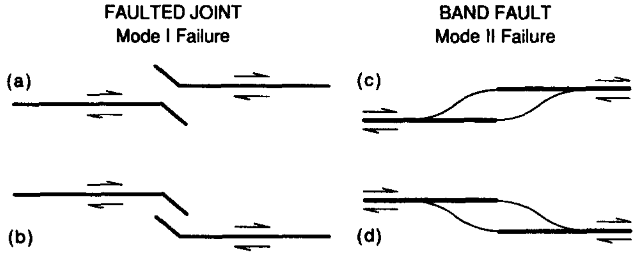

Fig. 2. Cartoon showing the differences between mode I (opening) and mode II (shear) failure on fault segments subjected to right-lateral shear (Lawn & Wilshaw 1973). In right-lateral shear, the transfer zones between segments of faulted joints are bridged by tension cracks if the step is right (b), whereas they are unbridged if the step is left (a). In contrast, transfer zones between segments of band faults are bridged by short ramp faults whether the segments step to the right (d) or left (c).

scribed along strike-slip faults in outcrops in southern Maine (Swanson 1988, 1989), and at regional scales; for example, the Caleveras fault zone in central California (Aydin & Page 1984, Woodcock & Fischer 1986), and in the Middle East (Woodcock & Fischer 1986). Our results supplement these previous studies because the structures we describe clearly have both the internal fault pattern and the displacement distribution of the classic duplex structure.

The objectives of this paper are to document the occurrence and kinematics of duplex-like structures along strike-slip and normal band faults, and to investigate the conditions responsible for their formation.

RAMPS AND DUPLEX STRUCTURES ALONG STRIKE-SLIP FAULTS

The Garden Area (Fig. 1) of Arches National Park is a nearly-complete exposure of Entrada Sandstone, of approximately 1.5 km^2 with little vegetation cover on the SW limb of the Salt Valley anticline, and provides an excellent site for studying faults and joints within the Moab Member of the Entrada (Dyer 1983, 1988). The outcrop consists of a series of N–S-trending hummocks with up to 5 m of relief. The grooves bounding the hummocks formed along zones of joints and the band faults are oblique to the hummocks. The rocks are practically undeformed; the limb of the anticline here dips only 7–10° to the southwest, and the strain accommodated by slip on faults and joints accumulated to perhaps 2%.

The fractures described in this paper occur in the 10 m thick white sandstone of the Moab Member of the Entrada Sandstone. Underlying the white sandstone are about 70–95 m of red, cross-bedded sandstone of the Slickrock Member of the Entrada Sandstone, and overlying are about 12 m of thinly-interbedded claystone, sandstone and limestone of the lower part of the Morrison Formation (Dyer 1988).

Band faults

The earliest structures formed in the Garden Area were band faults, which are composed of individual deformation bands, or bundles of anastomosing deformation bands, within which grains are crushed and slip is distributed to accommodate a few mm or cm of offset. Band faults were described in detail in similar rocks about 100 km west, in the San Rafael Desert, by Aydin (1977, 1978), and represent a mode of faulting common in porous sandstones (Dunn *et al.* 1973, Aydin 1978, Aydin & Johnson 1978, 1983, Smith 1983).

Figure 3 shows the distribution of zones of strike-slip band faults in the Moab Member in the Garden Area. Throughout the Garden Area, each set of band faults shows a consistent sense of horizontal offset of markers. The apparent offset could be produced by various components of slip on a fault, however; slip vectors on the faults were calculated in several places using offset cross-bedding with different attitudes. The measurements indicate that the net slip vector plunges 5–10° W, parallel to the contact between the Moab Member and the overlying Morrison Formation. In a few places slickensides are exposed and the striations plunge westward within a few degrees of horizontal. Thus the slip is approximately parallel to fault traces in the Garden Area, and we call them strike-slip faults.

Individual zones of band faults can be followed across the outcrop for distances up to about 1 km. There are two sets of strike-slip band faults in the Garden Area, and the sense of slip is consistent throughout the area; one set strikes approximately N30°E, and offsets markers in a right-lateral sense, the other set strikes approximately N60°E, and offsets markers in a left-lateral sense. Thus, the two sets of faults form a conjugate pair.

Fault segmentation

Individual zones of band faults, which can be followed for distances of over 1 km (Fig. 3), are composed of segments of zones of deformation bands ranging in length from about 0.5 to 20 m. Detailed maps of individual band fault traces (Fig. 4) show the segmented nature of the traces, which are approximated as continuous lines on the map (Fig. 3). Figure 4(a) shows traces of isolated segments of a band fault. One can envisage lengthening and joining of the segments to form a continuous trace, as in Fig. 4(b). Some of the segments shown in Fig. 4(a) are composed of series of even shorter segments.

Fault segments are nearly co-linear, but step short distances (from a few mm to dm) to the left or right. Individual faults can have both right and left steps (Fig. 4b), although left-lateral faults (striking N60°E in the Garden Area), have predominantly right steps, and right-lateral faults (striking N30°E) have predominantly left steps. Thus, the majority of the steps in the area are compressional (Segall & Pollard 1980, 1983).

Interconnection of segments

We have noted that band faults are composed of series of segments (Fig. 4a), and that slip on the segments is

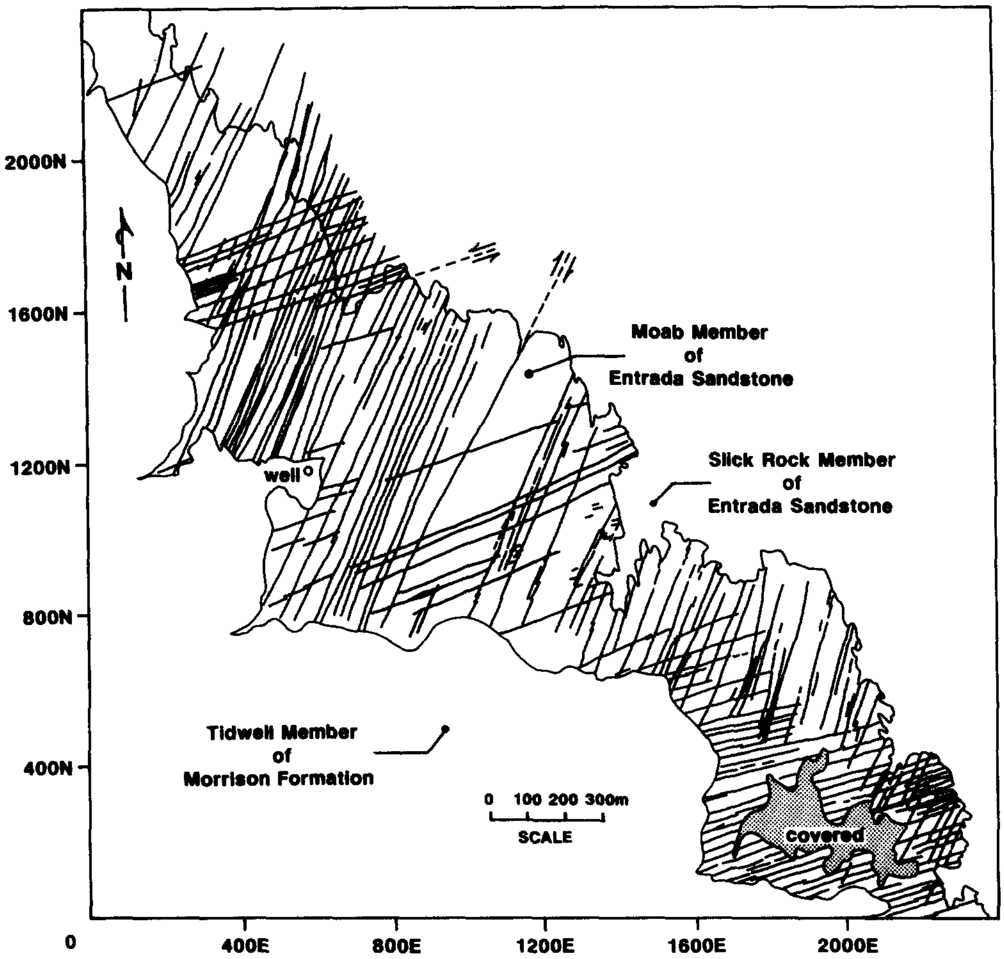

Fig. 3. Traces of zones of band faults in the Garden Area. The band faults trending N30°E are invariably left-lateral, and those trending N60°E are invariably right-lateral in the area.

essentially parallel to the traces on the outcrop surface. At the transfer zone between adjacent fault segments, the segments branch and lengthen to form a continuous fault (Fig. 4b). The connecting faults form different patterns and shapes, with different degrees of complexity and number of connectors; some of the variation in connecting faults at steps is shown in Fig. 5.

The simplest structure in the transfer zone consists of overlapped segments with no connecting faults (Fig. 4a). The rock between the faults apparently absorbs the deformation produced by slip on the faults. A slightly more complex structure consists of a single, connecting ramp fault (Figs. 5a and 6a). The ramp curves gently from the left segment, and has an angular contact with the right segment. A still more complex structure is formed where each segment extends and curves to join the other. The basic form resulting from two connecting ramps is insignificantly modified by addition of more ramps (Figs. 5c–g). The connecting faults at steps between segments of band faults in the Entrada Sandstone

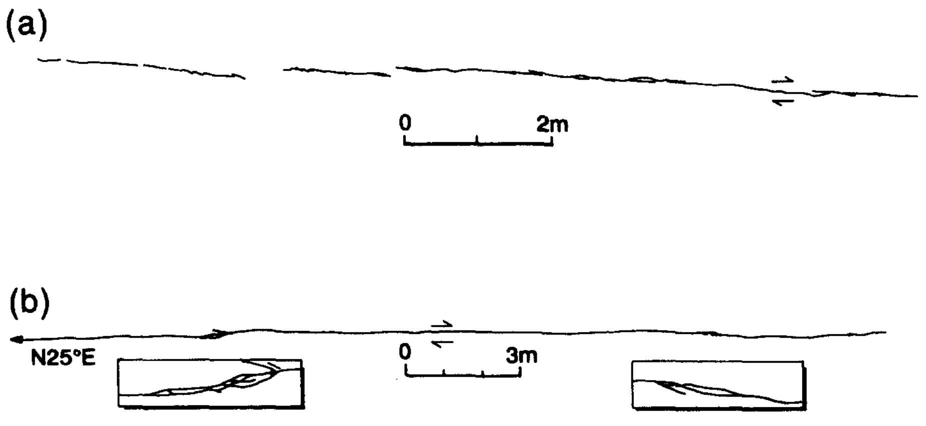

Fig. 4. Traces of band faults showing their segmented nature. In (a) some segments are still isolated, although the segments are themselves composed of smaller segments. In (b) a continuous band fault is shown. The segments are joined by ramp-like structures. Note the similarity between the structures formed at the two steps (inset).

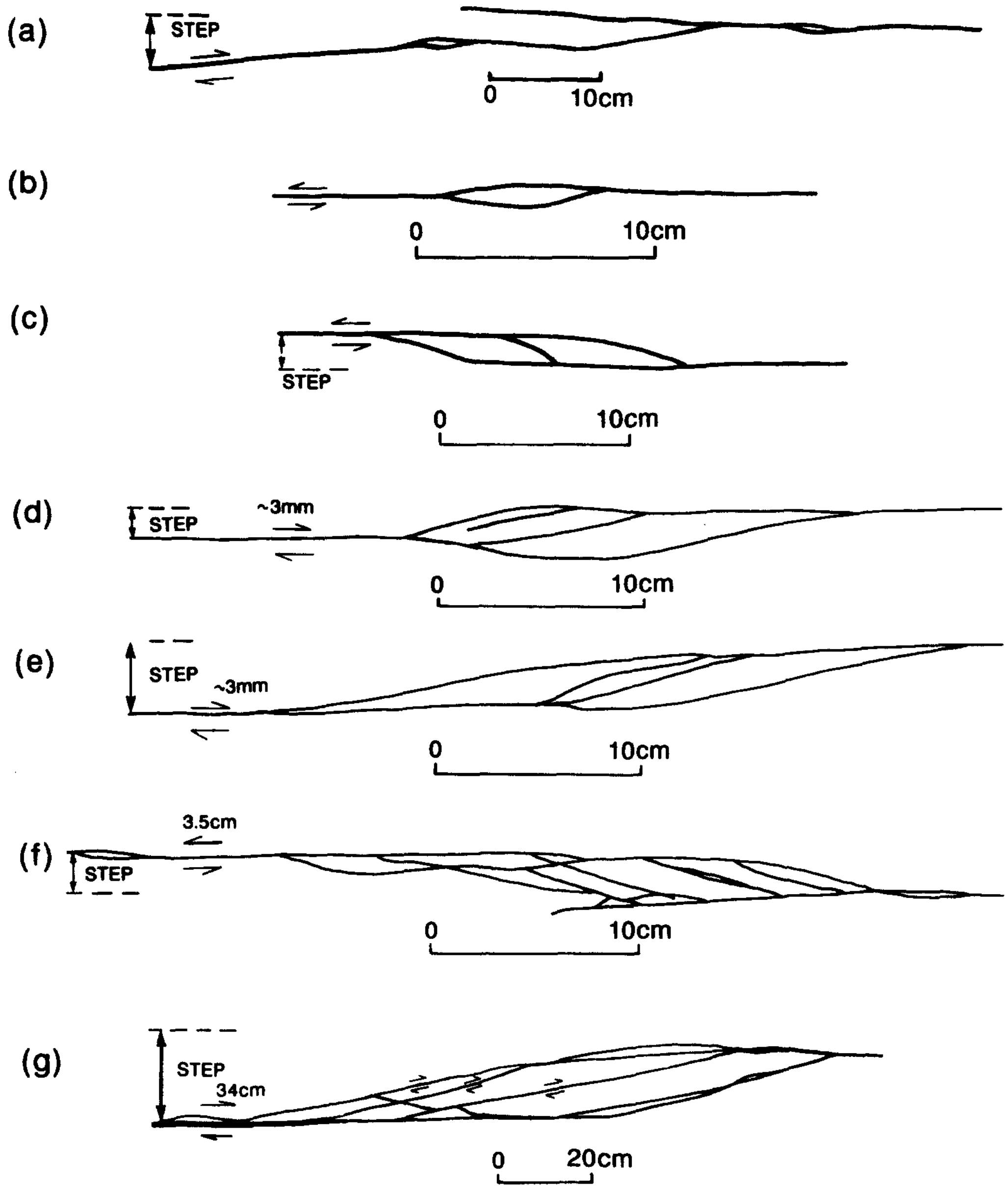

Fig. 5. Maps of duplex-like structures in the Entrada Sandstone.

have the same geometry as those in duplex structures described from thrust sheets.

Duplex-like structures

Clearly, the patterns of faults described above have the essence of fault patterns within duplex structures, that is, two fault segments connected by band faults at a low angle to the segments and dipping opposite to the transport direction. Figures 5 and 7 show some of the duplex-like structures observed in the Entrada Sandstone. They range from small structures about 10 cm long, with a few ramps (Fig. 7a) or many ramps (Fig. 7b), to large structures several metres long, with several ramps (Fig. 7c).

One of the problems with interpreting the structures described here as duplex structures is that slip along the ramp faults generally is unobserved. In principle, the ramp faults could be conjugate to the stepping fault segments so that the sense of slip on the ramps would be opposite to that of the fault segments. In most places we can determine the sense of slip along fault segments because they intersect cross-beds with different orientations or intersect other band faults. The transfer zones between fault segments are, however, small areas and are exposed on bedding surfaces, so there generally are insufficient markers to document the sense of slip on individual ramp faults.

Some of the transfer zones contain short, back-facing faults. The ramp faults are inclined about 30°, whereas the back-facing faults are inclined about 120° to the stepped fault segments, and face in the opposite direction to the ramps. A single back-facing ramp can be seen in the lower left of Fig. 5(g). A few of the back-facing faults have been offset a few millimetres by the ramp faults, and the sense of slip recorded by the offsets is invariably the same as that on the fault segments. Thus, we have some evidence that the duplex-like structures

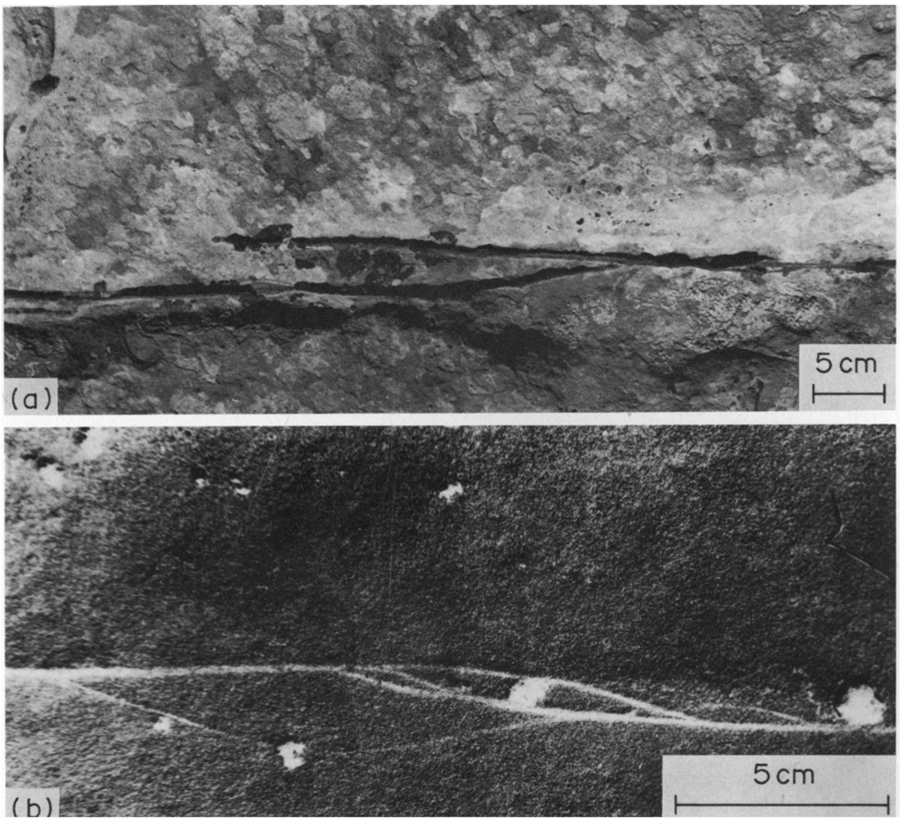

Fig. 6. Duplex-like structures in the Entrada Sandstone along strike-slip faults in the Garden Area.

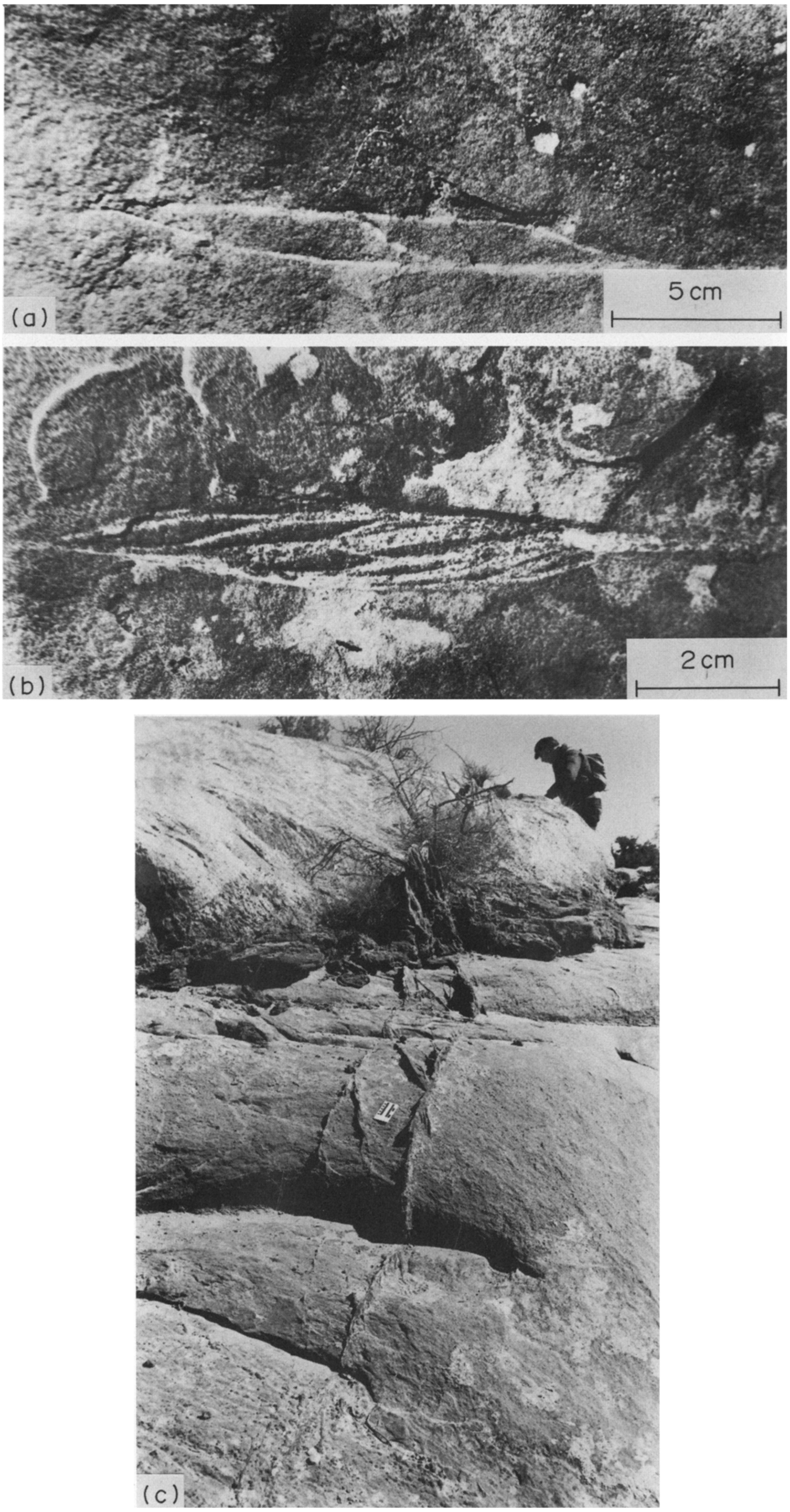

Fig. 7. Size range in duplex-like structures in Entrada Sandstone of the Garden Area. The structures range in size from a few centimetres (a) to several metres (c).

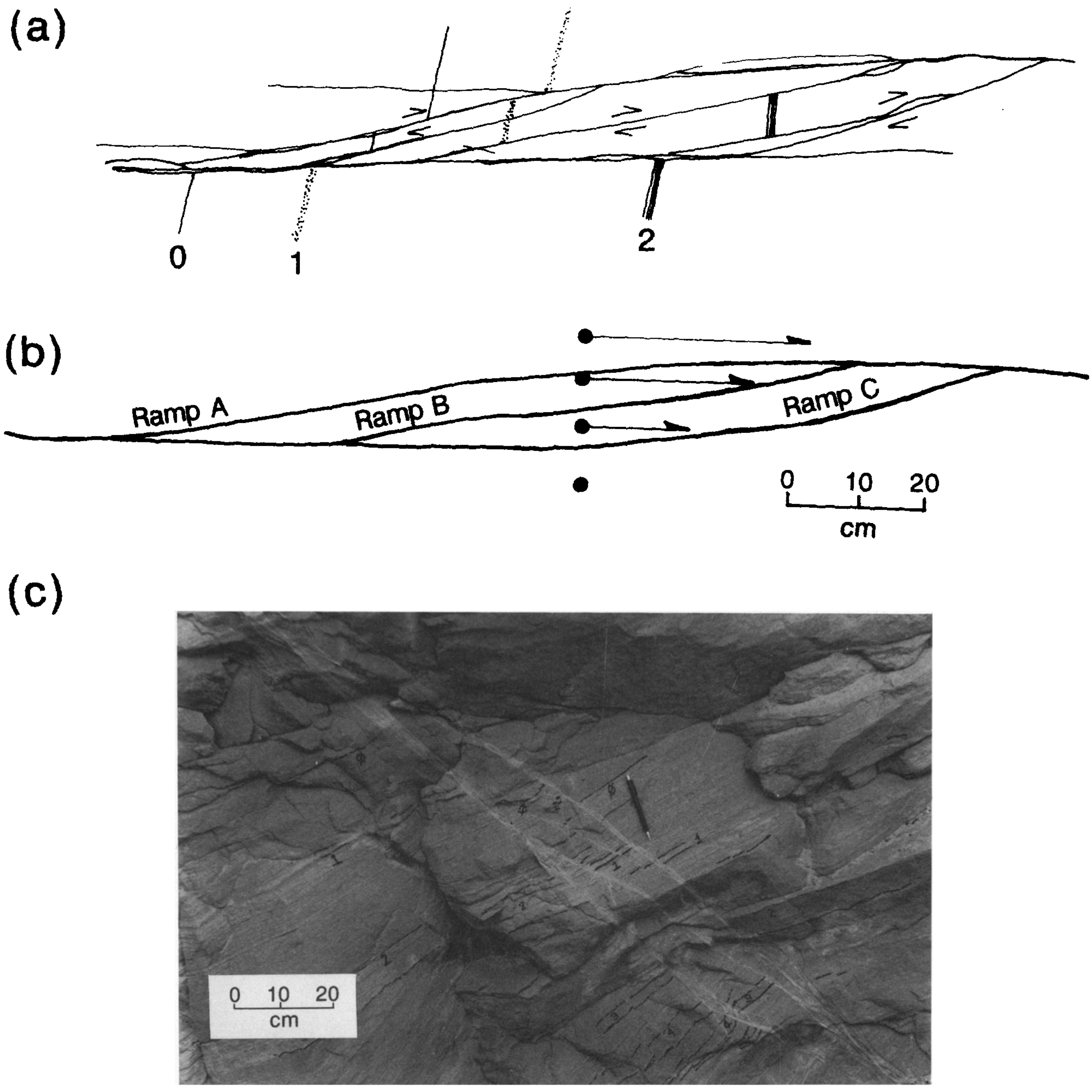

Fig. 8. Three Penguins duplex structure, near the entrance to Arches National Park. This structure in on a normal fault, formed at a compressional step between segments. A simplified map of the structure is shown in (a), the relative displacement of each horse with respect to the lower segment is shown in (c). The complete structure is shown in (c).

along strike-slip faults in Entrada Sandstone have the same type of kinematics as the classic duplex structures along thrust faults. After examining hundreds of structures in transfer zones between stepping band faults, we conclude that the patterns of faulting within these structures are the same as those within duplex structures in thrust sheets, and that the sense of slip on the fault segments and the connecting ramp faults are the same as the slip in the classic ramp and duplex structures in thrust sheets (Rich 1934, Boyer & Elliott 1982).

THE THREE PENGUINS DUPLEX: A NORMAL-FAULT DUPLEX

More detailed information concerning the formation of ramps and duplex structures in massive sandstone is provided in the Three Penguins Area of Arches National Park, about 100 m west of the visitor center at the park entrance (Fig. 1). There are spectacular normal band faults in Entrada Sandstone and Navajo Sandstone in the Three Penguins Area, and a series of duplex structures are exposed along road cuts there.

The normal band faults at the park entrance are identical in form to the strike faults in the Garden Area. They are segmented, and the steps tend to be opposite to the sense of slip—left steps on faults with dextral slip as viewed in a vertical plane. Also, ramp and duplex structures occur within the transfer zones between segments of the normal faults.

The similarity between the duplex structures along strike-slip and normal faults is emphasized by comparison of examples shown in Fig. 5. Figure 5(g) shows a duplex structure along a normal fault, whereas the other parts of Fig. 5 show duplex structures along strike-slip faults. The duplex structure along the strike-slip fault shown in Fig. 5(f) is quite similar to the duplex structure along the normal fault shown in Fig. 5(g). The normal-fault duplex is seen in a vertical roadcut, whereas the strike-slip duplex structures are seen on bedding planes. There is, however, a very significant difference in the amount of information one can obtain about the kinematics of the horses within the duplex structures. The normal faults cut bedding at a high angle so there are sufficient marker beds to document the sense of slip on the ramp structures.

Figures 5(g) and 8 show the Three Penguins duplex structure, which is exposed in a roadcut through the Navajo Sandstone near the entrance to Arches National Park (Fig. 1). Only the proximal ends of the two fault segments are shown and, with reference to the view in Fig. 5(g), the slip on the fault is right-lateral and the step is left-lateral indicating there was compression in the transfer zone. The duplex structure is about 1.3 m long and 16 cm high. Cross-beds that encounter the fault segments and ramps all are offset, and pairs of beds can be traced across the entire structure (Figs. 8a & c). The total offset across the structure is about 34 cm. The fault segments and larger ramps are composed of narrow zones of deformation bands up to 3 or 4 cm thick. The bedding within the horses between the ramps is not noticeably reoriented.

The essential features of the Three Penguins duplex are shown in Fig. 8(b). The structure consists of three approximately equally-spaced ramps inclined at about 10° to the fault segments. Within the transfer zone the two fault segments are joined by five ramps inclined at an angle of about 10° to the segments (Fig. 8a). Three of the ramps, however, were loci of the largest offsets, and these three bound two horses of sandstone. The amounts of offset are given in Table 1. Both of the fault segments extend beyond the outermost ramps of the duplex structure; however, the amount of offset on these extensions is smaller than the offset across the duplex structure. The extension of the lower segment offsets bedding plane number two (Fig. 8) by 5 cm, whereas the total offset across the structure measured on bedding planes zero and one is 34 cm. Thus, most of the displacement on one segment was transferred to the other segment along the ramp faults.

SIMULATION OF THREE PENGUINS DUPLEX

We have shown that transfer zone structures along strike-slip and normal faults in the Entrada Sandstone at Arches National Park, Utah, have the geometry and kinematics of duplex structures. We continue by simulating the formation of the Three Penguins duplex using the data in Table 1.

Bedding is at a high angle to the fault segments in the Three Penguins duplex, and is not visible at the steps along strike slip faults in the Garden Area. Bedding cannot be an important factor in the development of

Table 1. Offset and spacing of ramp faults shown in Fig. 8. The step height, *h*, is approximately 14 cm. Total displacement is approximately 34 cm. All ramps are at an angle of approximately 10° to the segments. Final ramp spacing is the observed ramp spacing, and the initial ramp spacing is the ramp spacing before displacement and initial spacing is the sum of the final ramp spacing and displacement. Unless units are given, the value has been normalized with the step height, *h*

Ramp	Offset (cm)	Final ramp spacing (cm)	Displacement	Final ramp spacing	Initial ramp spacing
A	16	n/a	1.12	n/a	n/a
B	12	20	0.85	1.42	2.27
C	6	20	0.42	1.42	1.84

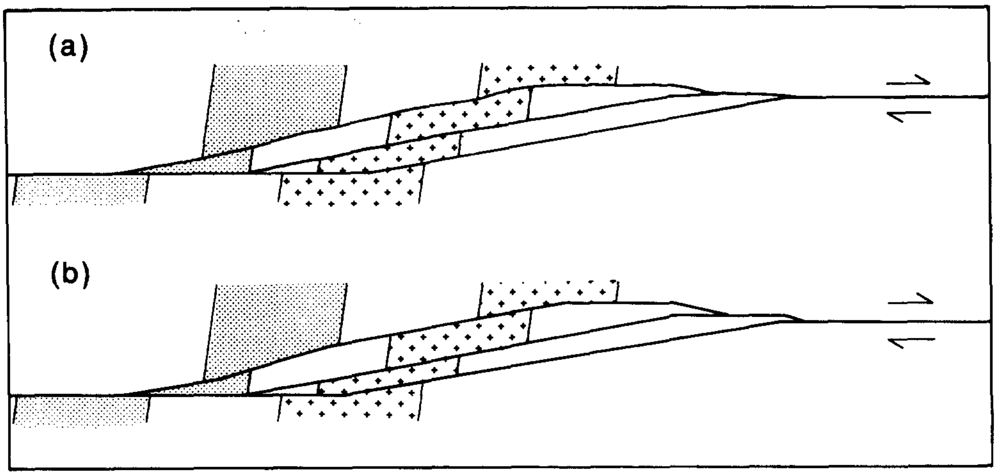

Fig. 9. Simulations of the Three Penguins duplex structure. (a) Using the mechanical model, with a traditional ramping sequence. (b) Kinematic model, using the same scenario as in (a). This figure should be compared with Fig. 8(a).

these structures because, as we have shown, the geometry and kinematics of strike-slip, normal and thrust-fault duplexes are the same, whereas bedding is at a different orientation in all these examples.

We have very good constraints on the displacements on each of the ramps in the Three Penguins duplex (Table 1). The layering that is used to determine offsets is cross-bedding, and the unit that contains the duplex is essentially homogeneous. Thus the structure is very well suited to simulation using existing mechanical and kinematic models for duplex structures (Berger & Johnson 1980, Cruikshank *et al.* 1989, Kilsdonk & Fletcher 1989). We simulate the formation of the Three Penguins duplex using the mechanical model developed by Berger & Johnson (1980), for a homogeneous viscous body moving over a stepped surface, modified by Cruikshank *et al.* (1989) for multiple ramps. The model traces the displacement of passive markers representing bedding, which play no mechanical role in the models and can be orientated at any angle to the fault segments.

Figure 9(a) shows the results of the simulation, which produces the geometric elements of the Three Penguins duplex (Fig. 8b). Figure 9(b) shows the same simulation as in Fig. 9(a), except the kinematic rather than the mechanical model is used (Cruikshank *et al.* 1989). The results are essentially identical. The simulation does not allow footwall deformation. In a homogeneous material deformation would be symmetrical (Kilsdonk & Fletcher 1989), and the structural relief shown in Fig. 9(a) would be distributed symmetrically about the mid-height of the step.

DISCUSSION

We have shown that the duplex-like structures occur at steps between segments of strike-slip and normal faults in Entrada Sandstone. These structures have the geometry of duplex structures described along thrust faults. Where the kinematics can be established, they are the same as the kinematics of duplex structures along thrust faults. Bedding is either absent or at a high angle to the structures, and thus had no significant role in constraining the geometry of the structure. We have shown that, although the geometric and kinematic features of the Three Penguins duplex can be reproduced using models following the Boyer & Elliott (1982) scenario for duplex structures, the sequence of formation and activation of horses proposed by Boyer & Elliott (1982) is inessential to the formation of the Three Penguins duplex.

Ramp formation

Detailed study of several duplex-like structures along strike-slip faults in sandstone suggests that another assumption in the Boyer & Elliott (1982) scenario is unnecessary. The traditional duplex structure, as envisaged by Boyer & Elliott (1982), evolves by the sequential accretion of horses and the sequential formation of new ramp faults. Thus, the geometry of the bounding faults is controlled by the history of movement along the fault segments and ramps. This scenario was used in our simulation of the Three Penguins duplex. However, several duplex-like structures at steps in strike-slip fault segments have accommodated small offsets, even though there are several horses in the duplex, and the basic form resulting from the connection of fault segments by two ramps is insignificantly modified by addition of more ramps (Figs. 5c–g). The strike-slip offsets across the two duplex structures shown in Figs. 5(d) & (e) are only about 3 mm (about $\frac{1}{7}$ the step height), yet there are two or three horses in the structure. The strike-slip offset across the duplex-like structure shown in Fig. 5(f) is about 3.5 cm and the step height is about 2 cm, yet there are at least five horses in the structure.

We suggest that, in the case of the duplex structures in sandstone, many of the horses may form simultaneously, or form well before the horses have been pushed over their ramps. We propose that the formation of the ramp faults is more a phenomenon of fracturing than one of kinematics. Fractures typically attain great lengths with very small amounts of offset. Zhao *et al.* (in preparation) derive a relationship between the half length, a, of a band fault and the amount of offset (measured in metres), ΔU, on the fault. For the Entrada Sandstone the relationship becomes:

$$a = 10^6 \Delta U^2. \qquad (1)$$

Thus 10^{-3} of offset will allow the fault to extend for a distance of 10 m. Almost zero offset is needed for a band fault to extend sufficiently to bridge a transfer zone. The formation of the ramp faults may have nothing to do with the sequence of movement of the various horses. The multiple ramp faults may well be fractures that form prior to the translation of the first horse, and the duplex geometry may be established before much displacement occurs. Thus, one should distinguish between ramp faults that are formed with the sequential accretion of horses from ramp faults that are formed when fault segments are interacting.

Structural thickening

In studying the duplex structures along strike-slip faults in the Garden Area, we have found another use for the result of the kinematic model of the duplex structure. The kinematic model assumes that the bounding faults are originally straight and that parts of them become deformed as a result of thickening at the ramp structures. In the case of some strike-slip duplex structures, the assumptions of the kinematical model lead to more structural thickening than one would expect from the offset observed. This can be explained in terms of initial curvature of the bounding faults, and one can compare the apparent thickening in a structure with the amount of expected thickening from the offsets on the bounding faults and, thereby, estimate the initial shape of the bounding faults.

For example, in Fig. 5(d), the total offset, ΔU, is about $0.2h$, where h is the step height. The apparent structural relief, r_a, is approximately h and the ramp angle, θ, is in this case 10°. Cruikshank *et al.* (1989) showed that for the simple kinematic model, the structural relief, r, for a single ramp is given by,

$$r = \Delta U \sin(\theta). \qquad (2)$$

This relationship will provide an upper bound for the structural relief on duplex structures where the ramps are well-spaced, such as in Fig. 5(d), where, for the purpose of calculation we assume that all the displacement occurred on a single ramp.

Equation (2) indicates that for a ramp angle of 10°, and an offset of $\Delta U = 0.2h$, the structural relief would be about $0.03h$. Thus, from the kinematic model, the offset accommodated by the duplex structure accounts for less than 3% of the apparent structural relief. Most of the apparent structural relief for the duplex structure must be due to the original curvature of the bounding faults, and the faults must have always appeared much as they do in Fig. 5(d). The geometry of the ramps shown in Fig. 5(d) may be largely a result of interaction between fault segments.

The apparent structural relief in several duplex-like structures is far greater than expected from simulations. We suggest that although the kinematics of these structures are the same as duplex structures along thrust faults, the geometry of the ramps and the tips of the fault segments may be a result of interaction between fault segments, and that the curvature in the fault segments is established before much displacement occurs.

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