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Unweaving the joints in Entrada Sandstone, Arches National Park, Utah, U.S.A.

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Abstract—On the southwest limb of Salt Valley Anticline, Arches National Park, Utah three sets of joints are developed in the Entrada Sandstone covering an area of about 6 km^2. Within the 20 m thick Moab Member, a single joint set is is found in three distinct areas, separated by a second set of joints at a 35° angle to the first set. Joint interaction features show that the second set is younger than the first. This illustrates that joints of a single set do not have to fill the entire area across which the stresses that formed the joints were acting. The underlying Slickrock Member contains a third set of joints, which is at an angle of 5°–35° to joints in the Moab Member. The Slickrock set nucleated from the lower edges of joints of all orientations in the overlying Moab Member. Thus, the fracture pattern evolved both horizontally, within the same unit, and vertically between units. The sequence of jointing is determined by establishing the relative ages of each joint set. Each joint orientation is best interpreted as representing a direction of maximum compression, ruling out the possibility that the joints are a conjugate set. The joints, and an earlier set of deformation bands, record a 95° counterclockwise rotation of the direction of maximum compression.

INTRODUCTION

Joints are spectacularly developed and displayed on the flanks of Salt Valley Anticline in southeast Utah (Figs. 1 and 2a). Joints south of Klondike Bluffs on the southwest flank of the anticline appear in at least three sets. Zones of joints at some places within the Entrada Sandstone have weathered as long, narrow grooves to produce elongate rock fins, while in other places there has been almost no erosion along joint traces. Areas with little erosion are ideal for studying joint patterns. Although the joint pattern is very simple in some locations (e.g. Cruikshank *et al.* 1991a), there are sites with multiple sets of joints; the Arches National Park and vicinity provides an excellent area for studying the geometry of either a single joint set, or multiple joint sets, at a kilometre scale. While the spectacular joint patterns around Salt Valley have attracted attention and are featured in several textbooks (e.g. Davis 1984), there have been few detailed studies of the joints (Dyer 1983, Cruikshank *et al.* 1991a).

According to studies of sheet structures by Holzhausen (1977, 1989), each joint set should represent a different direction of maximum compression. This implies that joint sets which appear to be conjugate are independent. One purpose of this investigation is to determine the age relations of joints in the various sets to establish whether their ages differ. Another is to determine whether there is a pattern to the change in direction of the maximum compression in space and time. This investigation also aims to determine if there are different joint sets in the Moab Member and the underlying Slickrock Member. A final objective is to ascertain whether joints in one set influenced those in another set. To answer these questions, joints were mapped at a scale of 1:4500 over an area about 6 km long, and 0.5–1.5 km wide. Within the mapped, area joint orientations change abruptly by up to 35° laterally within the same unit, and vertically between units.

Previous studies

In the Garden area—3–4 km south of the current map area—Cruikshank, Zhao and Johnson (Cruikshank *et al.* 1991a,b, Zhao & Johnson 1991, 1992) studied joints, faulted-joints, and deformation bands (Aydin 1978) within the Moab Member of the Entrada Sandstone over an area of about 1 km^2. They showed that in order to understand the deformation represented by fractures, it is important to distinguish between deformation bands and faulted-joints. Deformation bands form in shear and have a few mm–cm of shear offset, while faulted-joints form as extension fractures (joints) but *later* slip a few mm–cm. Thus, a fracture which originally formed as a tension crack may now show shear displacements. We use the term *proto-joint* to describe a fracture that formed as an opening-mode (mode I) fracture, but may have slipped since formation.

The sequence of deformations established for the Garden area were (Zhao & Johnson 1992): (1) formation of a set of conjugate, strike-shift deformation bands with maximum compression oriented about N45°W, (2) local formation of joints along the traces of a few deformation bands, (3) formation of a systematic joint set trending N15°W–N5°W, parallel to the maximum compression direction. The joint segments that formed along the deformation bands slipped at this time, with a

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sense of slip opposite to that of the deformation bands, and (4) the final deformation recorded in the Garden area was shear offset of a few mm–cm along the systematic joint set, forming faulted-joints. Some traces of zones of proto-joints had right-lateral offsets in the southern part of their traces, no offset in the central area, and left-lateral offsets in the northern part of the Garden area. The sequence of deformations in the Garden area can be explained as a counterclockwise rotation of the direction of principal compression, from about N45°E to N5°W. The sequence of structures in the current study area records a larger counterclockwise rotation in the direction of maximum compression, from about N65°E to at about N30°W.

Dyer (1983, 1988) studied proto-joints in the Moab Member of the Entrada Sandstone at three locations. Dyer's domain B (1983, chapter 2; 1988, Fig. 3) is on the southwest limb of Salt Valley Anticline and corresponds to the southern part of the Anniversary Arch domain in this paper (south of 5000N, Fig. 4). Dyer noted that proto-joints in the Slickrock Member have a very different orientation from those in the overlying Moab Member (e.g. 4700N 1200W, Fig. 4). He also studied the Garden area (Dyer 1983, p. 83) and near the Arches National Park campground (Dyer 1988, Fig. 2), on the east flank of Salt Valley (Fig. 1a). Dyer (1988) focused on the interpretation of cross-joints found between an older systematic joint set.

Geologic setting

Salt Valley Anticline is a breached, asymmetric, salt-cored anticline at the northeast edge of the Paradox basin (Fig. 1a). Jurassic and Cretaceous sedimentary rocks exposed on the flanks of Salt Valley Anticline dip up to about 15°; within the core of the valley, however, bedding is vertical or overturned (Shoemaker *et al.* 1958, Elston *et al.* 1962, Doelling 1985). The salt is part of the late Paleozoic Paradox Formation, and started to move soon after the Paradox evaporites were covered with younger sediments. Unconformities in sedimentary rocks overlying the Paradox Formation suggest that there were several periods of rapid salt movement throughout the Mesozoic and Cenozoic, and deformed Quaternary deposits in Salt Valley and neighboring salt-anticline valleys indicate that the salt is still moving (Colman *et al.* 1988, Oviatt 1988).

The fractures we mapped are in the Moab and Slickrock Members of the Jurassic Entrada Sandstone (Fig. 1). The Entrada Sandstone rests unconformably on the Jurassic Navajo Sandstone. The Navajo Sandstone thins considerably over the anticline, and may not have been deposited over the entire crest. Although the normal thickness of the Navajo Sandstone in this area is on the order of 150 m, a well near the Rock Corral area (~6 km N of study area) went through 55 m of Navajo Sandstone directly into the Paradox Formation (Doelling 1988, p. 27). The Entrada Sandstone was deposited over the entire anticline, although it may be slightly thinner over the crest of the anticline (Dyer 1983, Doelling 1988).

The Moab Member is a light-colored, clean, fine- to medium-grained sandstone, about 20–30 m thick. Underlying the Moab Member is the Slickrock Member, 60–160 m of dark-red, massive, fine-grained sandstone. The lowest member of the Entrada Sandstone is the Dewey Bridge Member. The Dewey Bridge is a series of interbedded siltstones and shales, about 10–20 m thick. The Entrada Sandstone is overlain by interbedded sandstones, cherts, and shales of the Cretaceous Morrison Formation.

Joints in the Entrada Sandstone appear to be related to the salt-cored Salt- and Cache-Valley structures, and do not reflect a regional pattern (Kelley & Clinton 1960, Doelling 1988). These joints are approximately parallel to the axis of Salt Valley; near Fiery Furnace, on the northeast side of Salt Valley, they change orientation and become parallel to Cache Valley. On the northeast flank the joint spacing increases away from Salt Valley. Throughout most of the Salt Valley area, joints are almost vertical, whereas bedding may dip up to about 15°. Although the pattern is related to the local structure, the joints are not surficial features, since they intersect the current topography (Dyer 1983). It is important to realize that Salt Valley Anticline was well established at the time the Entrada Sandstone was deposited, and that fractures in the Entrada Sandstone can represent only part of the history of the anticline.

The study area is located in the central portion of the southwest flank of Salt Valley Anticline, at the northwest corner of Arches National Park (Fig. 1a). The area is marked by a NW-striking dip-slope of the Entrada Sandstone, the dip being 7°–15° to the SW. The ground surface is essentially the stripped upper surface of the Moab Member, which forms a NE-facing cuesta overlooking Salt Valley (Fig. 1c). The axis of Salt Valley Anticline in this area strikes about N45°W.

Within the mapped area, all proto-joints are within 10° of vertical, so mapped traces appear as relatively straight lines. Each line in Fig. 4, however, represents the trace of a zone of joints (Hodgson 1961, Dyer 1988, Cruikshank *et al.* 1991a). In their simplest forms, the traces are composed of en échelon proto-joint segments, generally stepping a few cm–m, that are misaligned up to 10° from the trace of the proto-joint zone. Individual segments range from a few metres to tens of metres in length. The zones are segmented in both a lateral and vertical direction.

Mechanical conditions of jointing

A joint is a fracture that is developed in opening-mode (mode I) (Pollard & Aydin 1988). Thus, although a joint *forms* in response to pressure in a crack or to far-field tension, it *propagates* as a result of high tensile stresses developed at its tip.

One of the most important principles in joint formation is that joints propagate in the direction of maximum compression. The importance of high compression was documented in detail with numerous field examples for sheet structures, a type of horizontal joint, generally in

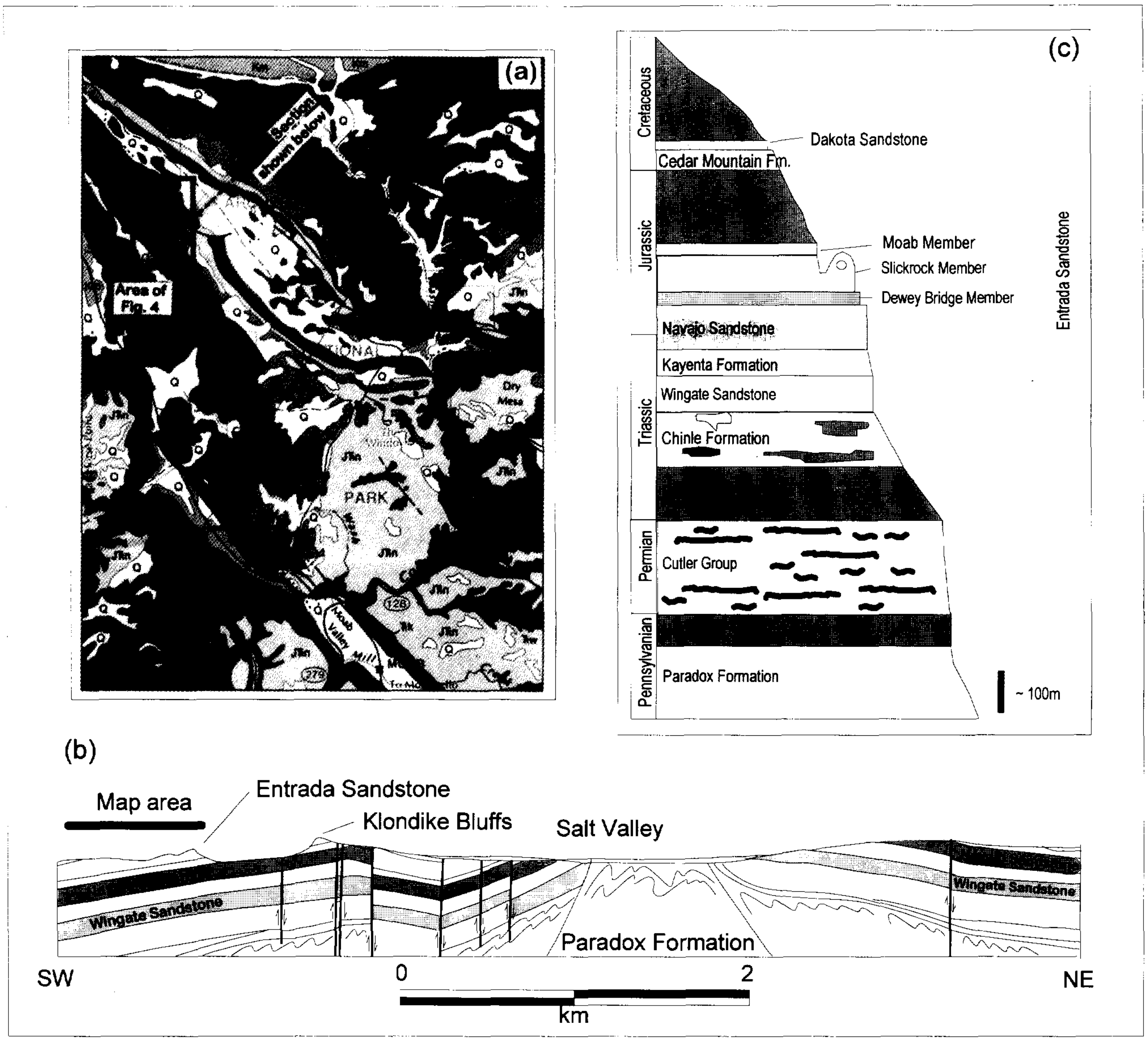

Fig. 1. (a) Simplified geologic map and stratigraphy for Arches National Park, located in southeast Utah. The study area is at the northwest corner of the park (map courtesy of Utah Geological Survey). (b) Cross-section through the Klondike Bluffs area (Doelling 1988, section J, p. 48). The Navajo and Wingate sandstones are shaded for reference. The study area is on the southwest edge of the section. (c) Simplified stratigraphy for Arches National Park. The joints shown in Fig. 4 are within the Moab and Slickrock Members of the Jurassic Entrada Sandstone.

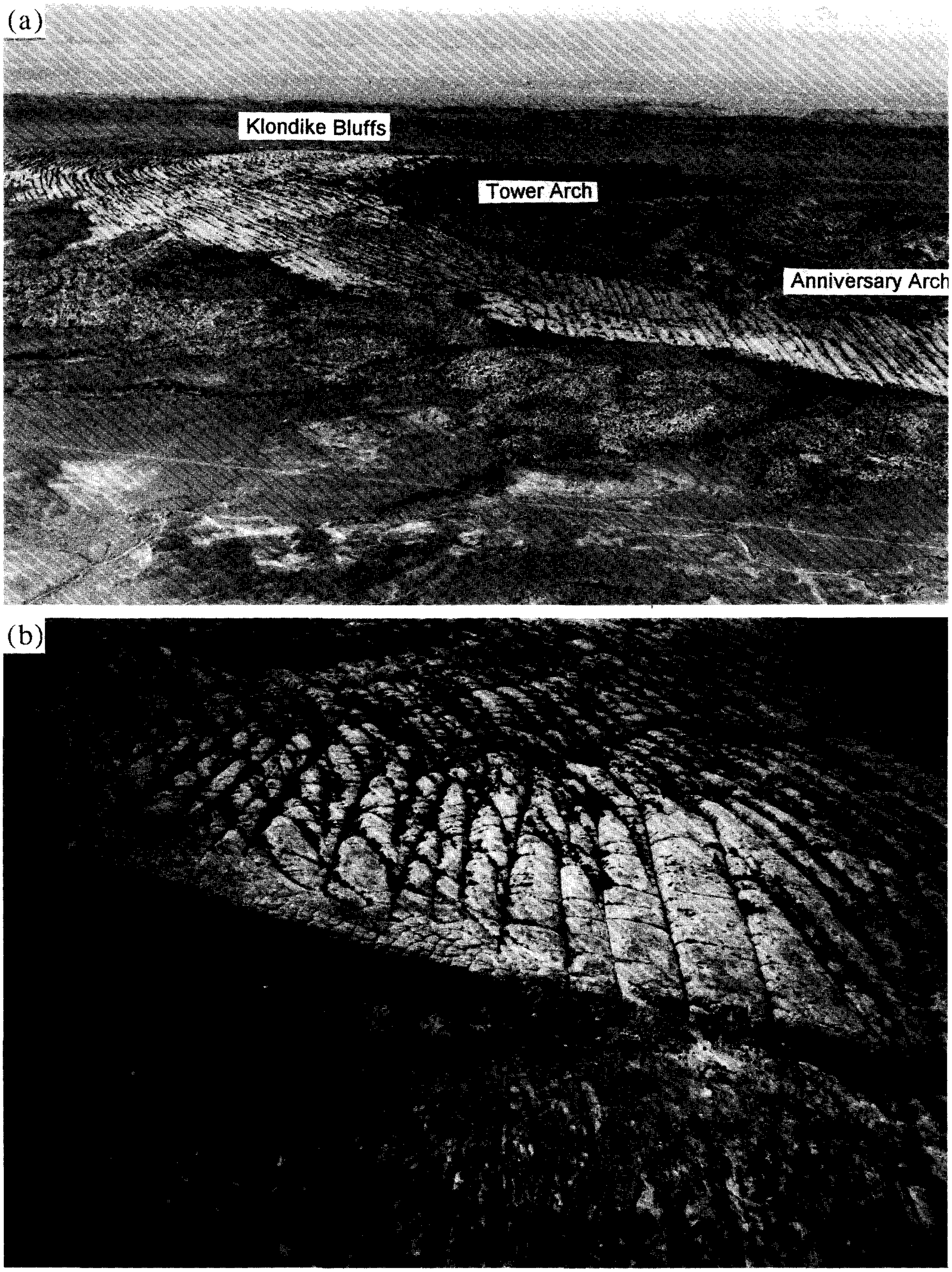

Fig. 2. (a) Oblique aerial photograph looking north across the study area. Photograph shows the grooves on a dip slope of the Moab Member of the Entrada Sandstone on the southwest limb of Salt Valley Anticline, in the vicinity of Klondike Bluffs. The grooves generally correspond to zones of proto-joints. An abrupt change in the orientation can be seen near the center of the photograph (below 'Tower Arch' label), which corresponds to the change in orientation shown in Figs. 3 and 4, near co-ordinates 5500N. (b) Oblique aerial photograph of the Klondike bluffs area, looking south, showing fault scarp and relation of joints to scarp. Notice that not all joints cross the fault surface. In the area where the systematic joints do not cross the surface, there is a polygonal-like joint network. The photograph covers the area shown in Fig. 7.

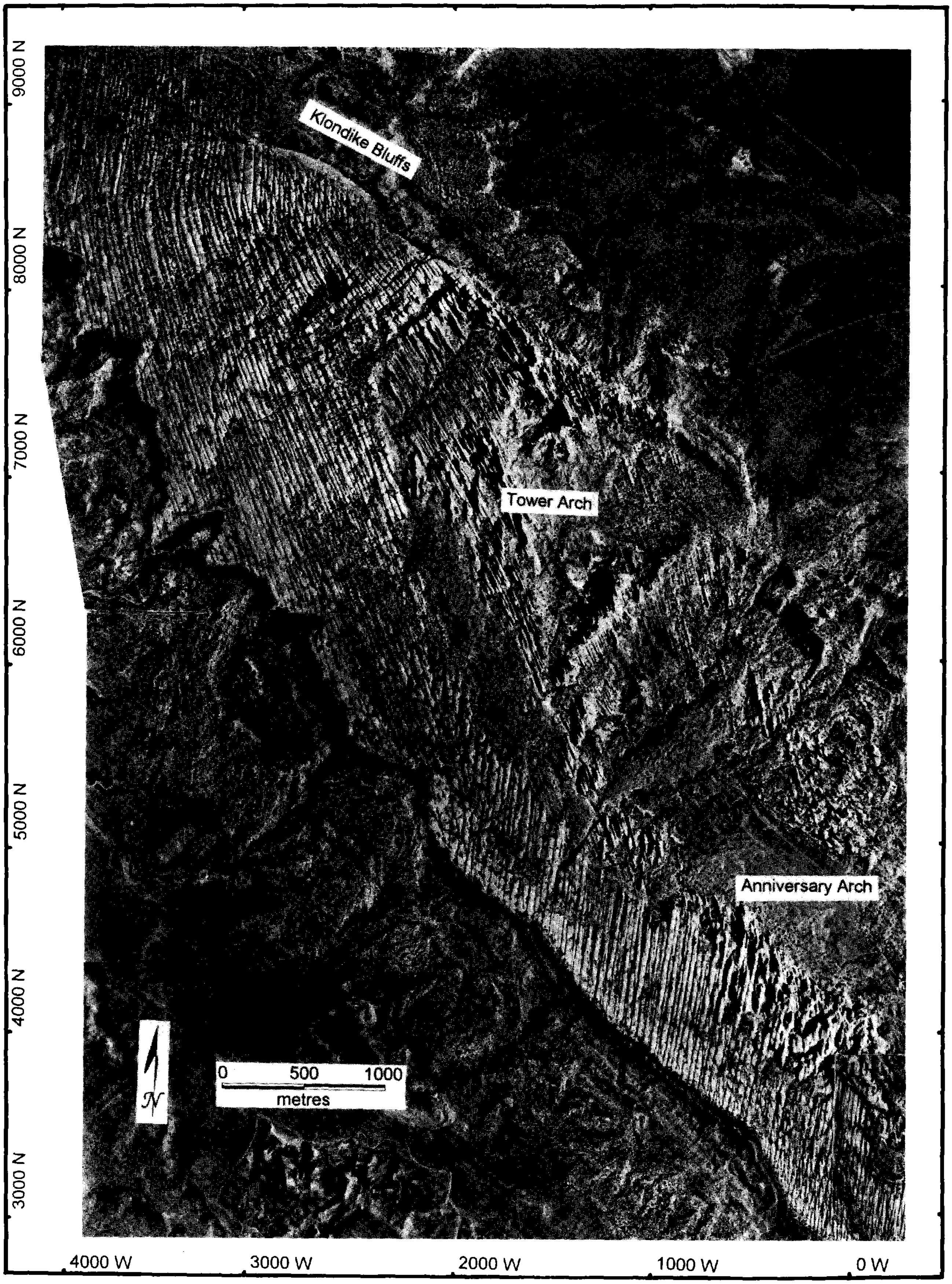

Fig. 3. Mosaic of aerial photographs of the area shown in Figs. 2(a) and 4. Salt Valley is in the northeast corner of the photograph. Zones of proto-joints show up well as lineations on the photographs. Most joints are exposed on a dip-slope of the Moab Member of Entrada Sandstone. The Entrada Sandstone forms a northeast facing cuesta overlooking Salt Valley. The Slickrock Member is more deeply dissected, and forms a series of tall fins, such as in the vicinity of Tower Arch. The coordinate system for the photograph is the same as in Fig. 4. The mosaic is composed of images AB4UPRM0001656A-77 and -78 available from U.S. Geological Survey EROS Data Center.

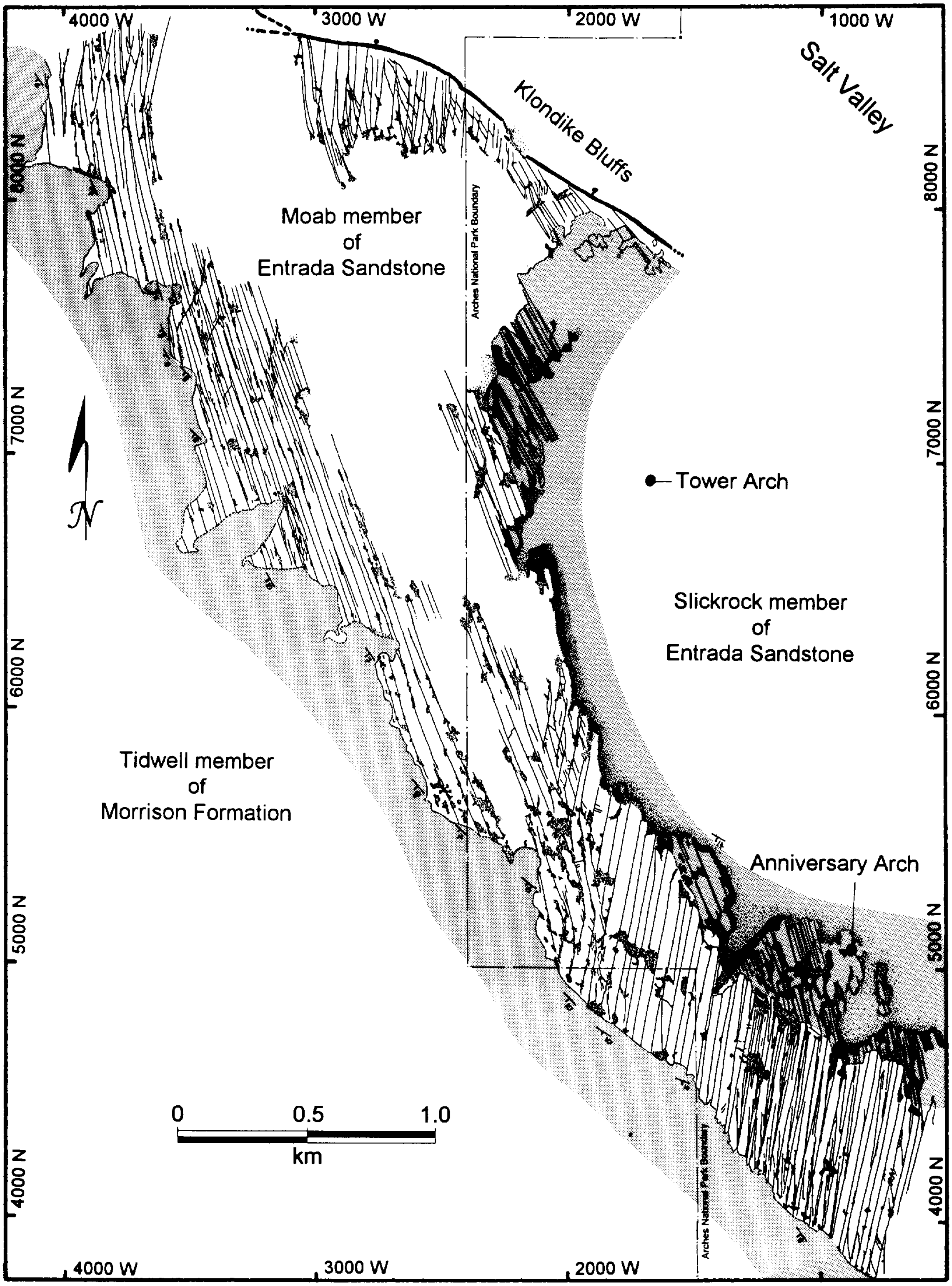

Fig. 4. Map showing traces of joints and faulted-joint in Entrada Sandstone on the northwest limb of Salt Valley Anticline. All the units in the area dip gently to the southwest. The co-ordinate system is aligned along true north, and is in metres from an arbitrary datum used in Cruikshank *et al.* (1991a). Mapped area covers parts of Sections 22, 26, 27, 34 & 35 T23S R20E, U.S. Geological Survey Klondike Bluffs 7.5' quadrangle. The blank area in the vicinity of (7500N 27500W) represents an area where zones of joints are wide, sediment filled grooves. This area could not be mapped with the same detail and quality as the rest of the study area.

granitic rocks, by Holzhausen (1977, 1989). His conclusion was verified theoretically by Cotterell & Rice (1980), who show that, even if perturbed, a mode I fracture has a strong tendency to reorient to become parallel to maximum far-field compression. A corollary of this principle is the idea that joints with different orientations formed under different stress states. Further, the notion of 'conjugate joints' is unfounded. Accordingly, since we recognize three distinct sets of joints in the southwest flank of Salt Valley Anticline, the joints must represent three different stress states, presumably of different ages.

Determining relative age of joints

There are several features than can be used to discern the relative ages of joints, namely abutting relationships, joint interactions, and secondary joints due to shear displacement on existing joints (e.g. Twiss & Moores 1992, fig. 3.10). These patterns are summarized in Fig. 5.

A propagating joint will re-orient itself to stay in the plane of minimum compression. A joint propagating as an opening-mode fracture will continue to propagate in its own plane unless the *tip* is subjected to some shearing. Thus, if a joint curves or changes direction, the joint tip was subjected to shearing. Joints will deviate from straightness either during formation of the joint (e.g. Figs. 5a–c), or in response to some changed stress state at some time after the joint formed (e.g. Fig. 5d).

When a joint's orientation is changed by its propagating into a steadily-changing stress field, the joint will gradually change orientation; the fracture is said to *veer*. Veering may result from stress perturbations produced either by other near-by fractures, or by bedding interfaces. Thus, if one fracture curves towards a sensibly straight fracture (i.e. a fracture which can be treated as a straight fracture) then locally the curved fracture is younger than the straight fracture (Fig. 5a). This interaction may be the *curving parallel* or *curving perpendicular* type (e.g. Dyer 1988), depending on the angle that the fractures approach each other (Thomas & Pollard 1993). If both joints veer, producing a double hook-shaped geometry (Fig. 5b), they were mutually interacting and are of similar age (Kulander *et al.* 1979, Pollard & Aydin 1988, Olson & Pollard 1989).

In cases where a fracture is propagating normal to the plane of view, fracture terminations with series of en échelon fractures near the tips probably represent a breakdown fringe (or gradual twist hackle Kulander *et al.* 1979) on the parent fracture, the tip of which is above or below our observation plane (Fig. 5c) (Pollard *et al.* 1982, Cruikshank *et al.* 1991a, fig. 24). Where such a fringe exists next to a sensibly straight fracture, and joint segments that make up the fringe turn towards the straight fracture, the fracture associated with the fringe is probably locally younger (Cruikshank *et al.* 1991a, Twiss and Moores 1992, fig. 3.10).

A proto-joint trace that abruptly changes orientation (i.e. a kink or wing fracture, Fig. 5d) forms in two-

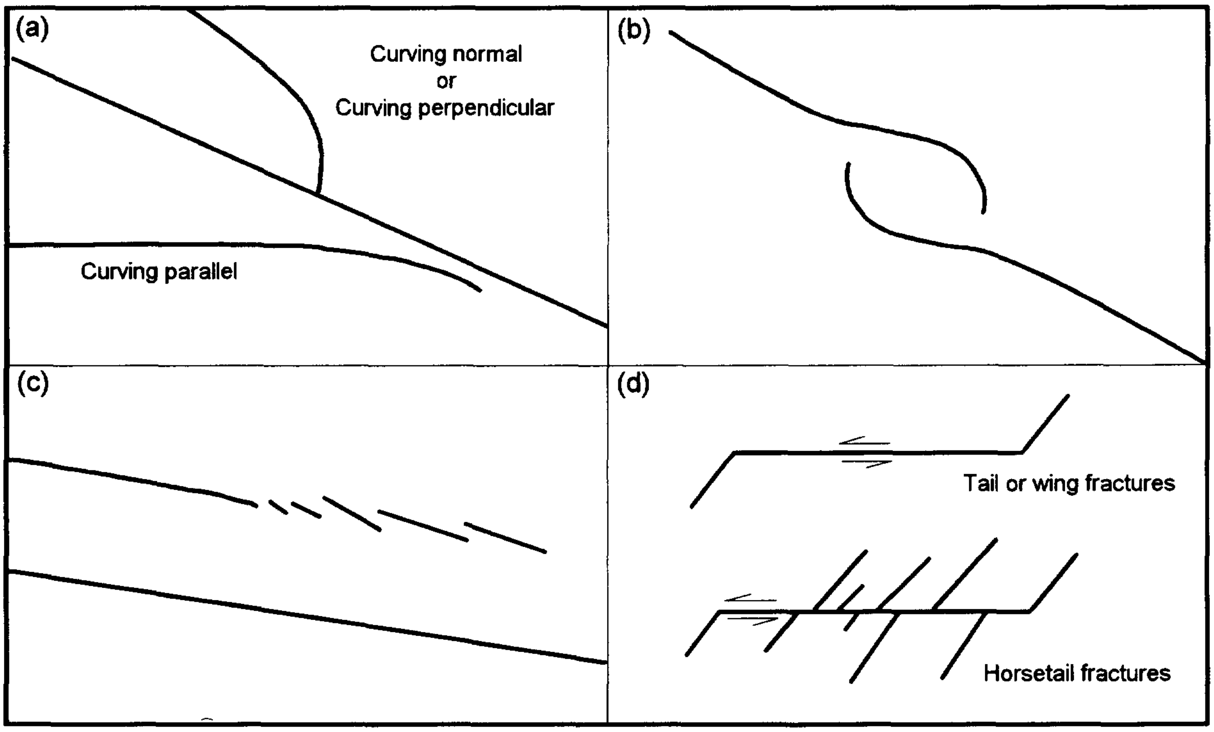

Fig. 5. Relationships used to determine relative ages of joints. In (a) the younger joint turns towards the older joint and becomes either parallel- or perpendicular-to the older joint. In (b) the joints are of a similar age, and produce a characteristic hook-shaped geometry. In (c) the younger joint is propagating normal to the plane of view. In this case the younger joint breaks down into a series of en échelon segments that turn towards the older joint. In (d) the younger joints are a result of left-lateral shear displacement on the older joint. These tail, or horsetail joints initiate from the tips of older joints, or from roughness elements along the length of the older joint (see Fig. 8). Similar patterns and relationships are discussed by Dyer (1988), and Twiss & Moores (1992, fig. 3.10 p. 42).

stages: first, a parent joint forms and, as the parent joint is later sheared, the tip may propagate at an abrupt angle to the parent fracture. Kinks are a diagnostic feature of faulted-joints. The kink angle gives the sense of shear on the older, parent joint (Cotterell & Rice 1980, Cruikshank *et al.* 1991a). A variation on the kink is a kink-like fracture that initiates from irregularities along the length of the fracture, called *horsetail* fractures (Fig. 5d) or pinnate joints (Price 1966, Engelder 1989).

The configurations described above provide a basis for establishing the relative age of most interacting or intersecting fractures. Using these rules we find a consistent relationship between proto-joints of different orientations in the Entrada Sandstone. Thus we can determine the relative age relationships between proto-joint sets, and understand complex-looking fracture patterns, such as that shown in Fig. 4, in terms of the sequential development of joint sets.

SEQUENCE OF FRACTURING

In the mapped area (Fig. 4) there are three sets of proto-joints. Each set has a definite spatial distribution and orientation. The limited spatial extent of some joint orientations allows us to define four proto-joint *domains*, a domain being an area of outcrop with a well-defined proto-joint pattern, usually dominated by single proto-joint set. The three proto-joints domains within the Moab Member are: *Klondike Bluffs domain* (north of 8600N, Fig. 4), *Anniversary Arch domain* (west of 2000W, and between 5000N and 8600N, Fig. 4), and the *Tower Arch domain* (east of 2000W and south of 6000N, Fig. 4). The transition between the Tower Arch and Anniversary Arch domains (5000N 1800W–6000N 2200W, Figs. 4 and 9) is a 400 m wide zone containing both NE-striking and NW-striking proto-joints. The transition between the Klondike Bluffs and Tower Arch domains (8400N–8800N, Figs. 4 and 7) is defined by the southern termination of a set of N-striking proto-joints. The upper and lower boundaries of domains in the Moab Member are, respectively, the contacts with the Morrison Formation and the Slickrock Member. There is one joint domain in the Slickrock Member, and it is found throughout the mapped area. The upper-boundary of this domain is the Moab-Slickrock contact.

The proto-joint network shown in Fig. 4 was preceded by the development of a network of deformation bands.

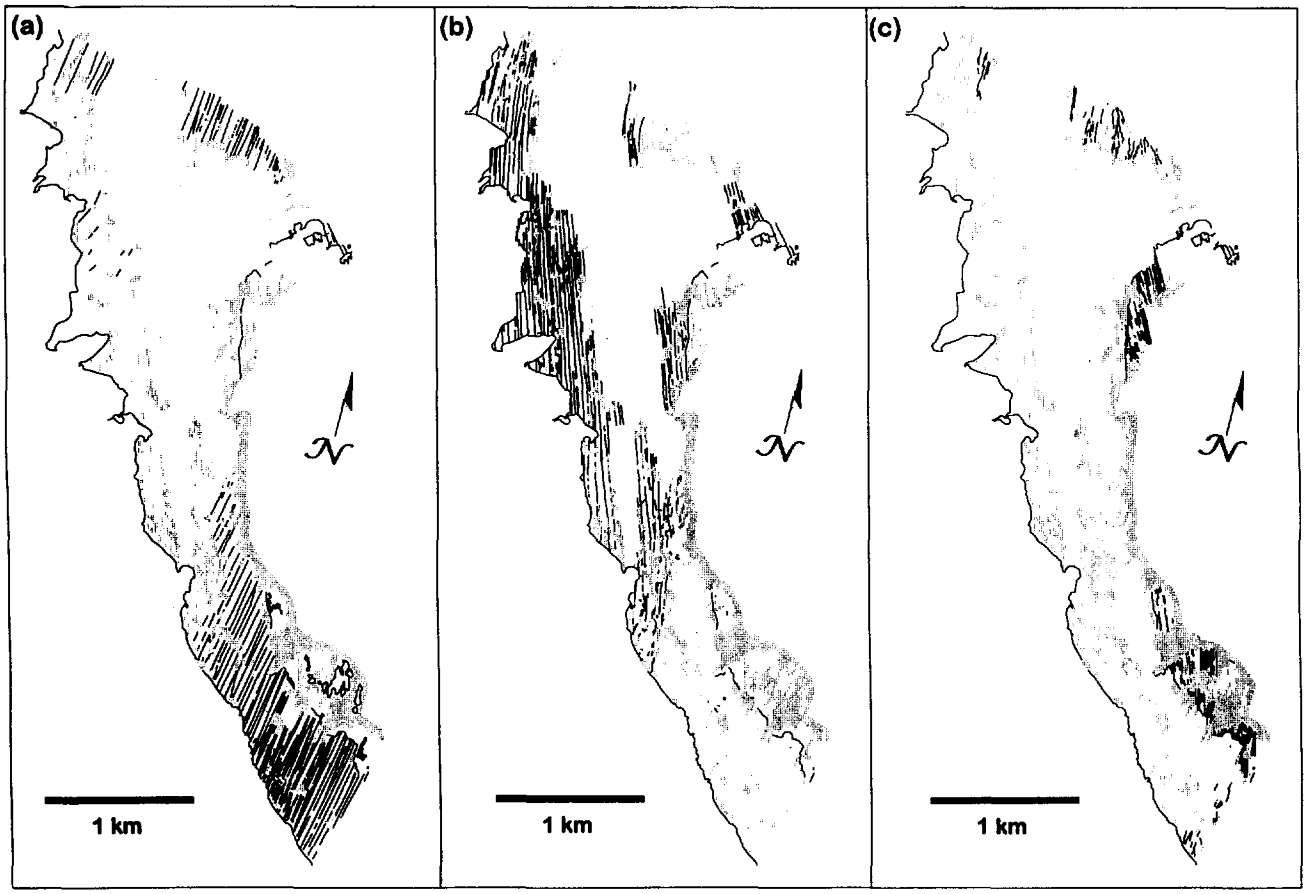

Fig. 6. Three jointing stages identified in the study area. A period of deformation recorded in deformation bands and movement on the Klondike Bluffs fault preceded the sequence of jointing shown here. (a) Joints in the Moab Member of the Klondike Bluffs and Anniversary Arch domains are the oldest set. (b) Joints of the Tower Arch domain form in the Moab Member. (c) NW-striking joints form in the Slickrock Member. These joints formed in response to a slightly different stress field from those in the overlying Moab Member, and nucleated from the lower edge of joints in the Moab Member. After formation of joints in the Slickrock domain, some blades grew upwards into the Moab Member, producing the NW-striking cross-joints. Figure 4 shows the result of the superposition of all these events.

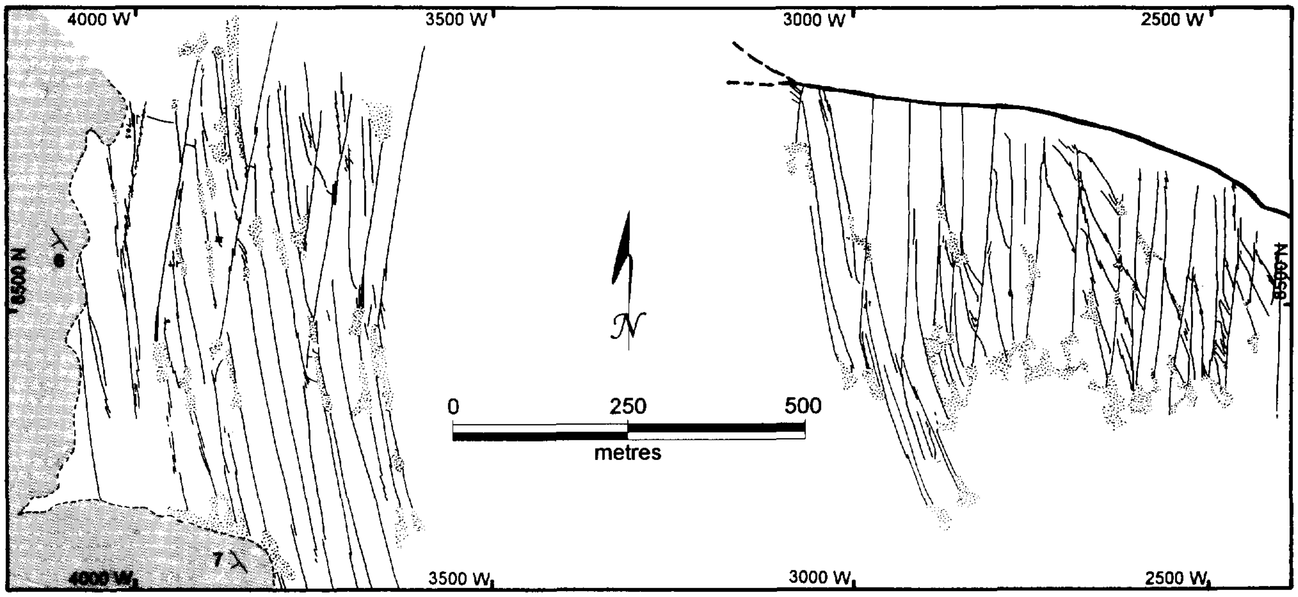

Fig. 7. Map showing joint traces in Entrada Sandstone in the Klondike Bluffs domain. All the joints shown cut pre-existing deformation bands. Some deformation bands are offset where joints have become faulted. Many joints striking NW are confined between NE-striking joints, and show curving-parallel or curving-perpendicular relationship to NE-striking joints. At the southern termination of some NE-striking joints there are a few NW oriented tail fractures. These relationships indicate that the NW-striking joints are younger than the NE-striking joints in the Klondike Bluffs region. Both orientations of joints show left-lateral offsets. The NW-striking joints are of the correct orientation to be related to shear on the NE-striking joints. Stippled areas are sand covered.

Jointing started with the development of a NE-striking proto-joint set at the northern (Klondike Bluffs domain) and southern (Anniversary Arch domain) ends of the mapped area within the Moab Member. The area between these two domains (Tower Arch domain) was then filled with a NW-striking set, again confined to the Moab Member. NW-striking joints then formed in the Slickrock Member underling the entire area. NW-striking joints in the Slickrock have propagated upwards into the Klondike Bluffs and Anniversary Arch domains. These stages in the evolution of the fracture pattern are discussed in more detail below.

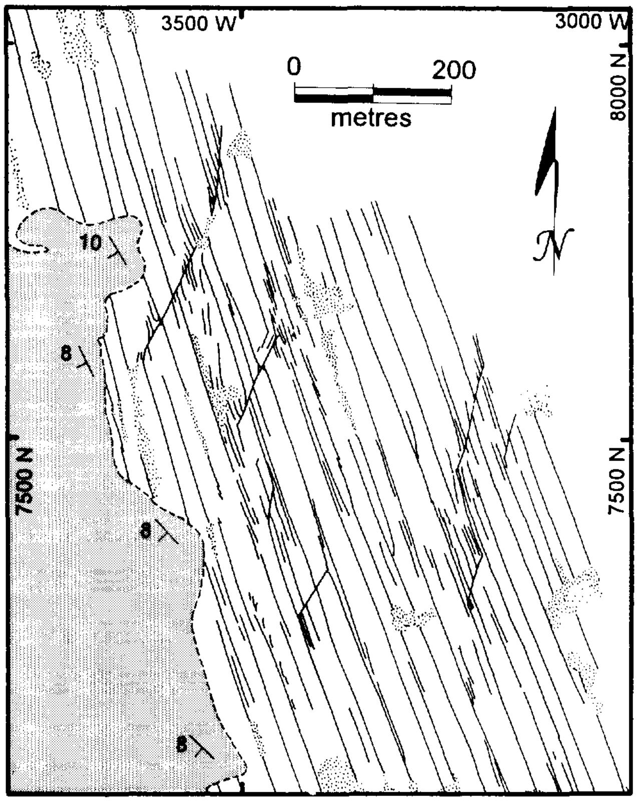

Fig. 8. Map of a portion of Fig. 4 showing details of tail and horsetail fractures formed along NE-trending joints. The NE-striking joints were sheared in a left-lateral sense. This indicates that the NE-striking joints are older than the NW-striking joints.

Deformation bands and faulting

The oldest fractures in the area are deformation bands, which are thin, segmented tabular zones of deformed sandstone across which there is a small amount of shear offset (Aydin 1978, Aydin & Johnson 1978, 1983, Antonellini *et al.* 1994). Deformation bands are present throughout the study area. Traces of individual deformation bands are irregular, as is the spacing between bands. There are at least two orientations of bands with strikes of about N55°–75°E but with opposite dip directions. Offsets across bands is oblique- or normal-shift, as opposed to strike-shift displacements observed in the Garden area 3 km to the south (Zhao & Johnson 1991, 1992). Thus, the earliest recorded deformation is that of maximum compression in a plane striking about N65°E.

The presence of deformation bands has not affected the development of systematic joints except where a slip surface has formed along a zone of deformation bands. As documented in the Garden area, joints formed locally along zones of deformation bands (Zhao & Johnson 1992) before the development of the systematic joint set. In the present study area jointing along zones of deformation bands followed formation of the systematic joint set; they terminate against members of the

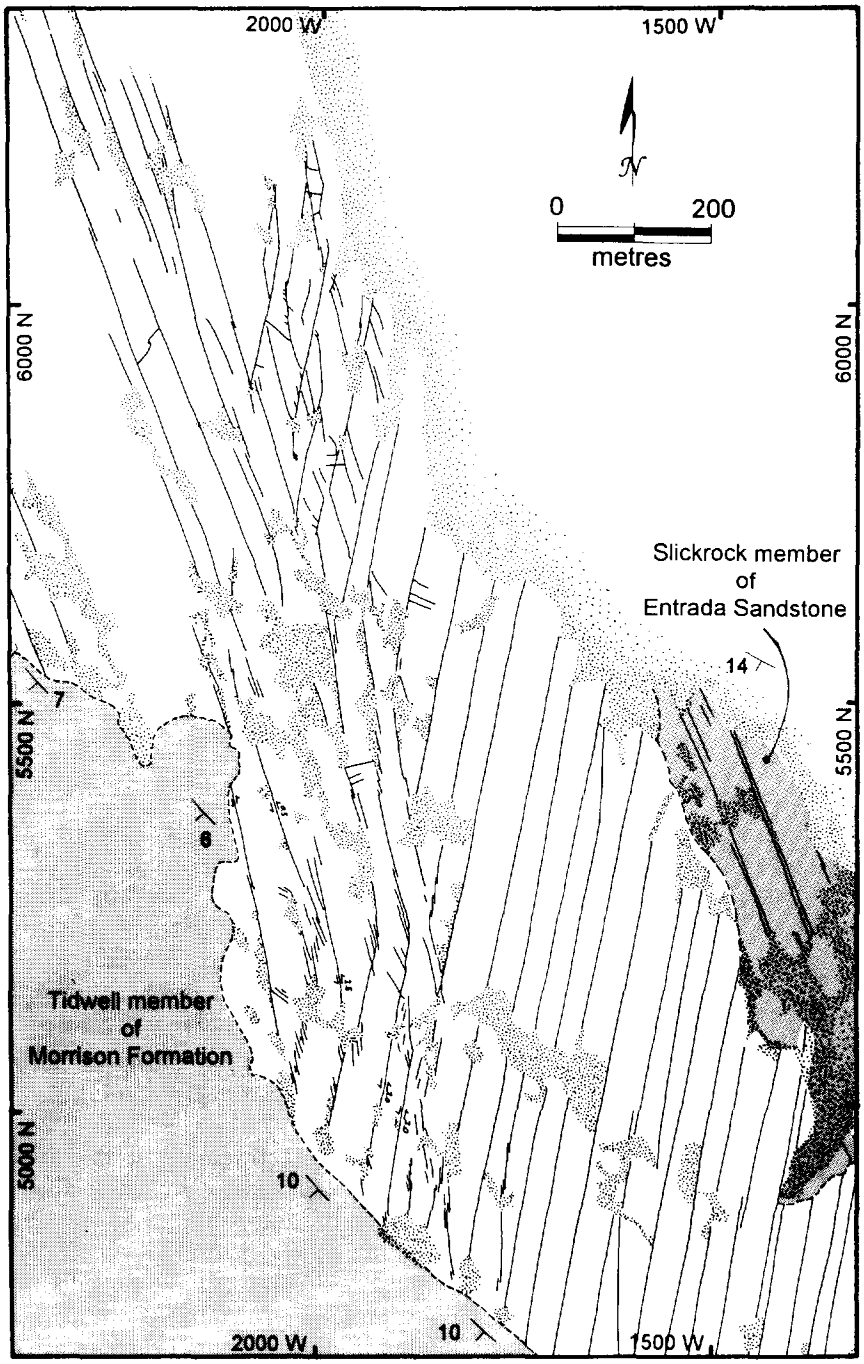

Fig. 9. Map showing details of the transition between the Tower Arch and Anniversary Arch domains. Proto-joints of the Tower Arch domain nucleate from the older proto-joints in Anniversary Arch area. At coordinate 5200N on the eastern margin of the map, the Slickrock Member of the Entrada Sandstone is exposed. Joints in the Slickrock are oriented about N20°W, while joints in the Moab Member strike about N10°E.

systematic sets shown in Fig. 4. Most E–W grooves seen in Fig. 3 represent weathering along joints formed within zones of deformation bands. Thus, these E–W grooves give a rough indication of the spacing and distribution of deformation bands in this area.

The northern boundary of the mapped area is at the Klondike Bluffs fault, a normal fault with down-throw to the north. The maximum fault offset, up to 20 m, is approximately equal to the thickness of the Moab Member in this area. Displacement on the Klondike Bluffs fault decreases from east to west. The displacement is about 20 m at about 8500N 2300W (Figs. 2 and 7), while 500 m further to the west, the displacement is only a few cm.

Patchwork of domains of first-formed northeast joints in the Moab Member

The oldest proto-joint set in the mapped area has a strike of about N5°–15°E (Fig. 6a), and is confined to the Moab Member of the Entrada Sandstone. The northern area of the NE-striking joints is the Klondike Bluffs domain, and the southern area is the Anniversary Arch domain. There are a few isolated segments of NE-striking proto-joints about 1 km south of the Klondike Bluffs fault (Fig. 6a). Proto-joints in each of these areas probably formed around the same time and under the same stress state, since they have similar orientation in each area and are, throughout, older than NW-striking joints.

Proto-joints in the vicinity of the Klondike Bluffs fault (Fig. 7) strike about N7°E, almost normal to the Klondike Bluffs fault. In the vicinity of 8750N 3400W, the joints intersect the fault slip surface; about 250 m to the east, however, the joints end within the zone of deformation bands near the fault, 10–20 m before the fault surface (Fig. 2). Near the fault, where the northeast set does not cross it, there is a series of joints with a polygonal-like pattern. Individual polygons are about 5 m across. Proto-joints on the northern side of the fault in the Moab Member have a pattern similar to that just south of the fault (Fig. 3).

The southern terminations of NE-striking joints in the vicinity of the Klondike Bluffs fault are abrupt. There are a few that show en échelon steps or kinks in the tip region. Several NW-striking kink-like fractures can be seen at the southern termination of a NE-striking joint at the west side of the blank area in Fig. 7. Some NE-striking joints appear to change orientation gradually (e.g. 8370N 2950W), and become parallel joints in the Tower Arch domain. This change is actually accomplished by a series of en échelon stepping segments.

Domain of northwest joints nucleating from patchwork joints

NW-striking proto-joints form two domains, the Tower Arch domain in the Moab Member, and the Slickrock domain. Joints in the Slickrock Member are consistently younger than through-going proto-joints in the overlying Moab Member. Within the Moab Member, the NW-striking proto-joints are younger throughout than the NE-striking proto-joints.

The pattern of jointing around the isolated NE-striking proto-joints 1 km south of Klondike bluffs confirms that the NW-striking joints are younger. This pattern is diagnostic. Multiple nucleation points along their length suggest that the fracture walls were being held closed at the time the fringe fractures formed. This is consistent with the notion that zones of joints formed with high compression parallel to the joints, minimizing interaction between joint segments (Holzhausen 1977, Cotterell & Rice 1980, Olson & Pollard 1989, Cruikshank *et al.* 1991a).

Joint patterns at the boundary between the Tower and Anniversary Arch domains (Fig. 9) again show that NW-striking joints nucleated from the older NE-striking set. NW-striking joints of the Tower Arch domain show left-lateral offsets, so the NE-striking, kink-like joints at the southern tips of these joints cannot be related to this shear offset. The numerous NW-striking tail and horsetail fractures on the NE joints are consistent with the left-lateral slip observed in the NE joints.

The NW joint set shows either no offset, or left-lateral offset of pre-existing deformation bands. In one location (6750N 3400W), on a joint oriented N15°W 80°E, the displacement vector was 5.5 cm in a direction 36°/N8°W. Thus the joint was faulted with a combination of 4.8 cm left-lateral and 2.5 cm normal offset (down towards the east). Offsets along joints in the Slickrock Member were not observed.

Joints in the Slickrock Member nucleating from joints in the Moab Member

Because there is only one joint domain in the Slickrock Member, spectacular transitions—such as between the Tower Arch and Anniversary Arch domains (Fig. 9)—are seen only in the Moab Member. Joints in the Slickrock Member do not show an abrupt change in orientation in this area. Whereas joints in the Slickrock domain are oriented only a few degrees counterclockwise with respect to joints in the Tower Arch domain, they are at a 35° angle to joints in the Anniversary Arch domain.

Throughout the mapped area, the orientation of joints in the Slickrock Member differ from that of joints in the overlying Moab Member. Strikes of joints in the underlying Slickrock Member strike up to 35° counterclockwise with respect to joints in the Moab Member in the Anniversary Arch domain, and 10° counterclockwise with respect to joints in the Tower Arch domain (a distance of about 2.5 km). Joints in the Slickrock Member are younger than those in the overlying Moab Member. In the northern part of the area (7000N, Fig. 4) the Slickrock joints strike about N30°W; however, in the vicinity of Anniversary Arch, the set strikes about N15°W. Thus there is a 15° *counterclockwise* rotation of the strike of joints moving from south to north. Over the same distance, proto-joints in the overlying Moab Member (Tower Arch domain) show a 7° *clockwise* change in orientation.

Joints in the Slickrock domain have nucleated from the lower edge of joints in all domains in the overlying Moab Member. In places where the contact is gradational, joint surfaces in the Moab Member can be followed continuously into joint surfaces of the Slickrock domain. Surfaces in the Slickrock can also be followed, without a change in orientation, back into the Moab Member as NW-striking cross-joints. Where the contact between members is abrupt—usually where there is a thin shale layer—joints in the Moab Member do not penetrate into the Slickrock Member; rather, they end abruptly.

In the Klondike Bluffs domain (Figs. 2 and 7), NW-striking proto-joints within the Moab Member are confined between the older NE-striking joints. They usually curve to become normal with the NW-striking joints, or break down into a series of echelon cracks. They do not intersect the NE-striking proto-joints. This pattern continues well to the north of the Klondike Bluffs fault, and is probably not related to the transition between two domains. This persistent set of NW-striking cross-joints is explained by the upward-propagation of NW-striking joint segments from the underlying Slickrock Member.

CONCLUSIONS

The fracture pattern on the southwest limb of Salt Valley Anticline evolved in a patchwork fashion, both laterally within the same unit and vertically between units. There are three proto-joints in the Moab Member, with the fourth domain in the Slickrock Member. Domain boundaries could not be related to structural boundaries. Nonetheless, domains in the Moab Member are separated from that in the Slickrock Member by lithologic variations, such as a shale interbed or a gradational change in sandstone composition.

The formation of one proto-joint set influenced the development of subsequent sets, either by serving as a nucleus for new fractures, or by limiting the spatial extent of subsequent fractures. Interactions between proto-joints in each domain allowed the determination of the following sequence of deformations:

Deformation bands, and faulting. There are at least two sets of deformation bands, striking N55°–75°E and dipping to either the south or north. Each set shows normal shift. Principal compression would lie in a plane striking about N65°E. One zone of deformation bands thickened and developed a slip surface (e.g. Aydin & Johnson 1978), forming the Klondike Bluffs fault.

N5°–10°E striking joints formed within the Moab Member in three different areas, one to three km apart. In places, the extent of the northern area of NE-striking joints was limited by the slip surface of the Klondike Bluffs fault. This set corresponds to the systematic joint set in the Garden area (Cruikshank *et al.* 1991a).

N15°–22°W striking joints in the Moab Member. These joints nucleated from the northern terminations of NE-striking joints in the Anniversary Arch domain and propagated to the north. In the Tower Arch area, NW-striking joints nucleated from along older NE-striking joints and propagated both to the north and south.

N20°–28°W striking joints in the Slickrock Member. Continued counterclockwise rotation of the stress field produce left-lateral offsets on NW-striking joints in the Moab Member, and may have helped form twists at the lower edge of joints in the Moab Member, which twisted further and became the systematic set in the underlying Slickrock.

Development of joints along existing deformation bands. The fractures within the Entrada Sandstone on the southwest limb of Salt Valley Anticline record a counterclockwise rotation in direction of principal compression, from about N65°E–N30°W—a 95° counterclockwise rotation. Previous studies in the Garden area, 3–4 km south of the present study area, recorded a counterclockwise rotation of about 50° (Zhao & Johnson 1992).

In summary, a network of joints on the southwest limb of Salt Valley Anticline is composed of several overlapping domains of differently-oriented joints. The network evolved both laterally and vertically in a patchwork manner through a series of stages identified by establishing the relative ages of joint domains. The development of one joint domain affected the development of a later one, either by providing a nucleus for new fractures, or by limiting the lateral extent of new fractures. Within the Moab Member of the Entrada Sandstone are three major overlapping joint domains. The strike of joints may change between domains by as much as 35°. Joints in northern and southern domains strike about N5°–10°E, while joints in the central domain strike about N10°–20°W. Where joint domains overlap, interaction between members of each domain indicates that joints in the northern and southern domains are older than those in the central domain. Joints within all three domains have become faulted, and offset pre-existing markers in a left-lateral sense. There is one joint domain in the underlying Slickrock Member, which extends under all three domains in the Moab Member. Joints in the Slickrock Member domain nucleated from the lower edges of joints in all three domains of the Moab Member.

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