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KENNETH M. CRUIKSHANK and ATILLA AYDIN

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Role of fracture localization in arch formation, Arches National Park, Utah

KENNETH M. CRUIKSHANK* ATILLA AYDIN } *Rock Fracture Project and Bailey Willis Geomechanics Laboratory, Department of Geological and Environmental Sciences, Stanford University, Stanford, California 94305*

ABSTRACT

Spectacular rock fins on the flanks of Salt Valley anticline in southeast Utah are formed by erosion along zones of joints. Within a rock fin, arches form where intense fracturing is localized. Fracture localization is controlled by shear displacement along existing horizontal or vertical discontinuities. Horizontal discontinuities may be shale layers, shale lenses, or bedding planes, whereas vertical discontinuities are usually preexisting joint segments. The roof and overall shape of an arch is controlled by existing shale layers, interfaces between sandstones of different properties, or secondary fractures due to shear on vertical joints. Joints that bound rock fins are related to the formation of the diapir-cored Salt Valley anticline. Shear displacement along existing discontinuities, which localizes intense fracturing, is probably related to the growth of Salt Valley anticline and its subsequent collapse due to dissolution of the anticlines salt core.

INTRODUCTION

Arches are structures formed by perforation of rock walls. Arches National Park in southeast Utah has >700 arches—with spans ranging from 1 to 93 m and heights up to 34 m—within an area of 29,695 ha (Stevens and McCarrick, 1988). Native American inhabitants of the region believed that arches were built by the Great Sky Father, whereas some early settlers believed that the arches were handcrafted by prehistoric native Americans (Barnes, 1978). Currently, localized erosion of rock fins by wind and water is considered to be the process responsible for the formation of arches (Barnes, 1978; Stevens and McCarrick, 1988). Arch formation cannot be due solely to weathering and erosion, however, because these processes are not restricted to the sites of arches in rock fins. There must be some factor that locally enhances the effects of erosion within a rather small part of a rock fin to produce an arch. How erosion is localized within a rock fin to form an arch is enigmatic. In the case of natural bridges (for example, Natural Bridge National Monument, Southeast Utah), a river or stream is assumed to be the agent providing localized erosion. Arches within Arches National Park, however, are not associated with fluvial activity.

In this paper we address mechanisms that locally fragment rock, making it more susceptible to erosion. Where such a fracture-damaged zone exists within a rock fin, the effects of erosion are locally enhanced and an arch will probably form. Local enhancement of erosion by fracture concentration probably accounts for the majority of arches within Arches National Park. We do not imply, however, that all arches within the park are controlled by a single mechanism. It should be remembered that the term "arch" has been applied to a geomorphic feature without regard to the mechanisms that shaped it, which makes it difficult when applying a mechanism to the localization of an "arch." We have examined all major named arches and many smaller arches and rock shelters. At all sites we see evidence for the fracture localization that we describe in this paper. Other factors may have assisted in locally accelerating the effects of erosion, such as undercutting of cliffs or channeled runoff from buttes. Each arch is unique, but in this paper we describe a common theme for the arches at Arches National Park.

Previous workers ascribed the dense network of fractures associated with arches to the presence of an arch, rather than as a factor that controlled the location and formation of an arch. The arch-forming fractures are concentrated along preexisting discontinuities—such as shale lenses and joints—that themselves participate in arch formation. In many sites we are able to demonstrate that the reason for fracture localization is shearing along preexisting discontinuities, together with the interaction between adjacent sheared discontinuities.

Geological Setting

Arches National Park is centered on the salt-cored Salt Valley anticline (Fig. 1b), which represents the northwest extent of the Paradox basin salt diapirs. Rocks of Jurassic and Cretaceous age are exposed on the flanks of the anticline, which dip up to about 15°. The majority of arches are within the Jurassic Entrada Sandstone.

The Entrada Sandstone is underlain by the Navajo Sandstone (Fig. 1c), a massive eolian sandstone with a thickness of 41–91 m (Dyer, 1983). The lowest member of the Entrada Sandstone, the Dewey Bridge Member, consists of interbedded fine-grained–silty sandstone and siltstone and rests unconformably on the Navajo. The Dewey Bridge Member ranges in thickness from ~6 to >30 m. The overlying Slickrock Member is a dark red, massive, fine-grained sandstone, whereas the upper Moab Member is a light-colored, clean, fine- to medium-grained sandstone. The Slickrock Member ranges from 60 to 160 m in thickness, whereas the Moab is ~20–40 m thick. The Navajo, Slickrock, and Moab sandstones are more resistant to weathering than the Dewey Bridge. The Slickrock Member is the major cliff-forming unit within the park (Lohman, 1975). The Entrada Sandstone is overlain by the Jurassic Tidwell Member of the Morrison Formation. The Tidwell Member consists of thin-bedded red sandstone and shale with local concentrations of chert (Doelling, 1988).

The majority of arches are composed of Entrada Sandstone, although arches are present in the overlying Morrison and underlying Navajo and Wingate Formations. Within the Entrada Sandstone, most of the

* Present address: M. King Hubbert Geomechanics Laboratory, Earth and Atmospheric Sciences Department, 1397 CIVL, Purdue University, West Lafayette, Indiana 47907-1397.

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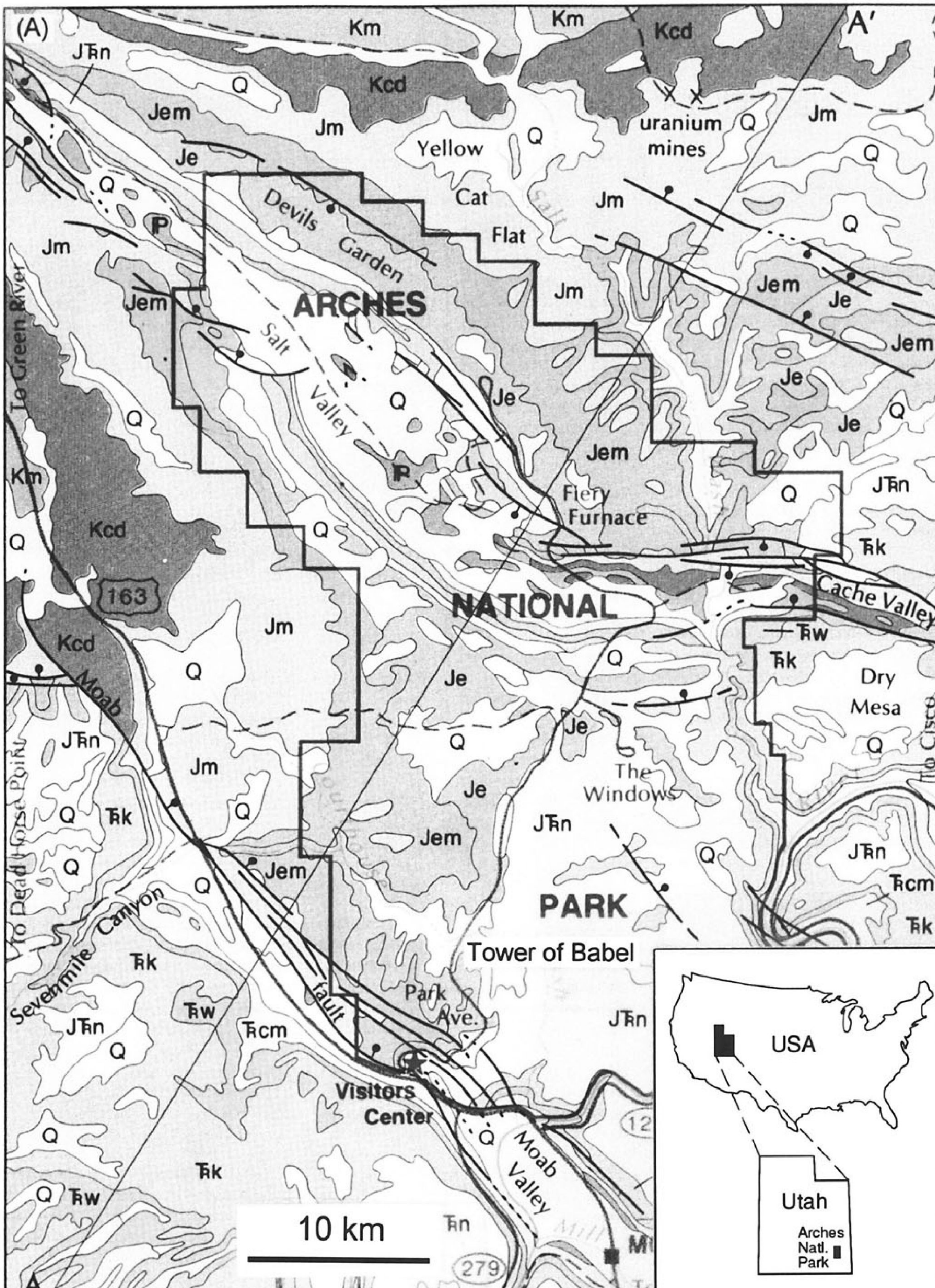
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Figure 1A. Simplified geologic map of Arches National Park and vicinity showing the location of the major named regions within the park (Doelling, 1985). The major structure of interest is the asymmetric Salt Valley anticline.

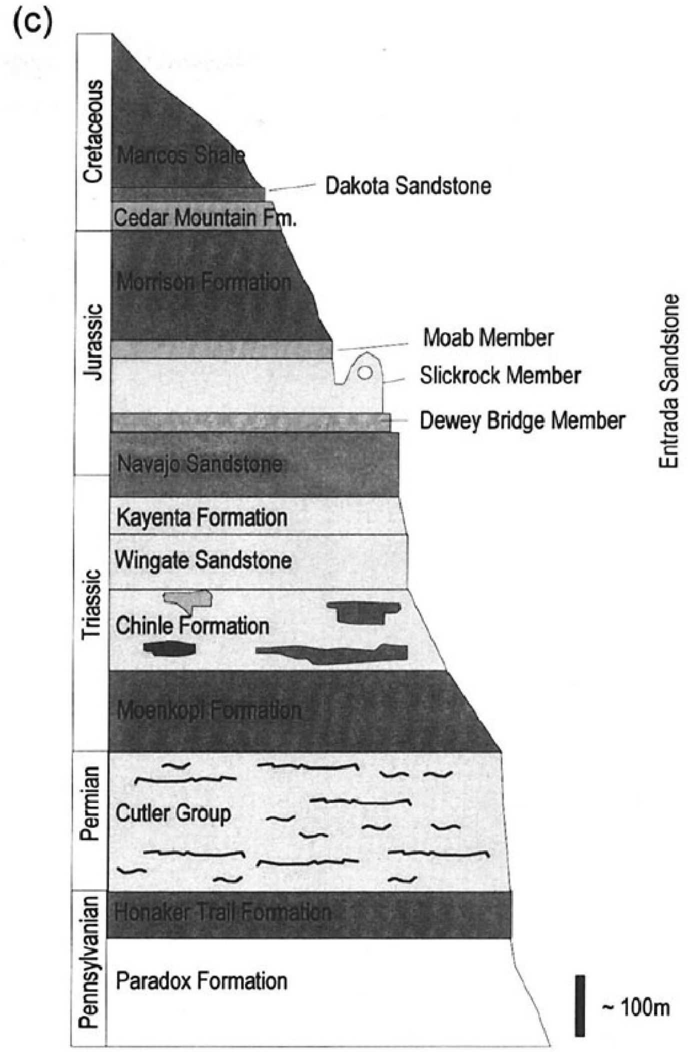


Figure 1C. Stratigraphic section for Arches National Park. The Entrada Sandstone is ~140 m thick (Phillips, 1989).

arches are in the Slickrock Member (Oberlander, 1977; Stevens and McCarrick, 1988).

Joints in Entrada Sandstone appear to be related to the Salt Valley structure and do not reflect a regional pattern (Kelley and Clinton, 1960; Doelling, 1988). These joints are approximately parallel to the axis of Salt Valley, and near Fiery Furnace on the northeast side of Salt Valley, joints change orientation to become parallel to the salt-cored Cache Valley anticline. On the northeast flank of Salt Valley, the intensity of jointing diminishes away from the valley. There are also many normal faults, with the down-dropped side toward the center of the anticline. On the southwest flank of the anticline, normal faults are older than the joints (Doelling, 1985; Dyer, 1988; Cruikshank and others, 1991); the normal faults have nucleated along zones of deformation bands (Aydin and Johnson, 1978; Zhao and Johnson, 1992). On the northeast flank of the anticline, joints predate the faulting, because many of the normal faults in the Devils Garden area formed along preexisting joint surfaces (Cruikshank, 1993). Thus, the jointing at Arches National Park—fin-bounding joint zones, and arch-localizing joint zones—are related to the Salt Valley anticline (Doelling, 1985; Dyer, 1988). The development of the Salt Valley anticline is discussed in detail by Doelling (1985, 1988).

Theories of Arch Formation

The first requirement to form an arch is the presence of a rock wall or fin that is strong enough to support an arch structure; rock fins are abundant in Arches National Park. Surface markings, such as hackle and plumose structures (Hodgson, 1961; Pollard and Aydin, 1988) on the walls of the rock fins, indicate that these walls are joint faces. Linear traces seen from the air (Fig. 2) are zones of joints (Hodgson, 1961; Dyer, 1983; Cruikshank and others, 1991); that is, the traces of joints are composed of numerous subparallel joint segments that are confined to a narrow zone. This pattern can be seen in both vertical and horizontal exposures (Hodgson, 1961). These zones of joints form a weak zone that weathering exploits, leaving behind majestic rock fins separated by narrow can-

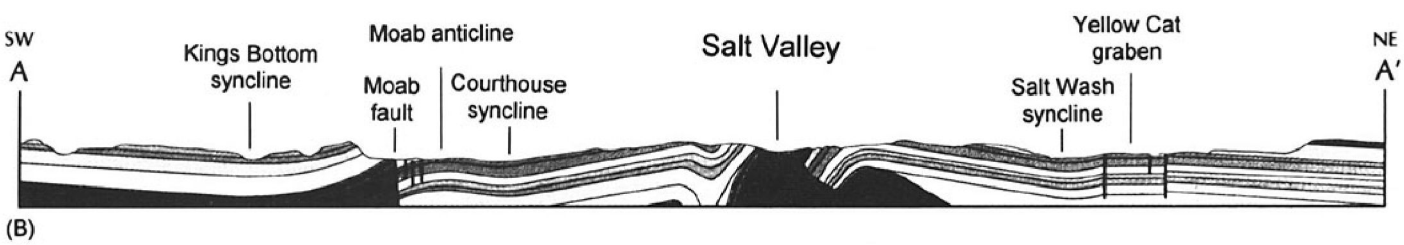


Figure 1B. Most of the arches are in the Jurassic Entrada Sandstone, which is exposed on both flanks of the anticline and forms spectacular dip-slope exposures.

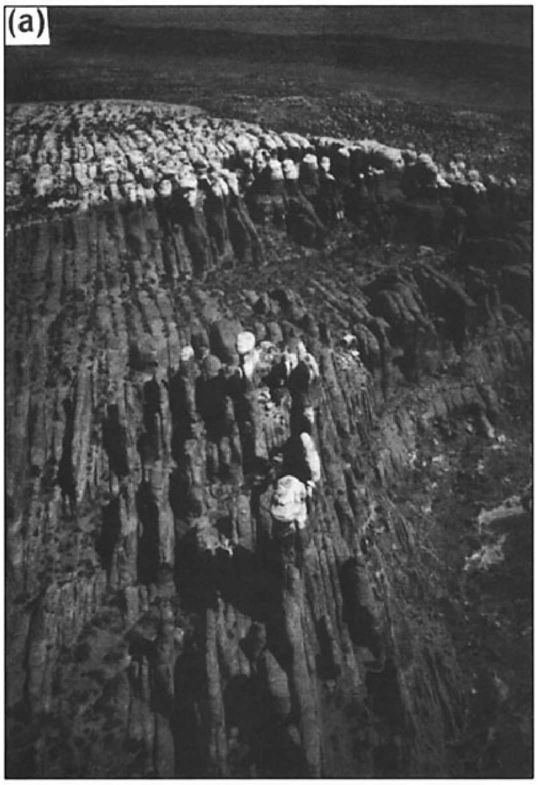
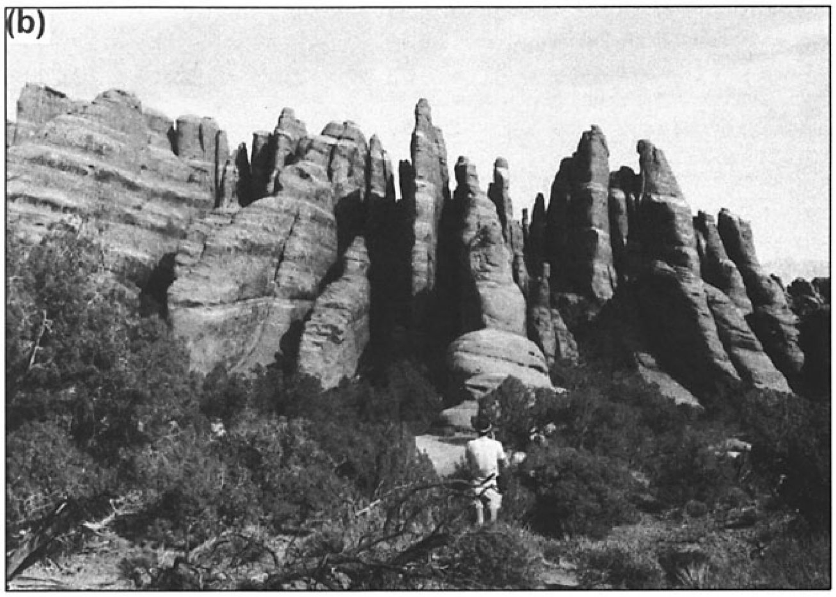



Figure 2. (a) Aerial view of fin-bounding zones of joints at Klondike Bluffs. Individual vegetation-filled traces are actually narrow zones of many individual joints. Erosion along these zones of joints leaves behind rock fins, in which arches form. Tower Arch is in a fin near the center of the photograph, below a white-capped tower. (b) View of well-developed rock fins in Fin Canyon, a few kilometers north of Arches National Park campground.

yons. Fin canyons are not formed by the weathering and widening of an individual joint; rather, fin canyons represent erosion of a zone of fractured rock. This correspondence between the systematic joint zones and eroded gaps bounding rock fins is an excellent illustration of the relationship between fracturing and erosion at Arches National Park.

In some areas—for example, ~1 km north of Fiery Furnace (Fig. 1)—there are few intact fins. In these areas, the entire rock mass has been extensively fractured, leaving little intact rock to form fins. In essence, the entire rock mass has been weakened uniformly so that large open areas formed within an outcrop of rock fins.

Rock fins illustrate the role that fractures related to the Salt Valley anticline play in controlling the local geomorphology. The unusual number and thinness of rock fins at Arches National Park is undoubtedly one of the reasons why there are so many arches within the park. The relationship between zones of joints and erosion resulting in the formation of rock fins has been accepted widely (Lohman, 1975; Doelling, 1985; Dyer, 1988; Stevens and McCarrick, 1988). The current debate over arch formation centers on the processes that control how and where these rock fins become perforated. In the following discussion, we review some arch localization mechanisms that have been proposed by previous workers.

Lohman (1975) and Blair (1975, 1987) suggested that arches form where lithologic variations in the Entrada Sandstone provided localized weak zones in rock fins. The weak lithologic zones are assumed to be either shale layers or weakly cemented zones. In the Windows section of the park (Fig. 1), arches are at the contact between the Dewey Bridge and Slickrock Members of the Entrada Sandstone. Here, erosion of shale in the underlying Dewey Bridge Member is thought to control arch localization in the Slickrock Member (Blair and others, 1975). Arches and alcoves in the Slickrock are associated with minor folds in the Dewey Bridge (Blair and others, 1975, Fig. 8); it is, therefore, reasonable that localized damage in the Slickrock Member from underlying folds may account for the localization of arches in this particular spot. Throughout most of the park, however, arches are well above the Dewey Bridge–Slickrock contact, so the contrast in rock types cannot be responsible for the majority of arches. Furthermore, as we will conclude below, slip along a lithologic contact may be responsible for local fracture concentrations and, consequently, the weakening of the Slickrock at the contact. Also, the Dewey Bridge–Slickrock contact is exposed in numerous places where there are no arches or indications of arches beginning to form.

Some authors have ascribed arch location within the Slickrock to weakly cemented zones. Blair (1975, p. 82), from field observation of the rock's reaction to dilute hydrochloric acid, inferred that there was less calcite cement in the Slickrock in the vicinity of arches. Blair used this observation to account for the large number of arches in the Devils Garden and Fiery Furnace sections (Fig. 1), where most of the arches are within the Slickrock Member, well above the contact with the Dewey Bridge Member.

Doelling (1985, p. 13) suggested that arches form where there had once been a sand dune against a fin, where the acidic nature of sandy soils would dissolve any cement, thus accelerating the breakdown of a fin in selected areas.

Fracture control of arches also has been considered. Blair (1975) suggested that arches may initiate at individual vertical fractures that are at a high angle to a fin. This is similar to the mechanism proposed in this paper in principle; however, a simple fracture by itself is unlikely to be an arch-forming mechanism, because numerous single fractures exist at a distance from all arches without creating any openings. In a few cases, such as Broken Arch (Fig. 3), the form of the arch has been modified by the opening of a vertical fin-normal joint. As we demonstrate later, however, the weakness of the perforated area is due to intense localized fracturing, the remnants of which can still be seen in the arch legs.

Exfoliation fractures also have been suggested as a control of arch formation (Hunt, 1956; Blair and others, 1975; Barnes, 1978). Exfoliation (or unloading) fractures are thought to form after the arch opening has been established by the release of residual stresses. The initial opening is formed by erosion of a weak zone, such as a preexisting shale layer. Fractures in the photographs of various investigators (for example, Blair and others, 1975, Fig. 6; Barnes, 1978, p. 139) do not have the characteristics of exfoliation fractures (Holzhausen, 1989); that is, they do not mimic topography, and their spacing does not decrease with distance from the erosion surface. In several instances, the highest densities are *within* the rock fin (for example, Broken Arch, Fig. 3).

In addition to being described as exfoliation fractures, the closely spaced fractures seen in the legs of arches also have been ascribed to loading of arch legs by the arch span (Blair and others, 1975; Stevens and McCar-

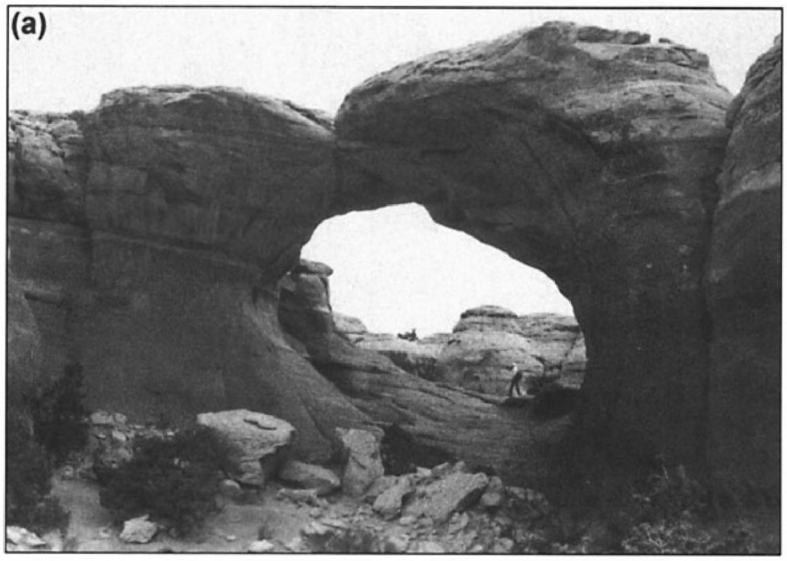
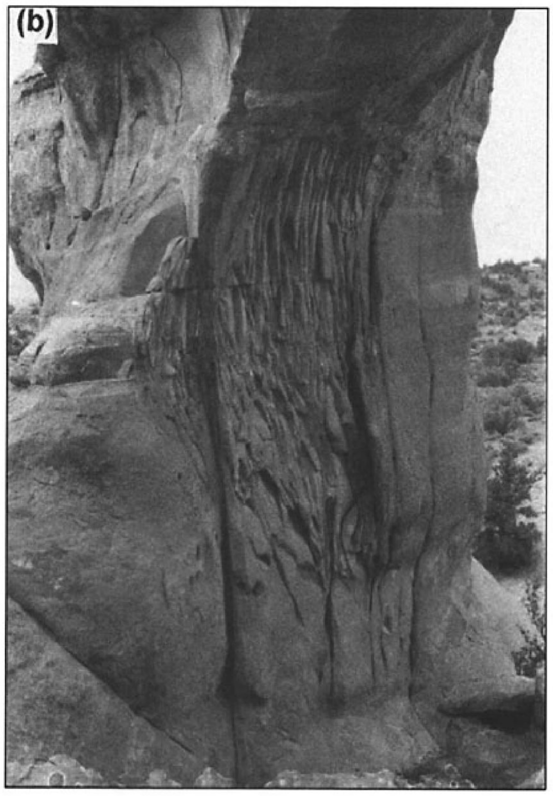
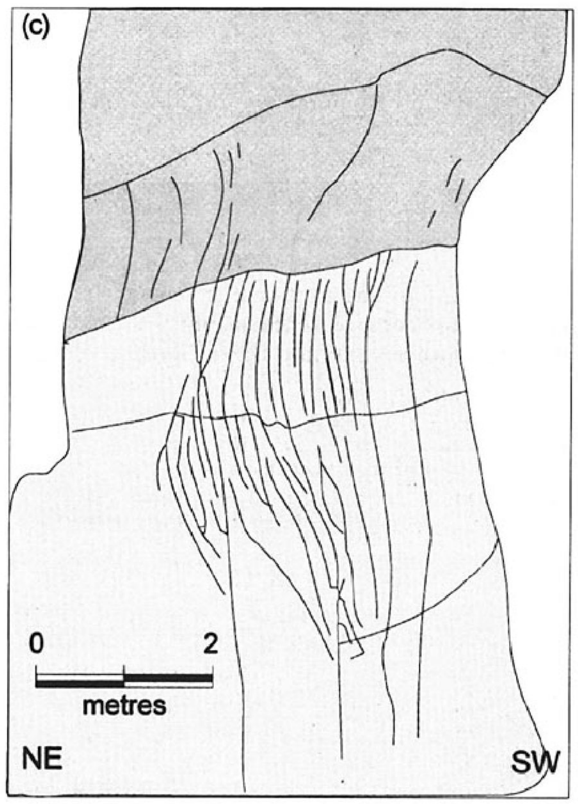


Figure 3. Broken Arch, near Arches National Park campground, shows the remnants of localized fracturing that locally accelerated erosion to form an arch. Note that the highest fracture density is in the middle of the arch leg and that many of the fractures start near the tips of vertical fractures. The vertical fractures are part of the fin-bounding joint zone. (a) View of the west side of Broken Arch. (b, c) The southeast leg of Broken Arch shows the fractures nucleating from vertical fractures. Also, these fractures end at a lithologic change which is at, or close to, the contact between the Slickrock and Moab Members of the Entrada Sandstone. This illustrates the role bedding may play in confining the localized fracturing by stopping fractures and leaving an intact roof.





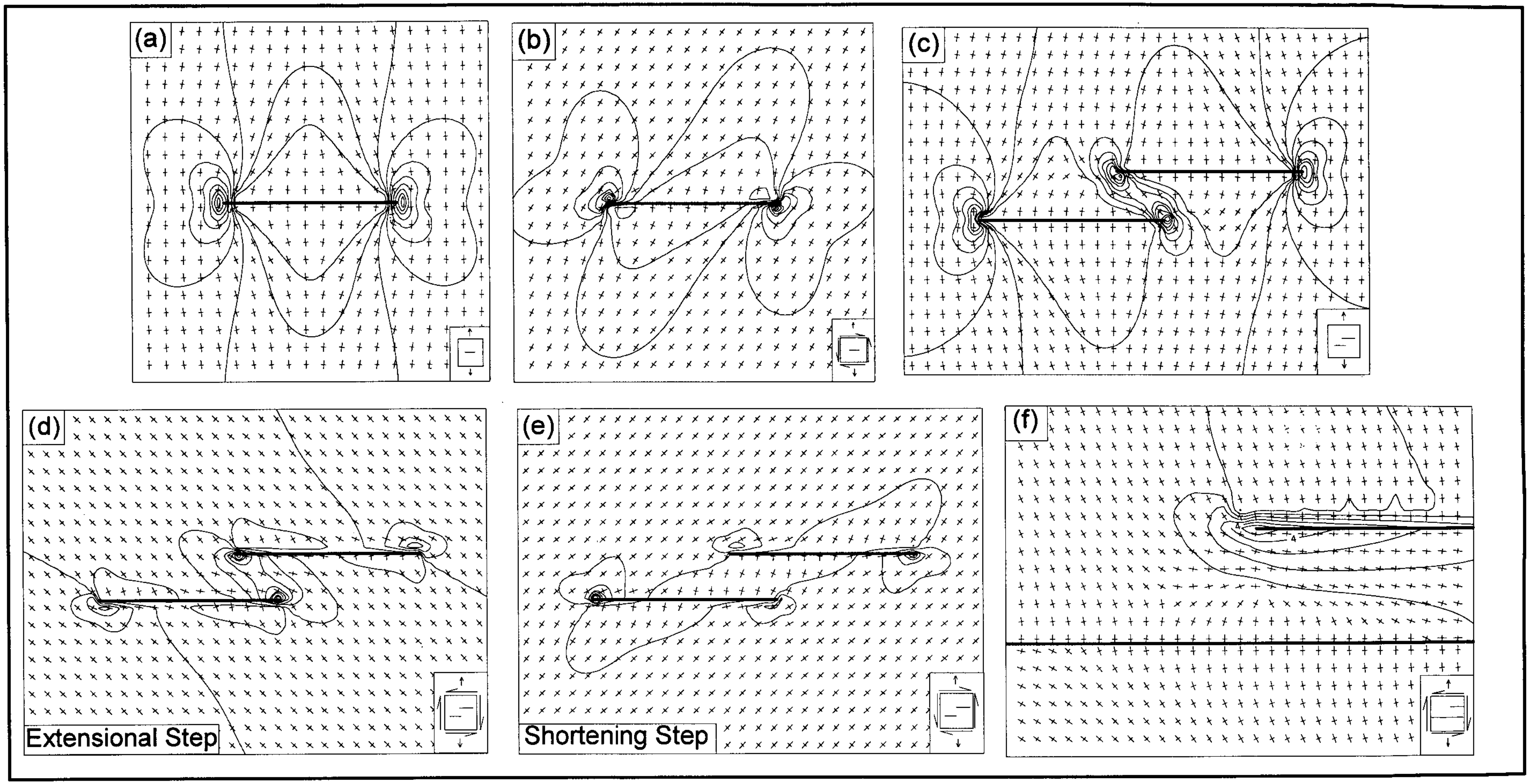


Figure 4. Maximum principal stress in the vicinity of a single fracture (a, b) and in the vicinity of two left-stepping fractures (c–e). Tension and right-lateral shear are positive. The contour interval is 10% of the maximum stress, which is at the fracture tips. The long axis of the cross symbol is in the direction of maximum stress (Pollard and Segall, 1987). Any opening-mode fractures that formed would be parallel to the direction of the short stroke. (a) Single fracture subjected to uniaxial tension normal to the fracture. (b) Single fracture in a plate subjected to right-lateral shear. The term "right-lateral" indicates that, to an observer standing on one side of the fracture and looking toward the other side, the other side is being moved to the right. (c–e) Shows the stress and orientation of the maximum stress around two interacting fractures with a large overlap. In (c) only tension normal to the fractures is applied to the system. (d) Superposed left-lateral shear. (e) Right-lateral shear, the area of overlap is an extensional step. (f) Left-lateral shearing of a fracture that terminates near a continuous boundary.

rick, 1988). There have been no *in situ* measurements of stress in rock fins to test this hypothesis, or calculations to show that the weight of an arch is sufficient to cause failure in the legs. The fracture pattern in the legs of arches also is present in very small, shallow rock shelters (for example, on the east side of the Landscape Arch trail) and in places where arch formation has not yet initiated or never will be initiated because of the thickness of the fin. Clearly, the fracture pattern can form before the arch. As we conclude below, the fracture pattern is not controlled by the presence of an arch, but rather the location and shape of an arch are controlled by these preexisting fractures.

In summary, an unusual number of arches in Arches National Park are related to the large number of thin rock fins within the park. Without regard to how an arch formed in one area or another, most previous workers make the following observations: the rock fins are controlled by a joint system developed during the evolution of the Salt Valley; arches are at all stratigraphic horizons where the rock can form a fin and support an arch; there is a dense network of fractures in the walls and legs of arches; and in a few places where the fin is very thick, shallow rock shelters are formed.

Most observers accept the role of joints in forming rock fins (Stokes, 1951, 1973; Stevens and McCarrick, 1988); however, a similar role of jointing in localizing arches has not been considered seriously or demonstrated. In this paper, we maintain that localization of fractures is the key to understanding the unusually high number of arches in Arches National Park.

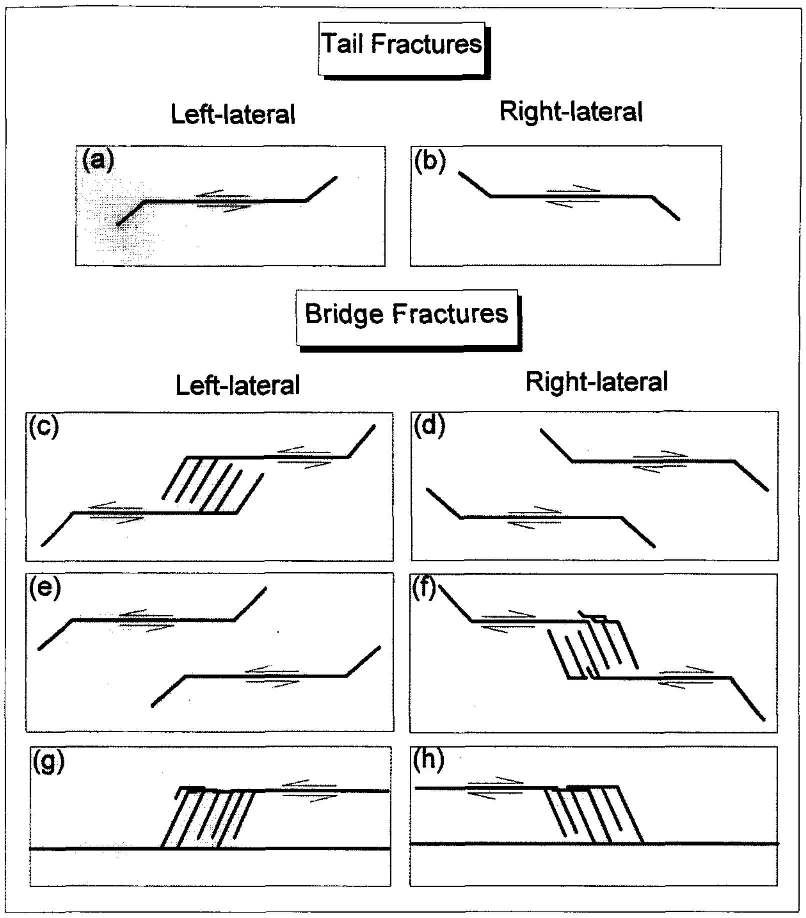


Figure 5. Schematic diagrams illustrating rules for understanding the effect of shear displacement on existing fractures. In all cases the left column is left-lateral shear, and the right column is right-lateral shear. (a, b) Single fractures. (c, d) Left-stepping fractures. (e, f) Right-stepping fractures. (g, h) Here, with only one termination, a similar pattern to (e) will be produced; however, fractures generally only nucleate from a fracture that terminates.

RULES FOR READING FRACTURE PATTERNS

Before describing details of fractures in arch legs, we present some rules for interpreting fracture patterns. These rules help in understanding the fractures observed in the vicinity of arches. We use linear-elastic fracture mechanics as a basis for our interpretation of fracture patterns (Pollard and Segall, 1987; Lawn, 1993). The mechanics of jointing is taken to be described by opening-mode (mode I) fracturing in an elastic material. We further assume that preexisting planar discontinuities in the rock—bedding planes, thin discontinuous shale layers, and shale lenses—act in the same way as preexisting fractures (that is, as weak surfaces). This is valid as long as the aspect ratio of a shale layer is similar to that of a fracture, or the failure occurs along the top or bottom boundaries of the layer. Similar tools have been used extensively in structural geology (Engelder and Geiser, 1980; Pollard and Segall, 1987; Pollard and Aydin, 1988). Using fracture mechanics as a guide, we can tell that these fractures are not related to loading of arch legs by the weight of the span, unloading of Entrada Sandstone due to erosion, or exfoliation. Rather, they are related to slip along existing discontinuities, such as joints that bound rock fins.

Mode I fractures always form in the plane of maximum stress (tension is positive). If there is only extension normal to a fracture, then it will extend in the plane of the parent fracture (Fig. 4a), because the rock is isotropic and nothing will cause it to take another path. In simple shear, however, any new fracture growth will extend at an abrupt angle to the parent fracture; for a horizontal fracture subjected to left-lateral shear (Fig. 4b), the top-right and bottom-left regions near the fracture tips are under lower stress (areas of few contours), while the other quadrants are under higher stress (area of many contours). Thus, if the parent fracture were to grow as an opening-mode fracture, it would change direction and grow into the quadrants that have the greater stress (see Figs. 5a and 5b). In this case, the fracture is said to kink. The angle of kinking is related to the amount of shear; the larger the applied shear relative to crack-normal stress, the greater the kink angle (Cotterell and Rice, 1980; Cruikshank and others, 1991). Joints will respond to local stress perturbations that reorient the principal stress direction. Such perturbations may be due to neighboring joints, bedding planes, or other anisotropies. When two fractures growing toward one another interact, shear on the fracture tips increases as the two frac-

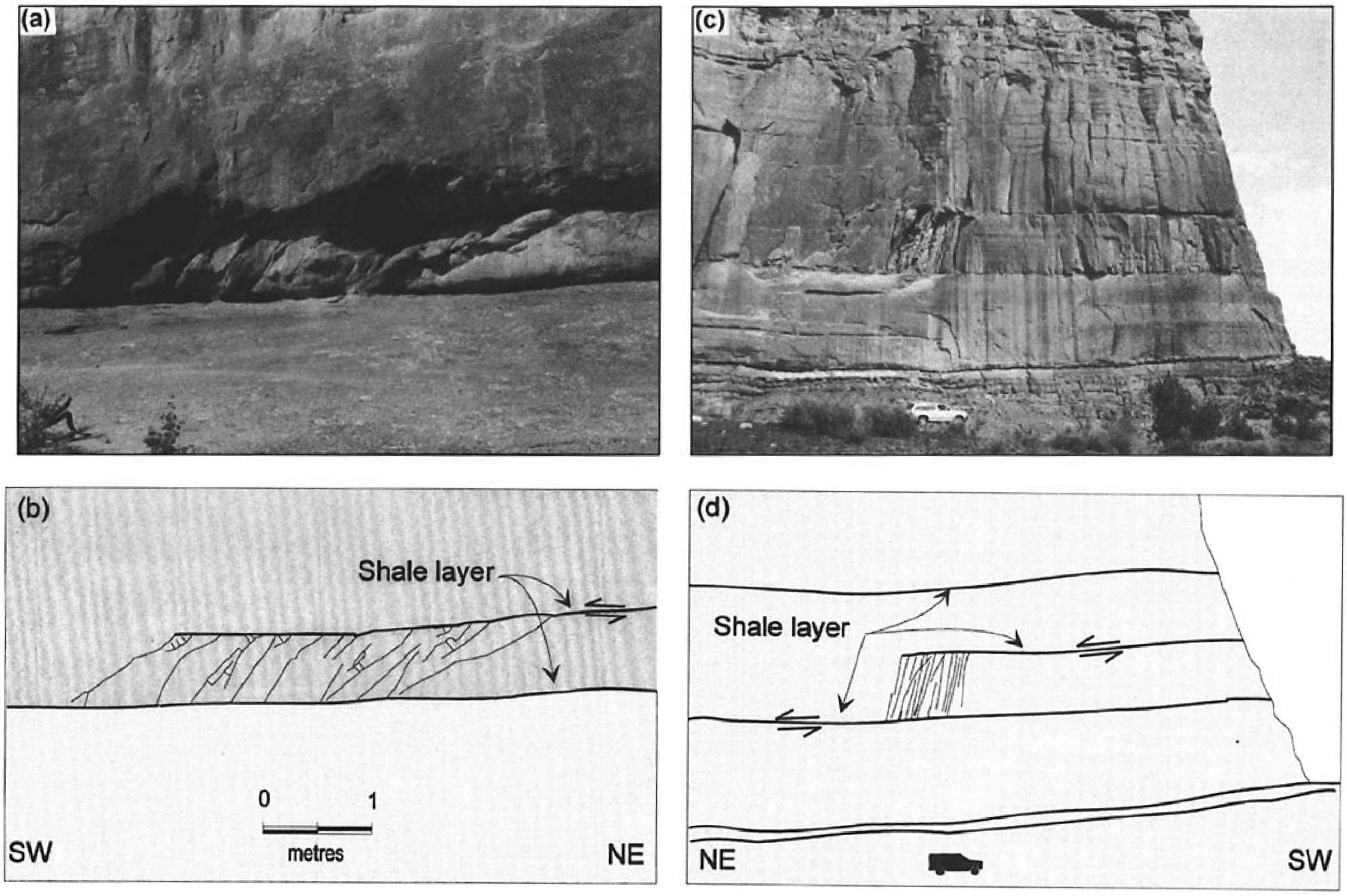


Figure 6. (a, b) Fractures along horizontal discontinuity in Herdina Park region, near Eye of the Whale Arch. The view is southeast. The fractures have been subjected to top-to-the-left shear. An arch has not formed because this exposure is not on a rock fin. Compare the fracture pattern with Figure 6b. (c, d) Fracture pattern on the northwest wall of the Tower of Babel. Note the concentration of fractures at the tip of the upper shale layer. The pattern indicates top-to-the-left shear.

tures come closer together. Under these conditions, the fractures will change direction gradually—first away from one another, and then toward one another (Olson and Pollard, 1989; Cruikshank and others, 1991).

When two parallel fractures with the initial fracture geometry in Figures 4d–4f are sheared, the region of overlap may either shorten (Fig. 4e) or extend (Figs. 4d and 4f). Opening-mode fractures will probably not form in the case of a shortening step (Fig. 4d); however, in the case of an extensional step (Fig. 4e), additional joints would form within the step at a high angle to the parent fractures. In addition to the fracture tip, the parent fractures would probably provide irregularities from which joints could nucleate. The fracture configuration and resulting stress distributions shown in Figures 4c–4f may be used to understand the zones of intense fracturing that are associated with arches (Figs. 5c and 5f–5h).

The two fractures in Figures 4c–4f may represent two thin shale layers, two bedding planes, or two vertical joints. In the case of two vertical joints, the reason we can have two straight, overlapped joints without any veering due to fracture interaction is that the fractures must have originally formed with compression parallel to the joints (Cotterell and Rice, 1980; Olson and Pollard, 1989; Cruikshank and others, 1991). High fracture-parallel compression makes it difficult for joints to grow out of plane, even when two fractures interact. The fin-bounding zones of joints at Arches National Park are composed of numerous segments with little interaction, so they probably formed with high compression parallel to the fractures. This allows the geometry shown in Figures 4c and 4d to be a reasonable starting configuration for our analysis of joint segments within a zone of joints.

In summary, a joint will propagate in its own plane unless there is shear at the fracture tip. The shear may arise from remote applied shear, (for example, Fig. 4b), shear induced by the presence of another fracture (for example, Fig. 4c), or an interface (for example, a bedding plane). If an existing fracture extends when it is subjected to applied shear, it will kink. If the amount of shear at the tip increases slowly, as the fracture propagates and interacts with another fracture, for example, then the fracture will veer. The direction of veering will follow the same direction rule as a kink.

The rules for reading secondary fractures are simple, and they are shown in Figure 5. *For a kinked fracture* (Figs. 5a and 5b), *when looking along the length of the parent fracture, if the sense of kinking is counterclockwise, then the fracture was subjected to left-lateral shear. A clockwise angle would indicate right-lateral shear.*

In the case of two overlapped fractures

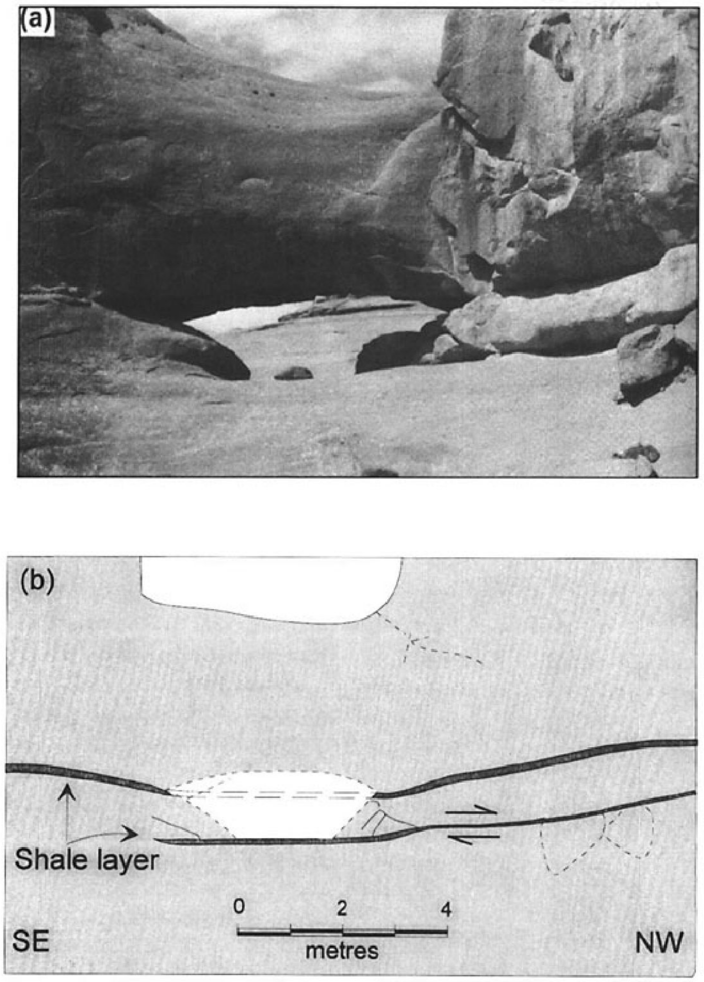


Figure 7. Eye of the Whale Arch, looking southwest. This arch formed where a shale layer ended. This is a similar situation to that shown in Figure 6, which is ~100 m south of Eye of the Whale Arch. The fracture pattern suggests that it was produced by left-lateral shear on the upper shale layer.

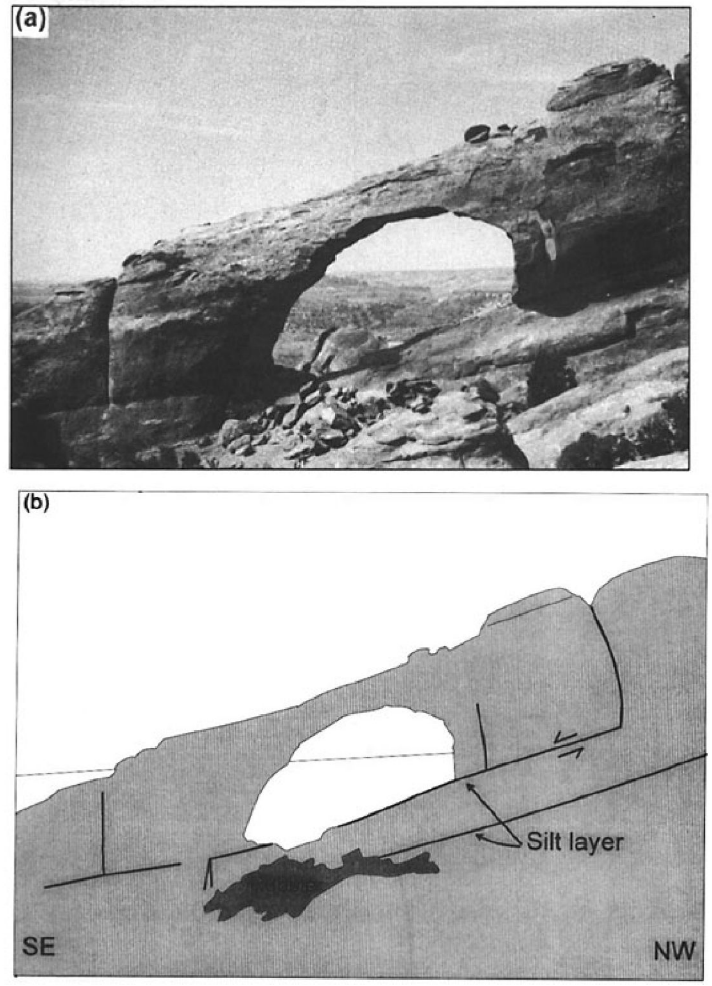


Figure 8. Photograph and sketch of the east face of Skyline Arch from Arches National Park campground. The form of Skyline Arch is controlled by tail fractures originating from the silt layer parallel to the base of the arch.

(Figs. 5c–5h), *a series of bridging fractures will exist if the step was an extensional step. This occurs when the sense of stepping is the same as the sense of shear (left-stepping fractures and left-lateral shear, or right-stepping fractures and right-lateral shear). When the step sense is opposite that of the sense of shear, tail fractures will form pointing away from the step; the step will not be bridged by fractures.*

The existence of kink-like secondary fractures on parent fractures indicates a two-stage fracturing process (Barton, 1983; Segall and Pollard, 1983; Martel and others, 1988). The first stage is the formation of the parent fracture, with the fracture normal to the principal tension direction. The second stage is when shear displacement is applied to the existing fracture, causing new fractures to grow at an angle to the parent fracture. If there is an abrupt change in the orientation of fracturing during the new increment of growth, the fracture is said to kink. If the parent fracture had grown into a domain where shear is resolved on the fracture tip, then the fracture would change orientation gradually, and the fracture is said to veer (Olson and Pollard, 1989; Cruikshank and others, 1991). Recognition of a two-stage development in a fracture pattern is essential in understanding the complex fracturing associated with arch localization and formation.

Just as the tip of a sheared joint nucleates new fractures, so will the end of a shale layer that is being sheared. Additional fractures also may form at irregularities in the discontinuity near the tip. Thus, one may use fracture kinematics to understand fractures that nucleate at the tip of a shale lens. Similar fractures also could be formed along a lithologic boundary that has localized patches of slip along the boundary and could help to localize arches in the Windows section of the park. The fractures would form where the boundary makes the transition from slip to no-slip.

FRACTURES ASSOCIATED WITH ARCHES

Although shear on an individual discontinuity (shale layer and lens, bedding interface or joint) will cause intense fracturing at its tip, at Arches National Park we have observed that the more common cause of fracture localization is the interaction between two slipping discontinuities. Fractures produced near the termination of a slipped discontinuity are called either *tail* (*or wing*) or *horsetail (or pinnate) fractures* (for example, Fig. 5a). Fractures produced by the interaction of two slipping discontinuities are called *bridge fractures* (for example, Fig. 5c). Bridge fractures tend to form at an extensional step between the termination of one fracture and the plane of the

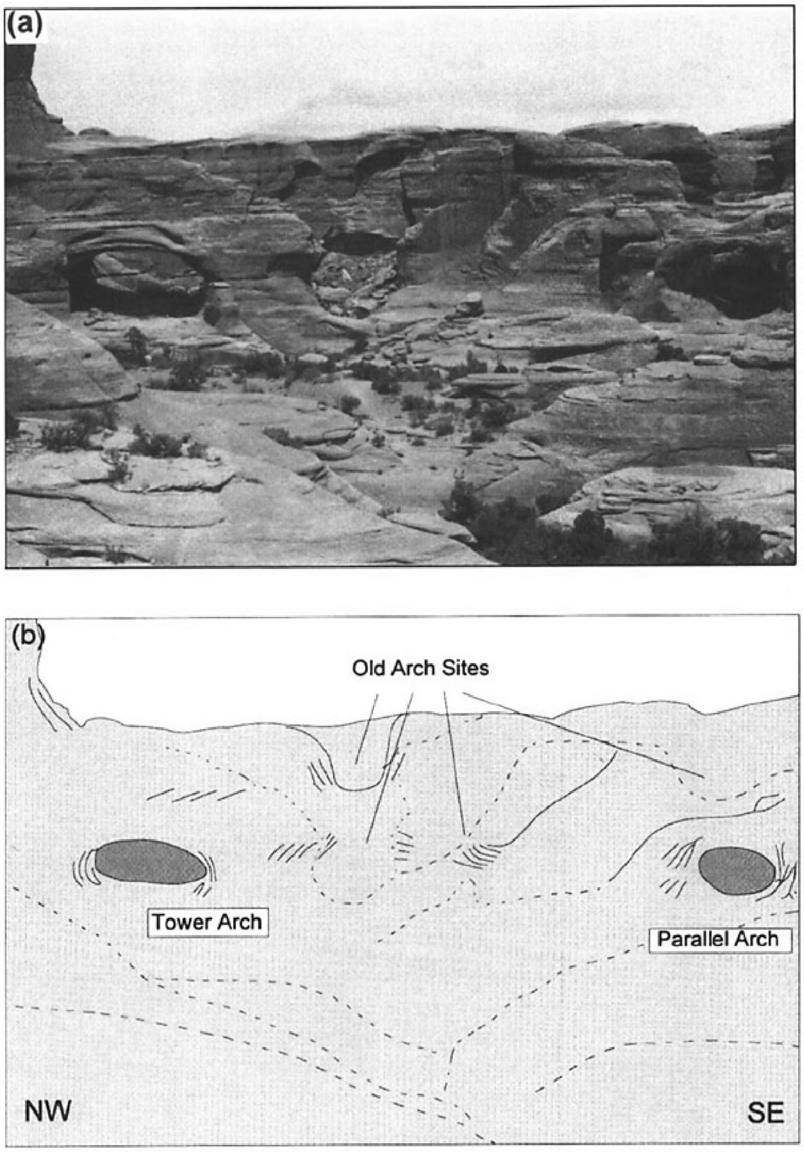


Figure 9. Tower Arch area in the Klondike Bluffs region. Tower Arch is on the left, and Parallel Arch is on the right. The view is northeast and is normal to the fins. This area shows several zones of intense fracturing. The positions of two of these zones are represented by arches, the third by a break in a rock fin.

second fracture. Segmentation of the fracture near the termination or irregularity therein would result in the formation of several bridging fractures (Cruikshank and others, 1991). Both tail and bridge fractures may be associated with either horizontal or vertical discontinuities. Within the park, horizontal discontinuities are present along sedimentary structures such as bedding planes, shale layers, and lenses, whereas the vertical discontinuities are always preexisting and fin-bounding systematic joints. In some instances, two or more periods of shearing patterns (for example, along vertical and horizontal discontinuities) are superposed, producing a more complex-looking fracture system.

Below, we describe the fracture localization associated with horizontal and vertical discontinuities. The fracture pattern associated with horizontal discontinuities tends to be simpler than that associated with vertical discontinuities, because horizontal discontinuities tend to be sedimentologic discontinuities, and there are few sedimentologic terminations in any one area of rock. Most vertical discontinuities tend to be within zones of joints, where there are many more terminations, so when sheared tail fractures form, grow, and interact, they produce a more complex-looking pattern. Also, during the development of a zone of joints, interactions between joint segments can lead to a more complex-appearing pattern. For this reason, we discuss horizontal discontinuities before vertical discontinuities.

Arches, Tail Fractures, and Bridge Fractures Associated with Horizontal Discontinuities

Tail and bridge fractures associated with horizontal discontinuities form as a result of shearing along nearly flat-lying lenses and layers of shale within the Entrada Sandstone. About 100 m southwest of Eye of the Whale Arch, in the Herdina Park region of Arches National Park, an upper shale layer terminates at the near left edge of the photograph (Fig. 6a), whereas a lower shale layer is continuous across the field of view. The two discontinuities are bridged by a large number of fractures that originated predominantly near the termination of the upper shale layer (for example, Fig. 6b). Several of these bridge fractures do not quite connect with the lower shale layer. Fractures at both ends of the upper shale layer suggest a top-to-the-left sense of slip. A similar fracture pattern also can be seen in the Tower of Babel in the Park Avenue region of the park (Figs. 6c and 6d). The dip direction of the tail fractures gives the azimuth of shearing.

About 100 m north of the fractures shown in Figures 6a and 6b is Eye of the Whale Arch (Fig. 7), which is controlled primarily by a series of tail fractures produced at the termination of a shale layer (Fig. 7b). An additional contribution is made by a series of fractures that are between two sheared interfaces below the lower shale unit (not seen in photograph). The echelon fractures produced by shearing between these two interfaces have eroded away, making the northwest side of the arch much more prominent than the southeast side (Fig. 7). These fractures combined with the fin-bounding fractures to produce the window of the arch.

Perhaps the most accessible arch showing evidence for shear along a shale layer and associated fracture localization is Skyline Arch, just behind the campfire circle at the park campground (Fig. 8). The floor of the arch is along a silt-rich layer in the more massive sandstone. The silt layer thins at the south end (left side of arch, Fig. 8), and a downward-pointing tail fracture is present. The same shale layer ends farther to the right of the arch, and a vertical tail extends upward to the skyline. A few smaller tail fractures can be seen ~5 m to the right side of the arch. The shearing and the associated gouge that produced the arch appear to be on at least two different levels. On the extrapolation of the shale layer on the left side of the arch, a series of low-angle echelon fractures are present in

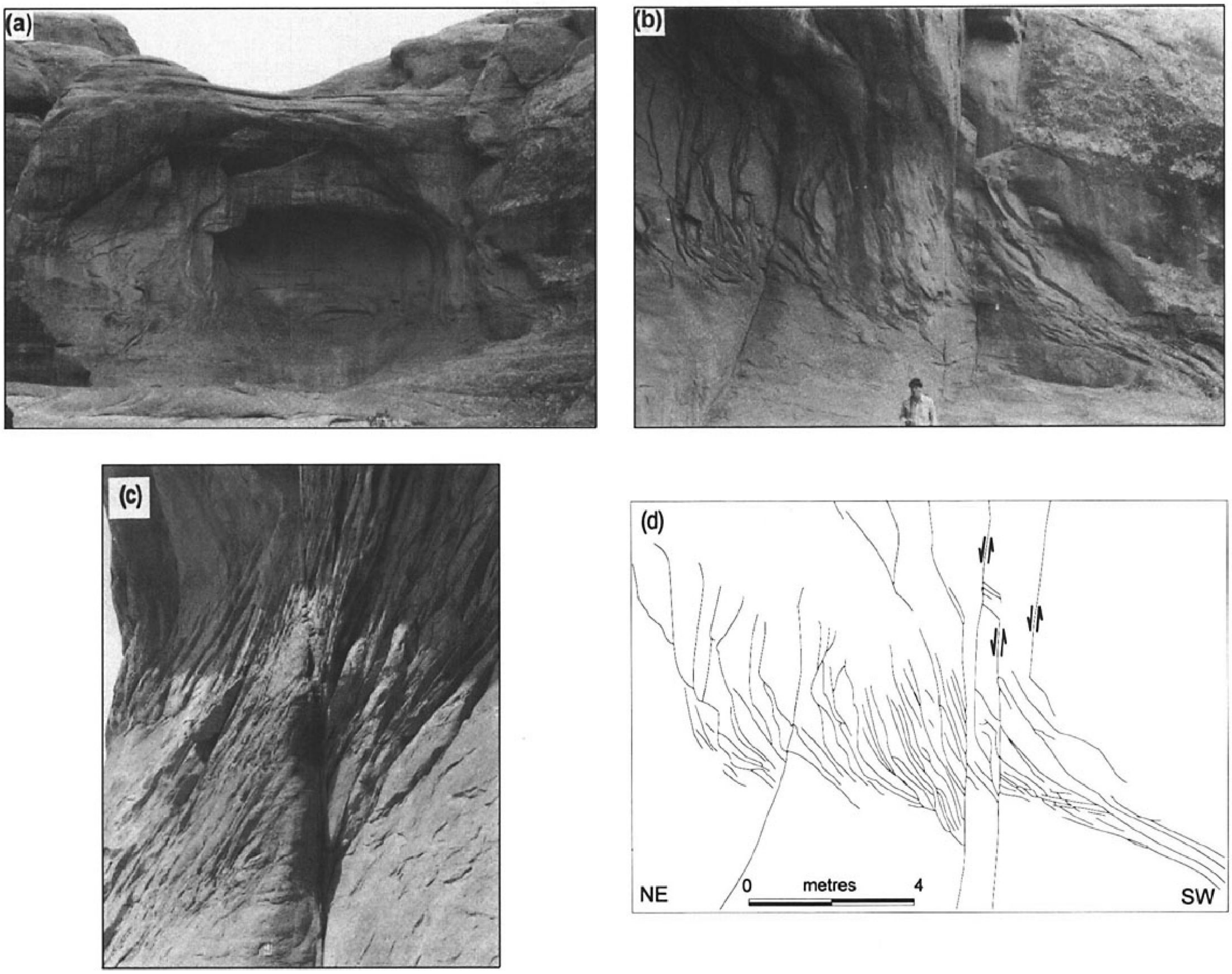


Figure 10. (a) Fractures around Parallel Arch in the Klondike Bluffs region (see Fig. 9). The center of the photograph corresponds to the wall of the fin that is behind the photographer. The arch is to the left. (b, d) Photograph and map of fractures in the southeast leg of Parallel Arch, where the rock fin abuts against a large outcrop. The center of the photograph corresponds to the wall of the fin that is behind the photographer. The arch is to the left. When joint segments within the zone of joints that form the fin were sheared, they interacted to form this complex-looking fracture pattern. The sense of shear appears to be left side down (down-to-the-northwest). (c) Photograph of fractures in the northwest leg of Parallel Arch, looking northwest. One set of fractures nucleated from the thorough-going, fin-parallel fracture in the center of the photograph. The inclined fractures on the left probably initiated on the fracture that forms the fin wall.

the intact rock, suggesting top-to-the-left shear in this view. Below the arch is another shale layer, which spawns tail fractures at its termination to the right of the arch. Old photographs of the arch show part of the opening of Skyline Arch filled by a large block, which is bounded by fractures parallel to the mapped tail fractures. This block fell out of the opening in November 1940 (Hoffman, 1981, p. 21). This is a clear example of the relationship between fractures due to shear and the removal of rock fragments by erosion. Without tail fractures segmenting a small part of the fin, it would have been difficult to explain the specific location of Skyline Arch.

Arches, Tail Fractures, and Bridge Fractures Associated with Vertical Discontinuities

Tail and bridge fractures associated with vertical discontinuities are present in all areas of the park, including the vicinity of Tower and Parallel Arches in the Klondike Bluffs region on the southwestern limb of the Salt Valley anticline, near Navajo Arch in the Devils Garden region, and Broken Arch near the park campground on the northeastern limb (Fig. 1). All of these areas show the basic pattern for shear displacement on vertical discontinuities; however, they also have some interesting variations. The Tower Arch area illustrates the discontinuous and patchy nature of the fracture localization, the area near Navajo Arch illustrates the role of multiple joint terminations within a zone of joints, and Broken Arch illustrates the interaction of vertical fractures with bedding surfaces.

Numerous zones of intense fracturing are present in the rock fins of the Tower Arch area on the southwestern limb of the anticline

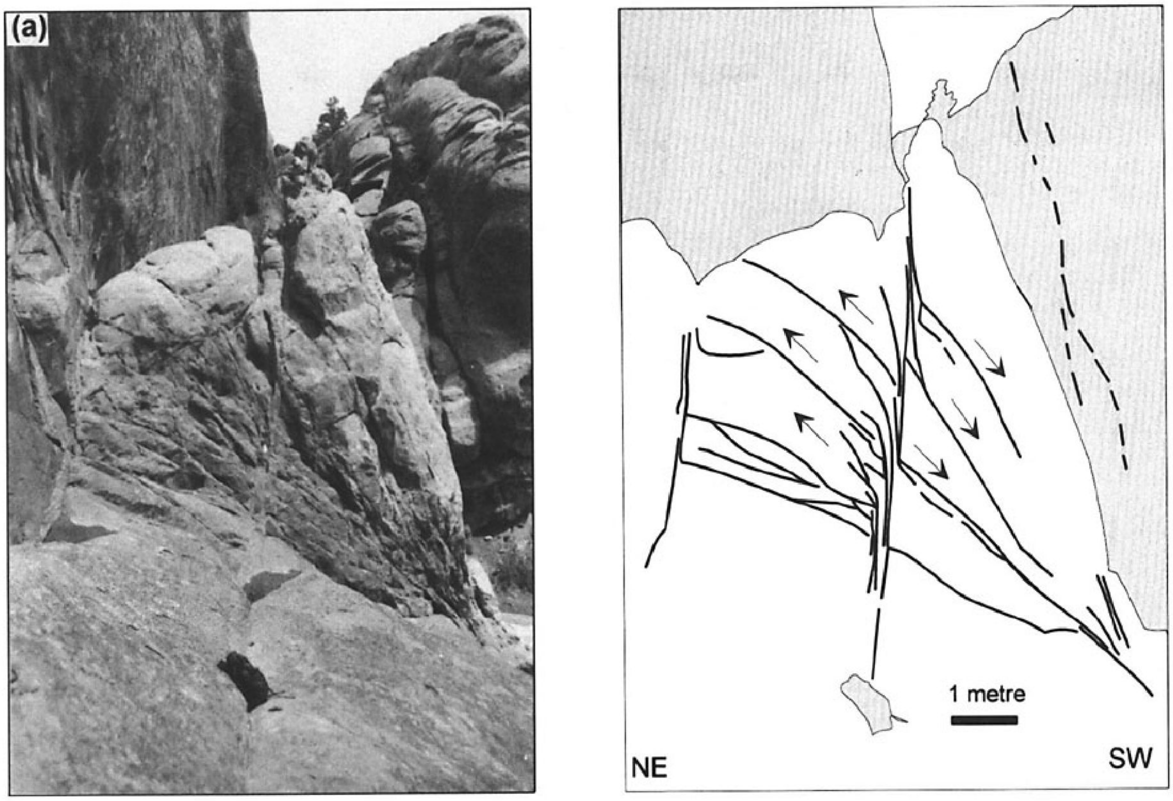


Figure 11. Fracture pattern in what once may have been the legs of an arch ~100 m south of Navajo Arch in the Devils Garden area. View is parallel to fin-bounding joint zones. Arrows show the direction of propagation of tail fractures that initiated from the tips of joint segments in the fin-bounding joint zone.

(Fig. 9). Where intense fracturing occurs, the fins are either undercut or perforated by an arch. The largest zone of intense fractures is in the center of Figure 9 and is on different stratigraphic levels. At the top of the photograph, there is a distinct U-shaped notch in the fin, with the axis of the notch normal to the photograph. This could have been the site of an arch if there had been sufficient intact material to form a roof. Some rubble from localized fragmentation can be seen below the U-shaped notch. Here, an arch-like alcove is beginning to form. There is an old opening in the same fin that contains Tower Arch, midway between Tower and Parallel Arches. The area between the old opening and Tower Arch is intact rock. In both of these locations, evidence of the same fracture pattern can be seen in the center of the photograph.

A complex fracture pattern developed within a zone of joints in the fin containing Parallel Arch when joint segments were sheared. Several vertical (fin-bounding) fractures are present in the south leg of Parallel Arch (Figs. 10c and 10d). Several of these segments terminate in the middle of the fin, some extend upward, and others downward. At the bottom termination of segments, the bridge fractures turn to the right (southwest), whereas at the top termination of the segments, the bridge fractures turn to the left (northeast). This indicates a down-to-the-left sense of shearing on these vertical joints.

Tail fractures associated with Parallel Arch indicate a sense of motion of down-to-the-northeast. The existence of bridge fractures that initiate at the parent fracture at an abrupt angle indicates that the shear was applied at some time after the initial fracture was formed. The bridge fractures are contained between the fin-bounding fractures and extend in the third dimension parallel to the fin. The fractures on the right of Figures 10b and 10c curve and end at a bedding surface. This illustrates how lithologic variations help to localize fracturing.

A similar fracture pattern exists in the north leg of Parallel Arch (Fig. 10d). A vertical fin-bounding joint extends up the entire length of the wall. One set of fractures nucleates from the vertical thorough-going joint. The sense of shear would suggest that the right (northeast) side had moved down relative to the left side. The inclined fractures on the left side of the photograph probably initiated on the fracture that forms the fin wall. Both sets of inclined fractures have a similar form. The bridge fractures in Figures 10b and 10c all appear to end at stratigraphic discontinuities. This further localizes damage done by fractures and leaves intact rock to form a roof for the arch (Fig. 10).

Many of the bridge fractures appear to branch, producing a very complex pattern (Figs. 10b–10d). In addition to the overall form of the bridge fractures, this branching provides a tool for reading the overall direction of propagation of a set of fractures. Surface markings show that the fractures propagated in the direction of branching. Branching has been taken to indicate rapid fracture growth (Cotterell and Rice, 1980); however, data are not available about the propagation velocity of the observed fracture.

Many small rock pillars that may have at one time been part of an arch are in the Devils Garden region, ~100 m south of Navajo Arch near the contact between the Slickrock and Dewey Bridge Members of the Entrada Sandstone (Fig. 11). This area illustrates how the existence of the multiple terminations within a zone of joints may yield a very complicated joint pattern as the result of shear. The vertical joint in the center of the photograph (Fig. 11a) is part of the fin-bounding joint zone. The fin wall—a joint surface—is on the left, and other members of the joint zone are in the background. Between the vertical, fin-bounding joints are a series of inclined fractures that connect the vertical joints. Based on the rules for interpreting tail and bridge fractures, one can determine that inclined joints that nucleated from *upper* terminations of vertical joints grew up and to the left. Still other inclined joints nucleated from the *lower* end of vertical joints and grew down and to the right. The directions of propagation are shown in Figure 11b. In the view of the photograph this gives a sense of shear of down-to-the-left (down to the northeast), similar to that associated with Parallel Arch (Fig. 10).

Broken Arch (Fig. 3) also has a complex-looking fracture pattern that initiated from the tips of joints parallel to the fin boundaries. Several vertical fractures are connected by a series of bridge fractures. Here, several of the vertical fractures and most of the bridge fractures terminate at a lithologic contact between the Slickrock and Moab Members of the Entrada Sandstone. By acting as an interface—the bridge fractures could not cross the lithologic contact—the contact has helped to form an intact roof for the arch. This interface probably has some shear offset, which contributed to the formation of the intense bridge fractures close to the interface. Nucleation of fractures at a lithologic contact may be responsible for fracture localization close to the interface between the Slickrock and Dewey Bridge Members.

The fracture patterns described above have been identified in all the arches we have looked at. Skyline and Eye of the Whale Arches are controlled by tail and bridge fractures that formed at the tips of horizontal discontinuities that were sheared. A spectacular example of this phenomenon may be seen in the Tower of Babel (Fig. 6). Navajo, Double, Partition, Onion, and Tunnel Arches in the Devils Garden region have well-developed bridge fractures, which originated from the fin-bounding joint zones.

Because intense fracturing commonly initiates on one side of a rock fin, it is possible for the opening to be much larger on one side of a fin than on the other. Such is the case with Eye of the Whale Arch and Baby Arch, which is located next to the Tower of Babel in the Park Avenue area. When Baby Arch is viewed from the road, the east side of the rock fin, only a small opening is visible in pristine-looking rock. From the west side, one can see intense localized fracturing and a much larger opening. The arch appears to be enlarging by erosion of fragmented rock from the west side.

SUMMARY AND CONCLUSIONS

In this paper we have described a consistent mechanism—localized intense fracturing due to shear on existing discontinuities—for localized erosion in rock fins to produce the arches in Arches National Park. The unusual number of arches is related to the tectonics of Salt Valley—the development of the anticline and its subsequent breach and collapse. These events produced zones of joints. Shear along vertical and horizontal discontinuities could have occurred at almost any time in the evolution of the anticline. The shearing is probably a result of the jostling of joint-bounded blocks as the anticline grew and collapsed. Weathering and erosion along the zones of joints formed the rock fins, and erosion of the local zones of intense fracturing formed openings in the rock fins, producing arches.

There is no need to invoke reasons such as weak cement, unloading, or exfoliation to explain the presence of arches, especially when these processes act on similar rocks in nearby regions without producing the same abundance of arches. Some of these processes may act on arches, but they are not the primary agents responsible for the initiation and formation of an arch.

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