Landscape Arch, Delicate Arch, and Double Arch in Arches National Park, Southeastern Utah

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Utah Geosites
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M. Milligan, R.F. Biek, P. Inkenbrandt, and P. Nielsen, editors

Cover Image: *Double Arch, consisting of two giant pothole arch spans joined at one end, is the third largest in the park. Photo courtesy of Ben Erickson.*

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Utah Geosites showcases some of Utah's spectacular geology, both little-known localities and sites seen by visitors to Utah's many national and state parks and monuments. The geosites reflect the interests of the many volunteers who wrote to share some of their favorite geologic sites. The list is eclectic and far from complete, and we hope that additional geosites will be added in the coming years. The Utah Geological Survey also maintains a list of geosites https://geology.utah.gov/apps/geosights/index.htm.

We thank the many authors for their geosite contributions, Utah Geological Association members who make annual UGA publications possible, and the American Association of Petroleum Geologists—Rocky Mountain Section Foundation for a generous grant for desktop publishing of these geosite papers.

Design and desktop publishing by Jenny Erickson, Graphic Designer, dutchiedesign.com, Salt Lake City, Utah.

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PRESIDENTS MESSAGE

I have had the pleasure of working with many different geologists from all around the world. As I have traveled around Utah for work and pleasure, many times I have observed vehicles parked alongside the road with many people climbing around an outcrop or walking up a trail in a canyon. Whether these people are from Utah or from another state or country, they all are quick to mention to me how wonderful our geology is here in Utah.

Utah is at the junction of several different geological provinces. We have the Basin and Range to the west and the Central Utah Hingeline and Thrust Belt down the middle. The Uinta Mountains have outcrops of some of the oldest sedimentary rock in Utah. Utah also has its share of young cinder cones and basaltic lava flows, and ancient laccoliths, stratovolcanoes, and plutonic rocks. The general public comes to Utah to experience our wonderful scenic geology throughout our state and national parks. Driving between our national and state parks is a breathtaking experience.

The "Utah Geosites" has been a great undertaking by many people. I wanted to involve as many people as we could in preparing this guidebook. We have had great response from authors that visit or work here in the state. Several authors have more than one site that they consider unique and want to share with the rest of us. I wanted to make the guidebook usable by geologists wanting to see outcrops and to the informed general public. The articles are well written and the editorial work on this guidebook has been top quality.

I would like to personally thank Mark Milligan, Bob Biek, and Paul Inkenbrandt for their editorial work on this guidebook. This guidebook could not have happened without their support. I would like to thank Jenny Erickson for doing the great desktop publishing and the many authors and reviewers that helped prepare the articles. Your work has been outstanding and will certainly showcase the many great places and geology of Utah. Last, but not least, Thank you to the American Association of Petroleum Geologists, Rocky Mountain Section Foundation for their financial support for this publication.

Guidebook 48 will hopefully be a dynamic document with the potential to add additional "geosites" in the future. I hope more authors will volunteer articles on their favorite sites. I would like to fill the map with locations so that a person or family looking at the map or articles will see a great location to read about and visit. Enjoy Guidebook 48 and enjoy the geology of Utah.

Peter J. Nielsen
2019 UGA President

INTRODUCTION

Arches National Park in southeastern Utah (figure 1) has the greatest concentration of natural rock arches in the world. The park is located in a geologic region called the Paradox fold and fault belt in the northern Paradox Basin and showcases spectacular and classic Colorado Plateau geology with its colorful sedimentary rocks, ancient sand dunes, cliffs, domes, fins, and pinnacles, as well as the arches. The arches in the park and the surrounding region were formed by a unique set of circumstances involving Middle Pennsylvanian (about 308 million years ago [Ma]) to Late Triassic (200 Ma) movement of subsurface salt layers, Middle Pennsylvanian to Late Cretaceous (about 70 Ma) deposition, and Tertiary and Quaternary (23 Ma to the present) folding, faulting, erosion, and salt dissolution. Massive, hard, brittle sandstones jointed by folding, resting on or containing soft layers or partings, and located near fold structures such as salt-cored anticlines undergoing dissolution, and a dry climate, all favor the formation of arches. Rarely do all these phenomena occur in one place, but they do in Arches National Park.

The Natural Arch and Bridge Society (NABS) stated, "A natural arch is a rock exposure that has a hole completely through it formed by the natural, selective removal of rock, leaving a relatively intact frame." They also make it clear that a natural bridge (which is at least partially formed by flowing water) is one type of natural arch (NABS website) (see A Bit of Perspective, below, for more explanation). Using their own criteria, Stevens and McCarrick (1988) catalogued over 2000 natural arches in Arches National Park; most have unique characteristics that could qualify them as geosites. However, the three most famous arches in the park, and perhaps the world, are Landscape Arch, Delicate Arch, and Double Arch, and thus these were selected as the geosites for this paper.

HOW TO GET THERE

Arches National Park is about 230 miles (370 km) or a 3-hour drive from Salt Lake City, Utah, via Interstate 15 (I-15), U.S. Highway 6, I-70, and U.S. Highway 191. Enter the park about 3 miles (3.8 km) north of Moab on U.S. Highway 191 (figures 1 and 2). Proceed through the entrance station (fee required) and follow Arches Scenic Drive (paved) 16.7 miles (26.9 km) northeast through the park to Devils Garden Trailhead that leads to Landscape Arch (figure 2). On popular summer, holiday, and weekend days, the Devils Garden Trailhead parking lot fills early, as do the parking lots for the Delicate Arch and Double Arch Trailheads. Follow the relatively easy, flat, well-signed sand and gravel trail to Landscape Arch, 38°47'27" N., 109°36'27" W., elevation 5290 feet (1612 m). There are "rustic" restrooms at the parking lot/trailhead. The round-trip walking distance to Landscape Arch is 1.6 miles (2.6 km).

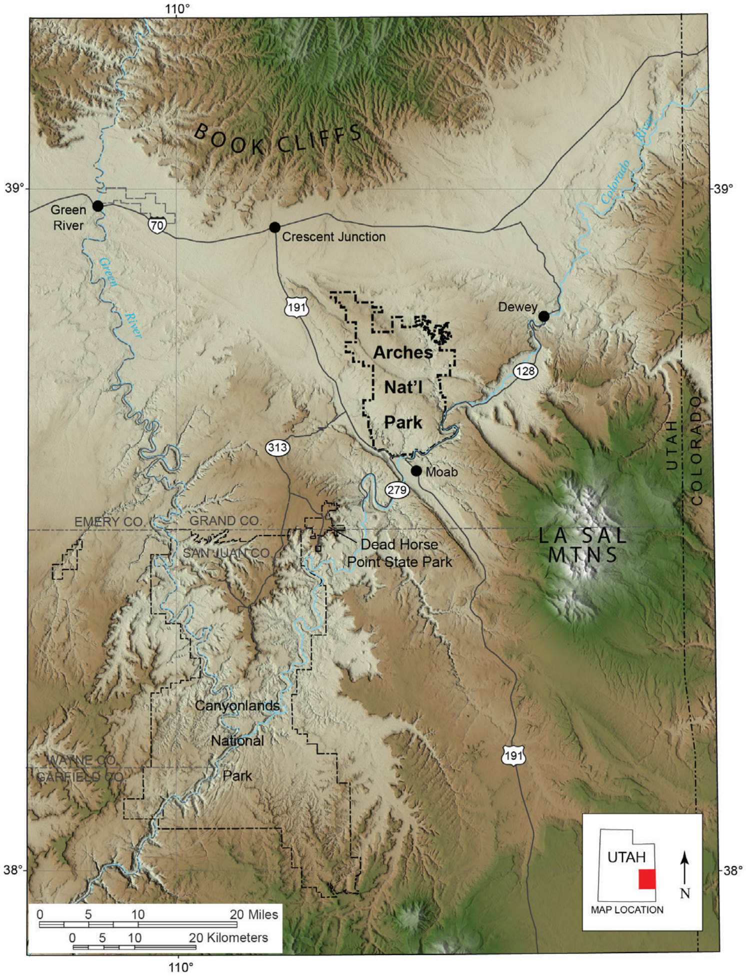


Figure 1. Location of Arches National Park, southeastern Utah, and surrounding parks, towns, and highways.

The Delicate Arch Trailhead and parking lot are reached by first proceeding 11.7 miles (18.8 km) from the park entrance on Arches Scenic Drive to the intersection with Delicate Arch Road. Follow Delicate Arch Road another 1.2 miles (1.9 km) to the trailhead and parking lot (figure 2). The 3-mile (4.8 km) round trip trail to see Utah's iconic free-standing Delicate Arch up close and personal is one of the more difficult hikes in the park, but well worth it. This steadily uphill trail, climbing 480 feet (146 m), also passes the historical Wolfe Ranch cabin and a wall of Ute Indian petroglyphs. The trail is well marked and heavily used as it is the most popular trail in the park. The first half mile is well-defined, but then it climbs steadily over slickrock and is marked with cairns. It has no shade—hikers should wear hats and carry at least 1 quart of water, more if it's hot! Just before getting to Delicate Arch, the trail traverses a narrow rock ledge for about 200 yards (180 m) and is about 5 feet (1.5 m) wide; however, it is solid rock and dips into a rock wall that can provide a secure pathway for those who may be nervous about heights. Once past this short stretch is the ultimate view of the most famous and spectacular site in Utah—Delicate Arch, 38°44'38" N., 109°29'57" W., elevation 4811 feet (1466 m). For most, the round trip should take about 2.5 to 3 hours depending how much lingering occurs at the arch. There are rustic restrooms at the parking lot/trailhead.

The Double Arch Trailhead and parking lot in the Garden of Eden area are reached by first proceeding 9.1 miles (14.7 km) from the park entrance on Arches Scenic Drive to the intersection with The Windows Road. Follow The Windows Road 2.5 miles (4.0 km) to the trailhead (figure 2) and relatively small parking lot. A relatively flat, gravel-surfaced trail leads to the base of Double Arch, 38°41'29" N., 109°32"25" W., elevation 5172 feet (1576 m). The round-trip distance to the arch is 0.5 miles (0.8 km).

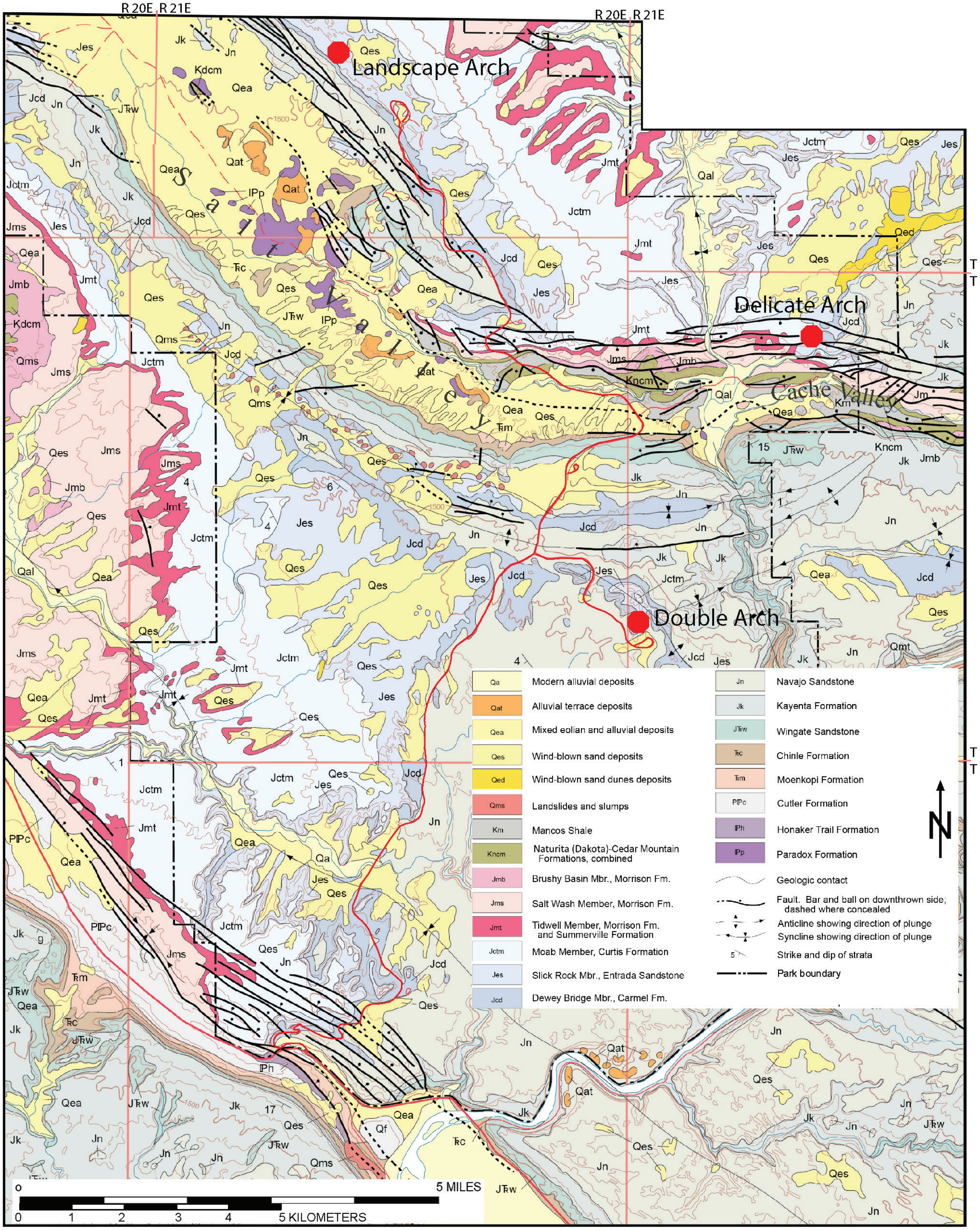


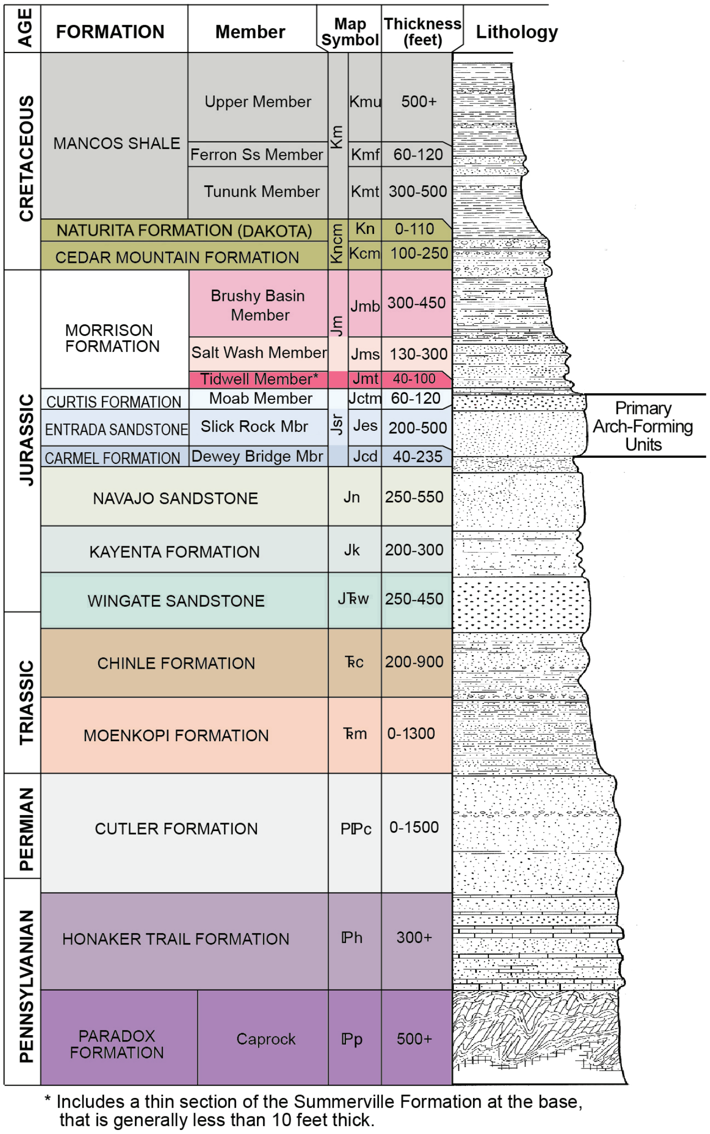
Figure 2. Geologic map of the Arches National Park area, Grand County, Utah, showing the locations of Landscape, Delicate, and Double Arches (red dots). Modified from Doelling (2010).

STRATIGRAPHY

Most arches in Arches National Park are formed in two geologic units: the Slick Rock Member of the Entrada Sandstone and the Moab Member of the Curtis Formation (figure 3). Landscape and Double Arches are in the Slick Rock Member whereas Delicate Arch includes both Slick Rock and Moab Members.

Entrada Sandstone

The Slick Rock Member of the late Middle Jurassic (160 Ma) Entrada Sandstone overlies the red-brown Dewey Bridge Member of the Carmel Formation (figure 3). The Slick Rock is a massive, well-indurated, red-orange or brown, very fine to fine-grained sandstone containing sparse and scattered medium to coarse grains (Doelling, 2010). The sand grains are held together with calcite and iron-oxide cement. It commonly weathers to form smooth cliffs and bare-rock slopes. Parts of the member are distinctly cross-bedded (eolian deposition), whereas other parts are planar bedded. In most places color variations form stripes or bands. In some cases, the banding is hardly noticed, in others it is pronounced. Locally, indentations parallel the banding (Doelling, 2010). Small holes called tafoni are commonly aligned along cross-bed laminae (the boundaries of ancient dune sets). Tafoni are created by differential weathering and case hardening in areas where groundwater has weakened the cement in the rock, commonly near small variations or imperfections. Once started, the voids provide space where water can accumulate and be protected from evaporation, further weakening cement in the rock and promoting growth. In case hardening, the mineral-laden water wicks toward the outer exposed face of the rock where the water quickly evaporates, depositing the cement, which strengthens the rock "case."



* Includes a thin section of the Summerville Formation at the base, that is generally less than 10 feet thick.

Figure 3. Lithologic column showing formations and members exposed in Arches National Park, including ages, map symbols, thicknesses, weathering habits, and lithologies. After Doelling (2010).

The Slick Rock Member of the Entrada Sandstone is perhaps the most important geologic unit in Arches National Park. Most of the arches in the park are positioned along its lower and upper contacts and along the easily weathered beds in the middle of the unit (Doelling, 2010). Where the Slick Rock is not exposed as a cliff, fin, or arch, the outcrop band is covered or partly covered by large irregular fields of self-derived wind-blown sand (figure 2). It was deposited in a coastal dune field and interfingers with sabkha deposits (figure 4A). The Slick Rock Member is normally 200 to 350 (60–110 m) feet thick within Arches National Park (Doelling, 2010).

The contact between the Entrada Sandstone and the underlying Carmel Formation is generally sharp, but locally extraordinarily irregular. In some cases, the Slick Rock Member of the Entrada intertongues with the Dewey Bridge Member of the Carmel (Doelling, 2010). Near the Arches National Park Visitor Center, the Dewey Bridge Member appears to be angularly planed off by the Slick Rock Member, but this is not an unconformity; it is instead attributed to soft-sediment deformation in the Dewey Bridge.

Curtis Formation

The Moab Member of the early Late Jurassic (155 Ma) Curtis Formation overlies the Slick Rock Member of the Entrada Sandstone and is about 60 to 120 feet (18–37 m) thick in the park (figure 3). Most of the member is pale-gray to nearly white (pale-gray-orange, pale-yellow-brown, or pale-gray on seldom-seen fresh surfaces), fine- to medium-grained, calcareous, thick to massive, cliff-forming sandstone that forms a prominent capping bench over Entrada cliffs. The sandstone is typically well indurated, has low-angle cross-bedding, and is generally strongly jointed (Doelling, 2010). The sandstone resembles the Navajo in color, cementation, and differential etching of cross-bed laminae. Outcrops form bare-rock, sloping, jointed benches on each side of Salt Valley. These strong northwest-trending joints with minor cross-joints form a "biscuit" pattern and are spectacular when viewed from an airplane (figure 5). The Curtis forms the upper

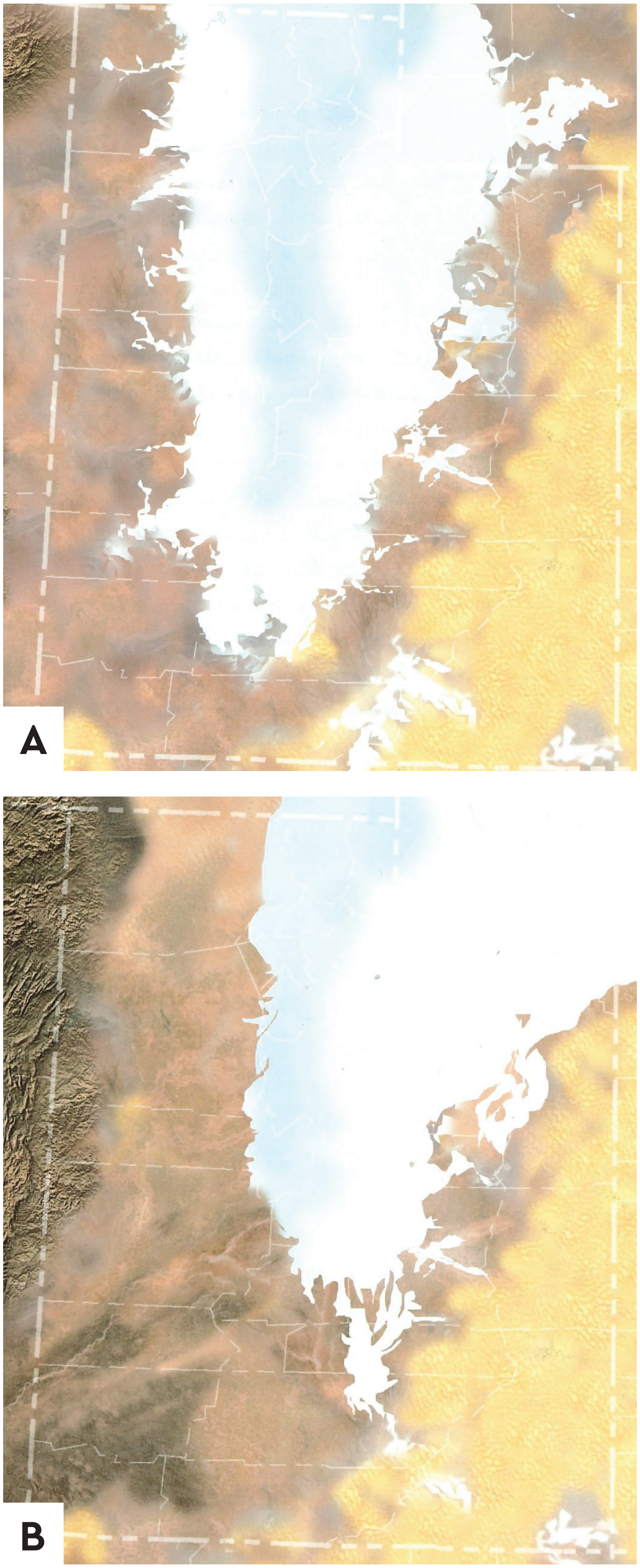


Figure 4. Paleogeographic maps of Utah during the late Middle to early Late Jurassic: (A) Entrada Sandstone – 160 Ma, and (B) Curtis Formation – 155 Ma. Modified from Blakey and Ranney (2008).

part of Delicate Arch and outcrops can be viewed along the Delicate Arch hike. The massive sandstone is a unique eolian facies of the Curtis only present in the Arches area—the Curtis of central and northeastern Utah is characterized by shallow marine, ledgy, slope-forming, pale-green-gray, silty sandstone (figure 4B).

The contact between the Entrada Sandstone and the Curtis Formation is the J-3 unconformity of Pipiringos and O'Sullivan (1978) and is sharp in most areas. In the north part of the park beds just above the unconformity consist of about 25 feet (7.6 m) of slope- or recess-forming, red-brown, thin-bedded, silty, fine-grained sandstone, similar, except for the color, to the Curtis in most parts of central Utah. In the central part of the park, these beds thin to a reddish siltstone indenture a few feet thick. In the south part of the park, the contact is just a subtle line between banded Slick Rock Member with truncated cross-beds below and monotone pale-gray Moab Member with no prominent bedding above.

STRUCTURE AND GEOLOGIC HISTORY

During the Pennsylvanian, southeastern Utah and southwestern Colorado subsided to form the Paradox Basin, a restricted shallow embayment of an open marine sea that lay to the southeast, and the Uncompahgre Highlands (Ancestral Rockies) were located to the northeast. Conditions were arid and high evaporation rates led to a net inflow of seawater and elevated salinity. The structural geology in Arches National Park, and of the fold and fault belt of the northern Paradox Basin, is primarily the result of the evaporite minerals deposited in the Pennsylvanian Paradox Formation, and their subsequent movement and dissolution (Doelling, 2010).

The fold and fault belt of the Paradox Basin extends southeast from Arches National Park into Colorado. This structural belt is characterized by a series of northwest-trending anticlines and faults that developed in response to movement caused by crustal forces or by shallow deposits of Pennsylvanian salt. Salt, which was deposited as part of the Middle Pennsylvanian Paradox Formation, has a low specific gravity, is ductile and less dense than the surrounding rocks, and behaves plastically. The salt moves due to high confining pressure from the weight of the overlying column of rocks or sediments. Salt movement can push up and raise overlying strata in some places, while the salt is squeezed and thinned in others. This movement (often piercing the strata above [diapiric movement]) progresses along zones of weakness or areas of low confining pressure, forming large folds (figures 2 and 6). Later, these folds collapsed when groundwater dissolved the salt.

The most important structural feature in the park is the Salt Valley–Cache Valley salt wall or diapir (figures 2 and 6). The diapiric salt wall formed mostly from Middle Pennsylvanian to Late Triassic time (Doelling, 2010). It was covered with sediment laid down

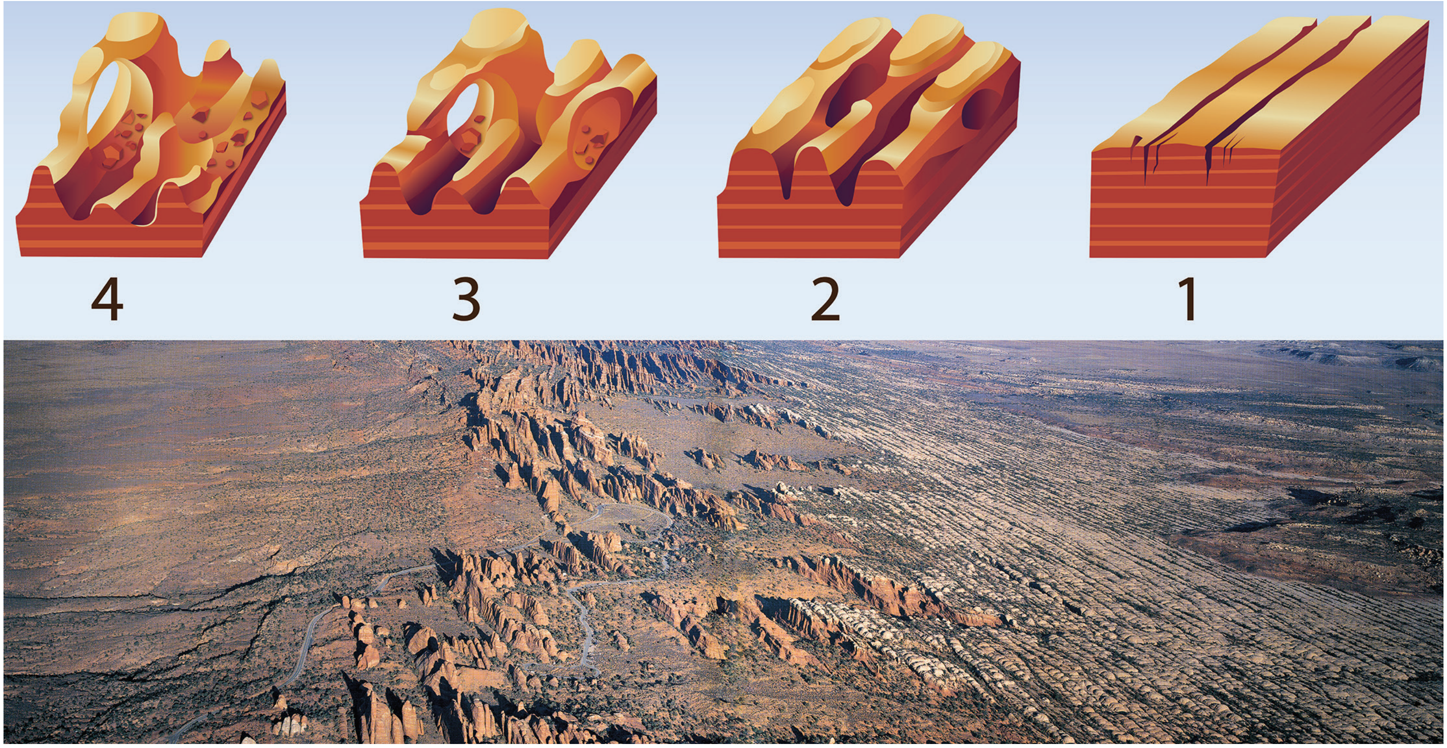


Figure 5. Rock arch development stages in Arches National Park (the order generally matches the outcrops from right to left in the photo below). 1 – Regional uplift by salt diapirism, then collapse due to dissolution of salt in the Pennsylvanian Paradox Formation, created northwest-trending joint systems in brittle Jurassic sandstones. 2 – Following the erosion of the overlying rocks, weathering and erosion processes by wind, water, ice, and temperature variations widened and deepened joints creating rock walls or fins. 3 – Continued erosion, including mass wasting (rock falls), from opposing sides of fins eventually led to breakthrough and the creation of wall arches. 4 – Free-standing arches, like Delicate Arch, are all that remain after other arches collapse and surrounding fins erode away. The enduring arches enlarge by continued weathering and erosion processes until they too collapse. Importantly, being in the open air actually slows the weathering process because rain and snow that fall on the arch evaporate quickly, leaving behind cements that running water would wash away. Also, pressures that develop in the arch actually strengthen the bounds between sand grains. The bottom photo is an aerial panoramic view northwest towards the Devils Garden area along the northeast flank of the Salt Valley anticline showing extensive jointing in the Moab Member of the Curtis Formation (right area of the photo) and fins in various stages of erosion; several arches are present in the area of the fins. Photo from Hamblin (2004).

in Late Triassic to Late Cretaceous time, but slow salt movement affected formation thicknesses. Thereafter, the area was folded and faulted, probably during the Late Cretaceous-early Tertiary (about 70 to 30 Ma) Laramide orogeny (a regional mountain-building event), that created many large folds throughout the Rocky Mountain region. In the Arches area, the axes of the anticlines were superimposed over the northwest-trending salt walls of the Paradox fold and fault belt. Many of the brittle sandstone formations were fractured (jointed) during the folding (figure 5). Tertiary faults paralleled and displaced the salt walls (figures 2 and 6).

With the uplift of the Colorado Plateau throughout the Tertiary (66 to 1.8 Ma), but accelerating in late Tertiary time (about 15 Ma) and continuing to the present, the Colorado River and its tributaries eroded the sedimentary formations and formed deep canyons, slopes, and cliffs, depending on erosional resistance. After erosion cut down deep enough, groundwater via faults and joints reached the upper parts of the region's salt walls, including those of the Salt Valley–Cache Valley feature, and dissolved the salt. The ensuing collapse created graben-valleys that overlie the salt walls today, as well displayed in Arches National Park (figures 2 and 6) and much of the Paradox fold and fault belt.

A BIT OF PERSPECTIVE

A quick search of literature ranging from tourist brochures to textbooks reveals myriad, often contradictory and exaggerated claims about natural stone arches (many communities have claimed theirs as the "biggest"). In an attempt to settle many arguments, and bring some science into the equation, a group of dedicated geologists, mathematicians, physicists, geographers, and enthusiasts formed the Natural Arch and Bridge Society (NABS) and set about establishing carefully crafted rules, definitions, and criteria. As a result, much better information is available, including careful measurements following well-defined criteria, of all the largest known arches in the world. While a surprise could be lurking somewhere, we can be fairly confident of how Utah arches fit in the world hierarchy. Below are a few of the more important facts. The interested reader is referred to NABS's excellent website at naturalarches.org for more detailed information.

1. NABS has chosen a simple definition for a natural arch: "A rock exposure that has a hole completely through it formed by the natural, selective removal of rock, leaving a relatively intact frame." They provide a detailed discussion, simplified here as: (1) it must be made of rock; (2) the rock must be substantially sur-

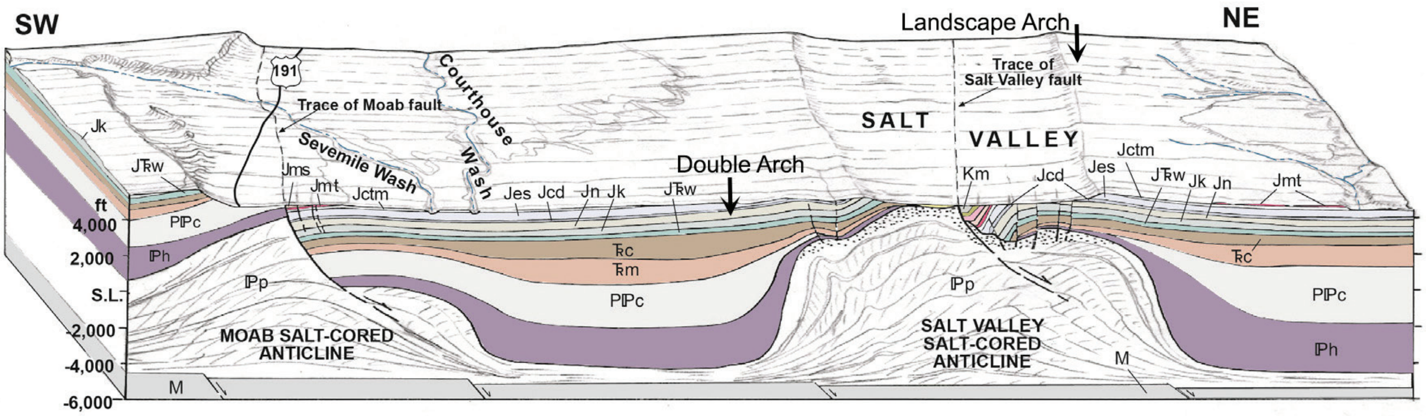


Figure 6. *Cross-sectional block diagram of the Arches National Park area drawn approximately to scale. Note the location of Landscape and Double Arches. Unit (formational) symbols correspond to those shown on figures 2 and 3. After Doelling (2010).*

rounded by air; (3) the hole must conform to the mathematical, or topological, definition of a hole (they provide a long discussion of "a hole"!); (4) the hole must have formed from natural, selective removal of rock; and (5) the frame of rock that surrounds the hole must still be relatively intact. See the NABS website for much additional discussion on the nuances of arch definition.

2. NABS has chosen to not make size (width, volume, height, etc.) of the opening part of the definition. They also leave it to the viewer to decide if a feature is an arch, a tunnel, or some other feature, and qualify arches with terms such as miniature, significant, major, and giant. Thus, any count of the world's arches is highly subjective. For example, Steven and McCarrick's (1988) "count" of arches in Arches National Park is based on their own criteria; other researchers would come up with a different number. For their own database, NABS defines a "significant" natural arch as having a product of two orthogonal opening dimensions of about 110 square feet (10 m^2) or more. But smaller openings (of which there are millions) are still arches—they just do not make it into the database.

3. NABS emphasizes that bridges are a type of arch. That they are not arches is one of the most common misconceptions that persists today. NABS actually defines at least 17 types of arches based on their shape and forming process; bridges fit into at least two of these types. Furthermore, many bridge-type arches are hybrids—only partially formed by or spanning flowing water or dry channels. For comparisons, all types of arches, including bridge-types, are considered together. Thus, there is no fundamental difference between a natural arch and a natural bridge.

4. Everyone wants to know how "big" an arch is. NABS established the "span" as the common criteria for comparing size. Their full definition is quite complex—for simplicity, here is an analogy. The span is the widest dimension through which you could slide one or more giant horizontal playing cards without overlapping or deforming the cards (the cards can step up or down, but not overlap past a vertical line) (see figure 7). The irregular third dimension (depth) of some arches can cause problems, but for most arches these simple criteria work fairly well. In the past, many arches were measured on diagonal or even twisted lines to come up with unrealistic, and non-comparable, dimensions.

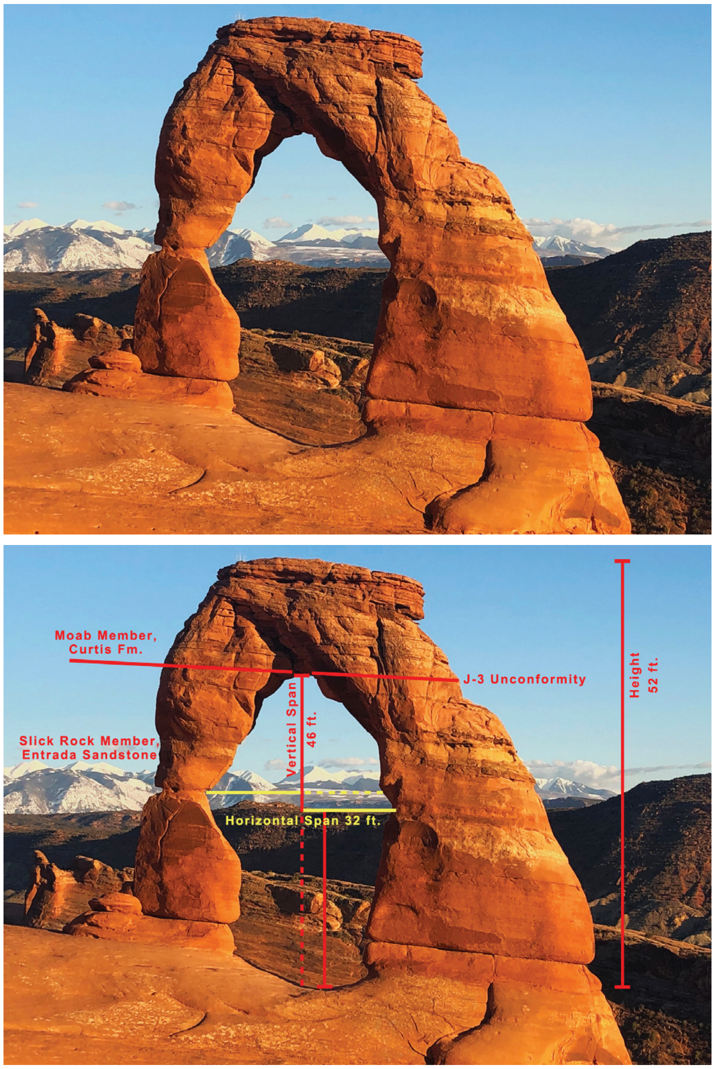


Figure 7. *A – Delicate Arch is the best-known rock arch in the world and is the symbol for Arches National Park. This free-standing arch is located on the north rim of Cache Valley.* **B** *– Delicate Arch has a height of 52 feet (16 m). The base and pedestals are Slick Rock Member of the Entrada Sandstone. The upper part or cap is Moab Member of the Curtis Formation. Photo courtesy of Michael D. Vanden Berg.*

A few arch statistics (from NABS newsletter "Arch Wednesday," February 20, 2019):

1. Number of known arches in the world – 9285 (per NABS "significant" criteria above).
2. Arches having a greater arch dimension (simplistically, the span-like line tilted at any angle, even vertical) of 75 feet (23 m) or more – 305 (3.3% of worldwide count).
3. Country that has the most documented arches – United States with 8181 (88.1% of worldwide count); France is second.
4. U.S. state with the most arches – Utah, with 4589 (56.1% of U.S. count; 49.4% of world count); New Mexico is second with 529; Nevada is third with 514.
5. Using the NABS definition of span, China has the largest known arches in the world (four with spans of 300 to 400 feet [90–120 m])—all massive bridge-type arches formed in limestone in karst topography. Landscape Arch in Arches National Park is the fifth largest with a span of 290 feet (88 m); Kolob Arch in Zion National Park is sixth at 287 feet (87 m).
6. However, Landscape Arch is the largest known sandstone arch in the world. Utah has the top six largest sandstone arches in the world, and six of the eight have spans over 200 feet (60 m). After Landscape and Kolob Arches, they are: ninth – Morning Glory Natural Bridge near Moab at 243 feet (74 m); eleventh – Rainbow Bridge in Rainbow Bridge National Monument at 234 feet (71 m); thirteenth – Sipapu Natural Bridge in Natural Bridges National Monument at 225 feet (69 m); and fourteenth – Stevens Arch along the Escalante River at 220 feet (67 m).
7. And (this is where we get to show our bias), we consider Landscape Arch to be the most mind-boggling and gravity-defying arch in the world!

DEVELOPMENT OF NATURAL ROCK ARCHES

Natural rock arches are quite common. What makes Utah unique is the gigantic size and number of very large arches. Utah has over 60% of the world's arches; Arches National Park has over half of Utah's arches. The exceptionally large arches in Arches National Park, Natural Bridges National Monument, and elsewhere in Utah require several criteria that must all come together in just the right way—a very rare occurrence indeed. These include:

- Very thick, isotropic rock—all of Utah's largest arches are in massive quartz sandstone; the homogenous nature of the sandstone allows for large conchoidal (curved) fractures that are required to produce the inherently stable arch shape.
- Weaknesses in or below the otherwise isotropic rock, such as bedding planes or joints, that act as "seed" sites for arch formation.
- Rock that is moderately, but not exceptionally, strong or brittle.
- High erosion and incision rates that create many deep canyons and exposed rock faces—big arches need big cliffs, fins, or canyons.
- Near-vertical, subparallel, properly spaced joints (fractures)—a variety of geologic events have produced abundant joints in Arches National Park.
- An arid climate—whereas small and medium sandstone arches are common in many environments, all of the largest sandstone arches are in areas having dry climates (giant limestone bridges are common in wetter karst environments).
- In some settings, loose sand that holds moisture against the base of sandstone fins, allowing the moist basal rock to weather and erode at higher rates than exposed rock, is needed to eventually form an arch (in contrast, rare rain and snow on exposed rock in the arid climate commonly evaporates in minutes to hours).

Closely spaced joints, subparalleling salt-cored anticlines, in the hard, brittle rocks with associated soft bedding-plane partings, indentations, and thin, soft rock layers favor the formation of arches, fins, and alcoves in Arches National Park (figure 5). Sandstones, typically of the Entrada and Curtis Formations, folded over a broad hinge zone called a "roll over," collapsed into salt-dissolution valleys or grabens along anticlinal rims (e.g., Salt Valley anticline). At the "roll over," the previously formed joints opened and allowed weathering and erosion to occur at a more rapid rate, creating thin fins of sandstone where most wall arches develop. Hence, most arches are located along the rims of the salt valleys where the favorable formations begin to "roll over" and collapse into the grabens (figures 5 and 6).

Weathering within the joints attacks weaknesses such as formational boundaries, bedding planes, and soft partings, forming alcoves and arches in and through the sandstone fins (figure 5). Loose sand accumulates between the fins; the sand holds slightly acidic rainwater against the fin walls by surface tension and capillary action. The natural cement holding the sand grains together is largely calcareous and dissolves in the slightly acidic water. The action is favored along more weakly cemented rock found along bedding-plane partings and indentations. Eventually, a horizontal crevice is opened through the fin along one of these weak planes. Stresses develop in the overlying rock because of gravity since the weight of the rock over the crevice is now supported only by the limbs of the newly formed arch (Doelling, 2010). Generally, fractures develop and blocks of rock drop from the arch (upward stoping) until the classical arch form is developed. This action is responsible for free-standing and wall arches (as defined by Stevens and McCarrick, 1988). Free-standing arches form in isolated fins or in thin walls projecting from cliff faces. Cliff-wall arches develop short distances behind the faces of cliffs. Alcoves are large arch-shaped recesses that have not yet eroded through a fin. Upward stoping probably continues and eventually the arch collapses (Doelling, 2010). Larger, more massive arches develop in thicker sandstone fins or walls. Large arches also commonly develop where a relatively thin rock wall or fin forms a prominence along a cliff face.

THE FAMOUS THREE

Landscape Arch (Devils Garden Area)

Landscape Arch in the Devils Garden area has an incredible span of 290 feet (88 m) (77 feet [23 m] high), ranking fifth in the world (according to the NABS; Wilbur, 2004; Willis, 2009a, 2012) and is mind-boggling due to its gravity-defying ribbon of rock that in places narrows to only 7 feet (2 m) in thickness (figure 8)! In terms of span, this arch is the largest in Arches National Park and is the largest known arch formed in sandstone in the world (NABS). Landscape Arch was named by Frank Beckwith, leader of the Arches National Monument Scientific Expedition, who explored the area in the winter of 1933–1934. The arch is entirely within a fin of the Slick Rock Member of the Entrada Sandstone (figure 3). It is classified as a free-standing arch, but originally began as a cliff-wall arch.

Figure 8. Landscape Arch, originally a wall arch and now a free-standing arch, is the largest in the park, and the largest sandstone arch in the world.

On September 1, 1991, June 5, 1995, and June 21, 1995, blocks of rock 73 feet (22 m), 47 feet (14 m), and 30 feet (9 m) long, respectively, broke and fell from the underside of the span of Landscape Arch (figure 9) (Natural Arch and Bridge Society, 2009). Out of safety concerns, the Park Service closed the trail beneath the arch. This concern is legitimate—nearby Wall Arch collapsed during the night of August 4, 2009 (Willis, 2009b). Landscape Arch is considered an "arc type" natural arch—an arch that is old and near the end of its life cycle (Natural Arch and Bridge Society, 2009). These arches exist, however, because they are also strong, especially when the slender arc of rock is slightly arched as in the case of Landscape Arch (Wilbur, 2007). In addition, each grain or slab that falls actually increases the compression between the remaining grains (Natural Arch and Bridge Society, 2007b). The rock falls that occurred in the 1990s indicate that it could soon (years?/hundreds of years?) collapse by natural processes. Its demise could be precipitated by an earthquake (Doelling, 2010).

Figure 9. Dramatic rock fall from Landscape Arch on September 1, 1991. From interpretive sign, Arches National Park; photograph taken by Royce Morrison.

Delicate Arch

The iconic Delicate Arch is located on the north side of the Cache Valley anticline (figures 2 and 7). The trail to Delicate Arch starts in the Salt Wash Member of the Upper Jurassic (155 Ma) Morrison Formation and crosses several faults (figures 2 and 3). Geologic formations and members exposed along the trail include the reddish to lavender Tidwell Member of the Morrison Formation with its large hackly white chert nodules; the red-brown Summerville Formation; the massive, light-colored, well-jointed Moab Member of the Curtis Formation; and the orange-brown, smooth-weathering Slick Rock Member of the Entrada Sandstone. Along the trail, there are excellent examples of deformation bands, jointing, alcoves with springs seeping at their bases denoted by vegetation, well-defined cross-bedding, and tafoni.

Delicate Arch is freestanding and has a horizontal span of about 32 feet (9.7 m) and a vertical span of 46 feet (14 m) as defined by the Natural Arch and Bridge Society (2007c) (figure 7). The top of the arch is about 52 feet (16 m) over the base. The Moab Member of the Curtis Formation forms the upper part of Delicate Arch; the Slick Rock Member of the Entrada Sandstone forms the pedestals. Both units are cross-bedded. The plane of weakness in this arch is the contact between the Slick Rock and the Moab Members about a third of the way below the top. This plane represents a sharp regional unconformity named the J-3 unconformity (Pipiringos and O'Sullivan, 1978). Cross-beds in the Slick Rock Member are truncated by the unconformity.

Double Arch (Garden of Eden Area)

Double Arch is the third largest in the park, consisting of two giant pothole arch spans that are joined at one end (figure 10). The largest opening of the two arches has a span of 148 feet (45 m) and a height of 104 feet (32 m) (Wilbur, 2010). It was the site for the opening scene in the 1989 film *Indiana Jones and the Last Crusade*.

Figure 10. *Double Arch, consisting of two giant pothole arch spans joined at one end, is the third largest in the park. Photo courtesy of Ben Erickson.*

Whereas most arches in the park are wall arches, Double Arch is a pothole arch and formed differently from wall arches (figure 11). In this region of the Colorado Plateau, potholes (also called water pockets) often develop on flat-lying sandstone by a long, slow process—it starts with some small weakness in the rock, maybe only microscopic in size: (a) water is held slightly longer in the weakness, (b) it gradually dissolves the cement around sand grains, (c) the wind and rain blow and wash the loose grains away, (d) over time the tiny depression helps hold the water a little longer allowing a little extra dissolution, (e) several small depressions gradually merge, and (f) organic agents – lichen, algae, and diatoms – aid in the process, loosening more sand grains that are removed by wind and rain. If allowed to continue long enough, potholes can become amazingly large.

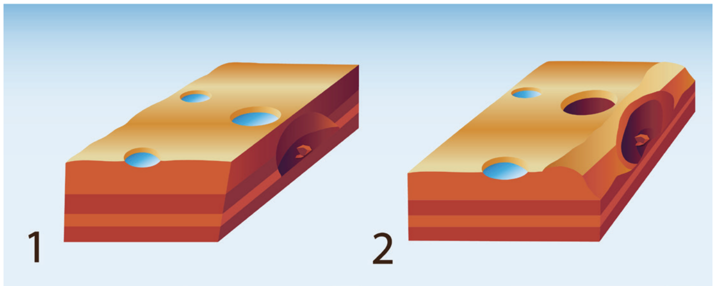


Figure 11. *Pothole arch development stages.* ***1*** *– Potholes developed on flat-lying sandstone at the same time an alcove is forming along the nearby cliff face. An alcove can be created where groundwater percolating down through pores in sandstone encounters a low-permeability bed that impedes continued downward flow. The groundwater then moves horizontally along the bedding plane to the cliff face where it exits the rock as seeps and springs. Along the flow path the groundwater dissolve cementing minerals weakening the sandstone relative to the rock elsewhere on the cliff face. The processes of weathering and erosion on the weakened rock eventually form a recess or alcove.* ***2*** *– Continued weathering and erosion cause both the pothole nearest the cliff face and the alcove to deepen vertically and horizontally, respectively, until they merge creating an arch.*

Alcoves also played a role in the formation of these two arches. Alcoves form near cliff faces where groundwater percolating down through pores in the sandstone encounters a low-permeability bed that impedes continued downward water flow, in this case the contact between the porous overlying Slick Rock Member of the Entrada Sandstone and the less-permeable, silt- and clay-rich underlying Dewey Bridge Member of the Carmel Formation (figure 3). Because the infiltrating groundwater's downward flow is restricted, it moves horizontally along a less resistant bedding plane and exits the rock near these low-permeability bedding planes, forming seeps and springs at cliff faces. The water dissolves and removes cementing minerals in the sandstone, causing the rocks there to weaken relative to the rocks elsewhere on the cliff faces. The processes of weathering and erosion proceed faster on the weakened rocks, eventually forming recesses or alcoves. Continued weathering and erosion by chemical and mechanical weathering, exfoliation, and rockfalls, caused potholes nearest the cliff faces and alcoves to enlarge vertically and horizontally, respectively, until they merged creating Double Arch (figure 11).

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