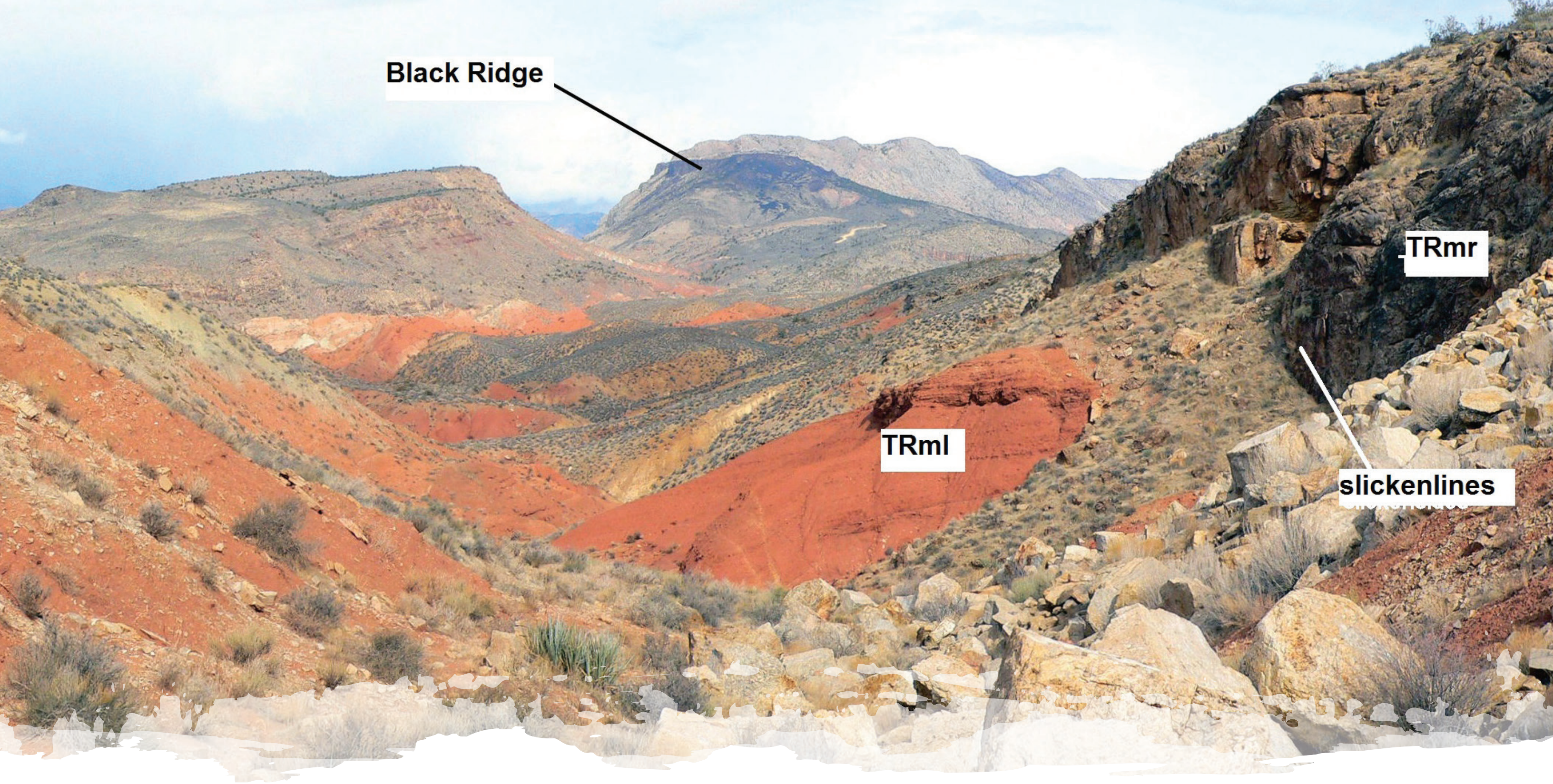

Hurricane Fault

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Utah Geosites
2019

Utah Geological Association Publication 48

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

Cover Image: *View north-northwest along Hurricane fault zone just west of State Route 9.*

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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.

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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

The Hurricane fault is the big earthquake fault in southwestern Utah. It stretches at least 155 miles (250 km) from south of the Grand Canyon northward to Cedar City and is capable of producing damaging earthquakes of about magnitude 7.0. The Hurricane fault is a "normal" fault, a type of fault that forms during extension of the earth's crust, where one side of the fault moves down relative to the other side. In this case, the down-dropped side (the hanging wall) is west of the fault; the upthrown side (the footwall) lies to the east. Like most long normal faults, the Hurricane fault is composed of discrete segments that tend to rupture independently (figure 1). The fault lies at or near the base of the Hurricane Cliffs, which form an impressive, little-eroded fault scarp several hundred feet high. Conspicuous, west-tilted, faulted slivers of mostly Triassic and Jurassic red beds are locally exposed at the base of the cliffs, and contrast strongly with gray Permian carbonates exposed in the cliffs themselves. Several Pleistocene basaltic lava flows flowed across and are now offset by the fault zone, dramatically recording long-term slip rates. Should you make the mistake of pronouncing the name "Hurricane" as one would when describing a mighty storm on the East Coast, you should stand to be corrected, for locals pronounce it as "Hurricun" even though pioneers named the town after ferocious winds common to the local area.

LOCATIONS

The Hurricane fault is one of the most prominent geologic structures in southwestern Utah. The eastern, upthrown side of the fault forms the Hurricane Cliffs, offering dozens of instructive places to view the fault. Three readily accessible sites—the Hurricane and La Verkin Overlooks and a polished, striated exposure of the Hurricane fault—reveal the variety of deformation seen along the fault (figures 2, 3, 4, and 5).

The La Verkin Overlook (37° 11' 55" N., 113° 15' 44" W.) is accessible by car on an unpaved 1.5 mile (2.5 km) dirt road that leads southwest off State Route 9.

The Hurricane Overlook (37° 11' 00" N., 113° 16' 44" W.) is at a trailhead off State Route 59.

The fault exposure showing slickenlines and a polished fault surface is partway up the Hurricane Cliffs on a relay ramp between strands of the Hurricane fault. Park at the wide pullout on the south side of Route 9, at 37° 13' 15" N., 113° 15' 31." W. Carefully cross the highway and hike 0.3 mile (0.5 km) north of the parking area to the fault exposure immediately west of and below Route 9 (at 37° 13' 30" N., 113° 15' 31.7" W.). This same fault surface is exposed in a road cut on Route 9, but is located at a dangerous curve with no shoulder; that site is best viewed driving slowly past as you head east. As a bonus, a small wash 450 feet (150 m) northeast of the parking area provides good exposures of the Permian-Triassic unconformity.

HURRICANE FAULT

The Hurricane fault marks the western boundary of the Colorado Plateau in southwestern Utah, forming the eastern boundary of a structural and stratigraphic transition zone with the nearby Basin and Range Province. Displacement increases northward along the Hurricane fault, from 800 to 1300 feet (250–400 m) at the Colo-

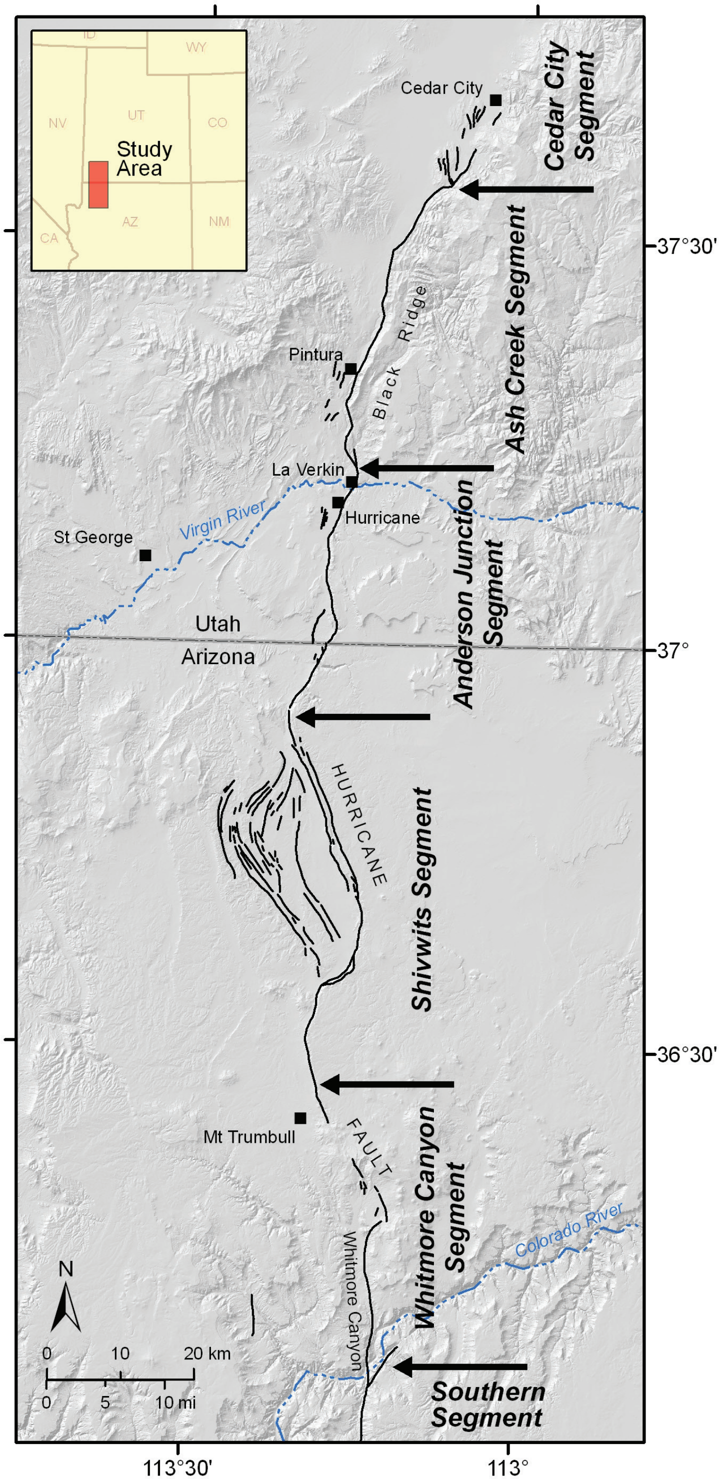

Figure 1. The six segments of the Hurricane fault zone, each of which has a different rupture history and rate of long-term slip; arrows indicate segment boundaries. The three geosites described here lie at the northern end of the Anderson Junction segment. The fault continues north of Cedar City but that section was not part of the study of Lund and others (2007) from which this figure is taken.

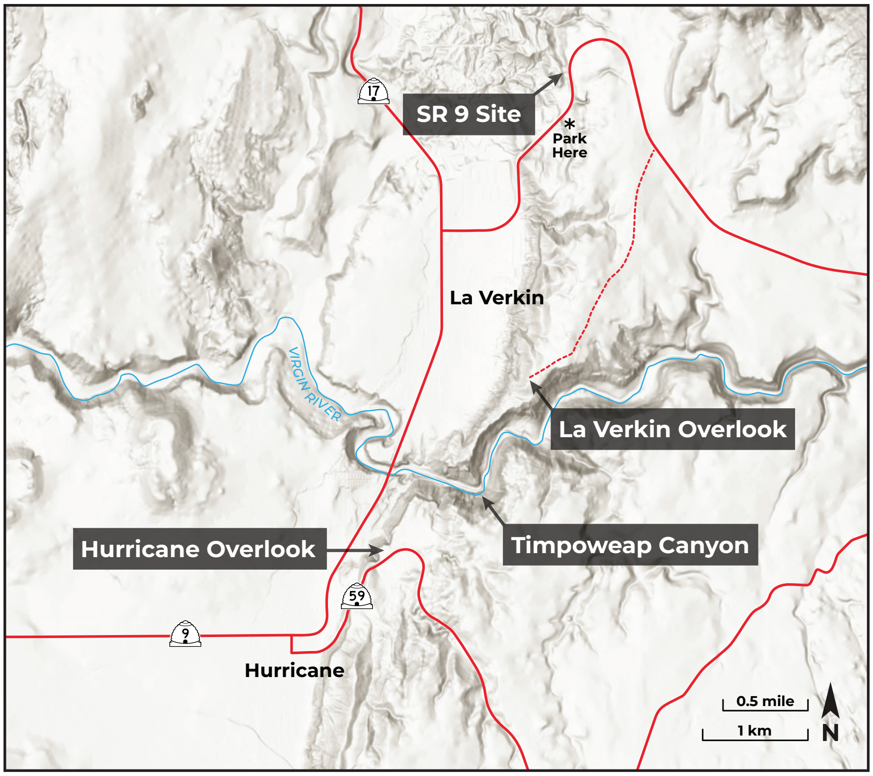

Figure 2. Locations of the Hurricane and La Verkin Overlooks and State Route 9 geosites.

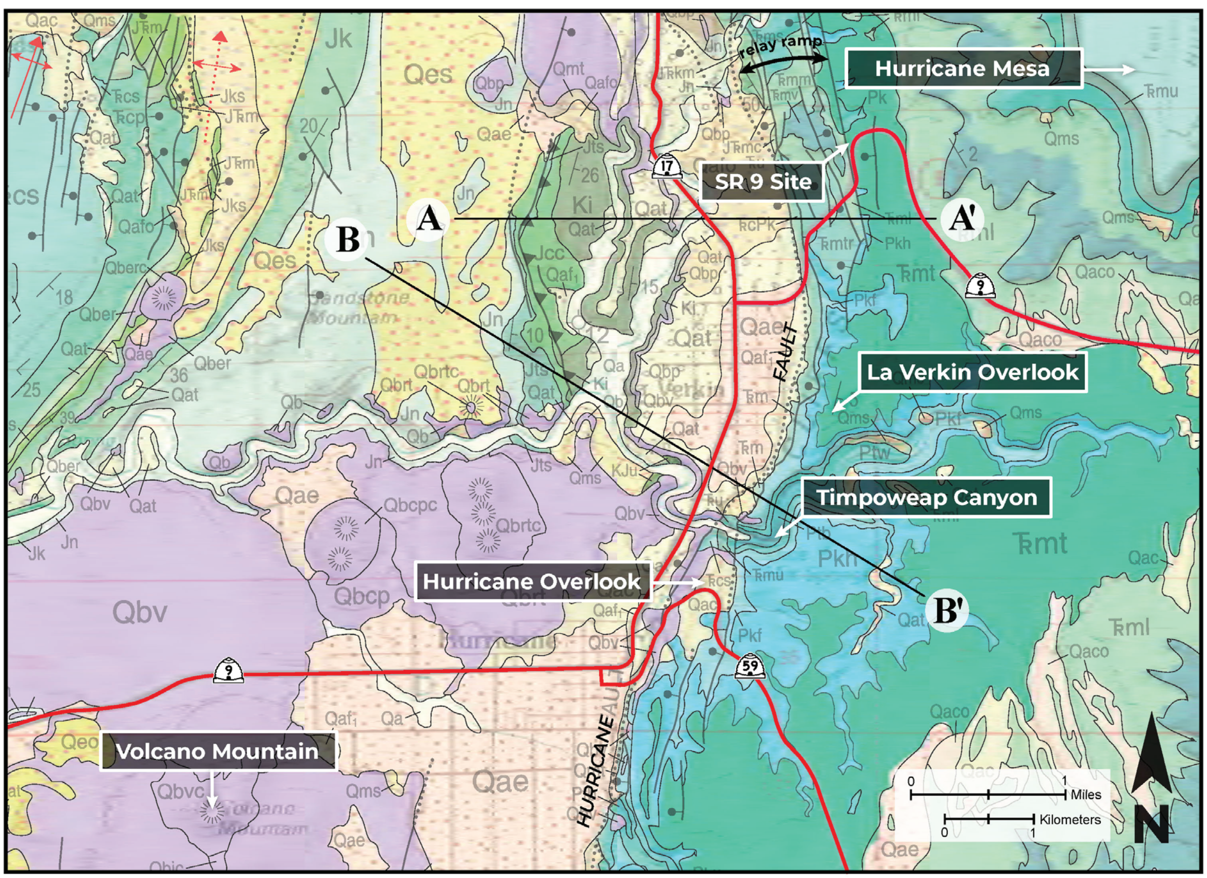

Figure 3. Geologic map of the Hurricane-La Verkin area. The northeast-plunging nose of the Virgin anticline is at upper left (see Quail Creek Reservoir geosite for more information on the anticline). The Virgin River crosses the Hurricane fault between Hurricane and La Verkin; the north wall of the canyon provides good exposures of the fault zone just north of the Hurricane Overlook. State Route 9 takes advantage of a break in the Hurricane Cliffs created by a relay ramp between parallel strands of the Hurricane fault zone; the relay ramp exposes a complete, though faulted, section of the Moenkopi Formation. Rock unit names are shown in figure 4; various surficial deposits are shown in yellow and light brown. Cross sections A-A' and B-B' are shown on figure 5. Modified from Biek and others (2009).

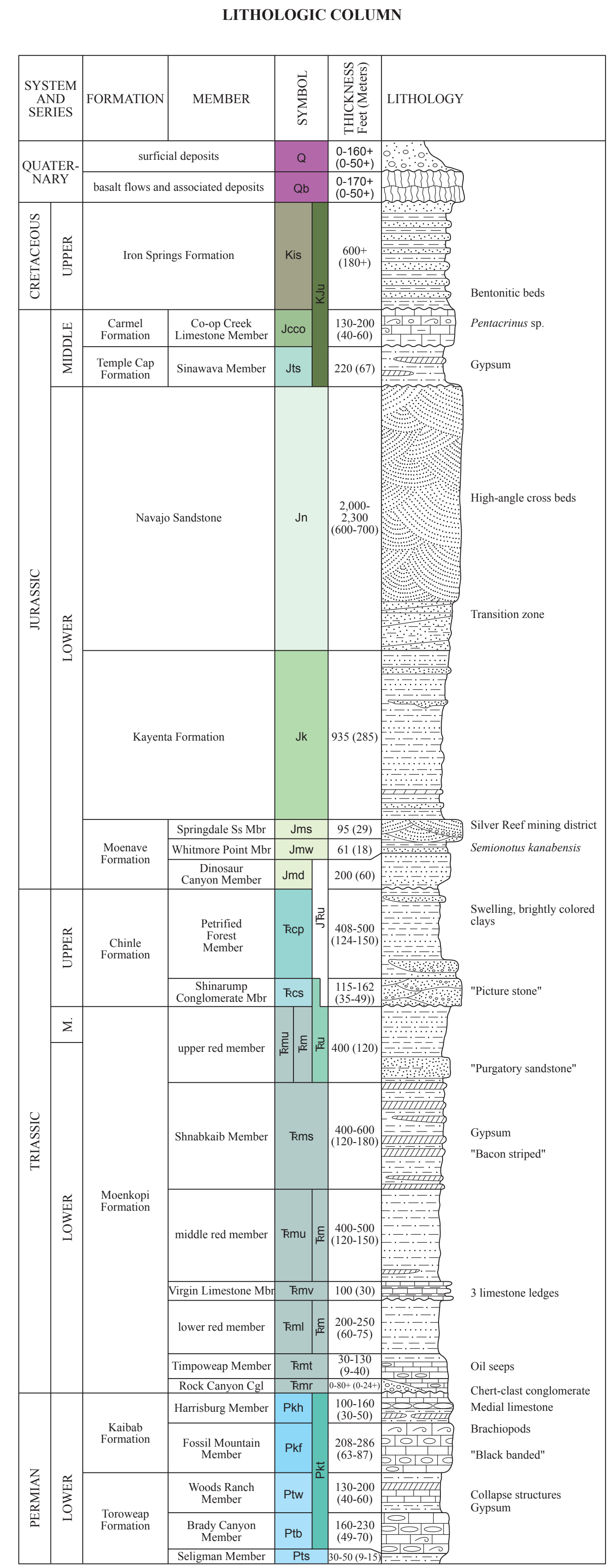

Figure 4. Stratigraphic column of rock units exposed in the greater Hurricane area. From Biek (2003).

rado River in the Grand Canyon (Karlstrom and others, 2007) to about 7500 feet (2300 m) along the north part of the fault near Cedar City (Hurlow, 2002). Anderson and Christenson (1989) found displacements of about 3600 feet (1100 m) and 4900 feet (1500 m) at the latitudes of St. George and Toquerville, respectively. This is the largest active normal fault in southwestern Utah.

Like most long normal faults, the Hurricane fault is composed of discrete segments that tend to rupture independently. The fault zone comprises six segments, three of which—the Cedar City, Ash Creek, and Anderson Junction—are in Utah (figure 1). The Anderson Junction and Ash Creek segments are linked by a structurally complicated segment boundary near Toquerville (Stewart and Taylor, 1996; Biek, 2003; Hurlow and Biek, 2003; Lund and others, 2007). This segment boundary is at the southern end of the Kanarra anticline, a Late Cretaceous frontal fold of the Sevier orogenic belt, and at the northern end of a relay ramp, which exposes a much-faulted yet complete panel of northwest-dipping Moenkopi Formation (figure 6).

In the Hurricane area, the fault juxtaposes Upper Cretaceous sandstone and mudstone of the Iron Springs Formation on the hanging-wall block against Lower Permian carbonates in the footwall block (Biek, 2003). Triassic red beds, tilted moderately to the west, are caught up in splays of the fault at the entrance to Timpoweap Canyon (figure 7).

In 2007, Utah Geological Survey geologist Bill Lund and his colleagues showed that the most recent surface-faulting event on the fault probably occurred in the Holocene (<10,000 years ago), at the north end of the fault near Cedar City (Lund and others, 2007). They further noted that multiple surface faulting earthquakes have occurred in the late Quaternary (about the past 125,000 years) along most, if not all, of the Utah portion of the fault. Based on dated basaltic lava flows that crossed and are now offset by the fault, they calculated an average slip rate of about 8 inches per 1000 years (0.21 mm/yr) for the Anderson Junction segment of the Hurricane fault since about 350,000 years ago. Near Ash Creek Reservoir, on the Ash Creek segment of the Hurricane fault, they documented an average slip rate of about 22 inches per 1000 years (0.57 mm/yr) since about 850,000 years ago for that segment of the fault. The fault is considered capable of generating damaging earthquakes of about magnitude 7.0 (Lund and others, 2007); the 1992 magnitude 5.8 St. George earthquake likely occurred on the Hurricane fault (Pechmann and others, 1995).

Faulting on the southern segments of the Hurricane fault began in the Pliocene, much later than for northern segments (Rowley and others, 1978; Hurlow, 2002). Billingsley and Workman (2000) described offset relationships of late Tertiary and Quaternary basaltic lava flows in Arizona and showed that, based on equal offset

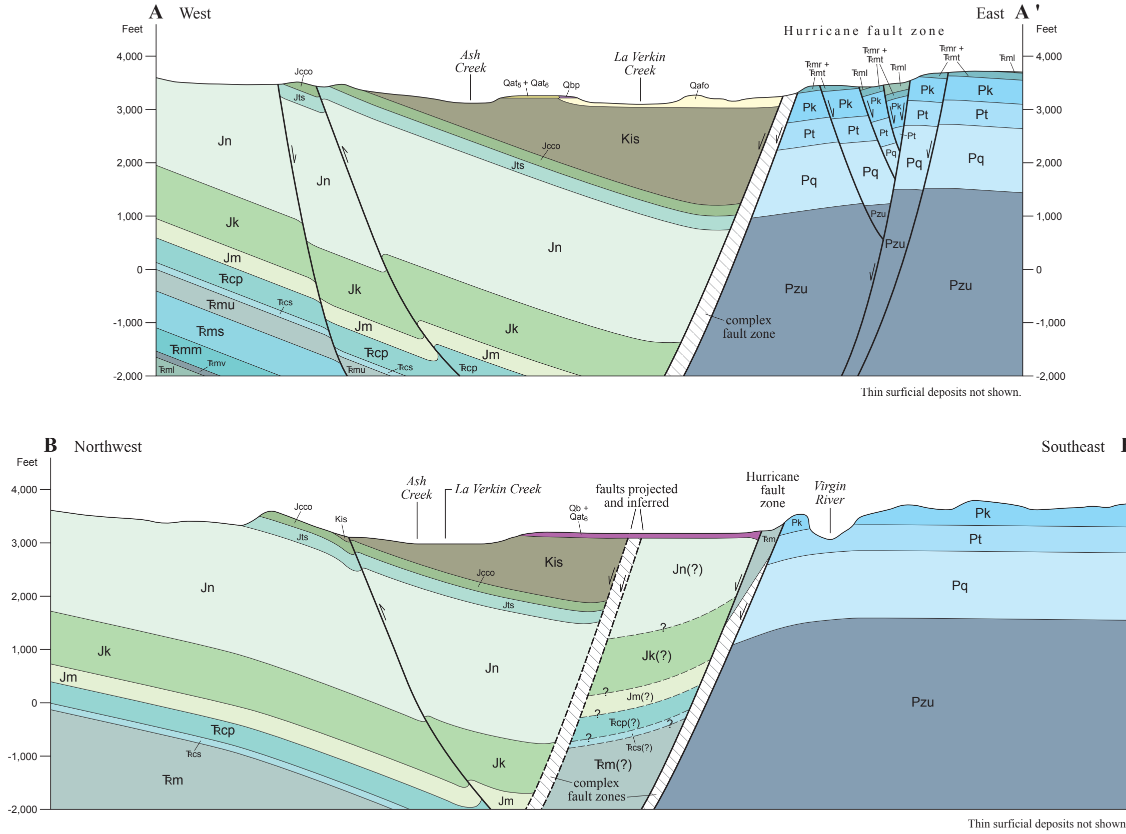

Figure 5. Cross sections through the Hurricane Cliffs between the La Verkin and Hurricane Overlooks. See figure 3 for section locations and figure 4 for rock unit names. Note that map (1:62,500) and cross sections (1:24,000) show different levels of detail and so do not match exactly. From Biek (2003).

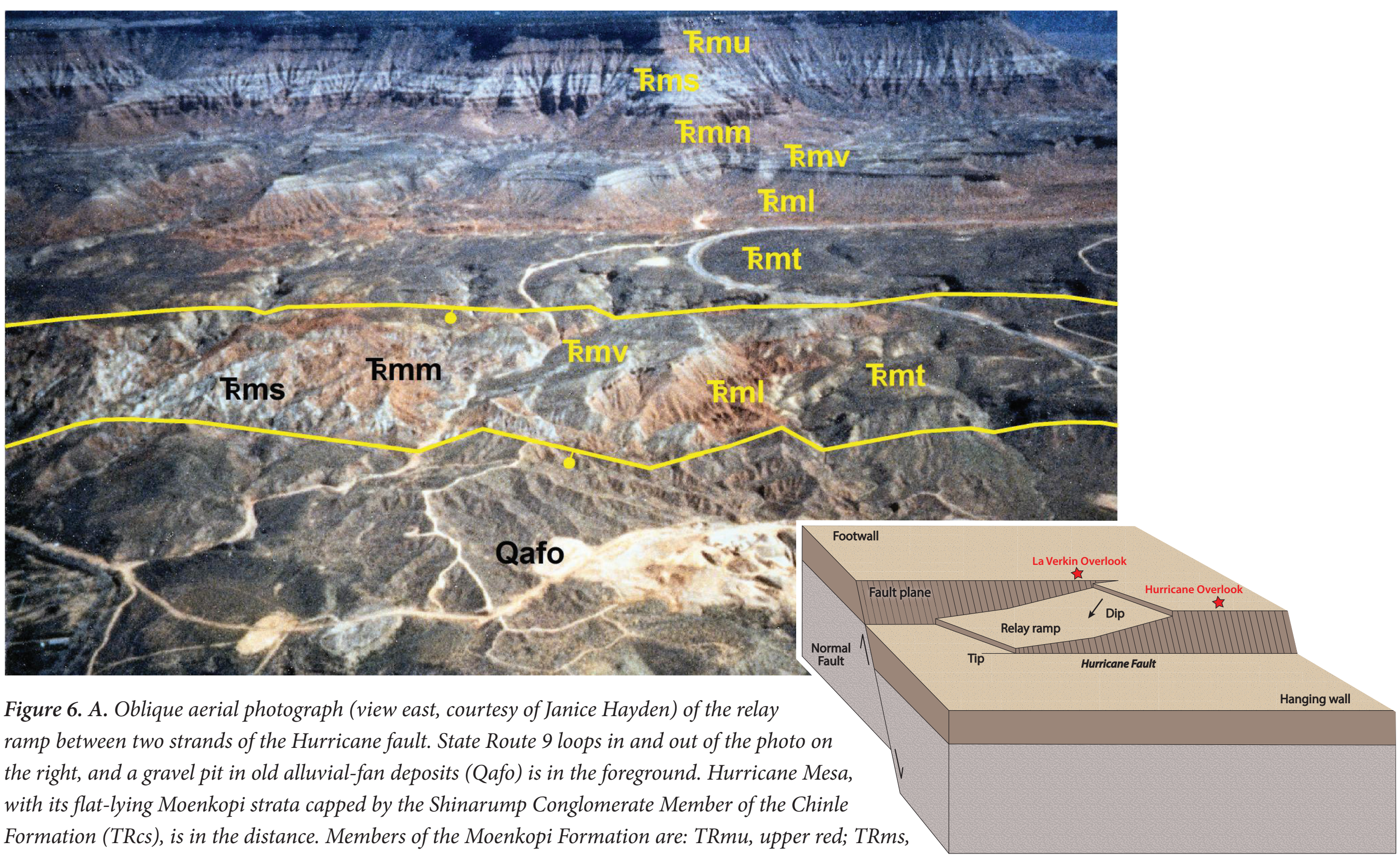

***Figure 6. A.** Oblique aerial photograph (view east, courtesy of Janice Hayden) of the relay ramp between two strands of the Hurricane fault. State Route 9 loops in and out of the photo on the right, and a gravel pit in old alluvial-fan deposits (Qafo) is in the foreground. Hurricane Mesa, with its flat-lying Moenkopi strata capped by the Shinarump Conglomerate Member of the Chinle Formation (TRcs), is in the distance. Members of the Moenkopi Formation are: TRmu, upper red; TRms, Shnabkaib; TRmm, middle red; TRmv, Virgin Limestone; TRml, lower red; and TRmt, Timpoweap. **B.** Inset block diagram shows the main features of a relay ramp.*

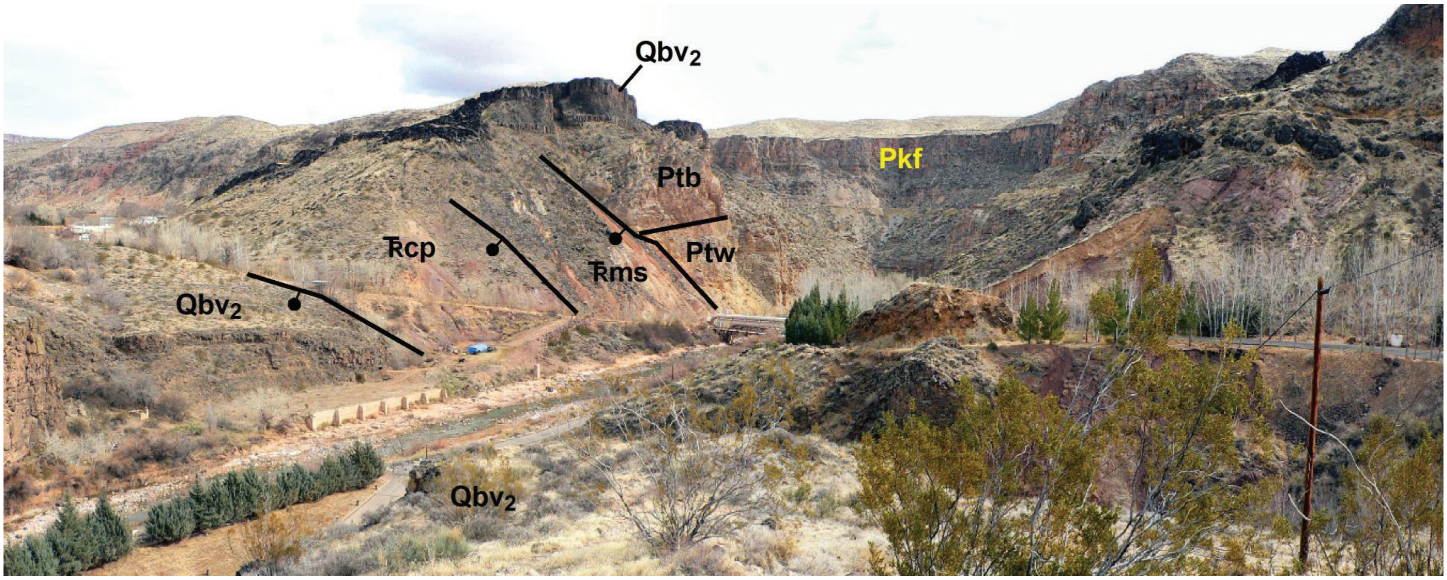

Figure 7. View northeast to the entrance of Timpoweap Canyon, where the Virgin River exits the Hurricane Cliffs. Three main strands of the Hurricane fault zone are shown. The fault zone is characterized by a west-dipping panel of Triassic strata caught between splays of the fault; these red beds act as a barrier to groundwater flow, causing warm water to rise through permeable Permian strata in the footwall and emerge as Pah Tempe Hot Springs. Here, the 350,000-year-old Volcano Mountain lava flow (Qbv2) is offset about 240 feet (73 m), yielding an average slip rate of about 8 inches per 1000 years (0.21 mm/yr). TRcp, Petrified Forest Member of the Chinle Formation; TRms, Shnabkaib Member of the Moenkopi Formation; Ptw and Ptb, Woods Ranch and Brady Canyon Members of the Toroweap Formation, respectively; Pkf, Fossil Mountain Member of the Kaibab Formation.

of lava flows and underlying Mesozoic strata, most normal faults on the Shivwits and Uinkaret Plateaus became active after 3.6 and possibly after 2.6 million years ago.

GEOSITES

La Verkin Overlook

The La Verkin Overlook offers expansive views in all directions—west across the St. George basin, north to Black Ridge, east towards Zion National Park, and south into Arizona (figure 8). The overlook is on brownish-gray limestone, cherty limestone, fine-grained sandstone, siltstone, and mudstone of the Timpoweap Member of the Moenkopi Formation. These Lower Triassic shallow-marine strata form a gently undulating surface on top of the Permian-Triassic unconformity (see State Route 9 geosite below) (Nielson and Johnson, 1979; Dubiel, 1994; Lucas and others, 2007); here, the intervening basal Rock Canyon Member, also described under the State Route 9 geosite, is thin or absent.

The Lower Triassic Moenkopi Formation of southwestern Utah, with its alternating reddish-brown, white, and gray layers, documents shallow-marine sedimentation along the western margin of the supercontinent Pangea, when what is now southwest Utah lay just north of the equator. The Moenkopi consists of three transgressive members (the Timpoweap, Virgin Limestone, and Shnabkaib Members that each record an interval of sea-level rise), each of which is overlain by an informally named regressive red bed member (the lower, middle, and upper red members, respectively, which record sea-level fall) (figure 9); the Rock Canyon Conglomerate Member locally forms the base of the Moenkopi Formation (Reeside and Bassler, 1921; Stewart and others, 1972; Dubiel, 1994). These members record a series of incursions and retreats of a shallow ocean across a gently sloping continental shelf, where sea-level changes of several feet translated into shoreline changes of many miles (Blakey and others, 1993; Dubiel, 1994).

Timpoweap strata unconformably overlie limestone, cherty limestone, and gypsum of the Lower Permian Harrisburg Member of the Kaibab Formation. These older, Lower Permian, strata were deposited when the flat landscape of the Pangean coast was alternately inundated by warm, shallow seas and exposed as broad coastal beaches and sabkhas (broad, flat surfaces near sea level where high evaporation rates commonly led to the accumulation of salts in sediments, such as today in some parts of the Arabian Peninsula) (McKee, 1938; Rawson and Turner-Peterson, 1979; Nielson, 1986).

This is also a good vantage point from which to contemplate long-term erosion rates for the St. George-Zion National Park area. Such rates can be calculated using known ages of basaltic lava flows and their height above major drainages. What we find is that long-term incision rates vary systematically west-to-east across the region (Hamblin and others, 1981; Willis and Biek, 2001). At St. George, west of the Washington fault, rates average 0.2 feet (0.06 m) per thousand years; between the Washington fault and Hurricane fault, rates average 0.4 feet (0.11 m) per thousand years; and east of the Hurricane fault, rates average 1.25 feet (0.35 m) per thousand years. Using these long-term incision rates, we can show, for example, that most of Zion Canyon was carved within

Figure 8. *Panoramic view from the La Verkin Overlook. Beginning at the right (northeast of the overlook), a complete section of the Moenkopi Formation is exposed below the Shinarump Conglomerate, which caps Hurricane Mesa. Black Ridge is carved from the east limb of the Kanarra anticline and is locally capped by the 850,000-year-old Pintura lava flow. This lava flow had its principal source west of the Hurricane Cliffs and has since been displaced over 1000 feet (300 m) by down-to-the-west movement on the Hurricane fault (which is mostly out of view at the western base of Black Ridge). The Pine Valley Mountains, an early Miocene laccolith intruded into the Claron Formation, form the skyline to the northwest. To the west and southwest, the Virgin River cuts through several basaltic lava flows between Hurricane and La Verkin. The basalt flow exposed in the footwall of the Hurricane fault zone, just south of the Virgin River, is 350,000 years old and erupted from Volcano Knoll; it has been displaced about 240 feet (73 m) by the Hurricane fault. Mollies Nipple, on the skyline at left, is capped by a basaltic lava flow that erupted at Ivans Knoll, immediately south of Volcano Knoll. The Ivans Knoll flow is about 1 million years old and has been displaced about 1300 feet (400 m) by the Hurricane fault.*

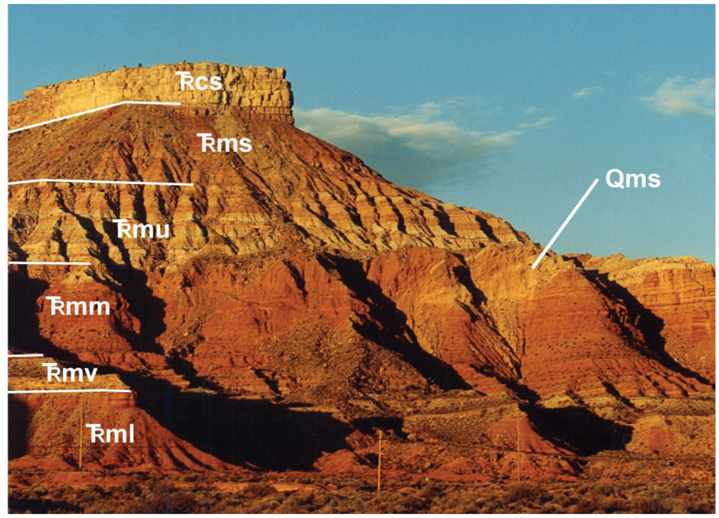

Figure 9. *View north to Hurricane Mesa from State Route 9 showing the lower red member (TRml), Virgin Limestone Member (TRmv), middle red member (TRmm), the "bacon-striped" Shnabkaib Member (TRms), and upper red member (TRmu) of the Moenkopi Formation. Hurricane Mesa, capped by the resistant Shinarump Conglomerate Member of the Chinle Formation (TRcs), has a World War II-era test track once used by the Air Force for testing ejection seats. Note landslide (area of disrupted bedding, Qms) in the down-dropped Shnabkaib and middle red strata at the right center of the photo.*

the past 2 million years (Biek and others, 2010). Variation in the amount and rate of long-term incision along the Virgin River is a function of relative base-level lowering along faults at and near the boundary of the Basin and Range. The rates are fastest east of the Hurricane fault, on its upthrown side, because it is the most active fault in the region.

Hurricane Overlook

Beginning in Miocene time in southwest Utah and continuing nearly to the present day, dozens of widely scattered basaltic lava flows poured out onto this landscape. Today, they constitute part of the Western Grand Canyon basaltic field, which extends across the southwest part of the Colorado Plateau and adjacent transition zone in southwest Utah, northern Arizona, and easternmost Nevada (Hamblin, 1963, 1970; Best and Brimhall, 1970, 1974; Best and others, 1980; Smith and others, 1999).

The Hurricane overlook is on one of these lava flows (the Volcano Mountain lava flow), which erupted about 350,000 years ago from a vent at Volcano Mountain (also known as Sullivan Knoll) just southwest of Hurricane. This lava flow is displaced about 240 feet (73 m) by the Hurricane fault, which is at the base of the cliffs. The lava flow is eroded to form the deep gorge of the Virgin River north of Hurricane. The cliffs reveal a single lava flow about 170 feet (50) thick; at its base is a 20- to 40-foot-thick (6-12 m) rubbly zone with pillow basalts (figures 10 and 11). The pillow basalt, which only forms when hot, fluid lava flows into water, shows that the flow temporarily blocked the Virgin River.

Figure 10. *Volcano Mountain lava flow and State Route 9 bridge over the Virgin River. This cliff reveals a single lava flow about 170 feet (50 m) thick; at its base is a rubbly zone with pillow basalts, indicating that the flow once blocked the ancestral Virgin River, creating a small lake into which lava flowed. This rubbly zone is overlain by about 10 feet (3 m) of dense, fine-grained basalt with prominent, widely spaced columnar joints (the lower colonnade), which in turn is overlain by about 100 feet (30 m) of similar basalt that is prominently and chaotically jointed (the entablature). The upper roughly 20 feet (6 m) of this exposure consists of vesicular basalt with few columnar joints (the upper colonnade). This same sequence is present in exposures on the upthrown side of the Hurricane fault.*

Three strands of the Hurricane fault are exposed at the entrance to Timpoweap Canyon, a short walk north of the Hurricane Overlook (figure 7). Pah Tempe Hot Springs (also known as La Verkin or Dixie Hot Springs) issues from the canyon bottom just east of the fault zone. The west-dipping panel of Triassic red beds caught in the Hurricane fault zone acts as a barrier to groundwater flow, whereas the fractured and cavernous Permian carbonates east of the fault act as conduits to groundwater flow. According to research by Brigham Young University geologists, as groundwater encounters the Hurricane fault, probably at depths of at least 2000 to 4000 feet (700-1300 m), it hits a Moenkopi seal and is forced laterally and upward, eventually discharging along the Virgin River (Dutson, 2005). The source of the hot water is thus structurally controlled and results from deeply circulating groundwater and the earth's natural geothermal gradient (here probably about 130°F/mile depth); it is not related to eruption of relatively young basaltic lava flows. Basaltic lavas in the region originated at far greater depth, rising to the surface though narrow conduits, thus precluding the basaltic magmas from being a significant heat source.

Pah Tempe Hot Springs has the highest recorded spring-water temperature in the St. George basin (Budding and Sommer, 1986). The springs average about 104°F (40°C), have a pH of 6.3, and discharge sodium-chloride-type water with a very high average of 9600 to 9900 mg/L total dissolved solids (TDS) concentration. They issue from and immediately above the bed of the Virgin River for a distance of nearly 1500 feet (500 m) upstream of the Hurricane fault. The average annual dissolved-solids discharge at the springs is about triple that of the Virgin River just upstream of the springs (Mundorff, 1970; Yelken, 1996). The high TDS concentration of the spring water contributes to poor downstream water quality, and is the reason Virgin River water is collected above the springs and piped to Quail Creek and Sand Hollow Reservoirs.

In April 1985, sinkholes appeared in the bed of the Virgin River—adjacent to an abandoned diversion structure and just downstream from the newly completed Quail Creek diversion structure—about 2 miles (3.2 km) straight-line distance upstream from Pah Tempe Hot Springs. The sinkholes captured an estimated 7200 acre-feet (about 9,000,000 m^3) of water over a period of several months. This stream-capture event acted as a natural aquifer test that was evaluated by Ben Everitt of the Utah Division of Water Resources and his colleague Martin Einert. Discharge at the hot springs surged from 11 to about 20 cubic feet per second (0.3-0.6 m^3/s), the temperature dropped about 9°F (5°C), and the TDS concentration dropped by about 2000 mg/L (Everitt and Einert, 1994). Within a year all parameters began to recover and returned to normal after about 2.5 years.

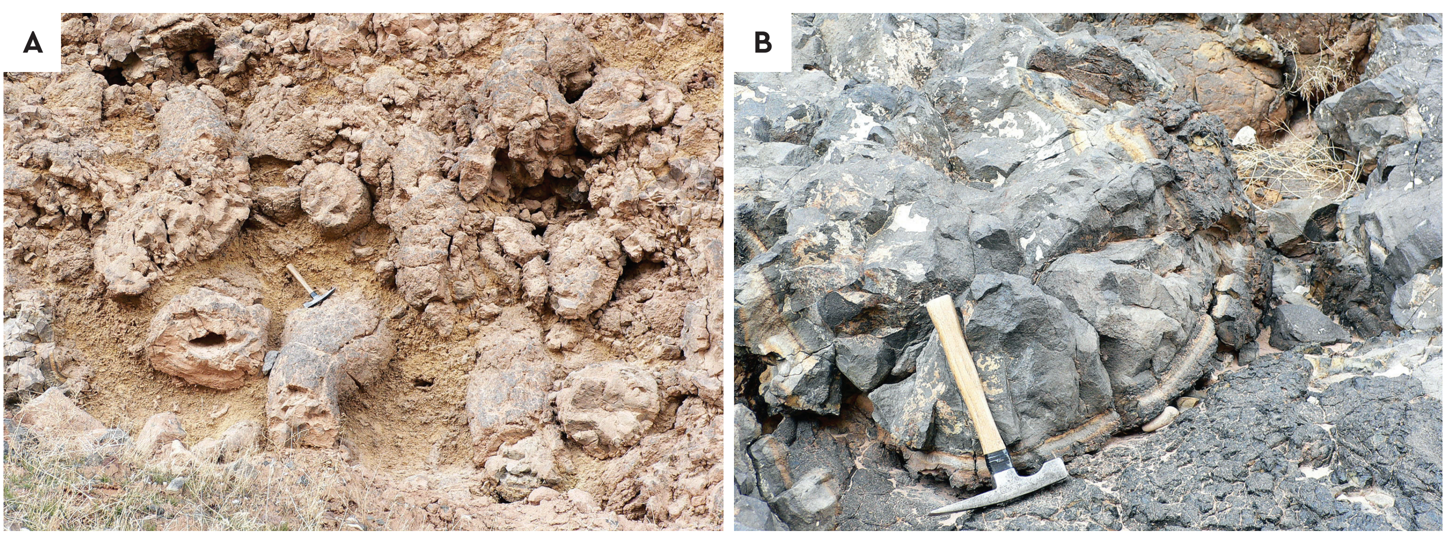

Figure 11. A. *Close-up of pillow basalt near the State Route 9 bridge; hammer for scale.* ***B.*** *Note altered, glassy rind on pillow.*

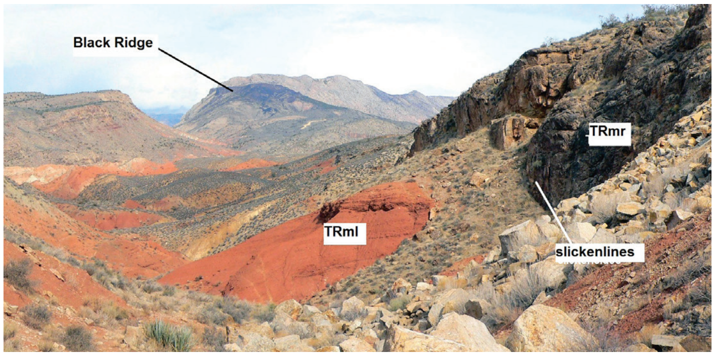

Figure 12. View north-northwest along Hurricane fault zone just west of State Route 9. The lower red member of the Moenkopi Formation (TRml) is down-to-the-west against the Rock Canyon Conglomerate Member (TRmr). Slickenlines are shown by white line. Black Ridge, capped by the 850,000-year-old Pinture lava flow, is on the skyline in middle of photograph.

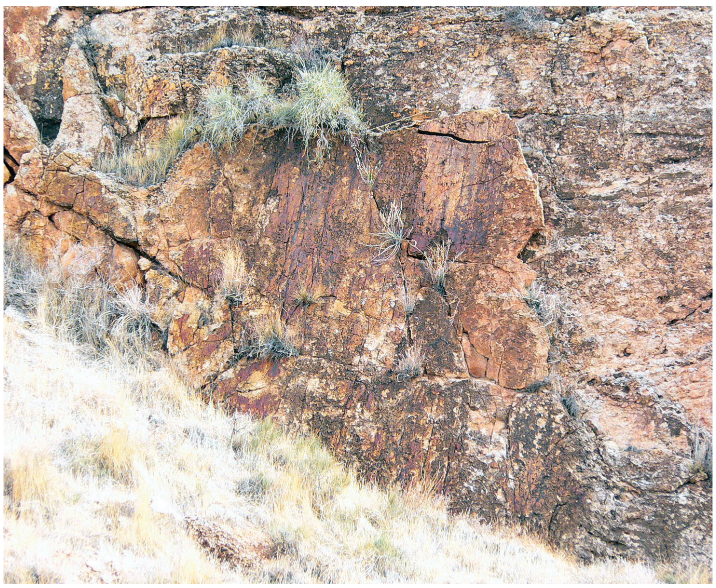

Figure 13. Slickenlines and polished fault surface developed on the Rock Canyon Conglomerate Member. Here, the fault plane and slickenlines are nearly vertical.

Figure 14. Here, a strand of the Hurricane fault exposes the Permian-Triassic unconformity. The fault places lower red (TRml) strata down on the west against the Rock Canyon Conglomerate Member (TRmr) overlain by the Timpoweap Member (TRmt). The Early Permian Harrisburg Member of the Kaibab Formation is exposed at the base of the wash, just out of view in this photo. View northeast.

Highway 9 Road Cut

In this area, the Hurricane fault zone forms a relay ramp between two en echelon faults (figure 6) (Biek, 2003). The ramp exposes a complete section of Moenkopi strata, cut by numerous down-to-the-east and down-to-the-west normal faults. This relay ramp also forms an easy way up the Hurricane Cliffs, a fact exploited by State Route 9.

Beautiful slickenlines on a polished fault surface, described below, are found 0.1 mile (0.15 km) up the road from the suggested parking area, but are located at a dangerous curve of State Route 9 (at 37° 13' 23.3", 113° 15' 29.6"). However, even more dramatic slickenlines are present to the north below the highway; to access this area, carefully cross the highway and walk about 1300 feet (400 m) north, to the north end of the highway fill (to 37° 13' 29.7", 113° 15' 34.0"), where the lower red member is faulted down-to-the-west against the Rock Canyon Conglomerate (figure 12). The fault plane dips 85 degrees west and slickenlines developed on Rock Canyon strata are nearly vertical (figure 13).

The Permian-Triassic boundary is exposed in the cliffs of a small box canyon just ahead of the parking area on the east side of the road (figure 14). In southwest Utah, this boundary is a major unconformity that spans 10 to 20 million years (Nielson, 1981, 1991; Sorauf and Billingsley, 1991). This is the TR-1 unconformity of Pipiringos and O'Sullivan (1978), the first regional unconformity of the Triassic Period in the western U.S. It also represents a period of dramatic, world wide sea-level drop and the largest global extinction event in the history of the world (see, for example, Ward, 2004). Erosion during this time produced an irregular surface, locally with several hundred feet of relief, upon which conglomerate and breccia of the Rock Canyon Conglomerate Member of the Moenkopi Formation was deposited in paleocanyons, karst depressions, and as regolith (Nielson, 1991; Higgins, 1997). Limestone of the overlying Timpoweap Member of the Moenkopi Formation was deposited in broader paleovalleys (Nielson and Johnson, 1979). The cliffs of this small box canyon are capped by Timpoweap strata that overlie channel-form conglomerates of the Rock Canyon Conglomerate. Cherty limestone of the Harrisburg Member of the Kaibab Formation (late Early Permian) is exposed at the base of the wash.

ACKNOWLEDGMENTS

My knowledge of southwestern Utah geology comes from years of geologic mapping supported largely by the Utah Geological Survey and U.S. Geological Survey. As the acknowledgments of the resultant geologic maps attest, I am indebted to a great many people for their help over the years. Thanks to Grant Willis and Mike Hylland (UGS) and Kimm Harty (UGS retired) for their insightful reviews and to Jenny Erickson (UGS) for drafting the figures.

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