Inverted Topography in St. George, Washington County, Utah

Janice M. Hayden
Dixie State University, 225 South University Ave, St. George, Utah 84770
hayden@dixie.edu

Cover Image: Photo looking west-northwest at the higher West Black Ridge, capped by the 2.3 million year old Twin Peaks lava flow, behind the lower “old airport ridge,” capped by the 1.2 million-year-old Cedar Bench lava flow.
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.

This is an open-access article in which the Utah Geological Association permits unrestricted use, distribution, and reproduction of text and figures that are not noted as copyrighted, provided the original author and source are credited. See the Utah Geological Association website, www.utahgeology.org, and Creative Commons https://creativecommons.org/licenses/by/4.0/ for details.

Suggested citation for this geosite:

Hayden, J., 2022, Inverted topography in St. George, Washington County, Utah: Utah Geological Association Publication, v. 1, p. 1-11., doi: 10.31711/ugap.v1i1.99.
INTRODUCTION

Washington County, Utah has several classic examples of inverted topography, where now topographically high ridges are capped by basalt that once flowed as lava down low stream drainages. This paper focuses on the ridges that trend north-south on either side of downtown St. George (figures 1 and 2).

The City of St. George boasts three of these ridges. West Black Ridge capped by the Twin Peaks lava flow, and “old airport ridge” capped by the Cedar Bench lava flow are both located to the west of downtown. Middleton Black Ridge capped by the Lava Ridge lava flow is located to the east of downtown. The two lower elevation ridges are now being covered with homes, some of which have spectacular views. These ridges also remain a favorite place from which to view firework displays during city celebrations and events. Visiting the water tank on the Red Hills, north of downtown offers an excellent perspective from which to view these ridges.

Figure 1. Map showing inverted valleys in St. George, Washington County, Utah.

Figure 2. Geologic map of the downtown St. George area (from Hayden and Willis, 2011). Note the north-south trending ridges both east and west of downtown that are capped by lava that flowed down stream valleys but, because of subsequent downcutting and erosion, now cap ridges, forming classic examples of inverted topography or “inverted valleys.” The sedimentary bedrock that comprise the ridges underneath the lava flows strikes generally east to west-northwest, just opposite that of the ridges, with northeastward tilting rock layers getting progressively younger from south to north. A significant portion of the map area is covered by recent Quaternary sediments. See figure 4 for A-A’ cross section and figure 8 for a partial stratigraphic column with unit names.
LOCATION

Traveling on I-15, use Exit 8 to access St. George Boulevard. Travel west to 1000 East then turn right to go north up the hill for one block. Turn left onto Red Hills Parkway and proceed 0.5 miles (0.8 km) before turning left into a parking lot. Just to the west of the parking lot you’ll see a large water tank built in 1948 with stairs and a railing. Community dances were held atop the tank on Friday and Saturday nights for many years (Washington County Historical Society, website). Should you miss pulling in to this first parking lot that is on the side of the stairs, another parking lot is located just to the west of the water tank. You can see the view from the parking lots, but it is more fun to climb to the top of the water tank, which is perched atop the Red Hills with a view down onto the city center. Look left and right for a great view of the inverted topography ridges that flank downtown St. George.

GPS location: 37°06’46.07”N 113°34’22.70”W.
Elevation: 3020 feet (921 meters) above mean sea level on top of the tank.

INVERTED VALLEYS AND BASALTIC LAVA FLOWS

The concept of inverted topography in the St. George area was first described in detail by Hamblin (1963, 1970, 1987) and Hamblin and others (1981). Typically, the lava flowed down the bottom of stream valleys and cooled, forming a hard surface (figure 3). Streams commonly re-established on top of the flows, as evidenced by thin gravel deposits, before slipping to the sides of the flows to preferentially erode the softer sedimentary bedrock. Continued downcutting then left the resistant lava flows isolated as elevated, sinuous ridges called inverted valleys; thus, flows that used to form the valley floors now cap the ridges. Because most small basaltic volcanoes are monocyclic, meaning that each vent produces only one eruptive cycle that may last less than a year to a few tens of years, the resistant flows document the local drainage pattern as it existed when the flow erupted (in contrast, flows from a single eruptive cycle may consist of several pulses of lava, called cooling units, that can be confused as separate flows).

Ages for these lava flows and their heights above major drainages provide a means for calculating long-term incision rates for major rivers and streams in the St. George area (Willis and Biek, 2001). The calculations reconfirm and expand on many of the findings of Hamblin and others (1981), who similarly documented incision rates in the St. George basin. However, the old axiom that “the higher the lava flow is above the current drainage the older it is” is only valid when comparing flows on the same side of active faults (figure 4). The eastern Middleton Black Ridge (Lava Ridge lava flow) has comparably greater inversion that do those flows to the west. This anomaly is because the ridges are on the opposite sides of the St. George fault, a late Cenozoic extensional, down-to-the-west fault.
that offsets strata about 400 feet (120 m) but does not offset exposed surficial deposits (Hayden and Willis, 2011). The comparably greater topographic inversion of this middle-aged flow (of the three flows) is directly attributable to its position on the footwall (upthrown part) of a separate, relatively more elevated structural block. Thus, position on structural blocks is important when estimating relative ages of lava flows based on the amount of “topographic inversion” (“stage” designations of Hamblin, 1963, 1970, 1987).

Hamblin (1963, 1970, 1987), Best and others (1966, 1980), Lowder (1973), Leeman (1974), Best and Brimhall (1970, 1974), Hamblin and others (1981), Nelson and Tingey (1997), Nusbaum and others (1997), Smith and others (1999), Downing (2000), and Biek and others (2009) all described lava flows in the greater St. George area, their tectonic setting, and their petrogenesis, and proposed that the geochemical variability between individual lava flows could be explained by their derivation from the partial melting of compositionally heterogeneous lithospheric mantle, and by fractional crystallization.

**Twin Peaks Lava Flow of West Black Ridge**

The oldest of the three lava flows is the lower Pleistocene Twin Peaks lava flow (Qbt) which caps West Black Ridge above the Dixie State University “D.” It is dark-gray basaltic trachyandesite with large plagioclase and quartz, and small olivine and clinopyroxene phenocrysts (Hayden and Willis, 2011). It has strong columnar jointing and weathers to large, angular, blocky rubble. There are two cooling units that are well exposed.

Geochemistry suggests that this flow, previously called West Black Ridge lava flow (Willis and Biek, 2001), erupted from vents at extensively eroded cinder cones at Twin Peaks, about 8 miles (13 km) to the north, and it is now considered the southernmost part of the Twin Peaks lava flow (Biek and others, 2009).

The flow yielded radiometric K-Ar ages of 2.3 ± 0.1 million years (Ma) (Best and others, 1980) and 2.24 ± 0.11 Ma (Hamblin and others, 1981), and an 40Ar/39Ar age of 2.34 ± 0.02 Ma (Biek and others, 2009). It is 20 to 80 feet (6-24 m) thick.

This flow, accessible to pioneers because of a landslide at the southern tip of West Black Ridge, was quarried and pounded into the ground with a pile driver fashioned from an old cannon to make the foundation for the Church of Jesus Christ of Latter-Day Saints St. George Temple, a process taking two years. The remnants of the road and quarry can be visited by taking an easy 2 mile (3.2 km) round-trip hike that begins at the city park located at the top of “old airport ridge” after continuing west on St. George Boulevard (figure 5). (Trailhead: 37°06'10.2"N 113°35'45.2"W)

---

**Figure 4.** Cross-section showing the three, north-south trending inverted topography ridges that bracket downtown St. George. Generally, the higher the ridge is above the current drainage, the older the capping lava flow. However, note that when comparing ridges on different structural blocks, the higher elevation block commonly weathers and erodes at a faster rate than the block that has been dropped down by normal faulting. The St. George fault separates Middleton Black Ridge (Lava Ridge lava flow, east of downtown) from West Black Ridge (Twin Peaks lava flow) and "old airport ridge" (Cedar Bench lava flow) on the west side of downtown. Older rock units that are not exposed at the surface in the map area are shown on the cross-section. (From Hayden and Willis, 2011.)

**Figure 5.** Photo looking west-northwest at the higher West Black Ridge, capped by the 2.3 million year old Twin Peaks lava flow, behind the lower "old airport ridge," capped by the 1.2 million-year-old Cedar Bench lava flow. These flows are quite young. Comparing the 4.5 billion-year-old age of Earth to the length of a football field, where one inch on the field represents 1.25 million years, these two flows occurred about two- and then one-inch shy of the endzone. Note the “D” on the slope between the two flows. Both lava flows are partially covered by sediment deposited by eolian, colluvial and alluvial processes (Qeca, figure 2). Much of the ridge slope is covered by rockfall blocks as talus deposits (Qmt, figure 2), but the Triassic-Jurassic sedimentary layers are exposed by roadcuts along Bluff Street and in drainages, and get progressively younger going left to right in the photo. Note that Petrified Forest Member of the Chile Formation underlies the south (left) end of both ridges, creating landslides (Qms, figure 2) that include the lava flows. Photo taken Aug. 24, 2018.
Lava Ridge Lava Flow of Middleton Black Ridge

The middle-aged of the three flows is the lower Pleistocene Lava Ridge flow (Qbl) that caps Middleton Black Ridge east of downtown (figure 6). It is a moderately jointed, dark-gray basaltic trachyandesite with prominent euhedral plagioclase phenocrysts up to 0.4 inch (1 cm) wide, common quartz and pyroxene phenocrysts, and small olivine phenocrysts (Hayden and Willis, 2011). It was previously called Middleton lava flow (Willis and Biek, 2001), but petrographic and limited geochemical data suggest it is the southern extension of the Lava Ridge flow (Biek and others, 2009). It consists of three flows in a road cut on Middleton Drive near the intersection with Red Rock Road (37°07’16.26”N 113°33’02.96”W) (Hamblin and Best, 1970), where the more mafic oldest flow, about 5 feet (1.5 m) thick, overlies alluvial gravel deposited on bedrock. It is overlain by another well-developed alluvial gravel, a lava flow about 20 feet (6 m) thick, another gravel, and then an upper lava flow about 15 feet (4.5 m) thick. A nearby roadcut on Interstate 15 reveals that only the upper flow continues south, capping Middleton Black Ridge and forming a two-mile-long (3.2 km), straight, narrow inverted valley where the flow was confined in a narrow channel, and a broad “foot” where it entered the more open channel of the ancestral Virgin River (figure 7). It erupted from a group of heavily weathered cinder cones on Lava Ridge, about 8 miles (13 km) north of St. George.

Samples taken from the upper flow on Middleton Black Ridge yielded a radiometric K-Ar age of 1.5 ± 0.1 Ma (Best and others, 1980) and an 40Ar/39Ar age of 1.41 ± 0.01 Ma (Biek and others, 2009). The lower two flows are probably about the same age. It is generally 20 to 40 feet (6-12 m) thick.

Cedar Bench Lava Flow of “Old Airport Ridge”

The youngest of the three lava flows included here is the lower Pleistocene Cedar Bench lava flow (Qbcb) that caps “old airport ridge” below the Dixie State University “D” to the west of downtown. It is a brownish-black trachybasalt with small phenocrysts of clinopyroxene and olivine. It has prevalent columnar jointing and is strongly weathered along joints, forming a mottled texture (Hayden and Willis, 2011). Previously called the Airport lava flow (Willis and Biek, 2001), it is now considered the southern extension of the Cedar Bench lava flow because of similar geochemistry (Biek and others, 2009). Two cooling units are well exposed along the southeast edge of the flow, which erupted from vents at two overlapping cinder cones about 10 miles (16 km) north of St. George.

The rock yielded a radiometric 40Ar/39Ar plateau age of 1.23 ± 0.01 Ma (Biek and others, 2009), which fits well with regional downcutting rates (Willis and Biek, 2001). The flow is typically 10 to 30 feet (3-9 m) thick. These three lava flows sit atop lower Pleistocene, poorly to moderately sorted, clay- to boulder-size, stream-deposited gravel (Qag) with mostly well-rounded cobbles and small boulders that are exotic to the quadrangle, including igneous rocks derived from the Pine Valley Mountains. These alluvial gravels are best exposed in road cuts.

Figure 6. Photo looking north-northwest at the northern part of Middleton Black Ridge, which is capped by the 1.4 million-year-old Lava Ridge flow. Like the other two lava flows, this one is partially covered by sediment (Qeca, figure 2). Talus (Qmt, figure 2) covers much of the slope of the ridge and the Jurassic-Triassic section is best exposed along roadcuts and in drainages. I-15 cuts through the flow near middle of photo. Photo taken Mar. 1, 2007 by Jerry D. Harris.

Figure 7. Photo looking north at the I-15 roadcut showing the red beds of the Early Jurassic-age main body of the Kayenta Formation (Jkm) below, separated from the black Lava Ridge lava flow (Qbl) above, by a tan layer of stream gravel (Qag), indicating that the lava flowed down an ancestral stream valley. Photo taken Aug. 26, 2006 by Jerry D. Harris.
Stratigraphy

These three lava flows unconformably overlie Triassic to Jurassic age sedimentary rocks that were tilted to the northeast as part of the broadly folded St. George syncline, a down-arched fold of rock layers (figure 8). The fold axis runs under downtown, through the south end of “old airport ridge,” and continues over the ridge to the south-southwest. There is a profound change in the direction of strike of these sedimentary rocks from west-southwest on the east side of town, to northwest on the west side of town. This change is shown nicely by the bend in the ridge of the Shinarump Conglomerate member of the Chinle Formation (TRcs).

Triassic Chinle Formation, Petrified Forest Member

The Petrified Forest Member (TRcp) of the Chinle Formation consists of highly variegated, light-brownish-gray, pale-greenish-gray, to grayish-red-purple, smectitic (swelling) shale, mudstone, siltstone, and claystone, with several lenticular interbeds of yellowish-brown, cross-bedded, resistant sandstone up to 10 feet (3 m) thick. There is a pebble to small-cobble conglomerate near the base with primarily chert and quartzite clasts. It also contains minor chert, nodular limestone, very thin coal seams and lenses as much as 0.5 inch (1 cm) thick, and locally abundant, brightly colored fossilized wood (Hayden and Willis, 2011).

Shale and mudstone layers of the Petrified Forest Member weather to a “popcorn” surface with abundant mudcracks due to expansive clays that cause road and building foundation problems. It weathers to badland topography and is prone to landsliding along steep hillsides. It is also the local primary source of radon gas (Solomon, 1992a, 1992b). It forms the well-developed strike valley of the Santa Clara and Virgin Rivers. It is well exposed only where protected from erosion by stream-terrace deposits and in road cuts along the south edges of Middleton and West Black Ridges. Where underlain by Petrified Forest beds, the lava flow capped ridges commonly exhibit a series of steps created by landslides.

The Petrified Forest Member was deposited in lacustrine, floodplain, and fluvial environments of a back-arc basin formed inland of a magmatic arc associated with a subduction zone along the west coast of North America. A significant portion of its sediment was supplied by volcanic ash (Stewart and others, 1972b; Dickinson and others, 1983; Blakey and others, 1993; Lucas, 1993; Dubiel, 1994; DeCourten, 1998; Lucas and Tanner, 2007). It is 700 feet (215 m) thick.

Moenaev Formation, Dinosaur Canyon Member

The Lower Jurassic Moenaev Formation (JTRm) trends across the middle of the map area. The Dinosaur Canyon Member (JTRmd) is interbedded, generally thin-bedded, reddish-brown, very fine to fine-grained sandstone, very fine grained silty sandstone, and lesser siltstone and mudstone with laminated cross-beds with common ripple marks and mud cracks that forms a ledgy slope (Hayden and Willis, 2011). Regionally it forms the base of Vermilion Cliffs step of the Grand Staircase (Gregory, 1950). It is locally exposed in excavations below basalt talus near the south end of Middleton and West Black Ridges, in stream drainages on either side of the ridges, and where protected from erosion by overlying stream-terrace deposits. Several outcrops exposed by construction have revealed plant fossils (Tidwell and Ash, 2006). It was deposited on a broad, low floodplain that was locally shallowly flooded (fluvial mud flat) (Clémens and others, 1989; Blakey, 1994; Peterson, 1994; DeCourten, 1998). It is 185 feet (55 m) thick (Kirkland and Milner, 2006).
Moenave Formation, Whitmore Point Member
The Whitmore Point Member (Jmw) is an interbedded, pale-red-dish-brown, greenish-gray, and grayish-red mudstone and claystone, with thin-bedded, reddish-brown, very fine to fine-grained sandstone and siltstone. It also includes yellowish-gray, dolomitic limestone that includes several 2- to 6-inch-thick (5-15 cm), bioturbated, cherty, dolomitic limestone beds with algal structures, some altered to jasper, and fossil fish scales (Hayden and Willis, 2011), likely of semionotid fish (Milner and Kirkland, 2006). It is nonresistant and poorly exposed in excavations along Bluff Street, in drainages next to Middleton Black Ridge, and beneath a few protective stream terraces now largely removed by construction along Riverside Drive. The nearby St. George Dinosaur Discovery Site at Johnson Farm (Harris and Milner, 2016) revealed exceptionally well-preserved theropod tracks (three-toed dinosaur tracks called *Eubrontes* and *Grallator*) near the base of the member. The site also includes swim tracks (Kirkland and Milner, 2006; Milner and others, 2006), other trace fossils (Lucas and others, 2006), and a variety of invertebrate fossils (Lucas and Milner, 2006). Note the dinosaur footprint symbol near the east edge of the geologic map (Fig. 2) for the location of the museum along Riverside Drive, which is definitely worth a visit. The member was deposited in low-energy lacustrine and fluvial environments (Clemmensen and others, 1989; Blakey, 1994; Peterson, 1994; DeCourten, 1998; and Milner and Kirkland, 2006) and is 55 feet (17 m) thick.

Kayenta Formation, Springdale Sandstone Member
The Lower Jurassic Kayenta Formation (Jks) is mostly grayish-yellow, moderately sorted, fine- to medium-grained, medium- to very thick bedded, ledge- to small-cliff-forming sandstone, with minor, thin, discontinuous lenses of intraformational conglomerate and thin interbeds of reddish-brown or greenish-gray mudstone and siltstone (Hayden and Willis, 2011). It contains locally abundant petrified and carbonized fossil plant remains. Theropod dinosaur tracks are common in upper horizon, known as the Springdale megatracksite (Lucas and others, 2005; Hamblin and others, 2006). The sandstone produced silver at the Silver Reef mining district 15 miles (24 km) to the northeast (James and Newman, 1986; Proctor and Shirts, 1991; Biek and Rohrer, 2006), and has local copper and uranium mineralization (James and Newman, 1986). It is resistant to erosion and forms isolated outcrops that protrude from beneath basalt talus along the slopes of the basalt-capped ridges and is completely exposed in washes east and west of Middleton Black Ridge. It was deposited in braided-stream and minor floodplain environments (Clemmensen and others, 1989; Blakley, 1994; Peterson, 1994; DeCourten, 1998; Lucas and Tanner, 2006). It is 115 feet (35 m) thick.

Kayenta Formation, Main Body
The main body of the Kayenta Formation (Jkm) is reddish-brown, thin-bedded siltstone and mudstone interbedded with very fine to fine-grained, planar to lenticular, mottled sandstone with climbing ripple marks (Hayden and Willis, 2011). The upper surface of sandstone ledges is commonly bioturbated. It forms a steep, ledgy slope to ledgy cliff that is mostly covered by talus but is best exposed by construction and roadcuts along Bluff Street, in the drainage on the east side of Middleton Black Ridge, and at the base of Red Hills along the northern edge of the map. The top of the formation is close to Red Hills Parkway, the road you took to reach the view from the water tank. The main body of the Kayenta was deposited in distal river, playa, and minor lacustrine environments (Tuesink, 1989; Blakey, 1994; Peterson, 1994). It is 810 feet (247 m) thick.

This member was quarried from the Red Hills by early settlers for the stone used to build the St. George Temple, Tabernacle, Historic Courthouse, Washington Cottonmill and many other buildings. A 0.6 mile (1 km) round-trip trail to the quarry begins at the north end of 700 West and goes along the edge of Red Hills Golf Course.

Navajo Sandstone
The Lower Jurassic Navajo Sandstone (Jn) is a reddish-orange, massively cross-bedded, moderately well-cemented sandstone with well-rounded, fine- to medium-grained, frosted quartz sand grains and locally common ironstone bands and concretions (Hayden and Willis, 2011). It forms the cliffs and slopes of the upper portion of the Red Hills. It is strongly jointed in two main joints sets: generally north-northeast-trending joints that are parallel, high-angle, and typically open, and northwest-trending joints that are commonly brecciated and strongly cemented. These joints are prominent in the outcrops on the north side of Red Hills Parkway in the area of “Dixie” rock. A local favorite just up the one-way road from the Red Hills Desert Garden parking lot is known as “the crack.”

Regionally this sandstone forms the White Cliffs step of the Grand Staircase (Gregory, 1950), although it does not happen to be white locally. The formation is also the principal aquifer in the area (Clyde, 1987; Hurlow, 1998; Heilweil and others, 2000, 2002; Rowley and Dixon, 2004) and springs are common at the lower contact with the Kayenta Formation. The sand was deposited in a vast coastal and inland dune field with prevailing winds principally from the north, and in rare interdunal ephemeral lakes and playas (Blakey, 1994; Peterson, 1994). Only the lower 200 feet (60 m) is present in the area shown on figure 2, but the Navajo’s total thickness is 1800 to 2000 feet (550-600 m) in Snow Canyon State Park.

Quaternary Age Sediments
Much of the map area is covered by Quaternary-age sediment deposited by several agents of gradation: streams, wind, debris flows, and landslides. Landslides (Qms) and broken blocks of rock called talus...
(Qmt) that cover many bedrock slopes are deposited as gravity pulls them down the hillsides. Piles of unconsolidated sand are deposited by wind (eolian) processes (Qes). Stream systems deposit alluvial sediment in the active channel of the Virgin and Santa Clara rivers (Qa1), and old stream deposits are preserved as terraces (Qat\textsubscript{2,3}) at higher elevations than current drainages. Some much older terraces (Qato) are not connected to present drainages. There are also units deposited by a combination of processes, such as both alluvial and colluvial (Qac) in minor drainage dissected areas, and both alluvial and eolian (Qae and Qae) in mostly broad, flat areas. The valley underneath downtown is an older alluvial and eolian surface (Qaeo), while the sediment covering part of the top of the lava flows is deposited by a combination of eolian, colluvial, and alluvial processes (Qeca).

**SUMMARY**

When trying to understand landscape development, it is helpful to know that whatever landscape you are seeing is DUE for a change. DUE stands for deposition, uplift, and erosion. Although these processes are not mutually exclusive, with one ending before another one can begin, it is meaningful to consider one at a time. Rock layers must be made through deposition before they can experience either uplift or erosion. Said in a different way, once the rock layers are deposited, they are subjected to (1) Earth’s internal energy, which drives plate tectonics that roughens up the surface of the Earth (uplift), and (2) external energy, which powers the hydrologic cycle that smooths the surface (erosion). The modern landscape you see is a result of that interaction. Usually, to shift regimes from deposition to erosion, base level must lower in some way. In southwest Utah this is commonly achieved by uplifting of rock layers, by, for example, movement on major faults. Once there is any topographic relief, erosion begins.

The inverted topography of these three basalt-capped ridges can be viewed as experiencing this simplified sequence twice. First, the Triassic-Jurassic sedimentary rock was deposited (along with younger sedimentary rock that was subsequently removed), then the area experienced compression that tilted the rock (St. George syncline); subsequent relative uplift allowed stream channels to be eroded into the layers. Much later, the area experienced deposition, but this time lava flows filled the stream valleys, and the area elevations were adjusted by tension (extension) that created normal faults (St. George fault). Now, with this most recent period of predominantly downcutting and erosion, the lava flows that filled the stream valleys instead cap the ridges, thus inverting the topography and giving the ridges the landform name of “inverted valleys” or “inverted topography.” As you look out on the ridges and the valley of downtown St. George from the vantage point of the water tank on the Red Hills, it can be quite a mind-expanding experience to think of how different the topography looked not so very long ago. But then again, many concepts in geology are mind-expanding. Now go take a closer look.

**REFERENCES**

Best, M.G., and Brimhall, W.H., 1970, Late Cenozoic basalt types in the western Grand Canyon region, *in* Hamblin, W.K., and Best, M.G., editors, The western Grand Canyon district: Utah Geological Society guidebook to the geology of Utah, no. 23, p. 57-74.

Best, M.G., and Brimhall, W.H., 1974, Late Cenozoic alkalic basaltic magmas in the western Colorado Plateaus and the Basin and Range transition zone, U.S.A., and their bearing on mantle dynamics: Geological Society of America Bulletin, v. 85, no. 11, p. 1677-1690.

Best, M.G., Hamblin, W.K., and Brimhall, W.H., 1966, Preliminary petrology and chemistry of late Cenozoic basalts in the western Grand Canyon region: Brigham Young University Geology Studies, v. 13, p. 109-123.

Best, M.G., McKee, E.H., and Damon, P.E., 1980, Space-time-composition patterns of late Cenozoic mafic volcanism, southwestern Utah and adjoining areas: American Journal of Science, v. 280, p. 1035-1050.

Biek, R.F., and Rohrer, J.C., 2006, Geology, mining history, and reclamation of the Silver Reef mining district, Washington County, Utah, *in* Bon, R.L., Gloyn, R.W., and Park, G.M., editors, Mining districts of Utah: Utah Geological Association Publication 32, p. 479-512.

Biek, R.F., Rowley, P.D., Hayden, J.M., Hacker, D.B., Willis, G.C., Hintze, L.F., Anderson, R.E., and Brown, K.D., 2009, Geologic map of the St. George and east part of the Clover Mountains 30' x 60' quadrangles, Washington and Iron Counties, Utah: Utah Geological Survey Map 242, 2 pl., 101 p., scale 1:100,000.

Blakey, R.C., 1994, Paleogeographic and tectonic controls on some Lower and Middle Jurassic erg deposits, Colorado Plateau, *in* Caputo, M.V., Peterson, J.A., and Franczyk, K.J., editors, Mesozoic systems of the Rocky Mountain region, USA: Denver, Colorado, Rocky Mountain Section of the Society for Sedimentary Geology, p. 273-298.

Blakey, R.C., Bashem, E.L., and Cook, M.J., 1993, Early and Middle Triassic paleogeography, Colorado Plateau and vicinity, *in* Morales, M., editor, Aspects of Mesozoic geology and paleontology of the Colorado Plateau: Museum of Northern Arizona Bulletin 59, p. 13-26.

Clemmensen, L.B., Olsen, H., and Blakey, R.C., 1989, Erg-margin deposits in the Lower Jurassic Moenave Formation and Wingate Sandstone, southern Utah: Geological Society of America Bulletin, v. 101, p. 759-773.

Clyde, C.G., 1987, Groundwater resources of the Virgin River basin in Utah: Logan, Utah State University, Utah Water Research Laboratory, 104 p.
DeCourten, F., 1998, Dinosaurs of Utah: Salt Lake City, University of Utah Press, 300 p.

Dickinson, W.R., Beard, S.L., Brakenridge, G.R., Erjavec, J.L., Ferguson, R.C., Inman, K.E., Knepp, R.A., Lindberg, F.A., and Ryberg, P.T., 1983, Provenance of North American Phanerozoic sandstones in relation to tectonic setting: Geological Society of America Bulletin, v. 94, p. 222-235.

Downing, R.F., 2000, Imaging the mantle in southwestern Utah using geochemistry and geographic information systems: Las Vegas, University of Nevada, M.S. thesis, 128 p.

Dubiel, R.F., 1994, Triassic deposystems, paleogeography and paleoclimate of the western interior, in Caputo, M.V., Peterson, J.A., and Franczky, K.J., editors, Mesozoic systems of the Rocky Mountain region, USA: Rocky Mountain Section of Society of Economic Paleontologists and Mineralogists, p. 132-168.

Gregory, H.E., 1950, Geology and geography of the Zion Park region, Utah and Arizona: U.S. Geological Survey Professional Paper 220, 200 p.

Hamblin, A.H., Lockley, M.G., and Milner, A.R.C., 2006, More reports of theropod dinosaur tracksites from the Kayenta Formation (Lower Jurassic), Washington County, Utah—implications for describing the Springdale Sandstone, in Harris, J.D., Lucas, S.G., Spielmann, J.A., Lockley, M.G., Milner, A.R.C., and Kirkland, J.I., editors, Tracking dinosaur origins—the Triassic/Jurassic terrestrial transition: New Mexico Museum of Natural History and Science Bulletin 37, p. 276-281.

Hamblin, W.K., 1963, Late Cenozoic basalts of the St. George basin, Utah, in Heylmut, E.B., editor, Guidebook to the geology of southwestern Utah: Intermountain Association of Petroleum Geologists 12th Annual Field Conference, p. 84-89.

Hamblin, W.K., 1970, Late Cenozoic basalt flows of the western Grand Canyon, in Hamblin, W.K., and Best, M.G., editors, The western Grand Canyon district: Utah Geological Society guidebook to the geology of Utah, no. 23, p. 21-38.

Hamblin, W.K., 1987, Late Cenozoic volcanism in the St. George basin, Utah: Geological Society of America Centennial Field Guide—Rocky Mountain Section, p. 291-294.

Hamblin, W.K., and Best, M.G., 1970, Road log, in Hamblin, W.K., and Best, M.G., editors, The western Grand Canyon district: Utah Geological Society guidebook to the geology of Utah, no. 23, p. 93-154.

Hamblin, W.K., Damon, P.E., and Bull, W.B., 1981, Estimates of vertical crustal strain rates along the western margins of the Colorado Plateau: Geology, v. 9, p. 293-298.

Harris, J. D., and Milner, A. R. C., 2016, Tracks in Deep Time: The St. George Dinosaur Discovery Site at Johnson Farm; University of Utah Press, 112 p.

Hayden, J.M. and Willis, G.C., 2011, Geologic Map of the St. George 7.5’ Quadrangle, Washington County, Utah: Utah Geological Survey Map 251DM, 20 p., 2 plates, scale 1:24,000.

Heilweil, V.M., Freethey, G.W., Stolp, B.J., Wilkowske, C.D., and Wilberg, D.E., 2000, Geohydrology and numerical simulation of ground-water flow in the central Virgin River basin of Iron and Washington Counties, Utah: Utah Department of Natural Resources Technical Publication 116, 139 p.

Heilweil, V.M., Watt, D.E., Solomon, D.K., and Goddard, K.E., 2002, The Navajo aquifer system of southwestern Utah, in Lund, W.R., editor, Field guide to geologic excursions in southwestern Utah and adjacent areas of Arizona and Nevada: U.S. Geological Survey Open-File Report 02-172, p. 105-130.

Hurlow, H.A., 1998, The geology of the central Virgin River basin, southwestern Utah, and its relation to ground-water conditions: Utah Geological Survey Water-Resources Bulletin 26, 53 p., 6 plates.

James, L.P., and Newman, E.W., 1986, Subsurface character of mineralization at Silver Reef, Utah, and a possible model for ore genesis, in Griffen, D.T., and Phillips, W.R., editors, Thrusting and extensional structures and mineralization in the Beaver Dam Mountains, southwestern Utah: Utah Geological Association Publication 15, p. 149-158.

Kirkland, J.I., and Milner, A.R.C., 2006, The Moenave Formation at the St. George Dinosaur Discovery Site at Johnson Farm, in Harris, J.D., Lucas, S.G., Spielmann, J.A., Lockley, M.G., Milner, A.R.C., and Kirkland, J.I., editors, Tracking dinosaur origins—the Triassic/Jurassic terrestrial transition: New Mexico Museum of Natural History and Science Bulletin 37, p. 289-309.

Leeman, W.P., 1974, Late Cenozoic alkali-rich basalt from the western Grand Canyon area, Utah and Arizona—isotopic composition of strontium: Geological Society of America Bulletin, v. 85, p. 1691-1696.

Lowder, G.G., 1973, Late Cenozoic transitional alkali olivine tholeiitic basalt and andesite from the margin of the Great Basin, southwest Utah: Geological Society of America Bulletin, v. 84, no. 9, p. 2993-3012.

Lucas, S.G., 1993, The Chinle Group—revised stratigraphy and biochronology of Upper Triassic nonmarine strata in the western United States, in Morales, M., editor, Aspects of Mesozoic geology and paleontology of the Colorado Plateau: Museum of Northern Arizona Bulletin 59, p. 27-50.

Lucas, S.G., Lerner, A.J., Milner, A.R.C., and Lockley, M.G., 2006, Lower Jurassic invertebrate ichnofossils from a clastic lake margin, Johnson Farm, southwest Utah, in Harris, J.D., Lucas, S.G., Spielmann, J.A., Lockley, M.G., Milner, A.R.C., and Kirkland, J.I., editors, Tracking dinosaur origins—the Tri-
assic/Jurassic terrestrial transition: New Mexico Museum of Natural History and Science Bulletin 37, p. 128-136.

Lucas, S.G., and Milner, A.R.C., 2006, Conchostraca from the Lower Jurassic Whitmore Point Member of the Moenave Formation, Johnson Farm, southwestern Utah, in Harris, J.D., Lucas, S.G., Spielmann, J.A., Lockley, M.G., Milner, A.R.C., and Kirkland, J.I., editors, Tracking dinosaur origins—the Triassic/Jurassic terrestrial transition: New Mexico Museum of Natural History and Science Bulletin 37, p. 421-423.

Lucas, S.G., and Tanner, L.H., 2007, Tetrapod biostratigraphy and biochronology of the Triassic/Jurassic terrestrial transition on the southern Colorado Plateau, USA: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 244, p. 242-256.

Lucas, S.G., Tanner, L.H., and Heckert, A.B., 2005, Tetrapod biostratigraphy and biochronology across the Triassic-Jurassic boundary in northeastern Arizona, in Heckert, A.B., and Lucas, S.G., editors, Vertebrate paleontology in Arizona: New Mexico Museum of Natural History and Science Bulletin 29, p. 84-94.

Milner, A.R.C., and Kirkland, J.I., 2006, Preliminary review of the Early Jurassic (Hettangian) freshwater Lake Dixie fish fauna in the Whitmore Point Member, Moenave Formation in southwest Utah, in Harris, J.D., Lucas, S.G., Spielmann, J.A., Lockley, M.G., Milner, A.R.C., and Kirkland, J.I., editors, Tracking dinosaur origins—the Triassic/Jurassic terrestrial transition: New Mexico Museum of Natural History and Science Bulletin 37, p. 510-521.

Milner, A.R.C., Lockley, M.G., and Kirkland, J.I., 2006, A large collection of well-preserved theropod dinosaur swim tracks from the Lower Jurassic Moenave Formation, St. George, Utah, in Harris, J.D., Lucas, S.G., Spielmann, J.A., Lockley, M.G., Milner, A.R.C., and Kirkland, J.I., editors, Tracking dinosaur origins—the Triassic/Jurassic terrestrial transition: New Mexico Museum of Natural History and Science Bulletin 37, p. 315-328.

Peterson, F., 1994, Sand dunes, sabkhas, streams, and shallow seas—Jurassic paleogeography in the southern part of the Western Interior basin, in Caputo, M.V., Peterson, J.A., and Franczyk, K.J., editors, Mesozoic systems of the Rocky Mountain region, USA: Denver, Colorado, Rocky Mountain Section of the Society for Sedimentary Geology, p. 233-272.

Proctor, P.D., and Shirts, M.A., 1991, Silver, sinners and saints—a history of old Silver Reef, Utah: Provo, Utah, Paulmar, Inc., 224 p.

Rowley, P.D., and Dixon, G.L., 2004, The role of geology in increasing Utah's ground-water resources from faulted terranes—lessons from the Navajo Sandstone, Utah, and the Death Valley flow system, Nevada-California, in Spangler, L.E., editor, Ground water in Utah—source, protection, and remediation: Utah Geological Association Publication 31, p. 27-41.

Solomon, B.J., 1992a, Geology and the indoor-radon hazard in southwestern Utah, in Harty, K.M., editor, Engineering and environmental geology of southwestern Utah: Utah Geological Association Publication 21, p. 164-172.

Solomon, B.J., 1992b, Environmental geophysical survey of radon-hazard areas in the southern St. George basin, Washington County, Utah, in Harty, K.M., editor, Engineering and environmental geology of southwestern Utah: Utah Geological Association Publication 21, p. 173-191.

Stewart, J.H., Poole, F.G., and Wilson, R.F., 1972b, Stratigraphy and origin of the Chinle Formation and related Upper Triassic strata in the Colorado Plateau region, with a section on sedimentary petrology by R.A. Cadigan and on conglomerate studies by W. Thordarson, H.F. Albee, and J.H. Stewart: U.S. Geological Survey Professional Paper 690, 336 p.

Tidwell, W.D., and Ash, S.R., 2006, Preliminary report on the Early Jurassic flora from the St. George Dinosaur Discovery Site, Utah, in Harris, J.D., Lucas, S.G., Spielmann, J.A., Lockley, M.G., Milner, A.R.C., and Kirkland, J.I., editors, Tracking dinosaur origins—the Triassic/Jurassic terrestrial transition: New Mexico Museum of Natural History and Science Bulletin 37, p. 414-420.

Tuesink, M.F., 1989, Depositional analysis of an eolian-fluvial environment—the intertonguing of the Kayenta Formation and Navajo Sandstone (Jurassic) in southwestern Utah: Flagstaff, Northern Arizona University, M.S. thesis, 189 p.

Washington County Historical Society website, https://wchsutah.org/churches/st-george-temple.php, accessed Jan. 30, 2019.

Washington County Historical Society website, https://wchsutah.org/water/stgeorge-old-water-tank.php accessed Jan. 30, 2019.

Willis, G.C., and Biek, R.F., 2001, Quaternary incision rates of the Colorado Plateau and major tributaries in the Colorado Plateau, Utah, in Young, R.A., and Spamer, E.E., editors, Colorado River origin and evolution—proceedings of the symposium held at Grand Canyon National Park in June 2000: Grand Canyon National Monograph 12, p. 119-123.