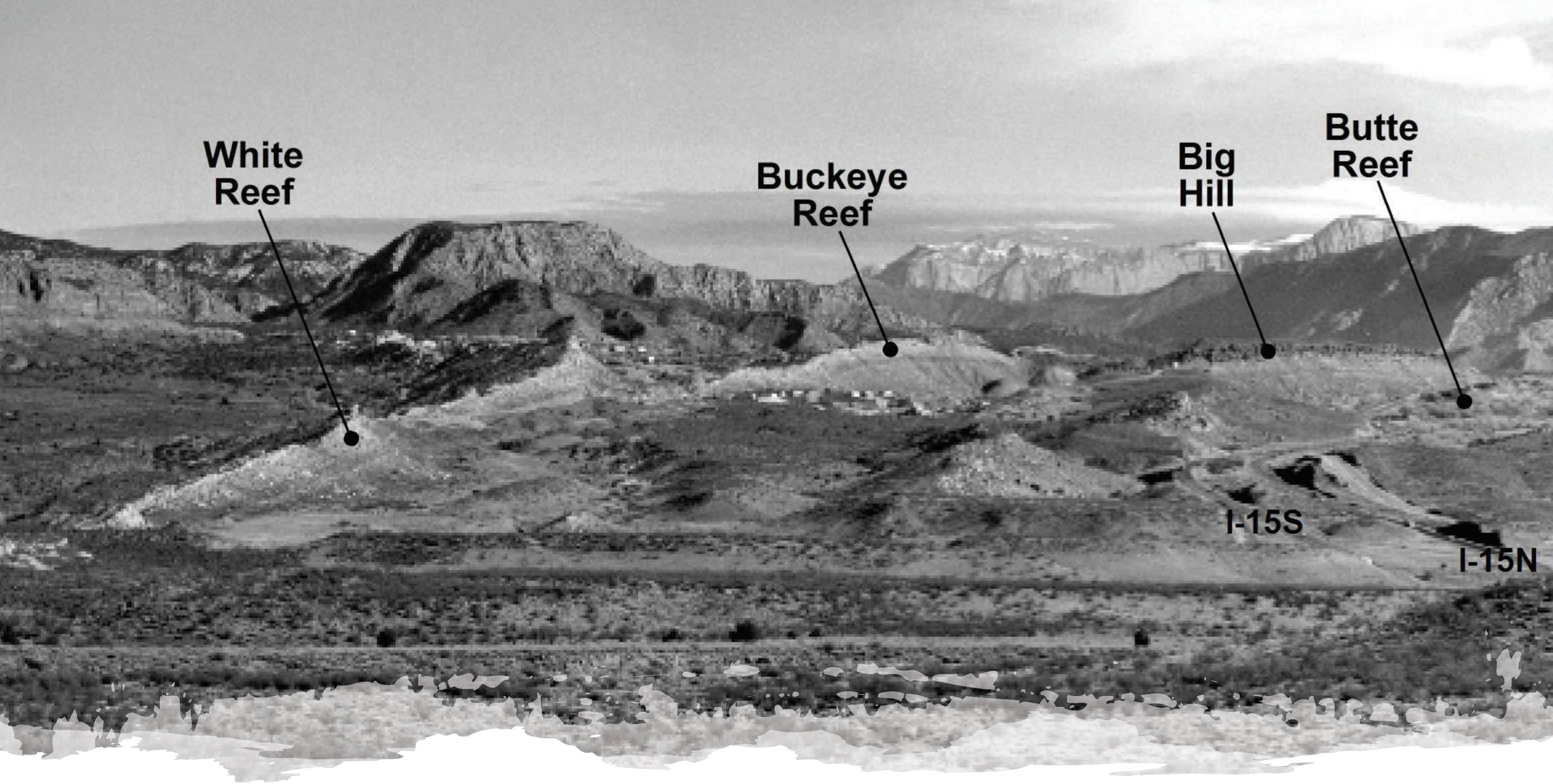

Silver Reef Mining District

Robert F. Biek[1] and J. Chris Rohrer[2]

[1]Utah Geological Survey, Salt Lake City, UT, bobbiek@utah.gov

[2]Utah Division of Oil, Gas and Mining, Abandoned Mine Reclamation Program, Salt Lake City, UT

Utah Geosites

2019

Utah Geological Association Publication 48

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

COVER IMAGE: View northeast to the Silver Reef mining district. Cottonwood Creek is in the foreground, the snow-capped peaks in the distance are in the Kolob Canyons section of Zion National Park, and Interstate 15 is on the right.

Utah Geosites 2019

Utah Geological Association Publication 48

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

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.

Suggested citation for this geosite:

Biek, R.F., 2019, Silver Reef Mining District, *in* Milligan, M., Biek, R.F., Inkenbrandt, P., and Nielsen, P., editors, Utah Geosites: Utah Geological Association Publication 48, 14 p., https://doi.org/10.31711/ugap.v1i1.93.

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 Silver Reef mining district in southwestern Utah is a geologic anomaly, a historical curiosity, and an ecological novelty. It is one of the few places in the world where economic disseminated silver chloride (chlorargyrite or horn silver) was produced from sandstone. The area is a little-known ghost town, now reborn as the upscale residential community of Silver Reef with deep ties to its history. The old Wells Fargo Bank Building, home of the Silver Reef Museum, is listed on the National and Utah State Registers of Historic Buildings, and several other historic buildings and sites make this a fascinating area to visit (figure 1). Finally, the mining district lies near the junction of the Mohave and Great Basin ecological provinces and so contains an assemblage of plants and animals common to both regions; its mines are habitat for bats, including species considered imperiled in the state. Proctor and Shirts (1991) provided a fascinating account of the discovery, disbelief, re-discovery, and development of this unusual silver chloride deposit, and we previously summarized the geology, mining history, and reclamation of the district (Biek and Rohrer, 2006).

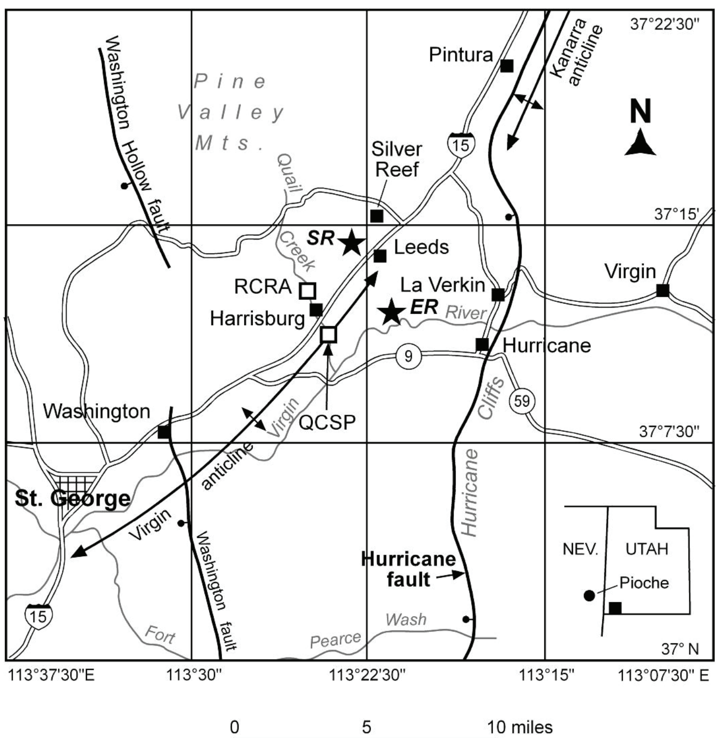

Figure 1. Location of the Silver Reef (SR) and East Reef (ER) areas of the Silver Reef mining district. Inset shows location of nearby Pioche, Nevada. RCRA=Red Cliffs Recreation Area, QCSP=Quail Creek State Park.

The Silver Reef mining district straddles the Interstate 15 corridor in central Washington County, about 15 miles (24 km) northeast of St. George. The district consists of four "reefs" on the northeast-plunging nose of the Virgin anticline: White, Buckeye, and Butte Reefs are on the anticline's northwest flank, whereas East Reef is on the anticline's east flank (a "reef" is a mining term for a lode or vein, and was also used by early pioneers to describe prominent ridges that were a barrier to travel) (figure 2). The district is noted for its uncommon occurrence of ore-grade silver chloride in sandstone that is unaccompanied by obvious alteration or (with the exception of copper) substantial base-metal ores. The ore horizons are contained in the Springdale Sandstone Member of the Kayenta Formation, which is repeated by thrust faults on the anticline's northwest flank.

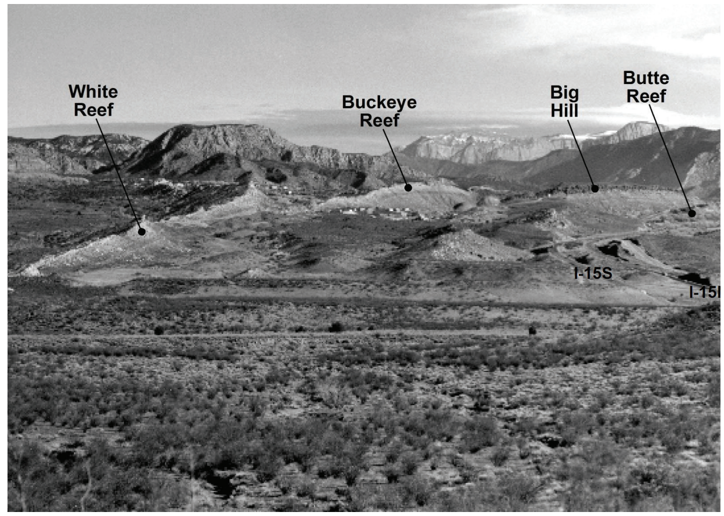

Figure 2. View northeast to the Silver Reef mining district. Cottonwood Creek is in the foreground, the snow-capped peaks in the distance are in the Kolob Canyons section of Zion National Park, and Interstate 15 is on the right.

High-grade silver chloride float was first discovered near Harrisburg in 1866, and in situ mineralization was found in 1868, but it was not until 1876 that the silver rush was underway in earnest (Proctor, 1953; Proctor and Brimhall, 1986). That it took 10 years between the discovery of silver in sandstone and the great Pioche Stampede, when miners in Pioche, Nevada, left for the new silver boom at Silver Reef, gives an idea of the difficulty early prospectors had in believing economic silver could be found in sandstone. Chlorargyrite is at best an inconspicuous mineral and is normally associated with the weathered portions of silver-bearing sulfide deposits such as Nevada's famous Comstock Lode. The principal mining activity in the district lasted only through 1888, with lessee operations through 1909, after which major mining essentially ceased. Prior to 1910, the district produced over 7 million ounces of silver from ore that averaged 20 to 50 ounces silver per ton, but varied from only a few ounces to about 500 ounces per ton (Heikes, 1920; Proctor and Brimhall, 1986; Eppinger and others, 1990). Sporadic production between 1949 and 1968 yielded about 10 ounces of gold, 165,000 ounces of silver, 34 short tons of copper, and at least 2500 pounds of uranium oxide. In 1979, a leach-pad operation was established between White and Buckeye Reefs to process tailings, but this venture soon closed with the collapse of silver prices.

Initial reclamation at White, Buckeye, and Butte Reefs, completed during 1996 to 1997 by the Utah Abandoned Mines Reclamation Program (UAMRP), involved 465 mine closures at a cost of $469,000. Reclamation of 184 mine openings at the East Reef area was completed in 2000 at a cost of $170,000. This initial reclamation of the Silver Reef mining district was restricted to immediate hazard abatement—the closure of adits and shafts for public safety. It was complicated by the fact that (1) the district was considered a "rural historic landscape" eligible for the National Register of Historic Places; (2) it is home to one of the state's largest Corynorhinus townsendii (Townsend's big-eared bat) maternity colonies and has numerous roosts for other bat species; and (3) the adjacent town of Silver Reef was experiencing a second real estate and population boom. Ironically, the historical status and other constraints at Silver Reef forced the UAMRP to toss normal reclamation convention on its head. While reclamation efforts usually strive to make the mining disturbance disappear, at Silver Reef the goal was to preserve the mining disturbance while keeping the reclamation invisible. The UAMRP used several mine closure techniques, with the majority of mines closed by backfilling. Much of the backfilling was done by hand to minimize the effects of heavy equipment on the landscape. Significant care was taken to preserve the appearance of nearby dumps, and in many cases, the fill was recessed slightly below grade to eliminate the fall hazard but maintain the appearance of the opening and collar features. Because of both cultural and biological concerns, reclamation made extensive use of steel gates and grates. Grates allow bats to come and go and they maintain ventilation in the mines. Much of the historical interest and value of Silver Reef derives from its surviving mine openings, mine dumps, and structures, now carefully preserved by UAMRP. Other reclamation efforts include the U.S. Environmental Protection Agency's encapsulation of the 5M heap leach pad, and Utah Department of Environmental Quality's remediation of tailings at the Leeds and Christy mills and fencing and other work at the Big Hill shaft.

LOCATION

The best place to learn about the history and geology of the Silver Reef mining district is at the Silver Reef Museum, located in the old Wells Fargo Building (37° 15.183' N., 113° 22.037' W.). Check the museum's informative web site (www.silverreefutah.org) for hours that they are open and for their calendar of events. An interpretative trail is open year round even when the museum is closed; the trail guide is available on their website. The museum itself is well worth the small entrance fee.

From the north (Cedar City/Salt Lake City) traveling south on I-15: Take I-15 south to Exit 23 for Leeds/Silver Reef. Turn right on Silver Reef Road and travel west toward the red cliffs area, about 1.5 miles (2.5 km). ***Follow directions below.**

From the south (St. George/Las Vegas) traveling north on I-15: Take I-15 north to Exit 22 for Leeds/Silver Reef. Drive north on Main Street through the Town of Leeds for about 1.3 miles (2 km). Turn left on Silver Reef Road at the sign for I-15 north. Cross under I-15 and head west toward the red cliffs area, about 1.5 miles (2.5 km). ***Follow directions below.**

***You will see signs for the Silver Reef Museum and the Cosmopolitan Restaurant. From Silver Reef Road turn left at the "Y" onto Silver Reef Drive and continue for about 0.25 mile (0.4 km) to the museum on the right at the corner of Silver Reef Drive and Wells Fargo Drive. The street address is 1903 Wells Fargo Rd., Leeds.

The mining district is also accessible from the south on hiking trails that are part of the Red Cliffs Desert Reserve administered by Washington County in cooperation with several state and federal agencies. A trail map and other information is available on the reserve's website www.redcliffsdesertreserve.com/trail. An entrance fee is required. See Biek (2003b) for a geologic map of this area.

For those with high-clearance vehicles, a trip to nearby East Reef, also part of the Red Cliffs Desert Reserve, is well worth the effort. There, you will find some of the best exposures of Late Triassic to Early Jurassic strata in southwestern Utah (including the Springdale Sandstone, the productive interval at Silver Reef), a relatively young basaltic lava flow and its inverted valley, and mine workings of the East Reef part of the Silver Reef mining district (Biek, 2003a). Again, check out trail maps at the reserve's website.

To access the East Reef area from Leeds, proceed north on North Main Street (Utah Highway 228) for 0.75 mile (1.2 km) past Silver Reef Road and the I-15 interchange, then turn right onto 900 North. Follow this dirt road for 3.8 miles (6 km) and park at the Historic Babylon trailhead (37° 12' 07.3" N., 113° 20' 55.2" W.). This road may be impassible when wet and the part of the road that traverses the East Reef lava flow is rough, thus a high-clearance vehicle is recommended. From the parking area, a short walk through the Springdale water gap showcases a complete section of the lower Kayenta, Moenave, and upper Chinle Formations, as well as dinosaur tracks and petroglyphs (Biek and Hayden, 2007).

Finally, although several state and federal agencies have worked hard on reclamation of the area, this is an old mining district still with potential hazards. Stay away from and do not enter old mine workings. Collapse or caving of backfilled adits, and caving of shaft collars beyond their steel grates, is not uncommon.

GEOLOGY

Because of its unusual mineral occurrence, the Silver Reef mining district has captured the attention of numerous geologists, mining engineers, and historians. Four "reefs," or low ridges of resistant sandstone, comprise the Silver Reef mining district, with White, Buckeye, and Butte Reefs on the northwest flank of the Virgin anticline and East Reef on the anticline's eastern flank. Because of its complicated structure on the folded and faulted northeast-plunging nose of the anticline, it was not until the early 1950s, through the careful work of Paul Proctor at Brigham Young University, that the structure and stratigraphy of the district were finally understood. Several books and countless articles were written on conflicting interpretations of the structure, stratigraphy, and genesis of ore deposits of the Silver Reef mining district, seemingly out of proportion to the size of the district and the wealth it generated (Proctor and Shirts, 1991; Biek and Rohrer, 2006).

Structure and stratigraphy go hand-in-hand in interpreting the geology of an area, and nowhere is this truer than in the Silver Reef mining district. Early geologists who studied the Silver Reef mining district concluded that the three western reefs were three separate stratigraphic layers and that their similarity was due to similar conditions of deposition (figure 3). To their credit, they noted the remarkable similarities among the three reefs, but at the time geologists did not understand the concept of thrust faulting, where older rock strata can be shoved on top of younger strata along gently dipping faults. We now know that only the section at East Reef is undisturbed by subsidiary faulting or folding, and it in fact offers one of the best sections of Moenave and underlying Chinle strata in all of southwestern Utah. Had all of this been known in the 1870s, the history of the Silver Reef mining district would be much less colorful and certainly less would have been written about the district.

Stratigraphy

Late Triassic and Early Jurassic strata of the Chinle, Moenave, and Kayenta Formations form the heart of the Silver Reef mining district. Figures 4, 5, and 6 show a simplified lithologic column, geologic map, and cross sections of the Silver Reef area.

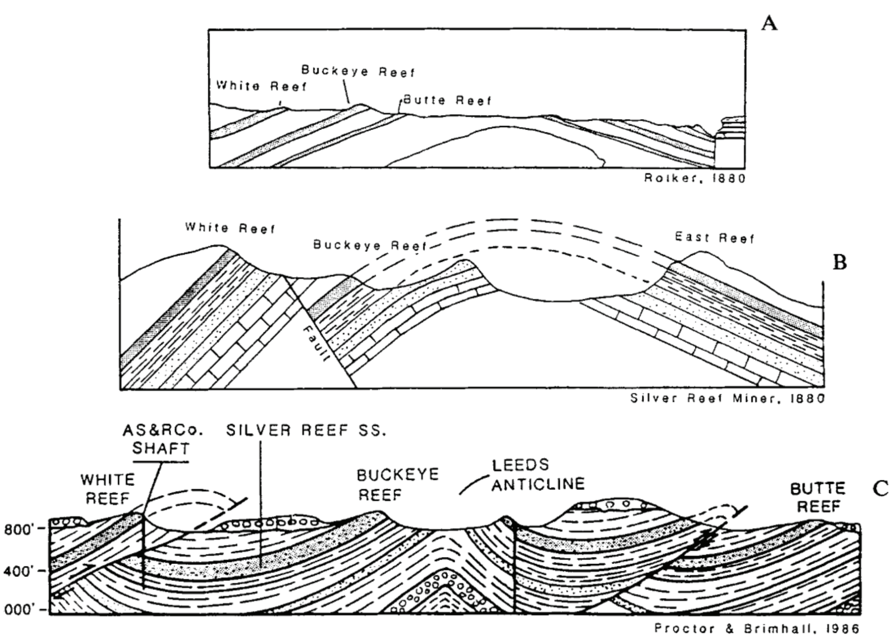

Figure 3. Cross sections (oriented northwest to southeast) showing historical development of fault theories for the Silver Reef area (modified from Proctor and Shirts, 1991), beginning with the idea that White, Buckeye and Butte Reefs were three similar but separate beds (A). Louis Janin, a mining engineer who helped organize the Leeds Mining Company and establish the town of Silver Reef, was apparently the first to conclude that the principal ore horizon was in fact a single bed cut by a fault between Buckeye and White Reefs. On March 31, 1880, the Silver Reef Miner published a cross section (B) showing Buckeye Reef was truncated at relatively shallow depth by a down-to-the-east normal fault, which had the effect of limiting the extent of ore-bearing horizons at Buckeye Reef. At the time, Henry Lubbock, Superintendent of the Christy Company, which operated the mines on Buckeye Reef, was in New York City trying to sell the Christy Mill and Mining Company; with the fault model in circulation, the value of his holdings was assumed to be diminished. He failed to find a buyer and sued the paper for libel. The District Court in Beaver rendered a verdict of not guilty, but the three-bed concept continued to be promoted by subsequent geologists. It was not until 1953 that Paul Proctor correctly showed that the ore horizons of White, Buckeye, and Butte Reefs on the anticline's northwest flank, and East Reef on the anticline's east flank, are all part of the same bed (then known as the Silver Reef Sandstone member of the Chinle Formation) (C).

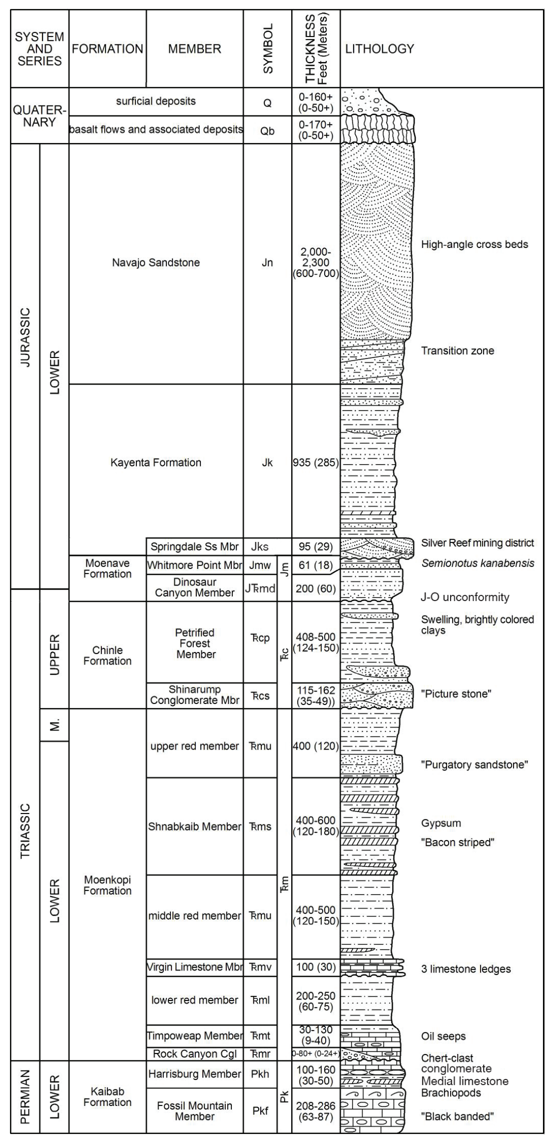

Figure 4. Lithologic column showing stratigraphic units in the vicinity of Silver Reef, Utah. Modified from Biek and Rohrer (2006).

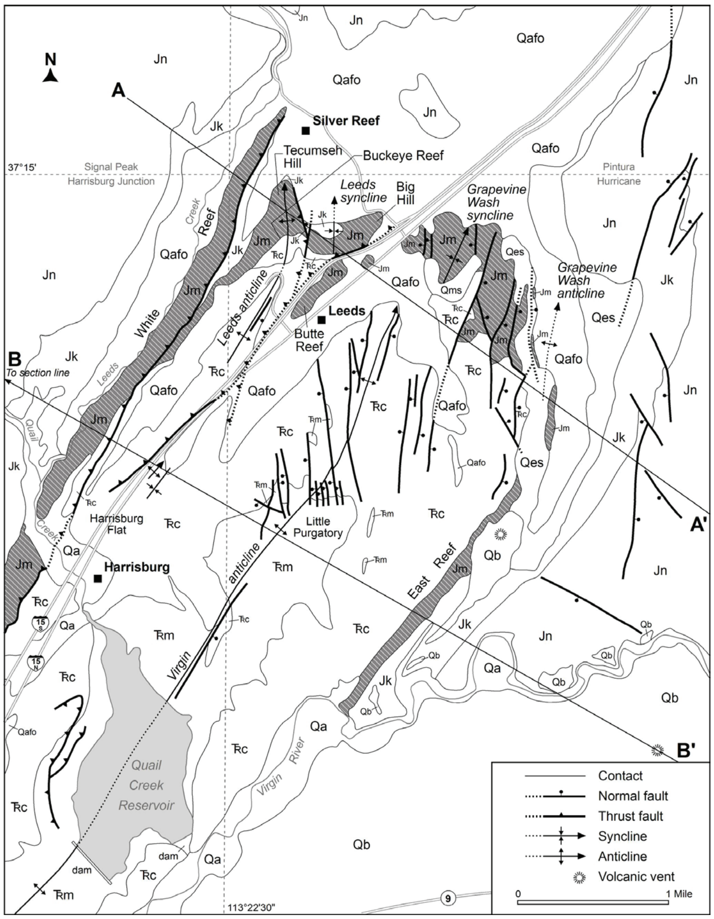

Figure 5. Simplified geologic map of the Silver Reef mining district. See figure 4 for explanation of map unit symbols. Note that Jm here includes the Springdale Sandstone (now reassigned as the basal part of the Kayenta Formation). Quaternary units include Qa=undifferentiated alluvium, Qafo=old alluvial-fan deposits, Qes=eolian sand, and Qb=undifferentiated basaltic lava flows. Harrisburg Junction, Hurricane, Pintura, and Signal Peak quadrangle boundaries also shown. Cross sections A-A′ and B-B′ shown on figure 6. From Biek and Rohrer (2006).

Chinle Formation

The Chinle Formation of southwest Utah has long been divided into the lower Shinarump Conglomerate Member and the upper Petrified Forest Member (Stewart and others, 1972), but preliminary research on this interval suggests Petrified Forest strata may in fact contain beds better assigned to both younger and older Chinle Formation (Martz and others, 2017). The Shinarump Conglomerate forms a prominent hogback around the Virgin anticline, whereas the Petrified Forest Member is both poorly and exceptionally well exposed in adjacent strike valleys. The Chinle Formation is Late Triassic in age, based principally on vertebrate and plant remains, and was deposited in a variety of fluvial and lacustrine environments of a low-relief, forested basin (Stewart and others, 1972; Dubiel, 1994). Shinarump strata were deposited principally in braided-stream channels that flowed north and northwest. The streams were probably similar to the modern Platte River that flows eastward from the Rocky Mountains and that consist of shallow, interconnected or braided channels and intervening gravel bars. The Petrified Forest fluvial systems mimicked this paleoflow, but with a much greater abundance of meandering stream deposits and floodplain mudstones (Dubiel, 1994). Amphibians, reptiles—including the crocodile-like phytosaur—freshwater clams, snails, ostracods, and fish made their home on this once vast, coastal lowland, and petrified conifer trees are common in Chinle strata; fossil cycads, ferns, and horsetails are also present (Stewart and others, 1972; Blakey and others, 1993; Dubiel, 1994; DeCourten, 1998).

The Shinarump Conglomerate consists of cliff-forming, yellowish-brown, fine- to very coarse-grained sandstone, pebbly sandstone, and minor pebbly conglomerate. Small, subrounded pebbles are primarily quartz, quartzite, and chert. Coarser sandstones

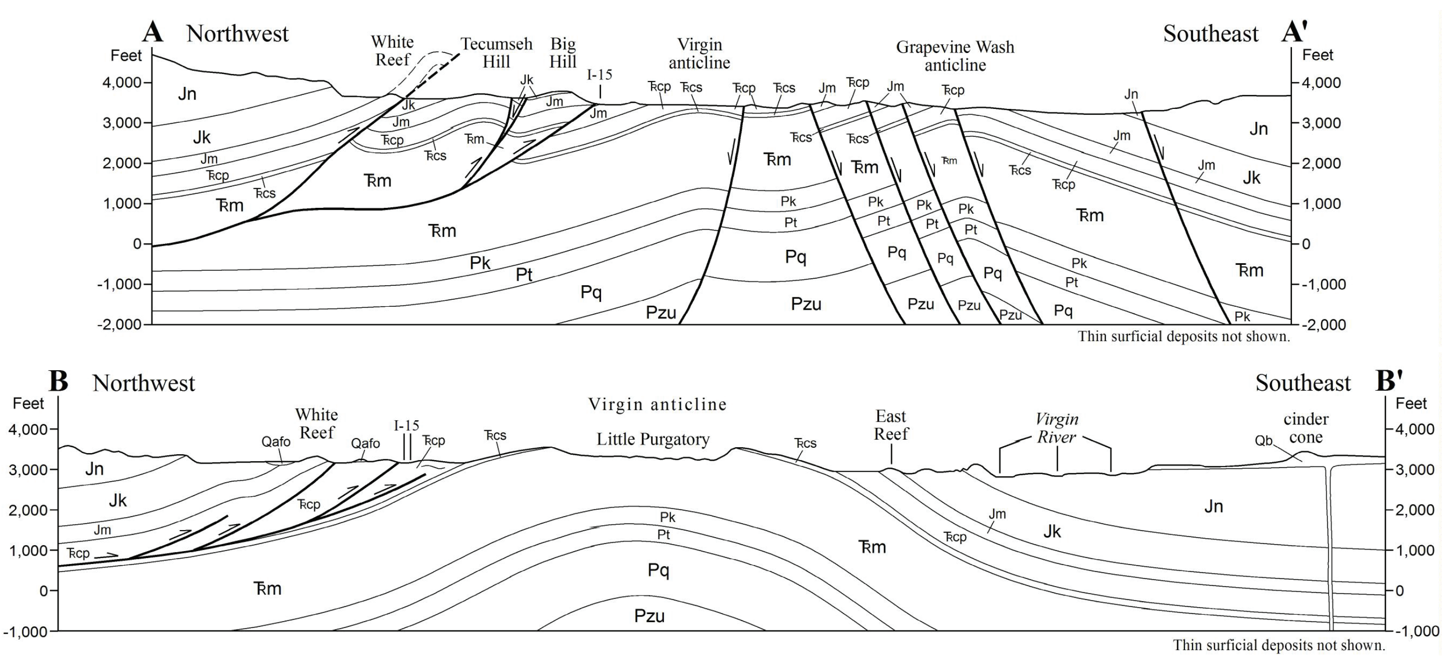

Figure 6. Simplified cross sections of the Silver Reef mining district. Note that Jm here includes the Springdale Sandstone (now reassigned as the basal part of the Kayenta Formation). See figure 4 for explanation of map unit symbols and figure 5 for cross section locations. From Biek and Rohrer (2006).

and pebbly sandstones locally contain poorly preserved petrified wood, commonly replaced in part by iron-manganese oxides. The Shinarump Conglomerate varies widely in thickness, from 5 to 200 feet (2–60 m), due to deposition over an eroded landscape.

Some of the best and most complete exposures of Petrified Forest strata in southwestern Utah are at East Reef, along the east side of the Virgin anticline (figure 7). The Petrified Forest Member consists of variably colored mudstone, claystone, siltstone, lesser sandstone and pebbly sandstone, and minor chert and nodular limestone. It contains a wider lithologic variation than might be expected given the prominent multicolored swelling mudstones that typify the member. These mudstones swell conspicuously when wet and give weathered surfaces a “popcorn” appearance—they are also responsible for numerous foundation problems and landslides in the region (Lund and others, 2008). The upper contact of the Petrified Forest Member is the J-0 unconformity, which represents a gap of about 10 million years during the Late Triassic and Early Jurassic (Pipiringos and O’Sullivan, 1978).

Moenave Formation

The Moenave Formation is divided into the Dinosaur Canyon and Whitmore Point Members (the former Springdale Sandstone Member is now reassigned as the lower member of the Kayenta Formation). These distinctive strata are locally famous for the variety of fossils and dinosaur tracks discovered near St. George in February 2000 by Sheldon Johnson, a retired optometrist who was using a backhoe to prepare his land for development (Kirkland and Milner, 2006). Sheldon donated the land to the City of St. George and a museum—the St. George Dinosaur Discovery Site at Johnson Farm—opened in 2005. The site contains thousands of dinosaur tracks in multiple track layers, including some of the best preserved tracks in the world, with skin and claw impressions, tail drag marks, squatting marks, and the first unequivocal evidence of swimming dinosaurs anywhere in the world (Milner and Kirkland, 2006; Milner and others, 2006). Most tracks are the three-toed Eubrontes, likely made by the crested, meat-eating dinosaur Dilophosaurus, which reached 20 feet (6 m) long, 7 feet (2 m) high at the hips, and weighed about 1000 pounds (450 kg). Many other types of tracks and huge, gar-like fish are also found at the site.

The Dinosaur Canyon Member consists of slope-forming, generally thin-bedded, very fine grained sandstone, silty sandstone, and lesser siltstone and mudstone, all uniformly colored reddish brown. Dinosaur Canyon strata were deposited in river and floodplain environments (Clemmensen and others, 1989; Blakey, 1994; Peterson, 1994; DeCourten, 1998); they span the Triassic-Jurassic boundary (Suarez and others, 2017).

If the Dinosaur Canyon Member is noted for its uniformity—mostly reddish-brown, thin-bedded, very fine grained sandstone and silty sandstone—the Whitmore Point Member must be known for its variety. It contains sandstone and siltstone similar to the Dinosaur Canyon, but also reddish-purple to greenish-gray mudstone and claystone and thin dolomitic limestone beds. The limestones contain fossil fish scales and bones of Semionotus kanabensis (Schaeffer and Dunkle, 1950). The fish fossils were originally thought to be restricted to the Triassic and so conflicted with fossil pollen from the Whitmore Point Member that indicated the unit is Early Jurassic (Peterson and others, 1977; Imlay, 1980). We later learned that Semionotus kanabensis is not age diagnostic, which finally resolved the long-standing debate on the age of the Early Jurassic Moenave, Kayenta, and Navajo Formations (Olsen and Padian, 1986). Whitmore Point strata were deposited in floodplain and lacustrine environments (Clemmensen and others, 1989; Blakey, 1994; Peterson, 1994; DeCourten, 1998; Kirkland and Milner, 2006; Milner and Kirkland, 2006).

Kayenta Formation

The contact between the Whitmore Point and Springdale Sandstone is a regional unconformity and corresponds to a pronounced break in slope, with the resistant Springdale Sandstone forming prominent cliffs and ledges above gentle Whitmore Point slopes (figure 8). The Springdale Sandstone forms the imposing ridges of

Figure 7. View north of the Petrified Forest strike valley at East Reef, just north of where Grapevine Wash passes through the reef. TRcs=Shinarump Conglomerate and TRcp=Petrified Forest Members of the Chinle Formation; JTRmd=Dinosaur Canyon and Jmw=Whitmore Point Members of the Moenave Formation; Jks=Springdale Sandstone Member of the Kayenta Formation (formerly of the Moenave Formation); Qb=East Reef basaltic flow and cinder cone. The white arksoic sandstone of Proctor (1953) is also shown. The southern end of Black Ridge near Toquerville is visible in the distance.

White, Butte, Buckeye, and East Reefs, and is host to the ore deposits of the Silver Reef mining district. In the district, the member was known as the Silver Reef sandstone, which was informally divided into the lower, white to brown Leeds sandstone and the upper, lavender Tecumseh sandstone (Proctor, 1953). At Silver Reef, Paul Proctor's careful geologic mapping and stratigraphic studies proved that the three reefs of the mining district were in fact one and the same bed, the Springdale Sandstone (since reassigned from the Moenave Formation to the overlying Kayenta Formation).

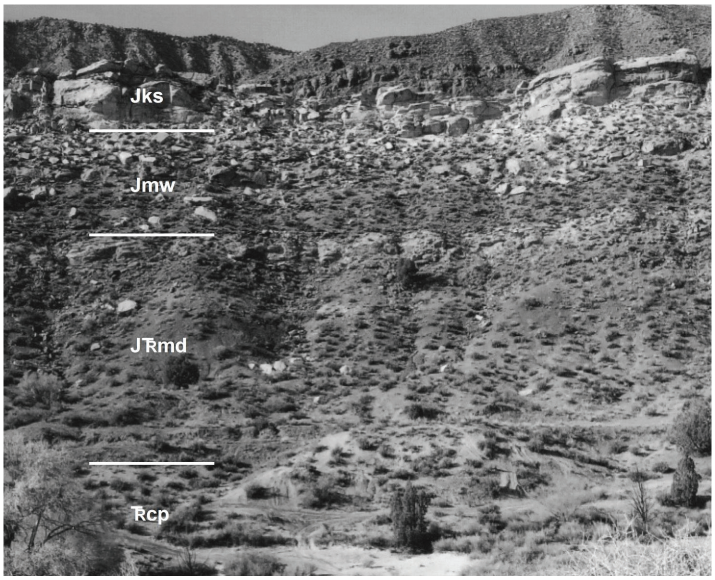

Figure 8. *View west to White Reef, just south of the old Barbee mill site. TRcp=Petrified Forest Member of the Chinle Formation; JTRmd=Dinosaur Canyon and Jmw=Whitmore Point Members of the Moenave Formation; and Jks=Springdale Sandstone Member of the Kayenta Formation. The Navajo Sandstone forms the distant hills.*

The Springdale Sandstone consists of thick-bedded, fine-grained sandstone with channel-form cross-stratification. Springdale sandstones are distinguished from overlying sandstones of the main body of the Kayenta by their more variable pastel colors of pale red, pale pink, and yellowish orange, as opposed to reddish-brown hues that dominate Kayenta beds (figure 9). Where exposed along the flanks of the Virgin anticline, including in the Silver Reef mining district, the Springdale Sandstone is distinctly lighter in color than in exposures elsewhere, suggestive of bleaching by hydrocarbons once trapped in the core of the Virgin anticline. The Springdale Sandstone contains thin, discontinuous lenses of intraformational conglomerate, with mudstone rip-up clasts and poorly preserved, petrified and carbonized fossil plant remains indicative of deposition in braided-stream and minor floodplain environments (Clemmensen and others, 1989; Blakey, 1994; Peterson, 1994; DeCourten, 1998).

Structure

The Silver Reef mining district, in the transition zone between the Colorado Plateau and asin and Range physiographic provinces, lies just 4 to 5 miles (6–8 km) west of the Hurricane fault, the

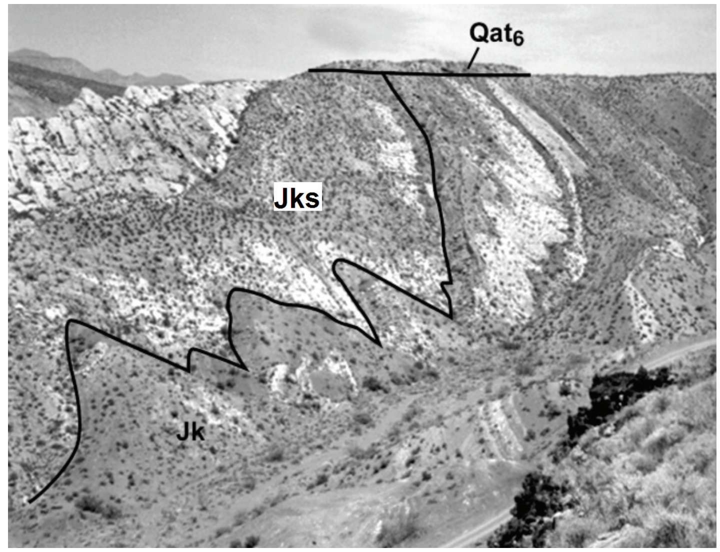

Figure 9. View north of East Reef immediately north of where Grapevine Wash passes through the reef. Southeast-dipping Springdale Sandstone (Jks) and Kayenta (Jk) strata are beveled flat and capped by old stream-terrace deposits (Qat6). The gradational Springdale-Kayenta contact corresponds to the base of the first laterally continuous mudstone bed. East Reef cinder cone forms the skyline on right.

largest active earthquake fault in southwestern Utah, capable of producing damaging earthquakes of about magnitude 7 (figure 1) (Lund and others, 2007; see also the Hurricane fault geosite). Strata in the mining district are typical of the generally flat-lying rocks of the Colorado Plateau. However, they were folded into the Virgin anticline and subsidiary folds and cut by thrust faults during the Sevier orogeny (see sidebar). In southwestern Utah, the transition zone includes two major down-to-the-west fault zones that step down from the Colorado Plateau to the Basin and Range Province. The mining district lies on the intermediate structural block thus created, bounded on the east by the Hurricane fault zone and on the west by the Gunlock-Grand Wash fault (figure 10).

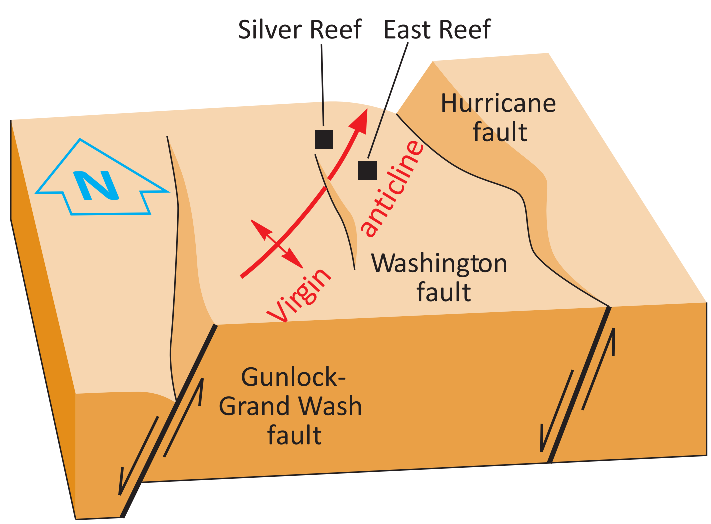

Figure 10. *Schematic block diagram showing the relationship between the Hurricane and Gunlock-Grand Wash faults. Both faults are "normal" faults that formed during regional extension, allowing rocks on the west side of the faults to slip down relative to rocks on the east side.*

The Sevier orogeny, or mountain-building episode, began in Utah by Middle Jurassic time, about 180 million years ago, as deformation associated with subduction of the Farallon oceanic plate along the western edge of North America spread eastward into western Utah (DeCelles, 2004). These eastward-directed compressional forces created the Sevier orogenic belt and associated broad deformation zone, which consists of, from west to east, a thrust belt with wedge-top basins, foredeep basin, forebulge, and back-bulge basin (DeCelles, 2004; Willis, 1999, 2000) (figure 11). Each of these four parts of the thrust system migrated eastward over time, and each created unique environments of deposition or erosion.

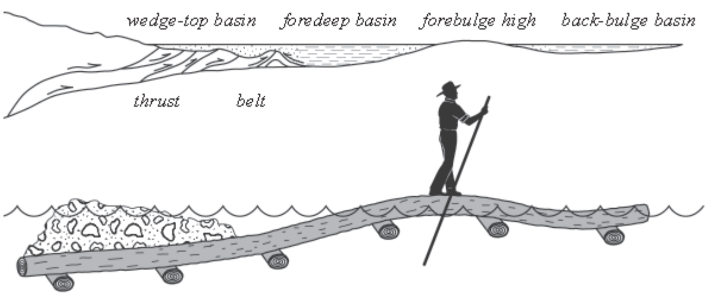

Figure 11. *Typical parts of a thrust system. The thickened, eastward-moving, leading-edge thrust wedge on the left overloads the Earth's crust, which flexes in response, similar to loading rock on a wooden raft floating on water. In Utah, the entire thrust system migrated eastward over time during the middle Mesozoic to early Tertiary, but this simple pattern is commonly complicated due to variations in crustal strength and pre-existing faults. From Willis (1999).*

Virgin Anticline

The Virgin anticline is a 30-mile-long (50 km), northeast-trending, symmetrical fold that trends parallel to, but is structurally distinct from, the Kanarra anticline to the north (figure 1) (Hurlow and Biek, 2003). Collectively, these two anticlines mark the eastward limit of significant Sevier-age compressional deformation in southwestern Utah. The flanks of the fold provide spectacular exposures of parts of the Lower Triassic Moenkopi Formation and overlying Upper Triassic Chinle Formation, including hogbacks of the Shinarump Conglomerate Member that dramatically outline the fold's shape (figure 12). Along the northern reaches of the anticline, the carapace of Shinarump stands in dramatic relief above the Virgin River lowlands (figure 13). The anticline has three structural domes along its length, all located south of the mining district. From south to north these are Bloomington dome, Washington dome, and Harrisburg dome, each of which exposes gypsum-bearing Lower Permian Harrisburg Member of the Kaibab Formation. The fold formed during the Sevier orogeny, about 85 to 72 million years ago, above a blind thrust fault that soles into Cambrian strata (Davis, 1999; Hurlow and Biek, 2003).

Figure 12. *View northeast towards Quail Creek Reservoir nestled in the eroded core of the Virgin anticline, showing White (WR), Buckeye (BR), Butte BUR), and East (ER) Reefs on the northeast-plunging nose of the anticline. The flanks of the anticline are neatly outlined by the resistant Shinarump Conglomerate Member of the Chinle Formation (TRcs), below which are ledgy slopes of the upper red member of the Moenkopi Formation (TRmu). The "bacon-striped" Shnabkaib Member of the Moenkopi Formation (TRms) forms the eroded floor of the anticline. The snow-covered Pine Valley Mountains are on the skyline at left and the Kolob Canyons part of Zion National Park is on the skyline at right; State Route 9 cuts across the Virgin anticline at the bottom of the photograph. Photo courtesy of Janice Hayden.*

Several west-dipping thrust faults are present along the west flank of the Virgin anticline and figure heavily in the history of the mining district. Proctor (1948, 1953) was the first to recognize the largest and westernmost thrust fault amid considerable controversy over structural interpretations of the district. Proctor's recognition of this and other thrust faults was the key to understanding that just one sandstone bed—the Springdale Sandstone—hosts the silver ore deposits of the Silver Reef mining district. This westernmost fault separates Buckeye Reef and White Reef and extends at least 7 miles (11 km) to the southwest (Biek, 2003b). The fault repeats the Springdale Sandstone in the reefs and farther south on the anticline's western flank (figure 5). Proctor and Brimhall (1986) estimated that in the Silver Reef mining district the Springdale Sandstone was displaced eastward at least 2000 feet (600 m) on this fault.

ORE DEPOSITS

Ore-grade silver chloride (chlorargyrite or horn silver) accounted for more than 90% of the silver-bearing minerals recovered at the Silver Reef mining district (Proctor, 1953). Chlorargyrite ($AgCl$) is a very soft, usually massive, inconspicuous silver mineral that is colorless or grayish white when underground, but when brought to the surface and exposed to sunlight, it develops like photographic film to a waxy grayish brown. Because this and other silver minerals are nearly invisible, the ore is conspicuous only where colorful copper and uranium minerals are present (Heyl, 1978). Samples assaying 10 to 15 ounces (280–425 gm) per ton silver can lack visible silver minerals (James and Newman, 1986). About

Figure 13. View north to the resistant Shinarump Conglomerate, which forms a whale-like carapace along the central part of the Virgin anticline near East Reef. The Hurricane Cliffs and Kolob Canyons part of Zion National Park are in the distance at right.

70% of the district's production came from the prolific Buckeye Reef (Heikes, 1920). Chlorargyrite was one of the important ore minerals at Nevada's famous Comstock Lode. Its presence at Silver Reef is unusual in that chlorargyrite is usually associated with the weathered, near-surface portions of silver-bearing sulfide deposits, where silver was leached out of the rock by groundwater or hydrothermal fluids and redeposited in localized concentrations.

Malachite, a green copper carbonate, is the most common copper mineral in the district; it typically replaces plant material and is locally found as stains on the rock. Azurite is locally present in combination with malachite. Carnotite is the predominant uranium and vanadium mineral. Like the chlorargyrite, uranium minerals are generally found in association with plant fragments and on bedding and fracture planes, but may occur disseminated within the sandstone.

Other minerals known to occur in the district include embolite (silver bromide), native silver, and argentite (silver sulfide). Native silver and silver sulfide are only known from early reports of the district and apparently occur at depth within the mines, mostly near or below the water table (Proctor, 1953).

Controls and Origin of Mineralization

The Silver Reef mining district is part of a broad area relatively enriched in silver mineralization (James and Newman, 1986). Anomalously high silver concentrations occur in the Springdale Sandstone throughout southwestern Utah, but were only economic at Silver Reef where concentrated around the nose of the anticline. The genesis of the Silver Reef ore deposits has been the subject of considerable debate since their discovery, but the consensus is that the metal deposits are of sedimentary origin later concentrated by reducing fluids in the northeast-plunging nose of the anticline (Proctor, 1953; James and Newman, 1986; Houser and others, 1988). The silver and other metals were likely derived from leaching of volcanic ash beds in the Chinle Formation and redeposited in the Springdale Sandstone, the first overlying permeable bed with organic material. The silver was probably transported as sulfide-poor, chlorine-rich brine that passed upward into anticlinal traps where it encountered reducing conditions or low-salinity groundwater that caused silver to precipitate. A low-sulfide brine accounts for the lack of lead and zinc, which are soluble in such a solution. James and Newman (1986) also noted evidence for petroleum residue in the Springdale Sandstone in the Silver Reef mining district, and both Shinarump and Springdale strata of the Virgin anticline are more strongly bleached than exposures elsewhere. The Virgin anticline may thus be a flushed-oil structure. Subsequent enrichment created high-grade areas and petroleum escaped from the system as erosion breached the Virgin anticline.

Ore Processing

Silver ore of the mining district was processed principally in local pan-amalgamation mills. Only the higher-grade ore, generally 20 ounces (550 gm) silver per ton or more, went to the stamp mills, where it was pulverized. The sandstone was easily crushed, freeing silver minerals in pore spaces and in associated carbonaceous debris. The pulverized ore was mixed with water in circular containers called mullers, to which was added "about a pound and a half of mercury per ton of crushed rock, 25 pounds of rock salt, and two pounds of crushed copper sulfate …" (Proctor and Shirts, 1991, p. 69). Continuous mixing and heating of the slurry eventually brought the silver minerals in contact with mercury, salt, and copper sulfate, forming a frosty, gray, paste-like amalgam of silver and mercury. The amalgam was skimmed off the mullers and sent to retorts for silver separation and recycling of mercury. The mills typically recovered only about 80% of the assayed silver.

Mining History

Two of the best accounts of the silver mining history at Silver Reef are by Stucki (1966) and Proctor and Shirts (1991). The summary below is extracted in large part from their research.

There are several tales about the discovery of silver at Silver Reef, none more colorful than that of "Metalliferous Murphy." Murphy was a Scottish assayer in the silver and lead mining town of Pioche, Nevada. Some claimed that he could find rare metals in any sample sent to him. As a practical joke, some Pioche miners broke up a grindstone and submitted it to him for assay. "In all soberness, after he had performed his assay work, and to the delight of all, he reported that it contained over $200 of silver per ton. Some say that he was hanged on the spot. Others claim he was tarred and feathered and run out of town on a rail. One happy ending of the story is that Metalliferous Murphy traced the origin of the grindstone to the Leeds, Utah area where he promptly went, located his claims, and became fabulously rich" (Proctor and Shirts, 1991, p. 26).

Proctor (1953), however, credits long-time mineral prospector John Kemple with discovery of silver at Silver Reef. Kemple spent the winter of 1866-67 at the old Harrisburg site, eight years after Mormon pioneers first wintered at the nearby confluence of Quail Creek and the Virgin River. Kemple doubtless recognized sandstone stained by green and blue copper carbonates; he assayed them and found them to contain silver. He sent samples to other assayers to confirm his finding and at least one refused to assay it, claiming Kemple must be crazy to ask him to assay a sandstone rock. Therein lies the problem—at the time, ore-grade silver was not known to occur in sandstone. Even Kemple doubted his own findings and moved on to the silver boomtown of White Pine, Nevada. Still, Kemple was drawn to southern Utah and returned to old Harrisburg the following year. After additional prospecting, he established the first mining claim in 1871. Kemple's original discovery shaft, now backfilled, is not far southwest of the Orson Adams home, recently restored and interpreted by the U.S. Bureau of Land Management.

In 1875, J.S. Ferris and Elijah Thomas discovered high-grade silver ore at White Reef, but it was William Tecumseh Barbee—agent of the Walker Brothers, well-known merchants and mining men of Salt Lake City—who set the silver rush in motion. On August 23, 1875, Barbee recorded the Barbee and Walker claims on White Reef and returned to Salt Lake City to report his findings. On the advice of their mining experts, the Walker Brothers refused further financing. Undeterred, Barbee and his co-workers returned and located 22 claims in October 1875; in November, they located the prolific Tecumseh claim on Buckeye Reef, where Barbee's high-graded discovery samples assayed $500 silver per ton. Barbee promoted the Silver Reef area in several articles in the Salt Lake Tribune and Pioche Record and soon generated a fever among miners in the region, especially from the Pioche area, which was playing out. The result was the Pioche Stampede, which began in October 1876, but interestingly the rush was not so much for mining claims (which were already staked out), but for business locations. Barbee even platted out the real estate development of Bonanza City, just south of Silver Reef, but that failed due to high property costs. Most businesses and miners settled in Silver Reef, a real estate promotion of the San Francisco-based Leeds Mining Company. Barbee eventually sold his interests at Silver Reef for $75,000 and continued prospecting in the West.

In 1877, the Leeds Mining Company built a mill on Leeds Creek (figure 14). Soon thereafter, three other mining companies established mills and consolidated mines at Silver Reef. In 1881, Rolker reported four companies at work in the Silver Reef mining district: The Christy Mining and Milling Company and the Leeds Mining Company were under San Francisco management, and the Barbee & Walker Mining Company and the Stormont Mining Company were under New York control. In addition, the Kinner mine at Buckeye Reef, and a few small claims at the south end of White Reef were privately worked. When all four mills were running, the population of Silver Reef leveled off at about 1500, comparable to the mining towns of Park City and Bingham at the time.

1. Barbee-Walker mine and mill
2. Silver Reef
3. Western Gold and Uranium mill
4. Hartman shaft
5. Christy mill tailings
6. Tecumseh Hill
7. ASARCO shaft
8. Savage shaft
9. 5M Inc. heap leach facility
10. Fire Clay Hill
11. Cemeteries
12. Big Hill shaft
13. Doyle shaft
14. Leeds Uranium shaft
15. Leeds
16. Interstate 15
17. Big Hill
18. California mine
19. Leeds mill

Figure 14. *Oblique aerial view to the northeast of White, Buckeye, and Butte Reefs. Photo taken January 2, 1994, courtesy of Utah Division of Oil, Gas & Mining.*

The principal mining activity at Silver Reef lasted only through 1888. The decline of the district is attributable to several factors. Silver prices steadily declined—the average price for silver was $1.20 per ounce in 1877, $1.11 in 1883, and just $0.93 in 1888—and costs increased as mines got deeper. Also important are reports that ore grade generally decreased with depth in the mines, and the host rock became more cemented and difficult to break. During the boom years, water was a significant problem only in mines of the Buckeye Reef, where it had to be pumped continually, but it played an important factor in closing of the mining district. Stucki (1966) reported that a three-month-long strike beginning on February 1, 1881, over wages that were to be cut from $4.00 to $3.50 per day, was the beginning of the end for Silver Reef. That may have been the first organized labor strike in Utah, and many miners left for Tombstone, Arizona, and other western mining camps. Those who remained eventually settled for the $3.50 daily wage. While the district's heyday ended in 1888, individual lessors continued to work the district from 1889 to 1909.

Stucki (1966) and Proctor and Shirts (1991) also described the more recent history of the district, including sinking of a 540-foot-deep (165 m) shaft at White Reef in 1929 by American Smelting and Refining Company (ASARCO); a U.S. Atomic Energy Commission drilling program to evaluate uranium mineralization in the early 1950s; and, in 1979, the construction of a leach-pad operation between White and Buckeye Reefs to process tailings by Hurricane-based 5M, Inc. (which later collapsed with the Hunt Brothers scheme to control silver prices). Mining interest in Silver Reef continued through the 1990s, but given the residential growth around Silver Reef, historical and ecological concerns, and the district's small size and potential, Silver Reef's mining days are over.

ACKNOWLEDGMENTS

This geosite summary was extracted from Geology, Mining History, and Reclamation of the Silver Reef Mining District, Washington County, Utah by Biek and Rohrer (2006). As the lengthy acknowledgments of that paper attest, we benefited greatly from the research of many geologists and historians who studied the Silver Reef mining district. We thank Grant Willis, Don Clark, and Mike Hylland (UGS), and Kimm Harty (UGS retired), for helpful reviews.

REFERENCES

Biek, R.F., 2003a, Geologic map of the Hurricane quadrangle, Washington County, Utah: Utah Geological Survey Map 187, 61 p., 2 plates, scale 1:24,000.

Biek, R.F., 2003b, Geologic map of the Harrisburg Junction quadrangle, Washington County, Utah: Utah Geological Survey Map 191, 42 p., 2 plates, scale 1:24,000.

Biek, R.F., and Hayden, J.M., 2007, Off the beaten path—spectacular geology of Utah's Dixie, *in* Lund, W.R., editor, Field guide to geologic excursions in southern Utah: Utah Geological Association Publication 35, 72 p.

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.

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 of Economic Paleontologists and Mineralogists, 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, Henrik, 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.

Davis, G.H., 1999, Structural geology of the Colorado Plateau region of southwestern Utah, with special emphasis on deformation bands: Geological Society of America Special Paper 342, 168 p.

DeCelles, P.G., 2004, Late Jurassic to Eocene evolution of the Cordilleran thrust belt and foreland basin system, western U.S.A.: American Journal of Science, v. 304, p. 105–168.

DeCourten, F., 1998, Dinosaurs of Utah: Salt Lake City, University of Utah Press, 300 p.

Dubiel, R.F., 1994, Triassic deposystems, paleogeography, and paleoclimate of the Western Interior, *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 Society of Economic Paleontologists and Mineralogists, p. 133–168.

Eppinger, R.G., Winkler, G.R., Cookro, T.M., Shubat, M.A., Blank, H.R., Crowley, J.K., Kucks, R.P., and Jones, J.L., 1990, Preliminary assessment of the mineral resources of the Cedar City 1° x 2° quadrangle, Utah: U.S. Geological Survey Open-File Report 90-34, 142 p., scale 1:250,000.

Heikes, V.C., 1920, Silver Reef (Harrisburg, Leeds) district—history and production, *in* Butler, B.S., Loughlin, G.F., Heikes, V.C., and others: U.S. Geological Survey Professional Paper 111, p. 585–586.

Heyl, A.V., 1978, Silver Reef, Utah, ores and the possibilities of unoxidized ores at greater depths, *in* Shawe, D.R., and Rowley, P.D., editors, Field excursion C-2, Guidebook to mineral deposits of southwestern Utah: Utah Geological Association Publication 7, p. 65.

Houser, B.B., Jones, J.L., Kilburn, J.E., Blank, H.R., Jr., Wood, R.H., II, and Cook, K.L., 1988, Mineral resources of the Cottonwood Canyon wilderness study area, Washington County, Utah: U.S. Geological Survey Bulletin 1746-C, 14 p., scale 1:24,000.

Hurlow, H.A., and Biek, R.F., 2003, Geologic map of the Pintura quadrangle, Washington County, Utah: Utah Geological Survey Map 196, 20 p., scale 1:24,000.

Imlay, R.W., 1980, Jurassic paleobiogeography of the conterminous United States in its continental setting: U.S. Geological Survey Professional Paper 1062, 134 p.

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.

Lund, W.R., Knudsen, T.R., Vice, G.S., and Shaw, L.M., 2008, Geologic hazards and adverse construction conditions, St. George-Hurricane metropolitan area, Washington County, Utah: Utah Geological Survey Special Study 127, variously paginated, 14 plates, scale 1:24,000, DVD-ROM.

Lund, W.R., Hozik, M.J., and Hatfield, S.C., 2007, Paleoseismic investigation and long-term slip history of the Hurricane fault in southwestern Utah: Utah Geological Survey Special Study 119, Paleoseismology of Utah, volume 14, 81 p., CD.

Martz, J.W., Kirkland, J.I., Milner, A.R.R., Parker, W.G., and Santucci, V.L., 2017, Upper Triassic lithostratigraphy, depositional systems, and vertebrate paleontology across southern Utah—a field guide prepared for the Society of Vertebrate Paleontology Annual Meeting, October 26–29, 2016, Salt Lake City, Utah: Utah Geological Association, Geology of the Intermountain West, v. 4, p. 99–180.

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.

Olsen, P.E., and Padian, K., 1986, Earliest records of Batrachopus from the southwestern United States, and a revision of some early Mesozoic crocodylomorph ichnogenera, *in* Padian, K., editor, The beginning of the age of dinosaurs—faunal changes across the Triassic-Jurassic boundary: Cambridge University Press, p. 260–273.

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.

Peterson, F., Cornet, B., and Turner-Peterson, C.E., 1977, New data on the stratigraphy and age of the Glen Canyon Group (Triassic and Jurassic) in southern Utah and northern Arizona [abs.]: Geological Society of America Abstracts with Programs, v. 9, no. 6, p. 755.

Pipiringos, G.N., and O'Sullivan, R.B., 1978, Principal unconformities in Triassic and Jurassic rocks, Western Interior United States—a preliminary survey: U.S. Geological Survey Professional Paper 1035-A, 29 p.

Proctor, P.D., 1948, Geologic map and sections of the Silver Reef mining area, *in* Stugard, F., Jr., 1951, Uranium resources in the Silver Reef (Harrisburg) district, Washington County, Utah: U.S. Geological Survey Trace Elements Memorandum Report TEM-214, scales 1:31,360 and 1:4560.

Proctor, P.D., 1953, Geology of the Silver Reef (Harrisburg) mining district, Washington County, Utah: Utah Geological and Mineral Survey Bulletin 44, 169 p.

Proctor, P.D., and Brimhall, W.H., 1986, Silver Reef mining district, revisited, Washington County, Utah, *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. 159–177.

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.

Schaeffer, B., and Dunkle, D.H., 1950, A semionotid fish from the Chinle Formation, with consideration of its relationships: American Museum Novitates, no. 1457, p. 1–29.

Stewart, J.H., Poole, F.G., and Wilson, R.F., 1972, Stratigraphy and origin of the Chinle Formation and related Upper Triassic strata in the Colorado Plateau region: U.S. Geological Survey Professional Paper 690, 336 p.

Stucki, A.B., 1966, A historical study of Silver Reef, southern Utah mining town: Provo, Utah, Brigham Young University M.A. thesis, 128 p.

Suarez, C.A., Knobbe, T.K., Crowley, J.L., Kirkland, J.I., and Milner, A.R.C., 2017, A chronostratigraphic assessment of the Moenave Formation, USA using C-isotope chemostratigraphy and detrital zircon geochronology—implications for the terrestrial end Triassic extinction: Earth and Planetary Science Letters, v. 475, p. 83-93.

Willis, G.C., 1999, The Utah thrust system—an overview, *in* Spangler, L.E., and Allen, C.J., editors, Geology of northern Utah and vicinity: Utah Geological Association Publication 27, p. 1–9.

Willis, G.C., 2000, Utah's Sevier thrust system: Utah Geological Survey, Survey Notes, v. 32, no. 1, p. 1–4.