Geology, Mining History, and Reclamation of the Silver Reef Mining District, Washington County, Utah

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ABSTRACT

The Silver Reef mining 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. The district is noted for its uncommon occurrence of ore-grade silver chloride in sandstone, 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 Moenave Formation, which is repeated by thrust faults on the anticline's northwest flank.

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. 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, nearly 70 percent of which came from the prolific Buckeye Reef. The mines were shallow, less than 350 feet deep, and most ore bodies were lens shaped, averaging 200 to 300 feet in length along strike by about half as wide and up to about 20 feet thick. The ore averaged 20 to 50 ounces silver per ton, but varied from only a few ounces to about 500 ounces per ton. 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 2,500 pounds of uranium oxide. A leach-pad operation established between White and Buckeye Reefs to process tailings opened in 1979, but this venture closed with the collapse of silver prices. The district continues to be periodically explored for silver.

Reclamation of the White, Buckeye, and Butte Reefs, completed during 1996 to 1997, involved 465 mine closures at a cost of $469,000; it was the largest single mine closure project for the Utah Division of Oil, Gas and Mining, Abandoned Mine Reclamation Program to date. Reclamation of 184 mine openings at the East Reef area was completed in 2000 at a cost of $170,000. Reclamation of the Silver Reef mining district was complicated by the fact that (1) the district is 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) because in the past three decades, the adjacent town of Silver Reef has experienced a second real estate and population boom and is now an upscale residential community.

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 was produced from sandstone. The district is a National Register-eligible historic site that straddles the Interstate 15 corridor in central Washington County, about 14 miles northeast of St. George (figure 1). This area is part of the burgeoning retirement, retail, and vacation center of southwestern Utah, affectionately known as "Utah's Dixie." The Silver Reef mining district lies near the junction of the Mohave and Great Basin ecological provinces and so contains an assemblage of plants and animals

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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. 477-510.

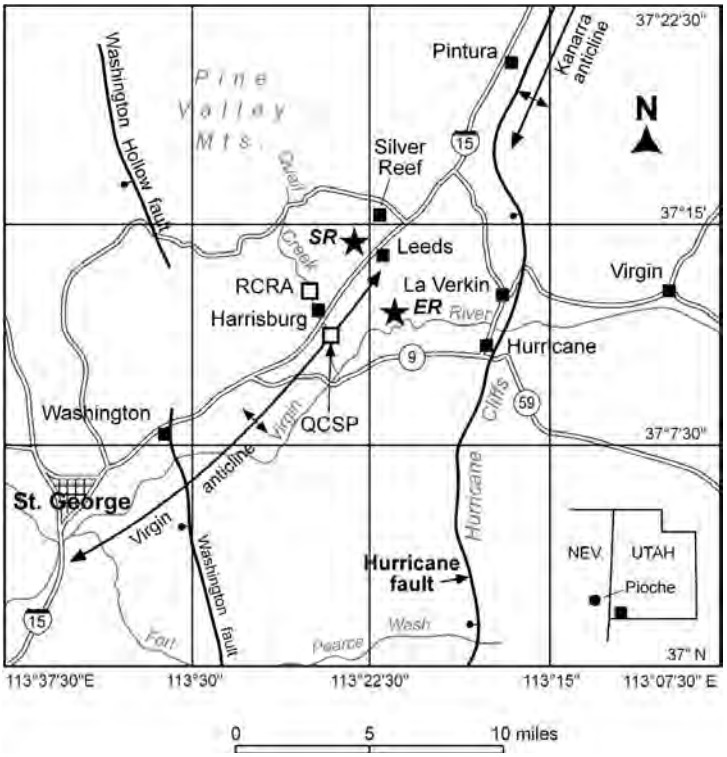

Figure 1. Location of the Silver Reef (SR) and East Reef (ER) areas of the Silver Reef mining district in southwestern Utah. Inset shows location of nearby Pioche, Nevada. RCRA = Red Cliffs Recreation Area, QCSP = Quail Creek State Park.

common to both regions; its mines are habitat for bats, including species considered imperiled in the state.

The Silver Reef mining district is noted for its uncommon occurrence of ore-grade silver chloride (chlorargyrite or horn silver) in sandstone, unaccompanied by obvious alteration or, with the exception of copper, substantial base-metal ores. High-grade silver chloride float was first discovered near Harrisburg in 1866, 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, which ushered in the silver boom at Silver Reef (and the final collapse of Pioche, Nevada), 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 Silver Reef mining district lasted only through 1888, with lessee operations through 1909, after which operations essentially ceased. Prior to 1910, the district produced over 7 million ounces of silver, nearly 70 percent of which came from the prolific Buckeye Reef (Heikes, 1920).

Because of its unusual mineral occurrence, the Silver Reef mining district has captured the attention of numerous geologists, mining engineers, and historians. However, because of its somewhat complicated structure on the folded and faulted northeast-plunging nose of the Virgin anticline, it was not until the late 1940s to early 1950s, through the careful work of Paul Proctor, 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. We attempt to summarize important elements of many of these publications, but our expertise in the district comes from having mapped the geology of the three quadrangles in which the district lies (Biek, 2003a, 2003b; Hurlow and Biek, 2003) and managing reclamation of the district (Rohrer, 1997, unpublished data). We are indebted to and rely especially heavily on the work of Proctor (1953), as well as Proctor and Shirts (1991), who provided a fascinating account of the discovery, disbelief, re-discovery, and development of this unusual silver chloride deposit.

In 1996 and 1997, the Utah Division of Oil, Gas and Mining, Abandoned Mine Reclamation Program (UAMRP) identified the area as a priority for reclamation due to its burgeoning housing development and sealed 465 mine openings at Silver Reef, and in 2000 completed reclamation of the East Reef area. The projects broke new ground in interdisciplinary teamwork as biologists, engineers, historians, and the construction contractor worked together to solve complex technical and legal issues. A unique combination of circumstances created special challenges for project planning and execution. The Silver Reef mining district is a "rural historic landscape" eligible for the National Register of Historic Places. It is also home to the state's third-largest *Corynorhinus townsendii* (Townsend's big-eared bat) maternity colonies, a species of bat considered imperiled in the state. The district is sandwiched between two subdivisions whose residents regularly explore the area. Finally, mine openings are numerous, closely spaced, and have a variety of configurations, which made

precise site identification and mapping mandatory. 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.

GEOLOGY

The Silver Reef mining district consists of four "reefs," or low ridges of resistant sandstone, along the northeast-plunging nose of the Virgin anticline. White, Buckeye, and Butte Reefs are on the anticline's northwest flank (figure 2), whereas East Reef is on the anticline's east flank. The ore horizons are in the Springdale Sandstone Member of the Moenave Formation, once known locally as the Leeds and Tecumseh Sandstones, which is repeated by thrust faults on the anticline's northwest flank to form the three reefs. 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 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.

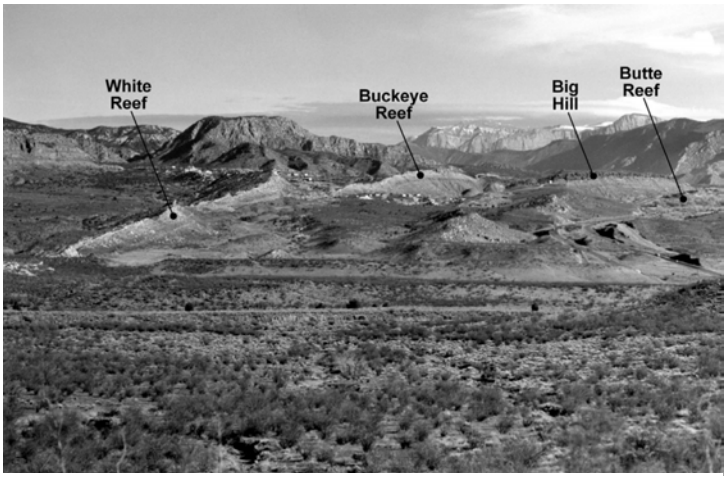

Figure 2. View northeast to the Silver Reef mining district. Cottonwood Creek is in the foreground, the snow-capped peaks in the distance are in the Kolob Canyons section of Zion National Park, and Interstate 15 and Leeds are on the right.

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 in fact three separate stratigraphic layers and that their similarity was due to similar conditions of deposition (figure 3). Rothwell (1880), Rolker (1881), Butler (1920), and others favored this interpretation. To their credit, early geologists noted the remarkable similarities among the three reefs, and in describing White and Buckeye Reefs, Rothwell (1880, p. 5) wrote, "The remarkable general resemblance between the beds of these two reefs; the curious coincidence of a series of red and gray sandstones and sandy shales with bands of greenish and red clay shales of the most marked characteristics, occurring in precisely the same stratigraphical order in each reef, and, above all, the occurrence fossil plants and silver ores in certain beds of similar appearance in each, naturally leads to the supposition that these reefs are composed of the same beds broken off between the reefs by a great fault." But finding no evidence of such a fault, he, like most others, interpreted them as two distinct beds.

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 a fault was present between Buckeye and White Reefs (Stucki, 1966), although Rothwell (1880) reported that Janin never gave the idea close examination. Even so, on March 31, 1880, the *Silver Reef Miner* published a cross section of the Silver Reef mining district (figure 4). In their cross section, 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 *Silver Reef Miner* reported that the Christy Company "… is entirely mistaken in its appreciation of the effect of its [the *Silver Reef Miner*] 'fault' theory upon the value of this and other property on Buckeye Reef; for if there were in reality a fault, and the silver-bearing beds of the White Reef were parts of those of Buckeye Reef, we should have a positive demonstration of the richness of the Buckeye beds

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 3. Oblique aerial view to the northeast of White, Buckeye, and Butte Reefs. Photo taken January 2, 1994, courtesy of DOGM.

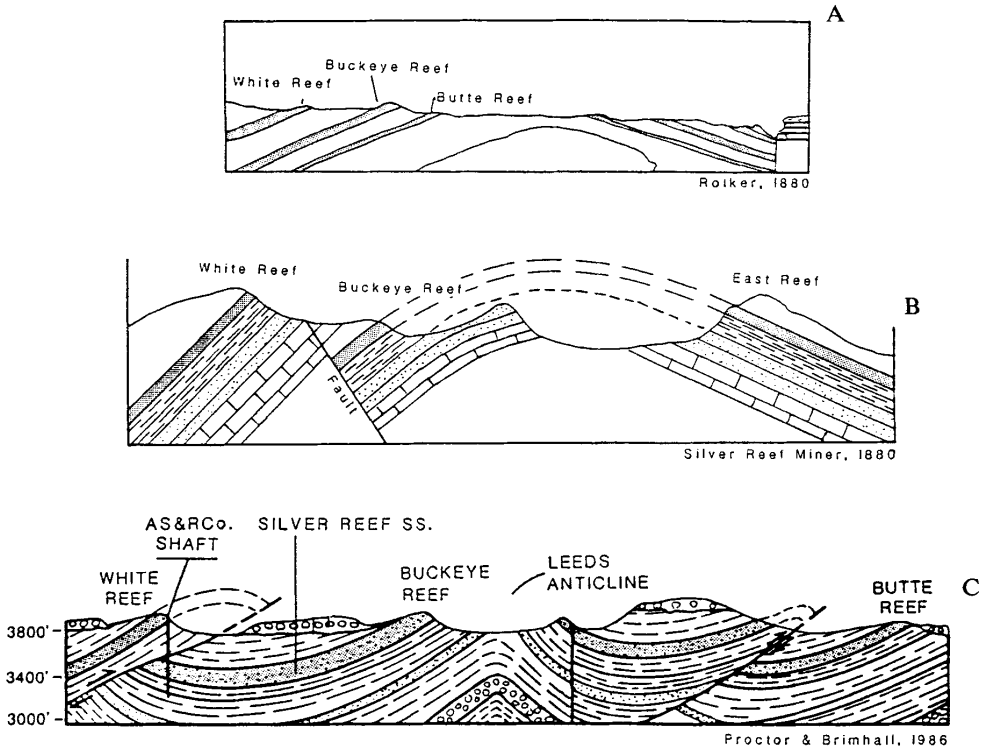

Figure 4. Cross sections showing historical development of fault theories for the Silver Reef area (modified from Proctor and Shirts, 1991).

down to the line of the assumed fault, …. No such demonstration now exists." Stucki (1966) and Proctor and Shirts (1991) recount some of the facts of the case and reprinted several of the cantankerous newspaper articles the case generated before it went to court. 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, when Paul Proctor unraveled the structure of the Silver Reef mining district, that the stratigraphy of the district was first understood. Proctor (1953) 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. Proctor and Brimhall (1986) subsequently revised Proctor's original, local terminology to mesh with newly defined regional correlations. Interestingly, there is still some disagreement by geologists familiar with the district. James and Newman (1986, p. 54) interpreted the sandstone of White and Buckeye Reefs to be in different stratigraphic positions, but admitted that "a major thrust fault could pass through the shale subparallel to its bedding …," and James and Atkinson (2002, p. 37) stated that White and Buckeye Reefs "… are separated stratigraphically by about 150 m (500 feet) of more argillaceous rocks in the Triassic Moenave Formation …." New 1:24,000-scale geologic mapping in southwestern Utah by co-author Biek (Biek, 2003a, 2003b; Hurlow and Biek, 2003) unequivocally reconfirms Proctor's findings.

Stratigraphy

Over 11,000 feet of Lower Permian to lower Tertiary sedimentary strata are exposed in the immediate vicinity of the Silver Reef mining district. To the northwest, a middle Miocene laccolith (quartz monzonite porphyry) forms the imposing massif of the Pine Valley Mountains (Hacker, 1998; Hacker and others, 2002), and Quaternary basaltic lava flows flank the district on the northeast and southeast. These strata provide a record of changing environmental conditions through 270 million years of geologic time. The sedimentary rocks were deposited in a variety of shallow-marine, tidal-flat, sabkha, sand-desert, coastal-plain, river, and lake environments reminiscent of the modern Caribbean Sea, Gulf Coast coastal plain, Sahara Desert, and coastal Arabian Peninsula, among other places. Hintze (1993), Biek (1999, 2000), and Biek and others (2000, 2003) provided popular descriptions of these units and their depositional settings. What follows are brief descriptions of the Chinle and Moenave Formations, which form the heart of the Silver Reef mining district; a Quaternary basaltic lava flow and old allu-

vial-fan deposits in the district are also described. Figure 5 traces the evolution of stratigraphic nomenclature in the district. Figures 6, 7, and 8 show a simplified lithologic column, geologic map, and cross section of the Silver Reef area.

Chinle Formation

The Chinle Formation in southwestern Utah consists of the Shinarump Conglomerate and Petrified Forest Members. 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 in which paleoflow was generally to the north and northwest; Petrified Forest fluvial systems mimicked this paleoflow, but with a much greater abundance of meandering stream deposits and flood-plain 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). In southwestern Utah, the TR-3 regional unconformity (Pipiringos and O'Sullivan, 1978) separates Early Triassic (Moenkopi Formation) and Late Triassic (Chinle Formation) strata and marks a change from mostly shallow-marine to continental sedimentation. In the Silver Reef mining district, the TR-3 unconformity is a disconformity with minor channeling at the base of the Shinarump Conglomerate Member. Dubiel (1994) assigned Chinle strata to the early Carnian to late Norian (Late Triassic) with an unconformity of several million years separating the two members. Biek (2003b) recognized an apparently gradational contact between the two members in the area immediately southwest of the Silver Reef mining district.

Shinarump Conglomerate Member: Because of its resistance to erosion, the Shinarump Conglomerate Member forms a prominent hogback along the Virgin anticline. It is nearly everywhere well exposed in cliffs along the core of the anticline. The Shinarump Conglomerate consists of cliff-forming, fine- to very coarse-grained sandstone, pebbly sandstone, and minor pebbly conglomerate. It is commonly thick to very thick bedded with low-angle cross-stratification, although thin, platy beds with ripple cross-stratification are locally present. The sandstones are predominantly pale to dark yellowish

<table>
<tr><th>Rolker (1880)</th><th colspan="2">Butler (1920)</th><th colspan="3">Proctor (1953)</th><th colspan="2">Proctor and Brimhall (1986)</th><th colspan="2">This paper</th></tr>
<tr><td rowspan="2"></td><td colspan="2">Colob</td><td colspan="3" rowspan="2">Navajo Sandstone</td><td colspan="2">Navajo Sandstone</td><td colspan="2">Navajo Sandstone</td></tr>
<tr><td colspan="2" rowspan="2">Kanab</td><td colspan="2">Duffin sandstone and shale</td><td>upper</td><td colspan="2">Kayenta Formation</td><td colspan="2">Kayenta Formation</td></tr>
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Leeds Ss.</td><td rowspan="4">Silver Reef Sandstone Mbr.</td><td rowspan="8">Chinle Formation</td><td rowspan="4">Springdale Sandstone Mbr.</td><td rowspan="8">Moenave Formation</td><td rowspan="4">Springdale Sandstone Mbr.</td><td rowspan="8">Moenave Formation</td></tr>
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<tr><td>Buckeye Reef</td></tr>
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<tr><td>Butte Reef</td><td rowspan="4">purple and red shale</td><td rowspan="4">Trail Hill sandstone and shale</td><td rowspan="4">lower</td><td rowspan="4">Dinosaur Canyon Mbr.</td><td>Whitmore Point Mbr.</td></tr>
<tr><td></td><td>Dinosaur Canyon Mbr.</td></tr>
<tr><td></td><td>Fire Clay Hill bentonitic shale</td><td rowspan="2">Petrified Forest Mbr.</td><td rowspan="2">Chinle Formation</td><td rowspan="2">Petrified Forest Mbr.</td><td rowspan="2">Chinle Formation</td></tr>
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Figure 5. Development of stratigraphic nomenclature at Silver Reef, Utah.

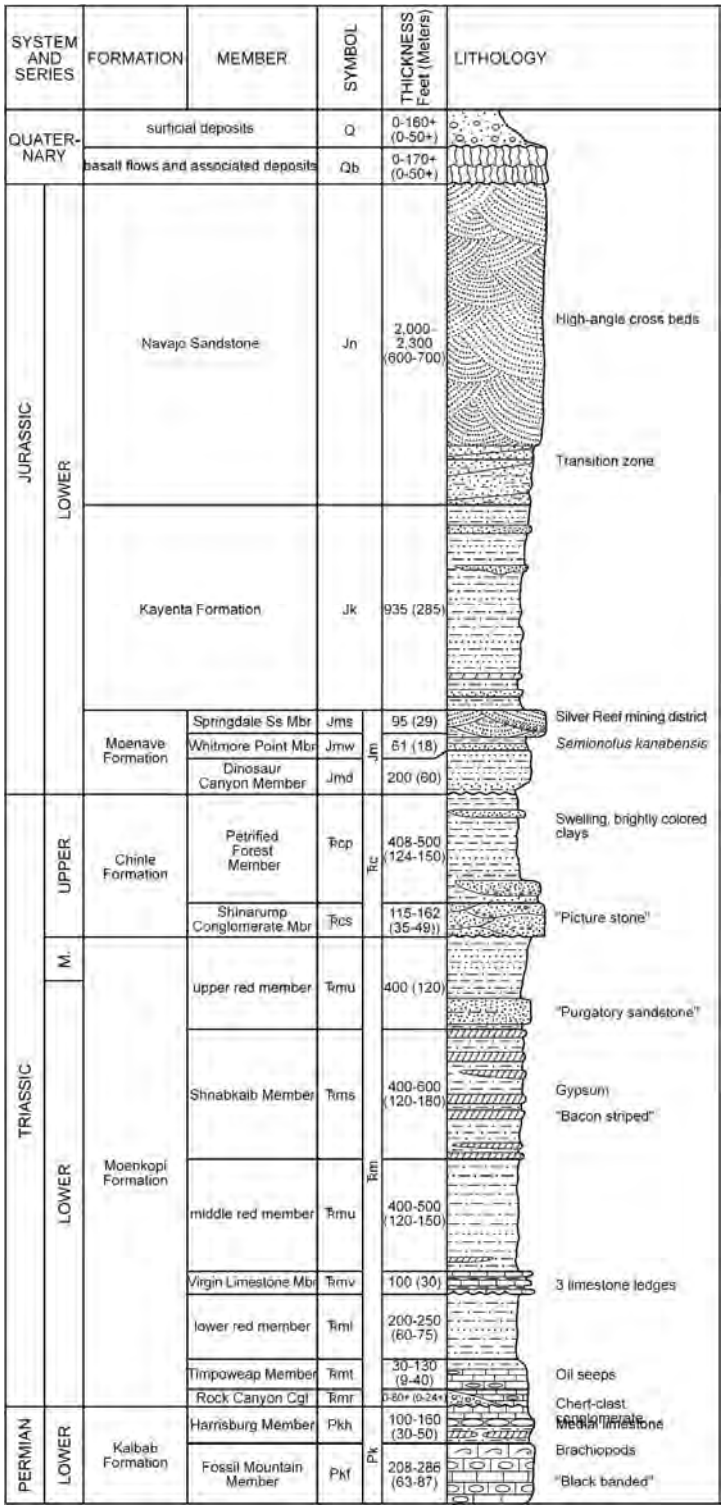

Figure 6. Lithologic column showing stratigraphic units in the vicinity of Silver Reef, Utah.

orange, but pale-red, grayish-red, very pale-orange, and pale-yellowish-brown hues are common. Small, subrounded pebbles are primarily quartz, quartzite, and chert. Coarser sandstones and pebbly sandstones locally contain poorly preserved petrified wood, commonly replaced in part by iron-manganese oxides. Small petrified logs several feet in length are common though not abundant. Plant fragments, replaced in part by iron-manganese oxides, are also common.

The Shinarump Conglomerate varies widely in thickness due to paleotopography and deposition in braided-stream channels, and to difficulty in placing the locally gradational upper contact. The member varies from 5 to 200 feet thick in southwest Utah (Higgins, 1998); Stewart and others (1972) measured 162 feet of Shinarump strata at East Reef. Southwest of Quail Creek Reservoir Shinarump strata are 104 feet thick, and at the southern end of Washington Black Ridge this unit is 165 feet thick (Biek, 2003b).

The upper contact with the Petrified Forest Member is well exposed along the east side of the Virgin anticline in the southwest corner of section 17, T. 41 S., R. 13 W. In this area, the contact corresponds to a prominent lithologic and color change, from yellowish-brown sandstone and pebbly sandstone of the Shinarump Conglomerate below to the bright, varicolored, swelling claystones of the Petrified Forest Member above. Along the northwest flank of the Virgin anticline, the contact appears to be gradational and intertonguing (Biek, 2003a, 2003b).

Petrified Forest Member: 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 9). 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 varicolored swelling mudstones that typify the member. Mudstones and claystones of the Petrified Forest Member are typically various shades of purple, although grayish-red, dark-reddish-brown, light-greenish-gray, brownish-gray, olive-gray, and similar hues are common. Bentonitic clays that swell conspicuously when wet are common and give weathered surfaces a "popcorn" appearance. These swelling clays are also responsible for numerous foundation problems and mass movements in the area. In the Silver Reef mining district, rotational slides are common below cliffs of Moenave strata on the northeast-plunging nose of the Virgin anticline.

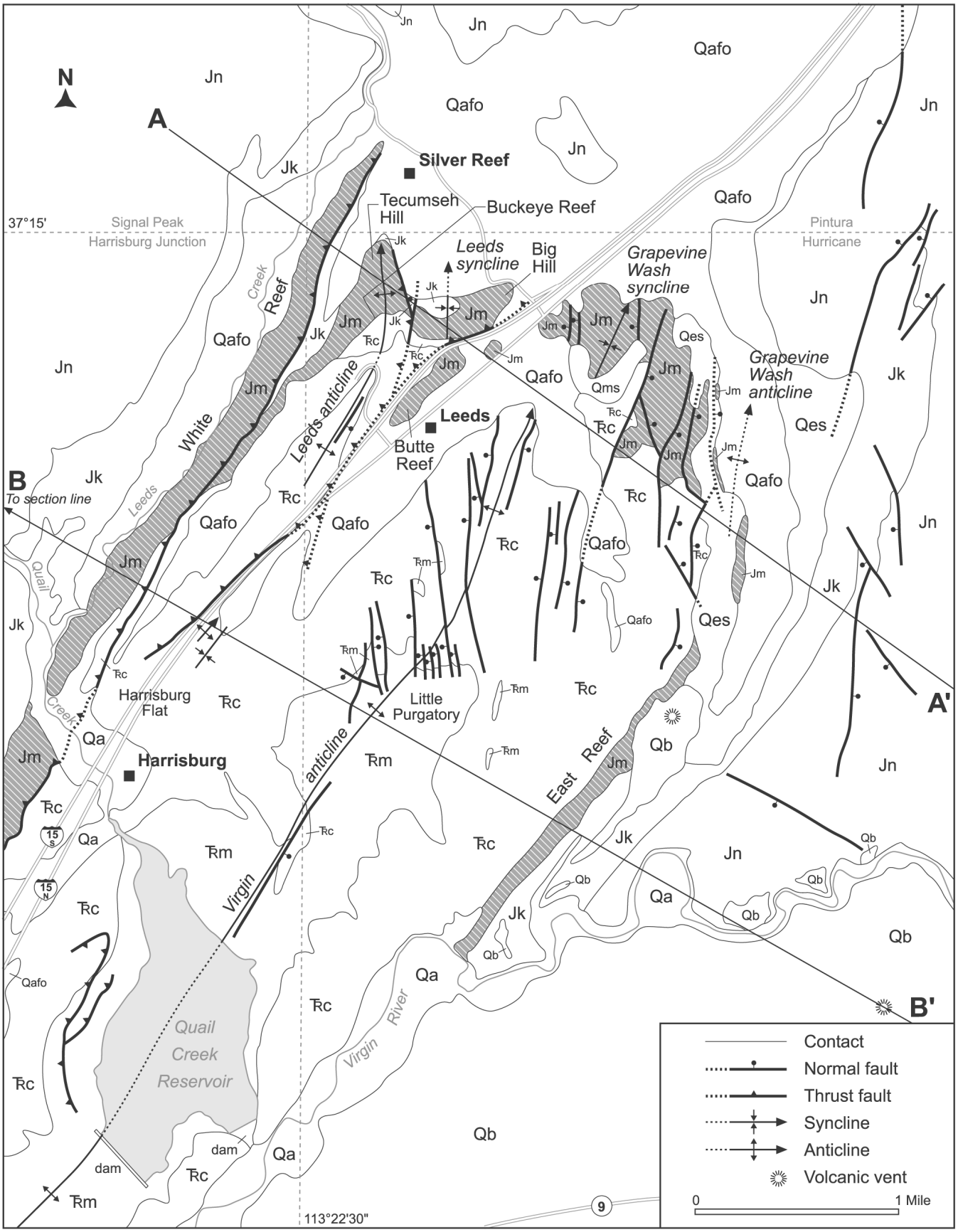

Figure 7. Simplified geologic map of the Silver Reef mining district. See figure 6 for unit names; Quaternary units include Qa = undifferentiated alluvium, Qafo = older alluvial fans, Qes = eolian sand, and Qb = undifferentiated basalt flows. Harrisburg Junction, Hurricane, Pintura, and Signal Peak quadrangle boundaries also shown.

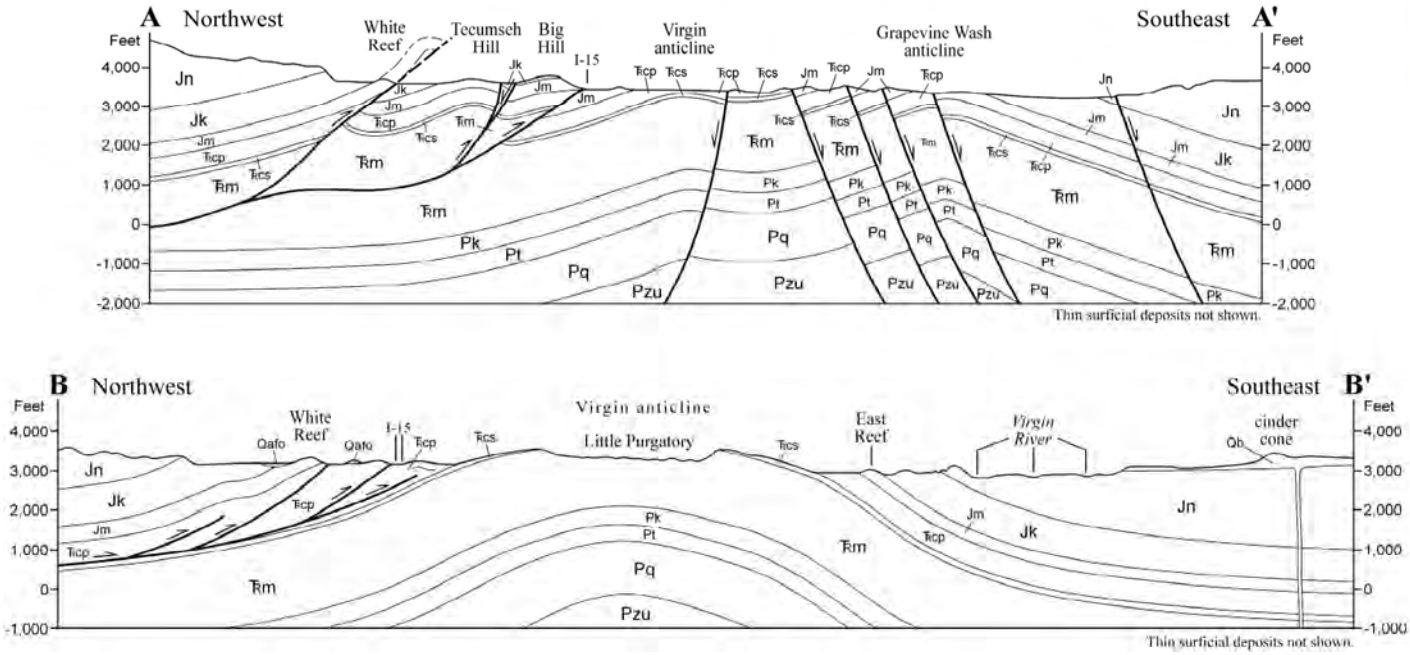

Figure 8. Simplified cross sections of the Silver Reef mining district. See figure 6 for explanation of symbols; additional symbols are Pt = Toroweap Formation, Pq = Queantoweap Sandstone, and Pzu = undifferentiated older Paleozoic strata.

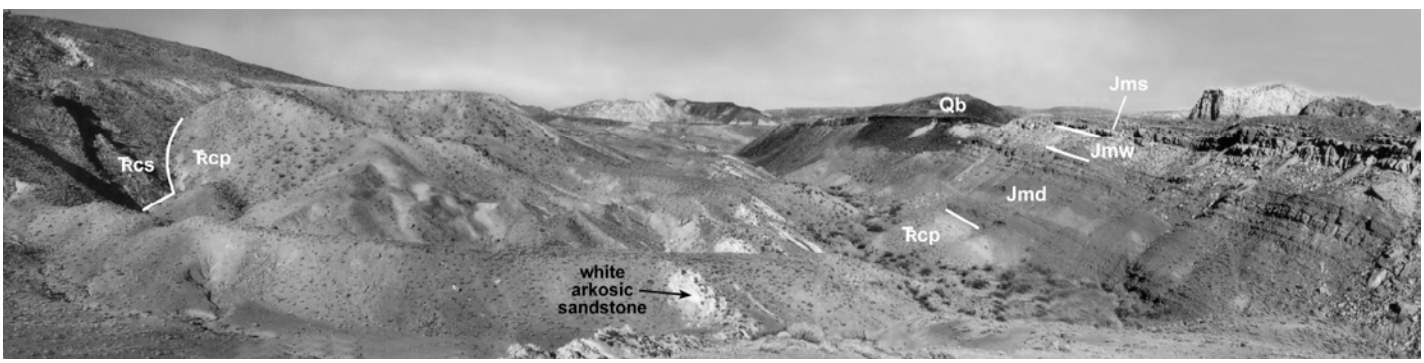

Figure 9. View north of the Petrified Forest strike valley at East Reef, just north of where Grapevine Wash passes through the reef. TRcs = Shinarump Conglomerate, and TRcp = Petrified Forest Members of the Chinle Formation; Jmd = Dinosaur Canyon, Jmw = Whitmore Point, and Jms = Springdale Sandstone Members of the Moenave Formation; Qb = East Reef basaltic flow and cinder cone. The white arksoic sandstone of Proctor (1953) is also shown. The Hurricane Cliffs near Toquerville are visible in the distance.

Sandstones of the Petrified Forest Member exhibit a wide variation in grain size and bedding characteristics and are generally restricted to the lower and middle parts of the member. Locally, such as north of Harrisburg Flat just west of Interstate 15, lower Petrified Forest strata include a 0- to 40-foot-thick, ledge-forming, yellowish-brown, medium- to coarse-grained, locally pebbly sandstone. This thick channel sandstone can be traced to the northeast where it forms the northeast-plunging, tightly folded Leeds anticline at Leeds Reef (Biek, 2003a). Along the west flank of Leeds anticline, at the border of the Harrisburg Junction and Hurricane quadrangles (figure 7), this thick, Shinarump-like sandstone is overlain by up to a few tens of feet of reddish-brown, slope-forming, thin-bedded siltstone and very fine-grained sandstone, which in turn are overlain by another smaller, Shinarump-like channel sandstone. Small pebble-size clasts in these sandstones are primarily chert and quartzite, and light-greenish-gray mudstone rip-up clasts are locally common. Proctor (1953), Cook (1960), and Proctor and Brimhall (1986) included this entire Shinarump-like sandstone sequence in their Shinarump Conglomerate. Faulting renders the true stratigraphic position of this sandstone uncertain, but it probably corresponds to the

basal Petrified Forest sandstones described at the southern end of Washington Black Ridge (Biek, 2003b) and at East Reef (Stewart and others, 1972).

Very pale-orange, very thick-bedded, coarse- to very coarse-grained, pebbly sandstone that varies from about 10 to 52 feet thick characterizes the upper-middle part of the Petrified Forest Member (Stewart and others, 1972; Biek, 2003a, 2003b). Green and yellow-ochre stains from iron, copper, and uranium mineralization are common in this sandstone. The pebbles are rounded chert and lesser quartzite clasts. Petrified logs – typically splintery, poorly preserved, and several tens of feet long – are common in channel deposits of the middle sandstone. This is the prominent white arkosic sandstone of Proctor (1953).

A silicified bed up to 1 foot thick is present a few tens of feet above the white arkosic sandstone. The best exposures of this bed are at Buckeye Reef, in the NE1/4NE1/4NE1/4 section 12, T. 40 S., R. 14 W., and at East Reef, in the SE1/4NW1/4SE1/4 section 19, T. 41 S., R. 13 W. This bed is moderate red to moderate reddish orange, with streaks of light greenish gray. It appears similar to a silicified peat or paleosol. This is the "agate bed" noted by Proctor (1953) and included in the informally named "Fire Clay Hill bentonitic shales" unit. Native Americans used chert from this bed as a source of stone for tools (Bassett, 1995).

Stewart and others (1972) measured 408 feet of Petrified Forest strata at East Reef. Proctor and Brimhall (1986) reported Petrified Forest strata are 446 feet thick in the structurally and stratigraphically complex Buckeye Reef area. The Petrified Forest Member was deposited in fluvial, flood-plain, and lacustrine environments (Dubiel, 1994). Mottled, variegated mudstones probably represent paleosols. Abundant bentonitic mudstones in the Petrified Forest Member are probably derived from alteration of volcanic ash erupted from a magmatic arc along the continental margin to the west (Dubiel, 1994). 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 forms a distinctive, three-part sequence that wraps around the northeast-plunging end of the Virgin anticline (figure 10). Moenave strata are complexly folded and faulted on the nose of the Virgin anticline, and thrust faults duplicate the formation on the northwest flank of the anticline. Steeply southeast-dipping, but otherwise undisturbed, Moenave strata are well exposed at East Reef. The Moenave Formation is divided into, in ascending order: the Dinosaur Canyon Member, which consists of moderate-reddish-brown, uniformly colored, slope-forming, very fine-grained sandstone and lesser interbedded siltstone and mudstone; the Whitmore Point Member, which consists of varicolored, thin-bedded, slope-forming claystone, mudstone, siltstone, very fine- to fine-grained sandstone, and several thin dolomite beds; and the Springdale Sandstone Member, which consists of ledge-forming, rounded-weathering, light-brown to lavender, fine- to medium-grained sandstone that hosts the ore minerals of the Silver Reef mining district. Marzolf (1994) and Blakey (1994) presented evidence to restrict the Moenave Formation to the Dinosaur Canyon and Whitmore Point Members, with a major regional unconformity at the base of the Springdale Sandstone; the Springdale Sandstone would thus be more closely related to the Kayenta Formation (see, for example, Lucas and Heckert; Molina-Garza and others, 2003). Following historical usage and until regional correlations are further refined we prefer to define the Moenave as a formation with three members.

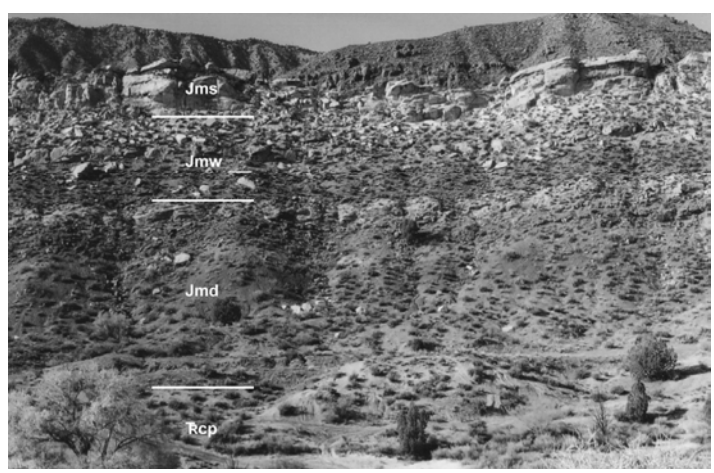

Figure 10. View west to White Reef, just south of the Barbee mill. TRcp = Petrified Forest Member of the Chinle Formation; Jmd = Dinosaur Canyon, Jmw = Whitmore Point, and Jms = Springdale Sandstone Members of the Moenave Formation. The Navajo Sandstone forms the distant hills. A west-dipping thrust fault that places Petrified Forest strata over the Kayenta Formation is present at the bottom of the wash.

The Moenave Formation is 356 feet thick at East Reef (Stewart and others, 1972) and 391 feet thick at Harrisburg Flat (Biek, 2003b). Proctor and Brimhall (1986) reported the Moenave Formation is just 261 feet thick in the Silver Reef mining district, but it is unclear whether their upper and lower contacts are the same as those used in this report; Wilson and Stewart (1967) reported Moenave strata there are about 355 feet thick. The Moenave Formation is Early Jurassic in age (Olsen and Galton, 1977; Peterson and others, 1977; Imlay, 1980; Clark and Fastovsky, 1986), and was deposited in a variety of fluvial and lacustrine environments (Clemmensen and others, 1989; Blakey, 1994; Peterson, 1994; DeCourten, 1998).

Dinosaur Canyon Member: The Dinosaur Canyon Member is exposed at the base of White, Butte, Buckeye, and East Reefs and in faulted blocks on the northeast-plunging nose of the Virgin anticline. The member consists of interbedded, mostly slope-forming, generally thin-bedded, very fine- to fine-grained sandstone, very fine-grained silty sandstone, and lesser siltstone and mudstone. Planar bedding and low-angle and ripple cross-stratification are common. Sandstone beds in the upper portion tend to be medium to thick bedded and commonly form ledges. Dinosaur Canyon strata are uniformly colored moderate red brown to moderate reddish orange, although beds are locally mottled very pale orange.

The contact with the overlying Whitmore Point Member is conformable and gradational and corresponds to the base of a laterally persistent, thin-bedded, 6- to 18-inch-thick, light-gray dolomitic limestone with algal structures (Biek, 2003a, 2003b). This bed appears bioturbated; weathers to mottled colors of yellowish gray, white, and grayish orange-pink; and contains light-brown to dark-reddish-brown, irregularly shaped chert nodules, some of which appear to fill burrows or root casts. About 25 feet of brown sandstone, typical of underlying Dinosaur Canyon strata, overlie the dolomitic limestone and are here included in the Whitmore Point Member. These strata point to the conformable, intertonguing nature of this member contact.

Stewart and others (1972) assigned 200 feet of strata to the Dinosaur Canyon Member at East Reef, but it is unclear if they used the same upper contact as this report. Biek (2003b) measured 163 feet of Dinosaur Canyon strata at Harrisburg Flat in the Harrisburg Junction quadrangle to the west. The Dinosaur Canyon Member was deposited in river and flood-plain environments (Clemmensen and others, 1989; Blakey, 1994; Peterson, 1994; DeCourten, 1998).

Whitmore Point Member: The Whitmore Point Member weathers to poorly exposed slopes except where protected by resistant cliffs and ledges of the overlying Springdale Sandstone Member. Even so, slopes on Whitmore Point strata are typically brightly colored and littered with a lag of resistant Whitmore Point lithologies, making the member an important marker horizon, one clearly recognized in Rothwell's (1880, p. 5) description of White and Buckeye Reefs cited earlier. Some of the best exposures are at East Reef, on the east side of the Virgin anticline.

If the Dinosaur Canyon Member is noted for its uniformity – mostly reddish-brown, thin-bedded, very fine- to fine-grained sandstone and silty sandstone – the Whitmore Point Member must be known for its variety. The Whitmore Point contains sandstone and siltstone similar to the Dinosaur Canyon, but also contains reddish-purple to greenish-gray mudstone and claystone and thin dolomitic limestone beds. The limestones are bioturbated and contain small, moderate-reddish-brown chert nodules and blebs, poorly preserved and contorted algal structures, and locally abundant fossil fish scales and bones of *Semionotus kanabensis* (Hesse, 1935; Schaeffer and Dunkle, 1950). The fish fossils were originally thought to be restricted to the Triassic and so conflicted with palynomorphs from the Whitmore Point Member that indicate the unit is Early Jurassic (latest Sinemurian to earliest Pliensbachian) (Peterson and others, 1977; Imlay, 1980). Olsen and Padian (1986) later found that *Semionotus kanabensis* is not age diagnostic, which resolved the long-standing debate on the age of the Early Jurassic Moenave, Kayenta, and Navajo Formations. Recently discovered dinosaur tracks in correlative beds near St. George also confirm an Early Jurasic age for the lower Moenave Formation in southwest Utah (James Kirkland, Utah Geological Survey, verbal communication, March 30, 2000).

The contact between the Whitmore Point and Springdale Sandstone is a regional unconformity with local channeling and mudstone rip-up clasts at

the base of overlying Springdale strata. The contact is at the base of thick- to very thick-bedded sandstones with low-angle cross-stratification and generally corresponds to a pronounced break in slope, with the resistant Springdale Sandstone forming prominent cliffs and ledges above gentle Whitmore Point slopes. Where Grapevine Wash passes through East Reef, in the NE1/4NE1/4SE1/4 section 19, T. 41 S., R. 13 W., the Springdale Sandstone fills a channel in Whitmore Point strata that is about 25 feet thick. Stewart and others (1972) assigned 61 feet of strata to the Whitmore Point Member at East Reef, on the east side of the Virgin anticline, but it is unclear if they used the same lower contact as this report. The Whitmore Point Member is 64 to 126 feet thick in the Harrisburg Junction quadrangle to the west (Biek, 2003b) but these thicknesses include about 25 feet of strata perhaps better assigned to the Dinosaur Canyon Member. The Whitmore Point Member was deposited in flood-plain and lacustrine environments (Clemmensen and others, 1989; Blakey, 1994; Peterson, 1994; DeCourten, 1998).

Springdale Sandstone Member: The Springdale Sandstone Member is well exposed at White, Butte, Buckeye, and East Reefs, and in faulted outcrops on the nose of the Virgin anticline. The Springdale Sandstone Member hosts 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). Co-author Biek found that the Leeds and Tecumseh sandstones are not mappable stratigraphic units but instead represent slight color variations that exhibit significant lateral variation.

The Springdale Sandstone Member consists predominantly of medium- to very thick-bedded, fine-grained or rarely medium-grained sandstone, with planar bedding and low-angle cross-stratification, that commonly weathers to rounded cliffs and ledges. Springdale sandstones are distinguished from overlying Kayenta sandstones by their more variable pastel colors of pale red, pale pink, pinkish gray, yellowish gray, pale reddish purple, pale yellowish orange, and dark yellowish orange, as opposed to moderate-reddish-brown hues that dominate Kayenta beds. Springdale strata also have common Liesegang banding; generally very thick bedding rather than thin to medium bedding typical of Kayenta strata; and characteristic small, resistant, 1/8- to 1/4-inch diameter concretions that give weathered surfaces a pimply appearance. Poorly cemented concretions up to 1 inch in diameter, which impart a pitted appearance to weathered surfaces, are also common in Springdale sandstones. The Springdale Sandstone contains thin, discontinuous lenses of intraformational conglomerate, with mudstone and siltstone rip-up clasts and poorly preserved, petrified and carbonized fossil plant remains indicative of deposition principally in braided-stream and minor flood-plain environments (Clemmensen and others, 1989; Blakey, 1994; Peterson, 1994; DeCourten, 1998).

The upper contact of the Springdale Sandstone Member is conformable and gradational, and commonly corresponds to a pronounced color, topographic, and lithologic change. The upper contact is well exposed but more difficult to pick at East Reef (figure 11). There, variously colored, ledge- and cliff-forming, thick- to very thick-bedded, fine-grained sandstone of the Springdale Sandstone is overlain by reddish-brown, slope-forming, thin- to thick-bedded, very fine- to fine-grained silty sandstone, sandstone, and mudstone of the Kayenta Formation. Wilson and Stewart (1967) noted that Springdale and Kayenta strata appear to intertongue in the Leeds area. The Springdale Sandstone Member is about 95 feet thick at East Reef (Stewart and others, 1972). It is 120 to 164 feet thick on the northwest flank of the Virgin anticline (Wilson and Stewart, 1967; Proctor and Brimhall, 1986; Biek, 2003b).

Quaternary Deposits

Basalt flows: Several basaltic flows surround the north and east sides of the Silver Reef mining district, but only one, the East Reef flow, is within the district itself. Flows that erupted from the Pintura area to the north and from the Hurricane area to the southeast range in age from about 0.14 to 1.0 million years old (Biek, 2003a; Hurlow and Biek, 2003). Basaltic rocks in southwest Utah are part of the western Grand Canyon basaltic field, a large area of late Tertiary to Holocene basaltic volcanism in northwestern Arizona and adjacent Utah (Hamblin, 1970; Best and Brimhall, 1974). Although relatively small in volume compared to other volcanic fields in the

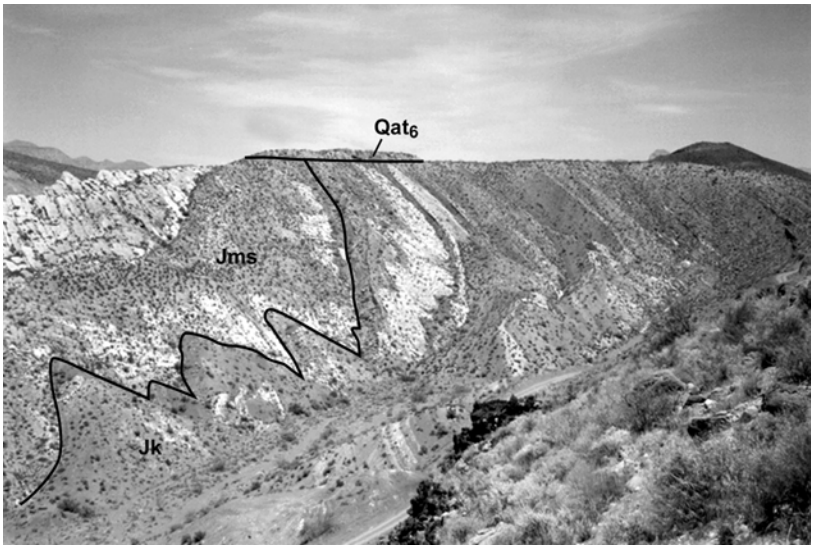

Figure 11. View north of East Reef immediately north of where Grapevine Wash passes through the reef. Southeast-dipping Springdale (Jms) and Kayenta (Jk) strata are beveled flat and capped by old stream-terrace deposits (Qat_6). The gradational Springdale-Kayenta contact corresponds to the base of the first laterally continuous mudstone bed. East Reef cinder cone forms the skyline on right.

western United States, these flows provide important constraints on local tectonic and geomorphic development (e.g., Willis and Biek, 2001).

The East Reef flow erupted from vents at two overlapping cinder cones at the north end of East Reef. The East Reef flow is a medium-dark-gray, fine-grained olivine basalt that is classified as a basanite on the TAS diagram of Le Bas and others (1986). The East Reef flow traveled at least 1.5 miles down the ancestral Grapevine Wash to the present confluence with the Virgin River. At the confluence, the East Reef flow now lies about 160 feet above the Virgin River. The margins of the flow are eroded and it maintains a relatively constant thickness of 25 to 30 feet along its length. The flow yielded a poorly constrained $^{40}Ar/^{39}Ar$ plateau age of 0.20 $\pm$ 0.16 Ma; the large standard deviation is probably due to abundant groundmass glass and low radiogenic yield. Long-term incision rates suggest that the flow could be about 400,000 years old.

Old alluvial-fan deposits: Pleistocene-age alluvial-fan deposits derived from the Leeds Creek drainage form an extensive surface along the northeast-plunging nose of the Virgin anticline. These old fan deposits are characterized by very large igneous boulders (quartz monzonite porphyry) derived from the Pine Valley Mountains, including some in excess of 10 feet in diameter. Most clasts, and all of the larger clasts, are from the Miocene-age Pine Valley intrusive complex; Jurassic Carmel and Cretaceous Iron Springs clasts are also common. The towns of Leeds and Silver Reef are built atop these old debris-flow deposits. These deposits are generally 0 to 50 feet above nearby drainages and range from 0 to about 40 feet thick. Higher-level alluvial-fan deposits cap Big Hill northwest of Leeds; they lie in excess of 200 feet above adjacent drainages.

Structure

Regional Setting

The Silver Reef mining district, in the transition zone between the Colorado Plateau and Basin and Range physiographic provinces, lies just 4 to 5 miles west of a major segment boundary on the Hurricane fault. Strata in the 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, and are partially covered by Quaternary basalt flows and cinder cones. In southwestern Utah, the transition zone encompasses the area between two major down-to-the-west normal fault zones – the Gunlock-Grand Wash faults to the west and the Hurricane fault to the east – that "step down" from the Colorado Plateau to the Basin and Range. Displacement on the Gunlock-Grand Wash faults decreases northward whereas displacement on the Hurricane fault increases to the north. As discussed by Schramm (1994), these faults may form a displacement transfer zone, in which decreasing slip on one fault is compensated for by increasing slip on another. Such a transfer zone would account for the relatively wide width of the transition zone in southwestern Utah. Stratigraphic separation on the Hurricane fault may approach 10,000 feet at the latitude of the Silver Reef mining district; tectonic displacement on the fault is probably about 3,600 feet.

Folds

Virgin anticline: The Virgin anticline is a 30-mile-long, northeast-trending, generally symmetrical fold that trends parallel to, but is structurally distinct from, the Kanarra anticline to the north (Hurlow and Biek, 2003). Collectively, these two anticlines mark the eastward limit of significant Sevier-age compressional deformation in southwestern Utah.

The Virgin anticline has three similar structural domes along its length, each eroded to the level of the Permian Kaibab Formation. From southwest to northeast these are Bloomington dome, Washington Dome, and Harrisburg Dome. The fold is made all the more visible by the resistant Shinarump Conglomerate Member of the Chinle Formation, which forms a hogback on Moenkopi strata exposed in Little Purgatory and near Quail Creek Reservoir (figure 7). In the Silver Reef mining district, the Virgin anticline is an open, upright, symmetrical fold with flank dips generally of 25-35°; it plunges to the northeast at about 10-15°. Numerous thrust and normal faults and subsidiary folds, discussed separately, complicate the anticline's structure in the district.

The age of formation of the Virgin anticline and subsidiary folds is difficult to determine because of inadequate cross-cutting relationships. The early Late Cretaceous Iron Springs Formation is the youngest bedrock unit involved in folding of the Virgin anticline. We believe the formation of the Virgin anticline is related to the Pintura anticline, a co-linear fold exposed to the north in the Pintura quadrangle. The Pintura anticline is unconformably overlain by the Canaan Peak Formation, the oldest beds of which are late Campanian (Late Cretaceous) in age (see, for example, Hurlow and Biek, 2003). The Virgin anticline thus likely formed between early and late Campanian time (about 84 to 72 million years ago), the youngest known age of the Iron Springs Formation and the oldest known age of the Canaan Peak Formation, respectively (Goldstrand, 1992, 1994), but both ages are poorly constrained. Davis (1999) suggested that the Virgin anticline formed above a blind, basal detachment in underlying Cambrian and Precambrian strata.

Leeds anticline, Leeds syncline, and other subsidiary folds: The Leeds anticline and Leeds syncline are 2- to 3-mile-long subsidiary folds on the northwestern flank of the Virgin anticline (Proctor, 1953) (figure 7). Both of these folds are Sevier-age structures related to formation of the Virgin anticline. The best exposures of the Leeds anticline are at Buckeye Reef, northwest of Leeds. There, the Springdale Sandstone forms the crest of the fold, which plunges about 10° north. South of Buckeye Reef, the axial surface bends to the southwest along Leeds Reef. The Leeds anticline is bounded on the east by what Proctor and Brimhall (1986) first mapped as a west-dipping thrust fault, which truncates the southeast limb of the anticline. Leeds Reef, which forms the exposed core of the Leeds anticline, is upheld by folded beds previously mapped as the Shinarump Conglomerate Member of the Chinle Formation (Proctor, 1953; Proctor and Brimhall, 1986) and that Biek (2003a, 2003b) reassigned to the basal Petrified Forest Member.

The Leeds syncline, which lies between and roughly parallel to the Leeds and Virgin anticlines, plunges gently northeast beneath the town of Leeds. A west-dipping thrust fault at the base of Big Hill truncates the syncline. Petrified Forest strata, mostly concealed by younger Quaternary deposits, form the eroded core of the syncline south of Big Hill, whereas west-dipping Shinarump Conglomerate strata of the Virgin anticline form its eastern limb.

Other subsidiary, Sevier-age folds are present on the nose of the Virgin anticline. A syncline comparable in size to the Leeds syncline, which Biek (2003a) called the Grapevine Wash syncline, lies east of the Virgin anticline axial surface in the NW1/4 section 8, T. 41 S., R. 13 W. The syncline plunges to the north-northeast at about 15°, parallel to the trace of the Virgin anticline axial surface. Based on limited exposures of Moenave strata to the southeast, just north of East Reef, Biek (2003a) mapped a subparallel fold he called the Grapevine Wash anticline. The presence of these subsidiary folds on the plunging nose of the Virgin anticline suggests that although the Virgin and Kanarra anticlines are co-linear and doubtless genetically related, they are separate structures.

Faults

Thrust Faults: Several west-dipping thrust faults are present along the west flank of the Virgin anticline. Proctor (1948, 1953) was the first to recognize the largest and westernmost thrust fault amid considerable controversy over structural interpretations of

the Silver Reef mining district (although Dobbin [1939] showed the Silver Reef area to be faulted in his small-scale map of the St. George basin). Proctor's recognition of this and other thrust faults in the district 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 to the southwest (Biek, 2003b). The fault repeats the Moenave Formation in the reefs, farther south at Cottonwood Creek, and west of Harrisburg Junction. The Moenave Formation is not duplicated at Harrisburg Flat, suggesting that the fault is not everywhere parallel to bedding but undulates between upper Petrified Forest and lower Kayenta strata. In the Utah Highway 9 road cut near Harrisburg, a prominent drag fold is exposed below the fault zone. Based on surface and subsurface data, the fault dips about 30° west-northwest (Proctor and Brimhall, 1986). Proctor and Brimhall (1986) estimated that in the Silver Reef mining district the Springdale Sandstone Member was displaced eastward at least 2,000 feet on this fault.

Proctor and Brimhall (1986) also described a smaller thrust fault between Buckeye and Butte Reefs. The only exposure of this fault is immediately north of Interstate 15, north of Leeds, where it places Petrified Forest and Dinosaur Canyon strata on the Springdale Sandstone. Biek (2003a) interpreted about 1,500 feet of displacement on this fault. This fault extends southwest where it truncates the east limb of the Leeds anticline at Leeds Reef. A north-striking splay of this thrust bounds the east side of Buckeye Reef, and a second thrust splay dies out in the west limb of the Virgin anticline southwest of Leeds. Biek (2003b) noted several smaller west-dipping thrust faults in Chinle and Moenkopi strata in the vicinity of Quail Creek Reservoir, south of the Silver Reef mining district.

Normal faults: A series of mostly north- and northeast-striking normal faults with both down-to-the-west and down-to-the-east displacements up to several tens of feet cut the Shinarump Conglomerate on the nose of the Virgin anticline. Four larger displacement, down-to-the-east normal faults are present to the northeast, where they bound a series of west-dipping Moenave blocks. The westernmost of these faults is well exposed in Grapevine Wash, where the fault plane dips 70° east-southeast with nearly vertical slickenlines, and places the middle sandstone of the Petrified Forest Member against Shinarump strata. Stratigraphic separation on this fault and the other three faults increases northward to several hundred feet along cross-section line A-A'. The relationship of these faults to the northeast-plunging nose of the Virgin anticline suggests that the faults formed in the Late Cretaceous, during folding of the Virgin anticline; some of the larger faults in the Grapevine Wash area may be reactivated reverse faults.

ORE DEPOSITS

Mineralization

Ore and Gangue Minerals

The Silver Reef mining district is noted for its uncommon occurrence of ore-grade silver chloride (chlorargyrite or horn silver) in sandstone, unaccompanied by obvious alteration or, with the exception of copper, substantial base-metal ores. Proctor (1953) noted that chlorargyrite accounted for more than 90% of the silver-bearing minerals at the Silver Reef mining district. 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. Heyl (1978) reported that the silver minerals are nearly invisible, and so the ore is conspicuous only where copper and uranium minerals are present. James and Newman (1986) noted that samples assaying 10 to 15 ounces per ton silver can locally be obtained at the surface with no visible silver minerals. Typical silver ore is thinly laminated sandstone and silty sandstone with carbonaceous plant fossils. 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. At Silver Reef, however, most chlorargyrite likely formed where it is now found and has not been extensively remobilized.

Table 1 lists ore and gangue minerals reported from the Silver Reef mining district. 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. Proctor (1953) noted that malachite is most common in the Leeds sandstone and rarely occurs in the Tecumseh sandstone, and Browning (1925) noted that copper is more common in White Reef than Buckeye Reef. Azurite is locally present in combination with malachite. These copper carbonates are generally uncommon, but Proctor (1953) noted that in favorable locations they may make up to 3-5% of the rock. Carnotite is the predominant uranium and vanadium mineral, with volborthite and autunite being less common. Like the chlorargyrite, these uranium minerals are generally found in association with plant fragments and on bedding and fracture planes, but may occur disseminated within the sandstone. Wyman (1955) reported that uranium production was in the Leeds sandstone and that limonite is closely associated with the uranium ore and locally forms pseudomorphs after pyrite.

Proctor (1953) discussed other minerals known or reported to occur in the district, including embolite (silver bromide), native silver, and argentite (silver sulfide). Native silver and silver sulfide are only known from early reports of the Silver Reef mining district and apparently occur at depth within the mines, mostly near or below the water table. Eppinger and others (1990) reported the rare vanadium minerals roscoelite, a vanadian member of the mica group, and montroseite, a vanadium iron oxide hydroxide. The ores are free of zinc, arsenic, tungsten, tellurium, antimony, and bismuth, and essentially free of gold, elements that are characteristic of hydrothermal deposits (Heyl, 1978).

The Springdale Sandstone, host to the ore mineralization of the Silver Reef mining district, is typically medium- to very thick-bedded, fine-grained or rarely medium-grained quartz arenite. Grains are subangular to subrounded, and minor fine-grained muscovite is locally present on bedding planes. Thin, discontinuous lenses of intraformational conglomerate with mudstone and siltstone rip-up clasts and poorly preserved, petrified and carbonized plant remains are also present. Where exposed along the flanks of the Virgin anticline, including in the Silver Reef mining district, the Springdale Sandstone is moderately silicified, bleached, and oxidized. It is distinctly lighter in color than in exposures east of the Hurricane fault, suggestive of bleaching by hydrocarbons. Proctor (1953) analyzed a representative split of 20 feet of typical sandstone from Tecumseh

Table 1. Ore and gangue minerals at Silver Reef, Utah (modified from Proctor and Brimhall, 1986). Italicized minerals are most important.

Ore Minerals
Argentite – Ag_2S
Autunite – $Ca(UO_2)_2(PO_4)_2 \bullet 10\text{-}12\ H_2O$
Azurite – $Cu_3(CO_3)_2(OH)_2$
Bornite – Cu_5FeS_4
Carnotite – $K_2(UO_2)_2(VO_4)_2 \bullet 3H_2O$
Chalcocite – Cu_2S
Chalcopyrite – $CuFeS_2$
Chlorargyrite – AgCl
Cuprite – Cu_2O
Embolite – Ag(BrCl)
Hematite – Fe_2O_3
Limonite – $FeO \bullet OH \bullet nH_2O$
Malachite – $Cu_2CO_3(OH)_2$
Native silver – Ag
Pyrite – FeS_2
Silver selenides?
Naumannite – $(Ag_2Pb)Se(?)$
Aguilarite – $Ag_2(S,Se)(?)$
Tenorite – CuO
Torbernite – $Cu(UO_2)_2(PO_4)_2 \bullet 8\text{-}12H_2O$
Uraninite – UO_2
Volborthite – approx. $Cu_3(VO_4)_2 \bullet 3H_2O$
Gangue Minerals
Augite
Biotite
Calcite
Chlorite
Dolomite
Garnet
Hematite
Hypersthene
Magnetite
Microcline
Muscovite
Orthoclase
Plagioclase
Quartz

beds and found about 95% quartz, 3% feldspar, and 1% each calcite and chlorite; a typical 10-foot core from near the base of the Leeds sandstone contained about 90% quartz, 6% feldspar, and 2% each calcite and heavy minerals. Wyman (1958) was apparently the first to report quartz overgrowths in the Springdale Sandstone.

Controls and Origin of Mineralization

Ore bodies of the Silver Reef mining district are restricted to the Springdale Sandstone Member of the Moenave Formation. Ore bodies are typically lens shaped and related to paleostream channels containing carbonized plant remains and intraformational conglomerates; ore also occurs in shear and fault zones and as thin films on bedding planes. The most prolific ore deposits lie at or near the boundary between the lighter gray Leeds sandstone and the overlying lavender Tecumseh sandstone.

The Silver Reef mining district is within a broad, silver-rich metallogenic province (James and Newman, 1986). Proctor (1953), Wyman (1958), Cornwall and others (1967), and Proctor and Brimhall (1986) noted anomalously high silver concentrations in the Springdale Sandstone south of the district (away from the crest of the Virgin anticline), and Biek (2003b) mapped several prospects with malachite and azurite staining, but none proved economic. Thus, there is significance to the fact that major ore bodies are concentrated around the nose of the anticline. Small, nearly vertical joints and normal faults with displacements up to a few feet localized mineralization in the Chloride Chief and Duffin mines (see figure 12a, b, c). Wyman (1958, p. 2) reported that "The amount of movement on these faults is directly related to their importance as a localizing influence in the emplacement of ore. For example, faults with large displacement are usually quite open and loose and have little important related ore. Conversely, those which are small and tight have no ore either. The most favorable structures are those which have six inches to one foot displacement."

The genesis of the Silver Reef deposits has been the subject of considerable debate since their discovery, and it remains equivocal. Proctor (1953) discussed models proposed by early workers in the district, including Newberry (1880), Rothwell (1880), and Rolker (1881). Crane (1920), Fischer (1937), Proctor (1953), Wyman (1960), Cornwall and others (1967), Heyl (1978), James and Newman (1986), Proctor and Brimhall (1986), Eppinger and others (1990), and James and Atkinson (2002) also discussed mineral occurrences and proposed models for the Silver Reef mining district. Houser and others (1988) summarized several of these models. These models fall into two basic theories: (1) The silver deposits are related to igneous activity, and (2) the deposits are of sedimentary origin, and either the metals were concentrated at the time of deposition of the sediments or were later concentrated by groundwater. Current, somewhat different models of Proctor (1953), Proctor and Brimhall (1986), James and Newman (1986), and James and Atkinson (2002) favor the latter theory of sedimentary origin enriched by post-depositional hypogene or supergene processes as described below.

Proctor (1953) reasoned that the mineralization was largely syngenetic, with metals derived from volcanic ash beds in the Chinle Formation, either as dissolved sulphates or eroded away as small mineral particles. Although the Springdale Sandstone does contain anomalous concentrations of silver throughout the region as described earlier, the only significant concentrations are at the Silver Reef mining district, a fact strongly suggestive of an epigenetic origin as described by James and Newman (1986). James and Newman (1986) suggested that groundwater leached metals from regional silver-rich rocks (presumably mostly from volcanic ash beds in the Chinle Formation) or igneous systems and redeposited them in the Springdale Sandstone, the first overlying permeable bed with organic material. The silver was probably transported as a sulfide-poor chlorine-rich brine and passed upward into anticlinal traps where it encountered reducing conditions or low-salinity groundwater that caused silver to precipitate. James and Newman (1986) also noted evidence for petroleum residue in the Springdale Sandstone in the Silver Reef mining district, and, as described earlier, Springdale exposures along the Virgin anticline are more strongly bleached than exposures elsewhere. Wyman (1958) believed that the Virgin anticline may be a flushed-oil structure. A low-sulfide brine accounts for the lack of lead and zinc, which are soluble in such a solution. Proctor (1953) and James and Newman (1986) argued that subsequent supergene enrichment created high-grade areas and petroleum escaped from the system as erosion breached the Virgin anticline. Poehlmann and

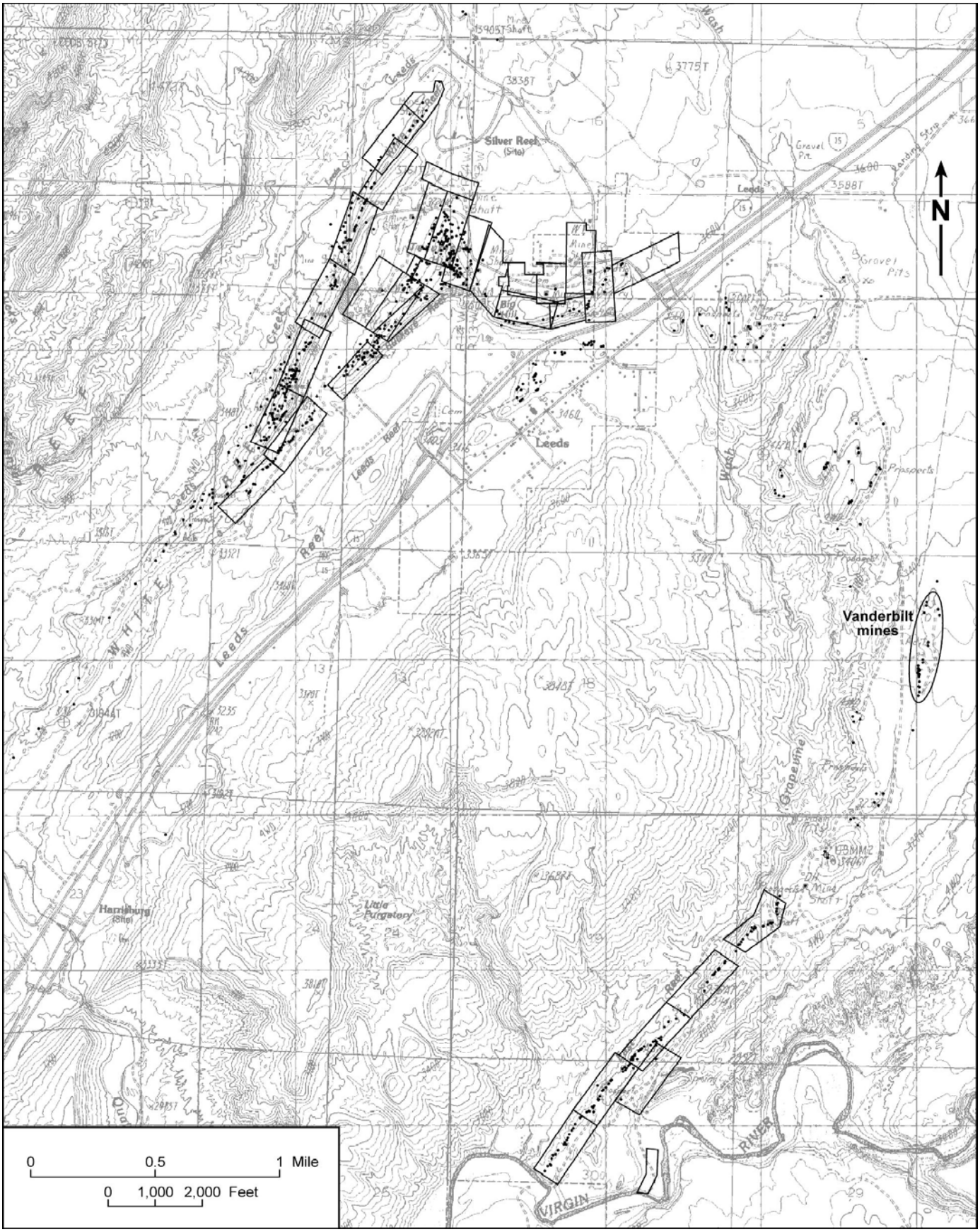

Figure 12. A. Principal mines (black dots) and patented claims of the Silver Reef mining district. See figures 12b and 12c for names of patented claims, major mines, mills, and other features. The Kemple discovery shaft is located just off this map at the south end of White Reef. The location of the Vanderbilt mines is also shown.

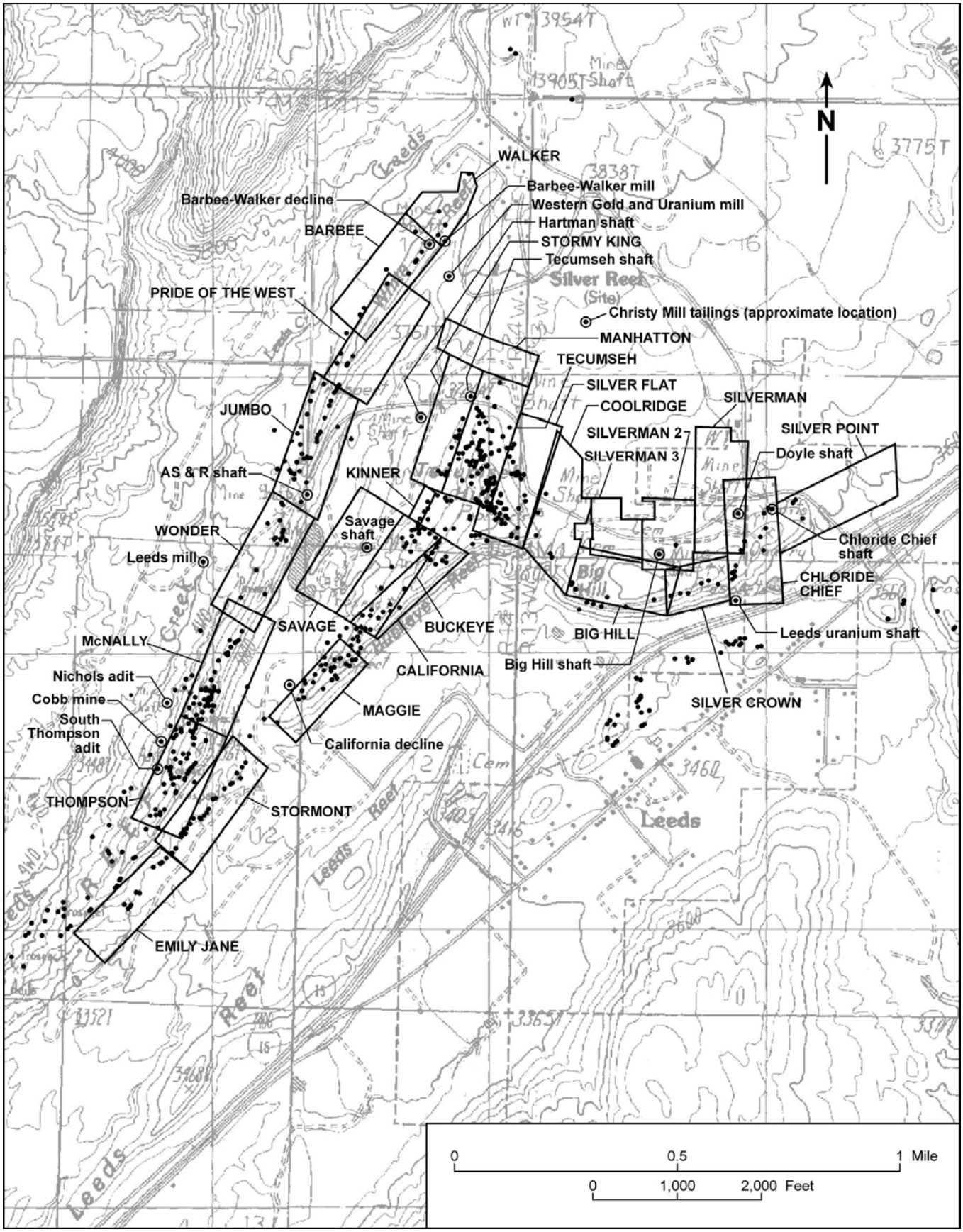

Figure 12 B. Principal mines (black dots) and patented claims of the White Reef and Buckeye Reef part of the Silver Reef mining district.

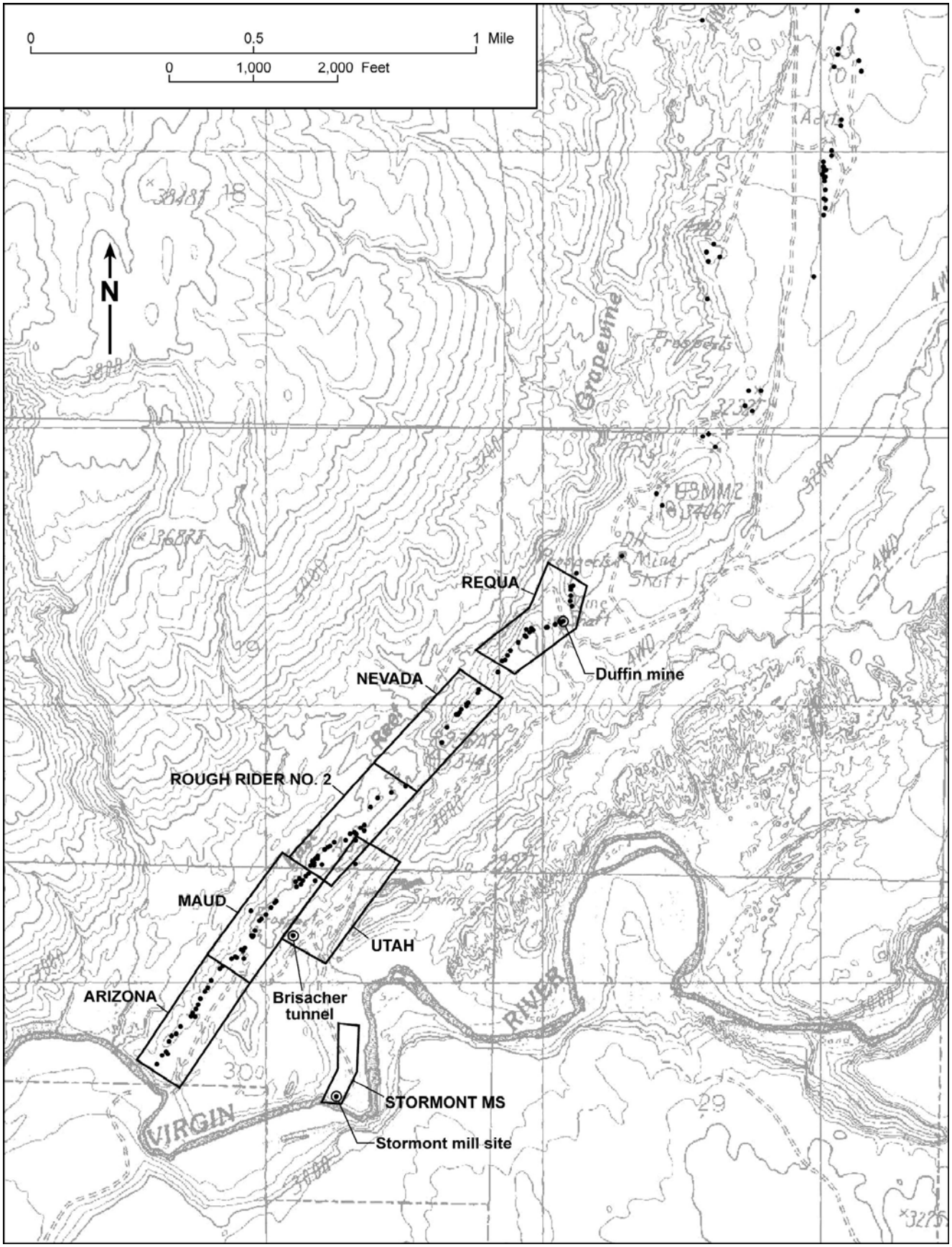

Figure 12 C. Principal mines (black dots) and patented claims of the East Reef part of the Silver Reef mining district.

King (1953) and James and Newman (1986) discussed several failed attempts to identify economic roll-front deposits as described in the model of Heyl (1978). Although most workers familiar with the area agree that the Silver Reef deposits formed from metal-bearing low-temperature brines along permeable zones in the Springdale Sandstone, there is no consensus on the source of the metals, the chemistry and migration routes of ore fluids, and mechanisms to explain the variable distribution of silver, copper, and uranium.

Mining History and Production

Mining History

Two of the best accounts of the silver mining history of the Silver Reef mining district are by Stucki (1966) and Proctor and Shirts (1991); the brief chronological summary below is extracted in large part from their research. Florin (1971) and Miller (1980) are among several authors who provided brief, popular accounts of Silver Reef. Mariger (1959) provided a detailed history of Silver Reef and nearby Leeds and Harrisburg, and reprinted many difficult-to-obtain articles first published in the *Engineering and Mining Journal* in the early 1880s.

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 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) 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. As described earlier, chlorargyrite, the principal silver mineral in the district, is at best an inconspicuous mineral. 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.

John Kemple and others organized the Union mining district in 1871, thereby filing the first mining claims at Silver Reef. The original claim holders were most of the family heads at Harrisburg, and some of the leaders of St. George. What happened to Kemple's Union Mining district is not known, but the strong concerns of the Mormon leaders likely "… made many of the faithful a little apprehensive about becoming too involved in mining activities" (Proctor and Shirts, 1991, p. 31). Although early settlers mined iron, coal, and base metals, they feared that precious metals of Silver Reef, with their associated and inevitable boom and bust cycles, would be just another passing episode that lay primarily outside the pioneers' goals and dreams. In fact, Silver Reef did become a boon to early settlers, many of whom originally tried to farm cotton as a money crop. With the end of the Civil War in 1865 and the coming of the Transcontinental Railroad in 1869, cotton held no further promise, and besides, most farmland was needed for food production. Supplying mining camps, including Silver Reef, with timber, cordwood, livestock, produce, and wine became an important source of income for struggling Mormon communities.

Kemple returned to Silver Reef in 1874 and reorganized the old Union mining district as the Harrisburg mining district. Stucki (1966) reported that 22 additional claims were staked by August 1874, covering the entire Silver Reef area. Most claims were recorded by residents of the Harrisburg-Leeds area, with the wives' names appearing on many of the notices. Stucki (1966) and Proctor and Shirts (1991) suggested that this may have been an attempt to control land in the area and protect the local Mormon

community from the influence of a boom-and-bust mining town. "Most of the early mining claims of the new Harrisburg mining district were later restaked, overstaked, 'jumped,' sold, abandoned, and otherwise taken over by more serious miners and prospectors" (Proctor and Shirts, 1991, p. 34).

In 1875, J.S. Ferris and Elijah Thomas discovered high-grade silver ore at White Reef (the Leeds Mine), 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 in 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 reporting on the Stormont mines at East Reef (see figure 12c), and the relative ease of finding ore that shows little expression at the surface, Rothwell (1880, p. 10) stated that "The property has been operated at intervals along its entire length by shafts and inclines sunk by tributers, who paid as a royalty 25 percentum of the net cash received from the ore produced. Each of these tributers sank his shaft without the slightest knowledge as to whether the beds contained pay-ore at the point selected for opening; and yet out of about twenty such shaftings, made at more or less regular intervals, there were but two or three that did not find "pay" on reaching the first ore-bearing bed, and even these few found silver-bearing rock which, though of too low grade to be available for tributers, would generally leave a margin of profit upon a fair cost of mining and milling."

Stucki (1966) and Proctor and Shirts (1991) described the chaotic period from 1871 to 1877 when the mines changed hands rapidly and many claims were called "poor man's mines" because they could be worked with little capital. The main problem faced by these early miners was the long distance required to ship ore to Pioche or Salt Lake City for processing. Eventually, big capital entered the scene, beginning with the Leeds Mining Company of San Francisco who built a mill on Leeds Creek in 1877 (see table 2). 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 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 1,500, comparable to the mining towns of Park City and Bingham at the time.

The principal mining activity at Silver Reef

Table 2. Silver Reef mills (after Rolker, 1881 and Proctor and Shirts, 1991)

Name	Place	Started Operations	Equipment	Ceased Operations
Leeds	Leeds Creek	February 1877	5-stamp steam	Converted to leaching plant 1886
Buckeye (Pioneer)	South of Leeds	October 1877	3-stamp steam	June 1879; dismantled for use at Stormont
Barbee and Walker	North end of White Reef on east side	March 1878	5-stamp steam	Burned down June 23, 1879; re-opened February 1880; ceased 1908; dismantled 1916
Christy	East of Silver Reef town	January 1878	5-stamp steam	March 1889
Stormont	East Reef at Virgin River	June 1877	10-stamp, with sluice boxes to process tailings	March 1887

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. Browning (1925) suggested that leakage from irrigation canals may have caused or contributed to high water levels at Buckeye Reef. 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.

Unpublished consultant reports of DeCamp (1919), Crane (1920), and Browning (1925) discuss limited activity in the district during the early 1900s. The Silver Reef Consolidated Mining Company gained control over much of the western part of the district in 1916, and through 1921 worked to rehabilitate and sample many of the mines on White Reef. In 1929, American Smelting and Refining Company (ASARCO) sank a 540-foot-deep shaft at White Reef that connected to the old Savage mine at Buckeye Reef and to the Leeds mine at White Reef. They drained the old mines and re-evaluated the district's potential, but dropped the option in the early 1930s.

In the early 1950s, the U.S. Atomic Energy Commission initiated a drilling program to evaluate uranium mineralization in the Springdale Sandstone in the Silver Reef mining district (Stugard, 1951; Poehlmann and King, 1953). Poehlmann and King (1953) reported that 357 holes were drilled totaling over 25,000 feet, and that 14 holes cut ore-grade U_3O_8, disclosing two new ore bodies. In addition, uranium mineralization was identified in 22 holes and many holes encountered ore-grade silver and vanadium. Most uranium exploration was in the Springdale Sandstone, particularly at Big Hill and Tecumseh Hill and on the nose of the Virgin anticline, but the white, middle sandstone bed of the Petrified Forest Member was extensively prospected at and to the north of East Reef, in section 17, T. 41 S., R. 13 W. Poehlmann and King (1953) noted that uranium mineralization was controlled by lithology and structure, with faults and joints serving as conduits for transporting mineralized solutions to favorable beds. Carnotite, the predominant uranium and vanadium mineral, appears as a cementing agent, and, more commonly, as a fracture filling and in association with carbonized wood fragments. Western Gold and Uranium, Inc. purchased many of the old mines in 1950 and shipped at least 2,500 pounds of uranium oxide and small amounts of other metals (Stucki, 1966; Houser and others, 1988; Eppinger and others, 1990) (see also table 3). They ceased operations at Silver Reef in 1958.

5M, Inc. (minerals, mining, milling, melting, manufacturing) of Hurricane, Utah, acquired claims from Western Gold and Uranium Corporation and was incorporated in 1973. In 1979, when silver was at an all-time high of about $50/ounce, 5M Inc. established a 250,000-ton leach-pad operation between White and Buckeye Reefs to process tailings, but this venture closed with the collapse of the Hunt Brothers scheme to control silver prices. In addition, 5M Inc. proposed a uranium and vanadium recovery operation, but the necessary Nuclear Regulatory Commission permits were never obtained and the operation never materialized. 5M Inc. records indicated that their holdings, including mine dumps and the Last Chance Pit on Buckeye Reef, ranged from a high of 39.25 ounces silver per ton to a low of 0.07 ounces silver per ton; the average of 61 samples was 3.66 ounces silver per ton. Traces of gold recovered were typically less than 0.01 ounces per ton. In 1984, Kerley Industries assumed leases and property from 5M Inc. and posted a reclamation bond. Kerley performed some exploratory drilling in 1984-85, but no subsequent mine development occurred.

In 1998, Silver Standard Resources, Inc., based in Vancouver British Columbia, drilled exploratory holes northwest of Leeds but did not pursue mining operations. A modest amount of mining interest in Silver Reef and East Reef by individuals continues, but these could be classed as hobbyist miners or speculators. Some unpatented claims are active, but production is probably negligible. Given the resi-

Table 3. Production from the Silver Reef mining district, compiled and estimated by Robert Gloyn, Utah Geological Survey.

Period	Tons mined	Ag (ounces)	Cu (pounds)	Au(ounces)
1875-1909	-	7,195,736	10,676,000	-
1910-1914	No production reported			
1915	56 estimated	378	35,568	-
1916	96	349[1]	8037[1]	-
1917	300	44[1]	80,000[1]	-
1918	No production reported			
1919	277	208	137,786	-
1920	116[1]	66	76,780	-
1921	41	532	-	-
1922	16	480	-	-
1923-1948	No production reported			
1949	240	2,328	11,000	1
1950	No production reported			
1951	52	369	2,000	1
1952-1955	No metallic minerals production reported, but Wyman (1954) reported 641 tons mined between 1953-54			
1956	706	11,257	3,600	4
1957	14,596	72,835	27,500	3
1958	22,000	56,040[1]	-	1
1959-1962	No production reported			
1963[2]	339	5,889	4,000	-
1964[3]	2,545	3,750	18,000	-
1965-1966	No reported production			
1967[3]	1,500	3,680	2,000	-
1968[3]	5,000 estimated	9,351	4,000	-
1969-1975	No production reported			
1976	Unknown			
1977-1978	No production reported			

[1] District production of silver, copper, and gold estimated from total county production of each commodity and total ore tonnage from individual districts.
[2] 200 pounds of lead were produced in 1963.
[3] Production for 1964, 1967, and 1968 from Washington County but not specifically stated as Silver Reef.

dential growth around Silver Reef, historical and ecological concerns, and the price of silver, it seems unlikely that full-scale corporate mining will return to the area in the foreseeable future.

Major Mines

On the basis of production and aerial distribution, Proctor (1953) divided the Silver Reef mines into six main groups (figure 12a, b, c):

1. The Thompson-Cobb area, including the South Thompson, Thompson, Cobb, Newton, Nichols, and McNally mines on White Reef.
2. The Leeds and Leeds No. 2 mines on White Reef.
3. The Barbee and Walker area on White Reef (figure 13).

Figure 13. View northwest to the Barbee and Walker mine at White Reef, approximately 1880. Mine hoisting works are in small building at top of reef, above the five-stamp mill. The building on the left is the blacksmith shop and the building on the right is the assay office. Note tailings from mill in foreground. Used by permission, Utah State Historical Society, all rights reserved.

4. The California-Kinner group, including the California, Maggie, Last Chance, Savage, Buckeye, and Kinner mines on Buckeye Reef.
5. Tecumseh Hill area, including the Silver Flat and very large Tecumseh mine, which covers parts of the Tecumseh, Manhatton, Stormy King, Silver Flat, and Manhatton patented claims.
6. The East Reef area, including the Vanderbilt, Toquerville, Duffin, Brisacher, and Maud mines.

The main ore deposits of the Silver Reef mining district are in Buckeye and White Reefs, with smaller deposits at Butte and East Reefs (Proctor, 1953). Most of the important mines in the Silver Reef mining district were under company management during the main productive period of the district. Many of these mines were interconnected and production came from a group of mines rather than a single mine. All of the mines were shallow, the deepest (probably the Maggie mine) reaching about 330 feet below the surface and about 900 feet down dip (Browning, 1925). The California-Kinner group includes some of the most important producers in the district.

Ore Processing

Silver ore of the Silver Reef mining district was processed principally in pan-amalgamation mills. The ore was hand sorted, with lower-grade ores and barren sandstone remaining on the dumps or in the stopes to support the roof of the mines. Only the higher-grade ore, generally 20 ounces 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) (figure 14). 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.

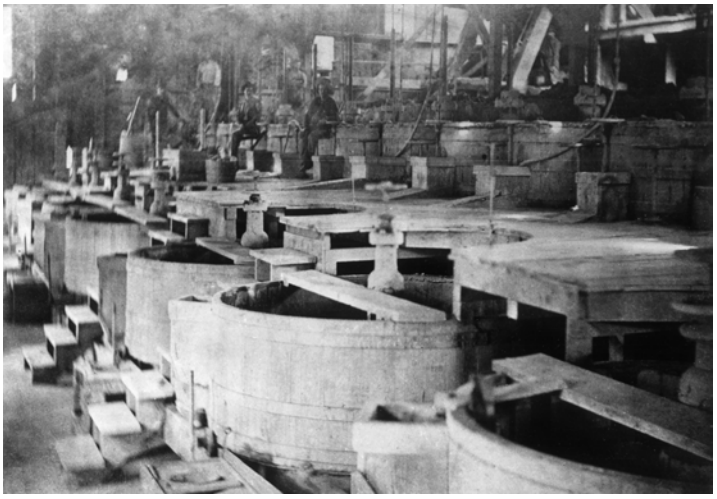

Figure 14. Wooden half-barrels called mullers, in which pulverized ore, water, and reagents were mixed, yielding amalgam of silver and mercury. Silver Reef mining district, approximately 1880, mill unknown. Used by permission, Utah State Historical Society, all rights reserved.

Because they had access to water of the Virgin River, the Stormont mill employed sluices to further process tailings (figure 15). The mills typically recovered only about 80% of the assayed silver. There is very little information on copper in the district, and some reports mentioned that copper was not recovered by the early mills as it interfered with ore

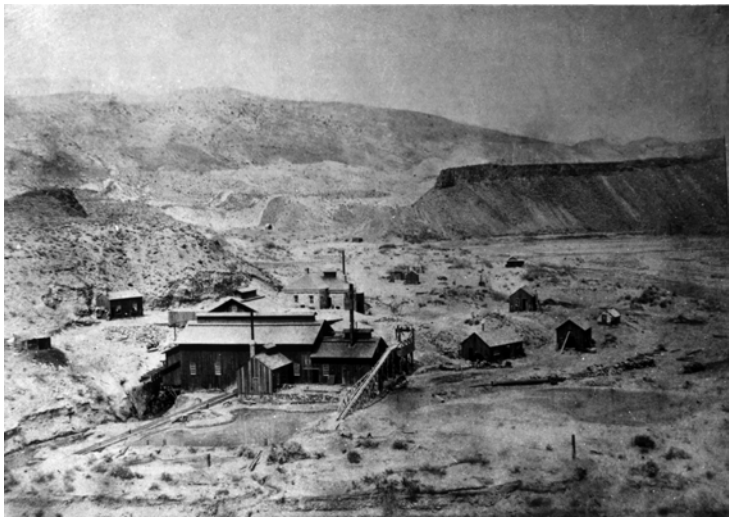

Figure 15. View northeast of the Stormont mill, 1880. Small community of Babylon is on terrace beyond mill. Note beautiful stone building of company headquarters; little evidence remains of the mill or nearby buildings. Mesa on right is capped by basaltic flow that erupted from Volcano Mountain, southwest of Hurricane, about 300,000 years ago. Used by permission, Utah State Historical Society, all rights reserved.

processing. In fact, Browning (1925) reported that copper ore was intentionally left in the stopes of White Reef even where associated with high silver concentrations. However, production reported in the U.S. Bureau of Mines Minerals Yearbooks indicates that over 10 million pounds of copper were produced during the early, productive years of the district.

Stucki (1966) and Proctor and Shirts (1991) discussed several early attempts to construct mills, including water-powered stone arrastra wheels on Quail Creek and Ash Creek. Of these, the Dupaix and Spicer Mill, an eight-stamp water-powered mill on Ash Creek about 1.5 miles south of Toquerville, operated for a short time in mid-1877, but failed due to the distance required to haul ore. Five mills were eventually established within the Silver Reef mining district (table 2) and are described by Stucki (1966) and Proctor and Shirts (1991).

Western Gold and Uranium Corporation began a flotation process to recover silver and uranium in late 1956. Wyman (1958), superintendent for the company, noted that their main ore supply was from underground mines at Big Hill and that by that time they had milled about 15,000 tons of ore. Sodium sulfide and Xanthate 5 reagents were used. A ton of yellow cake, representing uranium recovered from about 50 tons of ore, averaged 400 ounces silver and about 10% copper (Intermountain Industry and Mining Review, 1958).

5M Inc. built a sulfuric acid leach-pad operation between White and Buckeye Reefs in 1979. The pad consists of an asphalt lining 1.5 to 2 inches thick and about 220 feet wide by 600 feet long, upon which is piled about 250,000 tons of ore and tailings. We found no information on production from this facility, but the U.S. Bureau of Land Management in St. George has extensive files concerning reclamation of the site.

Production Statistics

From 1875 to 1910, the Silver Reef mining district produced over 7 million ounces of silver, nearly 70 percent of which came from the prolific Buckeye Reef (Heikes, 1920). The ore averaged 20 to 50 ounces silver per ton, but varied from only a few ounces to about 500 ounces per ton (Proctor and Brimhall, 1986; Eppinger and others, 1990). Wyman (1958) estimated that 600,000 tons were mined during the productive period of the district. Sporadic production between 1949 and 1968 amounted to about 10 ounces of gold, 165,000 ounces of silver, 34 short tons of copper, and at least 2,500 pounds of uranium oxide (U.S. Bureau of Mines Minerals Yearbook, various years).

Rothwell (1880) summarized early silver production from the district (table 4). In addition, Rolker (1881) noted that Barbee earned $17,000 from Salt Lake smelters for ore shipped in December 1875 and January 1876, and $23,000 from Pioche smelters for ore shipped in 1876. Heikes (1920) summarized silver production prior to 1910 (table 5). In preparing a report for the U.S. Geological Survey's (USGS) Mineral Resource Data System, Robert Gloyn used U.S. Bureau of Mines Minerals Yearbook and USGS Mineral Resources data to summarize production from the district for the period 1875 to 1987 (table 3).

Table 4. Silver production (ounces) of Silver Reef, 1877-1879 (Rothwell, 1880)

	1877	1878	1879
January	-	55,175	62,666
February	18,427	56,776	84,394
March	31,095	86,872	85,441
April	23,070	76,897	88,888
May	20,743	82,209	83,163
June	32,514	81,169	74,936
July	28,218	71,401	67,878
August	34,704	73,031	62,031
September	48,687	67,117	58,874
October	56,985	79,648	63,239
November	45,859	67,528	69,449
December	31,476	86,167	65,742
Total	371,778	883,990	866,702

Table 5. Silver production of Silver Reef, 1875-1909 (Heikes, 1920)

Period	Silver Recovered (ounces)	Total value[1]
1875-1880	3,319,054	$3,808,890
1881-1890	3,590,598	$3,966,118
1891-1900	206,069	$ 158,140
1901-1909	95,742	$ 53,994
Total	7,211,463	$7,987,142

[1] Average annual commercial silver price used to calculate total for each calendar year.

RECLAMATION

In the past three decades Silver Reef has experienced a second economic and population boom. Drawn by the striking scenery, mild climate, and historical setting, people are resettling a community abandoned for a century. Dozens of new homes in two subdivisions bracket the mining district and encroach to within 300 feet of mine shafts. The new residents embrace the area's past. They are restoring historic buildings in the old townsite and have established a museum that brings tourists by the busload to the old mining district (figure 16). Residents and visitors commonly walk, jog, and ride horses, mountain bikes, and ATVs through the area. Prior to reclamation, Utah Division of Oil, Gas and Mining, Abandoned Mine Reclamation Program (UAMRP) staff frequently observed people inside the mines.

Figure 16. The original Wells Fargo Express building, restored and converted to a museum and art gallery. The historic Barbee-Walker mine dump is visible in the background just to the right of the tree.

The landscape the miners left behind is at once historic, romantic, and deadly. In the late 1980s, concerned local residents brought the area to the attention of the UAMRP. The UAMRP is the state agency responsible for correcting problems created by past mining activities. The UAMRP concurred with the local residents' concerns and identified the area as a priority for reclamation. Reclamation in this case meant protecting public safety by closing mine openings. Legal restrictions attached to the UAMRP's funding limit noncoal reclamation to physical safety hazard abatement and preclude remediation of environmental problems or restoration of land back to pre-mining conditions. The UAMRP targeted the main Silver Reef area as the first phase of the work (Silver Reef Project, 1996-97), to be followed by the east limb of the anticline, from Leeds south to the Virgin River (East Reef Project, 2000). Over 500 mine features were inventoried at Silver Reef and 276 at East Reef. At the same time, the U. S. Environmental Protection Agency and the Minerals Regulatory Program of the Division of Oil, Gas and Mining were evaluating the defunct 5M Inc. heap leach facility, and the Division of Environmental Response and Remediation of the Utah Department of Environmental Quality was evaulating several abandoned mill tailings sites for environmental remediation action.

Wright (1992) briefly described early reclamation efforts at Silver Reef. Rohrer (1997) described a unique combination of circumstances that created special challenges for reclamation planning and execution. For instance, the Silver Reef mining district is a historic site eligible for listing on the National Register of Historic Places. Silver Reef is home to Utah's third largest maternity colony of the Townsend's big-eared bat, *Corynorhinus townsendii*, a species considered imperiled in the state. Moreover, much of the East Reef Project lay within the newly established Red Cliffs Desert Reserve, a preserve set up for the Mojave desert tortoise, *Gopherus agassizii*, a threatened species protected under the Endangered Species Act. The district is sandwiched between two subdivisions whose residents regularly explore the area, and many residents are strongly protective of the area's scenic and historic values. Mine openings are numerous and densely packed, commonly located within a few feet of each other, which made precise site identification and mapping mandatory (figure 17). Miners used a variety of methods to access the silver ore and consequently there is a range of mine openings (adits, deep and shallow shafts, inclines, pits, stopes), as well as broad areas prone to subsidence, which complicated the engineering of mine closures.

Much of the historical interest and value of Silver Reef derives from its surviving mining landscape, the aggregate appearance of mine openings, mine dumps, structures, and other features on the land. This is in turn a function of the geology and mining technologies used. For example, the sandstone tended to break into cobble-sized tabular and angular

Figure 17. Photo illustrating the density of mine features at Silver Reef. Seven separate mine openings, now closed, are visible.

blocks when blasted. These blocks stack easily. Consequently, mine dumps and waste rock piles often feature stacked-rock retaining walls. Since the ore-bearing rock generally occurred in paleostream channels, stopes are broad and planar. To support the roof, miners backfilled mined-out areas with the same angular waste rock, neatly stacked; some of this waste rock was mineralized, but of lower grade (generally less than 20 ounces of silver per ton) and thus not hauled to the surface. The Silver Reef landscape stands in marked contrast to those of other silver mining districts such as Park City and Eureka.

Ironically, the historic status and other constraints at Silver Reef forced the UAMRP to toss normal reclamation convention on its head. Usually the goal of reclamation is to make the mining disturbance disappear. At Silver Reef, the goal was to preserve the mining disturbance while keeping the reclamation invisible. Management of the historic landscape with respect to mine closures meant putting the primary focus on preserving the surface appearance of the mining district at the landscape scale. In short, this meant that alteration of individual mine openings was acceptable as long as the overall appearance of the area from intermediate distances (300 to 3,000 feet) was not changed.

Many techniques pioneered at Silver Reef were adopted and became standard procedure for subsequent UAMRP projects elsewhere in the state. Because of the density and number of mine openings, the key to inventory and subsequent engineering and construction tasks lay in accurately locating, precisely mapping, and permanently identifying each opening. Metal disks bolted to the rock near the opening provided for permanence (the lath and flagging markers also used tended to fade or disappear). A survey-grade global positioning satellite (GPS) system combined with detailed photogrammetric topographic mapping made it possible to unambiguously identify and relocate each mine opening or disturbance.

A successful system was developed to manage effects on cultural resources (Bassett, 1995, 1999). Mine openings were classified into three categories based on the types of cultural features at or near the openings:

Category 1- Site lacks cultural features other than mine opening and its dump.

Category 2- Site has associated retaining walls, timber props, shaft collar cribbing, notches in stone for timbers, machinery mounts, artifacts.

Category 3- Site has complex structural elements such as headframes, visible cribbing and lagging, professionally worked stone retaining walls, horse whim.

This classification allowed numerous less important sites to be freed from constraints and targeted protection measures to sites contributing most to the mining landscape. Where geotechnical conditions allowed, Category 2 and 3 sites were closed with steel grates or masonry walls.

Comprehensive above- and below-ground bat surveys were conducted in winter and summer to identify mine sites used by bats and to rate other sites for their potential for use by bats. Survey data were used to determine where bat-compatible closures were needed. In the East Reef Project, the UAMRP surveyed all work areas and access routes for desert tortoises and followed strict tortoise protection protocols. Interestingly, an incident that occurred during the East Reef Project work illustrates that the mine closure work at East Reef was itself ultimately beneficial to tortoise safety as well as human safety. University of Nevada tortoise researchers working independently of the UAMRP in the East Reef area using radiotelemetry to monitor tortoise activity tracked a tortoise to an abandoned mine shaft. A rescuer rappelled down the shaft and found not one, but two, trapped tortoises. Both had survived a 25-foot fall; one was still alive after apparently being stranded in the shaft for six months.

The UAMRP used several mine closure techniques (table 6). The majority of mines were 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, the projects made extensive use of steel gates and grates, including, at 42 by 47 feet, the largest rebar shaft grate ever built by the UAMRP, which now protects the ASARCO shaft. The grate designs are simple, but also flexible and adaptable to a wide range of situations. They satisfy both the needs of bats and the need to preserve the historic appearance of the mine opening. Grates allow bats to come and go and they maintain ventilation in the mines. Grates are visually unobtrusive, can be fitted around historic elements of an opening, and do not require raiding the dump for materials (figure 18). Finally, the adit grate is designed with a removable, lockable bar to allow re-entry into the mine by authorized people (figure 19). While intended primarily to permit future bat surveys, this feature was a valuable selling point for getting consent from the primary landowner, a mining company, which appreciated the ability to continue to conduct mineral exploration.

Besides the UAMRP mine closure projects, there have been other efforts to address the environmental legacy of mining at Silver Reef. In 1996, the U.S. Environmental Protection Agency, concerned about ground water pollution, capped the 5M Inc. heap-leach pad *in situ* to contain the material and prevent leaching of contaminants (U.S. Bureau of Reclamation, 1996). Other 5M Inc. surface facilities were dismantled and removed in 1997 by the UAMRP, working cooperatively with the Minerals Regulatory Program, using reclamation bonds forfeited by the mine operator. In the spring of 2000, the U.S. Environmental Protection Agency removed Leeds mill tailings from Leeds Creek. The Utah Department of Environmental Quality is currently evaluating several other mill tailings in the area for potential remediation.

Reclamation of the Silver Reef mining district improved public safety while maintaining historic preservation and bat and desert tortoise conservation. Landowner exposure to liability lawsuits was also significantly reduced. Pre- and post-reclamation appraisals of the land show a marked increase in property value directly attributable to the new land uses available as a result of mine closure work. Silver Reef is the single-largest mine closure project undertaken by the UAMRP to date, and in 1997, the U.S. Department of the Interior, Office of Surface Mining, Reclamation, and Enforcement selected Silver Reef as its annual reclamation award winner for the Western Region.

ACKNOWLEDGMENTS

We benefited greatly from the research of geologists and historians who studied the Silver Reef mining district, chief among them the late Paul Proctor.

Table 6. Silver Reef mine closure summary.

	Silver Reef	East Reef
Backfill (manual labor)	158	93
Backfill (heavy equipment)	143	43
Manganese steel adit bat gate (6”x24” grid with re-entry panel)	50	11
Rebar adit grate (8”x8” grid, no re-entry panel)	0	4
Rebar shaft grate (8”x8” grid, no re-entry panel)	88	2
Masonry wall (concrete block or native stone)	20	28
PUF (polyurethane foam) shaft plug	4	0
Other closure	2	3
TOTAL Number of Closures	465	184
No closure (site not hazardous)	71	92
Total mine closure costs	$468,896[1]	$167,184

[1] includes $44,047 for partial demolition and clean-up of 5M Inc. heap-leach operation.

Figure 18. The rebar grate is tremendously versatile. Here a standard grate with concrete grade beam caps the Big Hill shaft. The grate bars are easily fitted around the structural components of the headframe.

Figure 19. Typical adit grate installation designed to keep people out and let bats come and go. A removable bar permits authorized people to enter the mine for bat censuses or mineral exploration.

We appreciate the thoughtful reviews of Grant C. Willis, Michael D. Hylland, and Robert W. Gloyn, each with the Utah Geological Survey (UGS). Special thanks to Bob Gloyn for sharing his summary of mineral production from the district. Thanks to Rick Rymerson, U.S. Bureau of Land Management (BLM), for his assistance with BLM files of the Silver Reef mining district. Jim Parker (UGS) drafted the illustrations. Jan Morse, Utah Division of Oil, Gas and Mining GIS specialist assisted with preparing maps of the major mines of the district. Funding for geologic mapping of the Harrisburg Junction, Hurricane, and Pintura quadrangles, in which the Silver Reef mining districts lies, was provided by the Utah Geological Survey and the U.S. Geological Survey under several cooperative Statemap agreements. Major funding for the Utah Division of Oil, Gas and Mining, Abandoned Mine Reclamation Program's (UAMRP) reclamation efforts, including engineering and cultural studies, mine closure construction, and administrative costs, was provided by grants from the U.S. Office of Surface Mining, Reclamation, and Enforcement. The UAMRP also greatly appreciates the skillful work and sensitivity to delicate cultural and ecological resources demonstrated by its construction contractor, VCM Construction, Kamas, Utah. This paper was written in 2002 and revised in 2003.

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