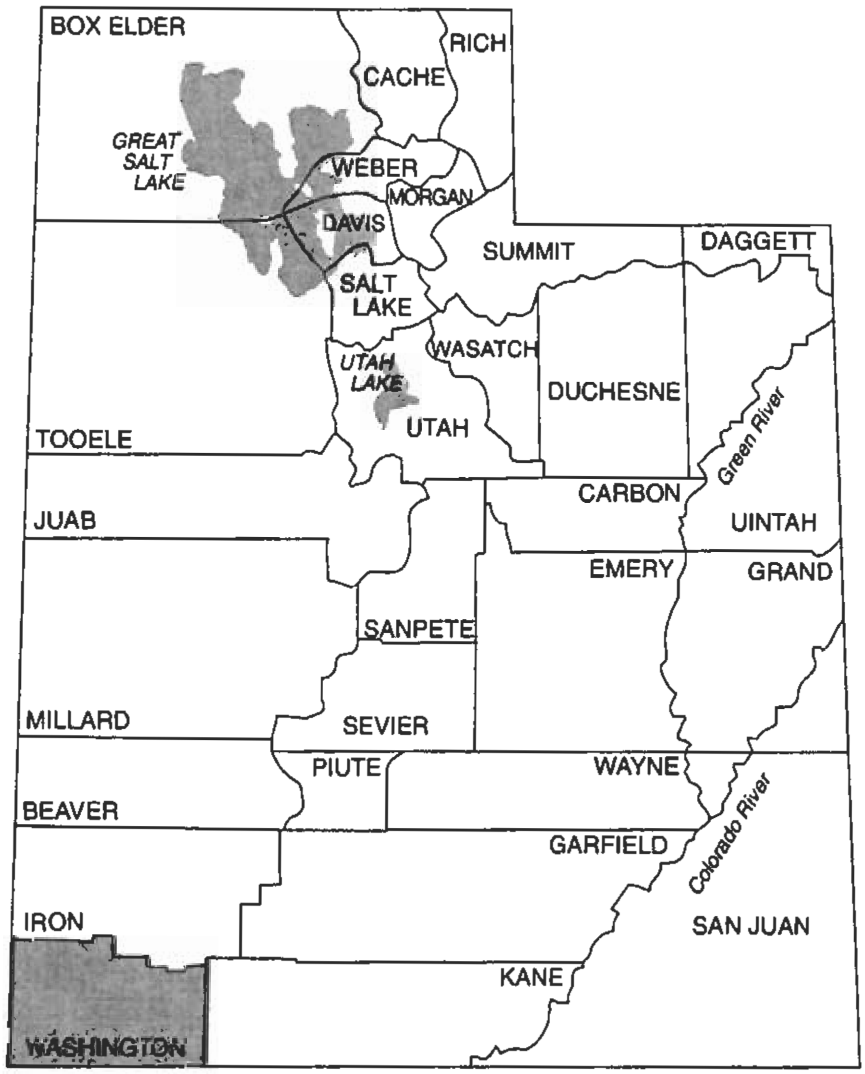
INTERIM GEOLOGIC MAP OF THE HARRISBURG JUNCTION QUADRANGLE, WASHINGTON COUNTY, UTAH

by
Robert F. Biek



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UTAH GEOLOGICAL SURVEY
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UTAH DEPARTMENT OF NATURAL RESOURCES

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Open-File Report

Utah Geological Survey
a division of
Utah Department of Natural Resources
in cooperation with
U.S. Geological Survey

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ABSTRACT

The Harrisburg Junction quadrangle lies in the transition zone between the Colorado Plateau and Basin and Range physiographic provinces. About 8,200 feet (2,550 m) of stratigraphic units ranging in age from the Upper Permian Harrisburg Member of the Kaibab Formation to the Upper Cretaceous Iron Springs Formation are exposed in the quadrangle. Three Pliocene or Pleistocene basalt flows, one cinder cone, and a variety of Quaternary deposits are also present.

The quadrangle lies on an intermediate structural block bounded on the east by the Hurricane fault zone and on the west by the Gunlock-Grand Wash faults. The dominant structural feature in the mapped area, the Virgin anticline, trends northeast through the quadrangle. It is at the core of the anticline, at Harrisburg Dome, where the oldest strata in the quadrangle are found; the dome itself is cut by an east-dipping axial backthrust that has placed Permian Harrisburg strata over the lower red member of the Triassic Moenkopi Formation. Several low-angle, comparatively shallow, west-dipping thrust faults repeat Triassic strata on the northwest flank of the anticline. Jurassic and Cretaceous strata in the northwest portion of the quadrangle dip gently to the north under the southern flank of the Pine Valley Mountains.

Primary economic resources in the quadrangle include sand and gravel, gypsum, building and ornamental stone, and clay. The Silver Reef mining district, which includes the northeastern portion of the quadrangle, produced approximately 8 million ounces (226,800,000 gm) of silver prior to 1910, and small amounts of gold, silver, copper, and uranium oxide between 1949 and

1968. The Navajo Sandstone, Kayenta Formation, and, locally, unconsolidated deposits are important ground water sources in this arid region. The principal geologic hazards in the quadrangle include earthquakes, landslides, rock falls, problem soil and rock, flash floods, and debris flows. Radon may locally be of concern.

CONTENTS

INTRODUCTION

The Harrisburg Junction quadrangle straddles the Interstate 15 corridor in central Washington County and covers an area of about 60 square miles (156 square km) between Washington City and the Town of Leeds (figure 1). The northwest part of the quadrangle laps up onto the southern flank of the Pine Valley Mountains, while the Virgin anticline bisects its southeastern portion. The oldest exposed rocks in the quadrangle, the Permian Harrisburg Member of the Kaibab Formation, are exposed in the core of the Virgin anticline at Harrisburg Dome. Strata become progressively younger across the limbs of the anticline and up onto the Pine Valley Mountains, where the youngest bedrock strata in the quadrangle, the Upper Cretaceous Iron Springs Formation, are exposed. Approximately 8,200 feet (2,500m) of Upper Permian to Upper Cretaceous sedimentary strata are exposed in the quadrangle. Three basalt flows, a cinder cone, and a variety of Quaternary deposits are also present.

(Figure 1 near here)

The Harrisburg Junction quadrangle lies in the transition zone between the Colorado Plateau and Basin and Range Provinces. Strata in the quadrangle, although folded into the northeast-trending Virgin anticline, are characteristic of flat-lying strata of the Colorado Plateau Province. The quadrangle also lies on an intermediate structural block bounded on the east by the Hurricane fault zone and on the west by the Gunlock/Grand Wash fault zone. Several small high-angle normal faults, splays of the Washington fault zone, offset a basalt flow that caps the southern end of Washington Black Ridge. The dominant structural features of the quadrangle, the Virgin anticline and low-angle faults on its northwest limb, formed during the Late Cretaceous Sevier orogeny.

The greater St. George area, including the Harrisburg Junction quadrangle, has been the focus of numerous topical geological investigations, many of which are cited under other sections of this report. Previous geologic maps of the area include that of Bassler and Reeside (1921), who prepared a simplified, 1:62,500-scale geologic map of Harrisburg Dome in their study of oil prospects in Washington County. Dobbin (1939) prepared a small-scale geologic map for his study of the structural geology of the greater St. George area. Proctor (1948, 1953) provided detailed geologic maps of the Silver Reef mining district. Cook (1957) mapped the Pine Valley Mountains, and later expanded that study to map the geology of Washington County at 1:125,000 (Cook, 1960). Haynes (1983) mapped geomorphic features of a portion of the Virgin River basin between Hurricane and Washington. Christenson and Deen (1983) mapped the surficial geology of the greater St. George area (1:31,250), including the southwestern corner of the Harrisburg Junction quadrangle, for their engineering geology report. Budding and Sommer (1986) published a 1:62,500-scale geologic map, modified from unpublished maps of K. W. Hamblin, of portions of the Hurricane and St. George 15-minute quadrangles. In their assessment of the mineral resource potential of the Cottonwood Canyon Wilderness Study Area, Houser and others (1988) produced a simplified 1:24,000-scale geologic map of the northwestern portion of the Harrisburg Junction quadrangle and adjacent areas. Noweir (1990) provided a sketch map of a portion of Harrisburg Dome in his study of the geology of the overthrust belt of southwestern Utah. Eppinger and others (1990) produced a 1:250,000-scale geologic map of the Cedar City 1^0x2^0 quadrangle, which includes the Harrisburg Junction quadrangle. D.B. Hacker is mapping the Saddle Mountain and Signal Peak quadrangles to the north and northwest. Willis and Higgins (1995) provided a detailed 1:24,000-scale geologic map of the adjacent Washington quadrangle and Higgins and Willis (1995) provided a similar geologic map of the St. George quadrangle as part of a multi-year project by the Utah Geological Survey (UGS) to produce detailed geologic maps of the rapidly growing St. George basin. This geologic map is part of that effort and was jointly funded through a cooperative agreement between the UGS and the U.S. Geological Survey under the National Geologic Mapping Act of 1992.

STRATIGRAPHY

Permian

Kaibab Formation

The Kaibab Formation consists of two members, the upper Harrisburg Member and the lower Fossil Mountain Member. Only the Harrisburg Member is exposed in the Harrisburg Junction quadrangle. The Kaibab Formation is late Early Permian to early Late Permian in age.

Harrisburg Member (Pkh): The Harrisburg gypsiferous member was named by Reeside and Bassler (1921) for exposures along the southeast side of Harrisburg Dome; it was later renamed simply the Harrisburg Member by Sorauf (1962). Because Sorauf's type section does not contain a complete section of the Harrisburg Member, Nielson (1981, 1986) established two reference sections. One section, typical of eastern facies along the Hurricane Cliffs, is located in Timpoweap Canyon (figure 1). A second section, typical of western exposures, including those of Harrisburg Dome, is located in Mountain Valley Wash, southwest of Bloomington (figure 1). These reference sections illustrate the fact that rapid east-west facies changes characterize the Harrisburg Member.

The Harrisburg Member consists of slope- and ledge-forming, interbedded gypsum, gypsiferous mudstone, and lesser thin-bedded limestone and cherty limestone that overlies a medial limestone interval. Harrisburg strata form the tightly folded core of Harrisburg Dome where only the upper part of the member, above and including the medial limestone interval, is exposed (figure 2). A wide variety of rock types are found along the crest and flanks of the dome itself, but because of poor exposures and tight folding, relations among them are unclear. The best exposures are located in the east-dipping cuesta immediately east of the dome's axis.

(Figure 2 near here)

On the northeast side of Harrisburg Dome, in the SESESW 1/4 section 9, T.42S., R.14W., the east-dipping cuesta is capped by about 30 feet (9m) of very rough weathering, thick to very thickly bedded, cherty limestone breccia that overlies very coarsely crystalline limestone that lacks chert. This carbonate sequence corresponds to the medial limestone described by Nielson (1981). The chert occurs as very coarse sand- to pebble-size angular fragments that forms both clast- and matrix-supported limestone breccias. The chert is white- to light-gray, but weathers moderate-yellowish-brown with iron-manganese stains. The host limestone is pale-red to moderate-orange-pink and weathers grayish-orange-pink to light-brownish-gray; no fossils were found in these beds. These limestones and cherty limestones are in fault contact with the lower red member of the Moenkopi Formation, which here consists of about 30 feet (9m) of pale- to dark-yellowish-orange mudstone and siltstone underlain by about 40 feet (12m) of moderate- to dark-reddish-brown gypsiferous mudstone and siltstone. The fault is interpreted as an east-dipping axial backthrust.

When traced southwest, to the NESW 1/4 section 17, T.42S., R.14W., these limestones appear thinner and more cherty, with both thin-bedded and nodular chert. There, they are underlain by about 50 feet (15m) of additional Harrisburg Member strata that consist of interbedded, laminated and massive gypsum and lesser thin-bedded, laminated limestone. About 200 feet (60m) of strata of the lower red member of the Moenkopi Formation are exposed below the Harrisburg Member. The upper about 20 feet (6m) are yellowish-orange gypsiferous mudstone and siltstone, similar to exposures to the northeast, that are also assigned to the lower red member (figure 3).

(Figure 3 near here)

In addition to the cherty limestone breccia and coarsely crystalline limestone described above, other limestone varieties are also found in the medial limestone interval along the main axis of Harrisburg Dome, especially along its crest. These include a brown-weathering, medium-gray, slightly fetid limestone that occurs in thin, laminated beds, a grayish-orange-pink intraformational limestone conglomerate, and a grayish-orange-pink to pinkish-gray oncolotic limestone. Similarly colored fine- to medium-grained limestone, with abundant light-brown- to moderate-reddish-brown-weathering, light-gray chert nodules and lenticular beds are common; silicified fenestrae bryozoans are occasionally found in these beds.

Outcrop patterns suggest that gypsiferous strata that normally overlie the medial limestone interval have been partially removed by erosion associated with the Permo-Triassic unconformity. Poorly exposed and contorted gypsum and gray gypsiferous mudstones, which lie stratigraphically above the medial limestones, form the bulk of exposures along the southern flanks of the dome. These strata are largely missing near the center of the dome in the NW 1/4 section 16, T.42S., R.14W., and are only locally preserved along the dome's northern end. This apparent overall northward thinning of gypsiferous strata above the medial limestone interval may be due in part to structural thinning of incompetent beds, but is likely mostly a result of pre-Moenkopi erosion. To the southwest, in the St. George and White Hills quadrangles, Higgins and Willis (1995) and Higgins (1997) documented in excess of 600 feet (182 m) of pre-Moenkopi erosion that locally entirely removed Harrisburg strata.

The incomplete section of Harrisburg strata exposed along the southeastern flank of Harrisburg Dome is about 250 feet (75m) thick. Reeside and Bassler (1921) assigned about 270 feet (82m) of mostly cherty limestones to the Harrisburg Member at Harrisburg Dome. Nielson (1981) measured two partial sections of Harrisburg strata on the Harrisburg Dome. The Harrisburg Member varies from 0 to about 300 feet (0-91 m) thick in the St. George quadrangle to the southwest (Nielson, 1981; Higgins and Willis, 1995). The Harrisburg Member was deposited in a complex sequence of shallow marine and sabhka environments (Nielson, 1981; 1986).

Triassic

The Permo-Triassic boundary in southwestern Utah is marked by a major disconformity that represents about 10 million years (Nielson, 1981). Erosion produced an irregular surface with several hundred feet of relief upon which conglomerates and breccias of the Rock Canyon Conglomerate Member of the Moenkopi Formation were locally deposited in paleocanyons. The overlying Timpoweap Member of the Moenkopi Formation was deposited in broader paleovalleys. However, Rock Canyon Conglomerate and Timpoweap strata are not exposed, and may not have been deposited, at Harrisburg Dome.

Moenkopi Formation

The Moenkopi Formation of southwestern Utah consists of three transgressive members - the Timpoweap Member, Virgin Limestone Member, and Shnabkiab Member - separated by three informally named red bed members (Lambert, 1984) that locally overlie the basal Rock Canyon Conglomerate Member. The transgressive members generally thicken, and the red bed members thin, from east to west across southwestern Utah. The lower two members of the Moenkopi Formation, the Timpoweap Member and Rock Canyon Conglomerate Member, are not exposed, and may not have been deposited, at Harrisburg Dome.

Reeside and Bassler (1921) measured 2,035 feet (620m) of Moenkopi strata on the south side Harrisburg Dome, and although it is difficult to be certain, their member contacts roughly coincide with those used in this report. Higgins and Willis (1995) reported that in the St. George quadrangle to the southwest, the seven members of the Moenkopi Formation total 2,150 feet (650 m) thick.

Lower red member (Trml): The lower red member forms a prominent strike-valley that encircles Harrisburg Dome and is almost completely concealed by younger Quaternary deposits. Isolated exposures of the upper part of the member are found in the NESW 1/4 section 9, T.42S., R.14W., in the SWNENE 1/4 section 9, T.42S., R.14W., and in several drainages that cut through the east flank of the dome. The best exposures of lower red strata are found along the west side of the east-dipping cuesta imediately east of the anticinal axis. These exposures show the lower red member consists of interbedded, laminated to thin-bedded, moderate-reddish-brown mudstone and siltstone with local, thin, laminated, light-olive-gray gypsum beds and veinlets; the member is locally irregularly colored yellowish orange. The upper contact was placed at the base of the lowest Virgin Member limestone bed.

Incomplete exposures make thickness determinations of the lower red member at Harrisburg Dome difficult. Based on outcrop patterns, the member appears to vary from about 150 to 200 feet (45-60m) thick. Along the flanks of the Bloomington Dome to the southwest, lower red strata vary in thickness from 25 feet (8 m) to 300 feet (91 m), probably due to attenuation faulting (Higgins and Willis, 1995). In the White Hills quadrangle, Higgins (1977) reported lower red thicknesses that varied from 0 to 200 feet (0-61 m) due to paleotopography. Reeside and Bassler (1921) assigned 335 feet (102 m) to this member at Harrisburg Dome and noted that the lower 60 feet (18 m) consists of yellow gypsiferous shale with thin black limestone beds. Their description suggests that these lower beds may belong to the Timpoweap Member. A few tens of feet (a few meters) of yellowish-brown, silty, gypsiferous beds, and thin-bedded, medium- to coarse-grained, intraformational pebbly sandstone and sandy limestone do overlie typical Harrisburg strata on the southeastern flank of the dome; however, thin limestones characteristic of the Timpoweap were not observed. I assign the silty gypsiferous beds to the lower red member and the underlying limy beds to the Harrisburg Member. The lower red member is unconformably overlain by the Virgin Limestone Member throughout southwestern Utah (Stewart and others, 1972). The lower red member was probably deposited in a tidal flat environment.

Virgin Limestone Member (Trmv): The Virgin Limestone Member forms a low, prominent cuesta that encloses all but the southern end of Harrisburg Dome. It weathers to well exposed limestone ledges and poorly exposed siltstone and mudstone slopes; it is locally concealed by younger Quaternary deposits, producing an outcrop pattern that thickens and thins irregularly. Along the dome's southwestern side, in the SW 1/4 section 17, T.42S., R.14W., three limestone ledges are exposed. The lower ledge is about 8 feet (2.4 m) thick and is overlain by about 50 feet (15 m) of very poorly exposed mudstone or siltstone; the two overlying limestone ledges are each about 2 feet (0.6 m) thick and are separated by about 22 feet (7 m) of similarly poorly exposed strata. Elsewhere, only the lower, and rarely middle, limestone beds are exposed.

Virgin limestones vary from very pale orange to yellowish-gray, finely crystalline limestone and silty limestone, to light-gray to light-olive-gray, coarsely crystalline, fossiliferous limestone with locally abundant circular and five-sided crinoid columnals, gastropods, and brachiopods.

Along the southwestern flank of Harrisburg Dome, the Virgin Limestone Member is about 85 feet (26 m) thick. In the St. George quadrangle to the southwest, Higgins and Willis (1995) report the Virgin Limestone Member is 134 feet (30 m) thick. The member varies considerably in thickness along the flanks of the Bloomington Dome due to structural complications; there, Higgins and Willis (1995) reported the Virgin Limestone Member varies from 225 feet (68 m) to an attenuated 25 feet (7.5 m) thick. Reeside and Bassler (1921) assigned 160 feet (49 m) of beds at both the Harrisburg and Washington Domes to this member. The Virgin Limestone is conformably overlain by the middle red member (Porborski, 1954; Stewart and others, 1972). The contact was placed at the top of the uppermost limestone bed.

Middle red member (Trmm): The middle red member forms very poorly exposed slopes in the core of the Virgin anticline. The best exposures are found along the southeastern side of Harrisburg Dome; elsewhere, middle red strata are mostly concealed beneath younger alluvial deposits. It consists of interbedded, laminated to thin-bedded, moderate-reddish-brown to moderate-reddish-orange siltstone, mudstone, and very fine grained sandstone. Thin, white- to greenish-gray gypsum beds and veins are common, especially in the upper part of the member.

The upper contact is nowhere well exposed in the Harrisburg Junction quadrangle. I placed the contact at the base of the first thick gypsum bed of the Shnabkiab Member. It appears sharp on aerial photographs and corresponds to a change from moderate-reddish-brown siltstone below to banded greenish-gray gypsum and pale-red mudstone above. Stewart and others (1972, p. 19) noted that in many places this contact corresponds to a transition zone that is 100 to 300 feet (30-100 m) thick. The middle red member is 400 to 500 feet (121-151 m) thick along the southeastern flank of Harrisburg Dome. Reeside and Bassler (1921) assigned 435 feet (133 m) of beds near Harrisburg Dome to what is now known as the middle red member. To the southwest in the St. George quadrangle, the middle red member is 372 feet (113 m) thick along the northeast side of Bloomington Dome (Higgins and Willis, 1995).

Shnabkaib Member (Trms): The Shnabkaib Member is well exposed in the core of the Virgin anticline where it forms a striking, red- and white-banded sequence of interbedded pale-red to moderate-reddish-brown, slope-forming mudstone and siltstone and white- to greenish-gray, ledge- or ridge-forming gypsum. Where protected by the resistant Shinarump cuesta, the Shnabkaib Member forms steep, ledgy slopes; elsewhere, and more commonly, it weathers to low, rounded, strike ridges that are upheld by resistant gypsum beds. The type section of the Shnabkaib Member is located at Shinob Kibe hill immediately south of the Harrisburg Junction quadrangle, in section 24, T.42S., R.15W. It was originally named the Shnabkaib shale member by Reeside and Bassler (1921), who stated that the name *Shnabkaib* is probably a corruption of an old Indian name meaning *Coyote Mountain*. Gregory (1950), however, indicated that the name *Shnabkaib* may be a misspelling of the Piute *Shinob* (Great Spirit) and *Kaib* (mountain), loosely translated as *Mountain of the Lord.*

The Shnabkaib Member consists of a repetitive sequence of interbedded pale-red to moderate-reddish-brown, slope-forming mudstone and siltstone and white- to greenish-gray, ledge- or ridge-forming gypsum. The mudstones and siltstones are commonly gypsiferous and generally occur in laminated to thin beds; strata with ripple cross-stratification are rarely exposed. Gypsum occurs as laterally continuous, massive beds; finely laminated, commonly silty or muddy beds; nodular horizons; and as secondary cavity fillings and cross-cutting veins. The gypsum beds vary from less than one inch to about 9 feet (0.01 to 3 m) thick. The Shnabkaib Member also contains thin, laminated, light-gray dolostone beds that, being more resistant than enclosing rocks, weather out and accumulate at the surface. Shnabkaib strata weather to soft, punky, gypsiferous soils.

The upper contact is gradational and was placed at the top of the highest, thick gypsum bed, above which are found laminated to thin-bedded, moderate-reddish-brown mudstone and siltstone beds of the upper red member. The contact marks a prominent color change from generally lighter colored Shnabkaib strata below, which are dominated by white, greenish-gray, and pale-red hues, to darker colored upper red beds above, which are uniformly colored moderate reddish brown.

Due to small-scale but widespread deformation in the core of the Virgin anticline, the thickness of the Shnabkaib Member is difficult to determine in the Harrisburg Junction quadrangle. I estimate it to be 600 to 700 feet (182-212 m) thick. Lambert (1984) reported the Shnabkaib Member is about 750 feet (128 m) thick on the east flank of the Washington Dome, and a comparable thickness east of Hurricane, at Hurricane Mesa and Little Creek Mountain.

Higgins and Willis (1995) reported the Shnabkaib Member is 996 feet (302 m) thick in the St. George quadrangle to the southwest. Proctor and Brimhall (1986) estimated Shanabkaib strata to be about 480 feet (146 m) thick south of the Silver Reef mining district. Reeside and Bassler (1921) assigned 630 feet (192 m) to the member at the Harrisburg Dome. Lambert (1984) suggested that Shnabkaib strata were deposited in a variety of supratidal, intertidal, and subtidal environments on a broad, coastal shelf of very low relief.

Upper red member (Trmu): The upper red member is well exposed below cliffs of Shinarump Conglomerate in the core of the Virgin anticline. Some of the best and most accessible exposures are found where State Highway 9 cuts through the flanks of the Virgin anticline. With the exception of a lower, cliff-forming yellow sandstone described below, the lower part of the member generally forms ledgy slopes. The upper part of the member forms ledges and low cliffs.

The upper red member consists of a generally upward-coarsening sequence of interbedded, mostly thin- to medium-bedded, uniformly colored, moderate-reddish-orange to moderate-reddish-brown siltstone, mudstone, and very fine- to fine-grained sandstone; a massive, yellow sandstone, described below, is present near the base of the member. Planar, low-angle, and ripple cross-stratification is common, as are well preserved ripple marks.

A prominent, normally cliff-forming, pale-yellowish-orange to grayish-orange, fine-grained sandstone with leisegang banding occurs about 50 feet (15m) above the base of the member; this sandstone is informally known as the "Purgatory Sandstone" (figure 4). It is medium to massively bedded with both planar and low-angle cross-stratification and includes minor, similarly colored, thin- to medium-bedded siltstone and very fine grained sandstone interbeds. This unit is 108 feet (33 m) thick southeast of the Quail Creek reservior, in the NE 1/4 section 35, T.41S., R.14W. It appears to thin to the south, probably due to faulting southwest of State Highway 9 along the west flank of the Virgin anticline, and appears to pinch out entirely in the NESE 1/4 section 8, T.41S., R.14W. This yellow sandstone reappears west of the county landfill, in the SE 1/4 section 8, T.41S., R.14W., and thickens to about 100 feet (30 m) feet thick near the southern boundary of the quadrangle. It appears to maintain a relatively constant thickness along the east flank of the anticline.

(Figure 4 near here)

The upper red member is 397 feet (121 m) thick southwest of the Quail Creek reservoir, in the SWSENW 1/4 section 35, T.41S., R.14W. Higgins and Willis (1995) reported the member is 363 feet (110 m) thick south of St. George, on the northwest flank of the Virgin anticline, in the SWNWNE 1/4 section 7, T.43S., R.15W. Proctor (1953) measured 376 feet (115 m) of what are now called upper red strata north of State Highway 9. Proctor and Brimhall (1986) reported just 284 feet (87 m) of upper red strata on the east limb of the Virgin anticline, apparently near Harrisburg Gap. Reeside and Bassler (1921) assigned 475 feet (145 m) to this member near

Harrisburg Dome. Despite these widely varying thicknesses, which may be due in part to differences in placing the lower contact, the upper red member appears to maintain a relatively constant thickness of about 400 feet (122 m) in the quadrangle.

Chinle Formation

The Chinle Formation of southwestern Utah consists of the Shinarump Conglomerate and the overlying Petrified Forest Members. The Shinarump Conglomerate forms a prominent cuesta along the flanks of the Virgin anticline, whereas the Petrified Forest Member is generally poorly exposed in adjacent strike valleys. The Chinle Formation is Late Triassic in age (Stewart and others, 1972) based principally on vertebrate and plant remains. Dubiel (1994) assigned Chinle strata to the early Carnian to late Norian with an unconformity of several million years separating the two members; no evidence of such an unconformity was found in the quadrangle.

Shinarump Conglomerate (Trcs): Because of its resistance to erosion, the Shinarump Conglomerate forms a prominent cuesta along both flanks of the Virgin anticline. It is nearly everywhere well exposed in cliffs along the interior of the anticline. The best exposures of the lower contact are found where State Highway 9 cuts through both the east and west flanks of the Virgin anticline. The upper contact is only well exposed at the southern end of Washington Black Ridge, in the SESE 1/4 section 13, T.42S., R.15W.

The Shinarump Conglomerate consists of a laterally and vertically variable sequence of cliff-forming, fine- to very coarse-grained sandstone, pebbly sandstone, and lesser pebbly conglomerate. It is commonly thick to massively bedded with both planar and low-angle cross-stratification, although thin, platy beds with ripple cross-stratification occur locally. The sandstones are predominantly pale- to dark-yellowish-orange, but pale-red, grayish-red, very pale orange, and pale-yellow-brown hues are common. Small, subrounded pebble clasts are primarily quartz, quartzite, and chert. Regionally, the Shinarump Conglomerate forms a generally fining-upward sequence from massive, conglomeratic, and planar stratified sandstone at the base to medium-grained, cross-stratified sandstone at the top believed to represent a change from braided streams systems to low sinuosity fluvial systems dominated by sand waves and point bar deposits (Dubiel, 1994). In the Harrisburg Junction quadrangle, however, pebbly conglomerates and pebbly sandstones are common in many exposures throughout the section and no such fining upward sequence is evident.

Shinarump strata are strongly jointed, with major joints trending subparallel to the strike and dip of bedding. Well-developed slickensides, with a wide variety of orientations, are common throughout the Shinarump Member and suggest minor movement along and between bedding planes, even where beds are not otherwise affected by faulting or subsidary folding. Where Shinarump strata have been faulted, the sandstones are non-calcareous and appear strain hardened. Shinarump strata are also nearly everywhere heavily stained by iron-manganese oxides, commonly in the form of liesegang banding. This banding invariably follows joints, so that large blocks become concentrically zoned in a variety of interesting patterns. Where these color bands occur in fine- to medium-grained sandstones, they are much sought after as "picture stone" or "landscape stone." Coarser sandstones and pebbly sandstones locally contain poorly preserved petrified wood, commonly replaced almost entirely by iron-manganese oxides; small logs several feet (a couple meters) in length are common though not abundant. Plant trash, replaced by iron-manganese oxides, is also common.

The Shinarump Conglomerate varies widely in thickness. Southwest of Quail Creek reservoir, in the SENW 1/4 section 35, T.41S., R.14W., Shinarump strata are 104 feet (32m) thick. At the southern end of Washington Black Ridge, in the SESE 1/4 section 13, T.42S., R.15W., these beds are 165 feet (50 m) thick. Proctor (1953) measured 115 feet (35 m) of Shinarump strata north of State Highway 9. Proctor and Brimhall (1986) reported Shinarump strata are 95 feet (29 m) thick in the Silver Reef mining district. To the southeast, near East Reef, Stewart and others (1972) measured 162 feet (49 m) of Shinarump beds. Higgins and Willis (1995) noted that Shinarump strata range from 5 to 200 feet (1.5-61 m) thick in the St. George quadrangle to the southwest. Such wide variations in thickness are likely due to paleotopography and deposition in braided stream channels, and, perhaps, to difficulty in placing the locally gradational upper contact.

The upper contact with the Petrified Forest Member is only exposed at the southern end of Washington Black Ridge, in the SESE 1/4 of section 13, T.42S., R.15W. There, the contact appears conformable and gradational and corresponds to a prominent bench. The uppermost Shinarump consists of pale--red to grayish-red, thin- to medium-bedded, platey weathering, fine-grained sandstone with well-developed ripple cross-stratification. Basal Petrified Forest strata are poorly exposed but consist of about 35 feet (10.5 m) of moderate- to dark-reddish-brown, very fine grained silty sandstone overlain by at least 42 feet (13 m) of fine- to very coarse-grained sandstone typical of the Shinarump Conglomerate. When traced to the west, to and across Grapevine Pass Wash, these reddish-brown, fine-grained silty sandstones grade into ledgy, thin- to medium-bedded sandstones and pebbly sandstones that are otherwise identical to underlying generally more massive Shinarump strata. The contact at the southern end of Washington Black Ridge is thus gradational and intertonguing and has been choosen to correspond to the base of the thick, reddish-brown silty sandstone; it is carried with difficulty to the west where it roughly corresponds to the first appearance of ledgy, thin- to medium-bedded sandstones. This sequence of lower Petrified Forest beds is similar, though thicker, than that reported by Stewart and others (1972) near East Reef, on the northeast flank of the Virgin anticline; they suggested that the lower sandstone may be a tongue of the Shinarump Conglomerate.

Basal Petrified Forest strata are also exposed west of Harrisburg Dome, in the east-central part of section 18, T.42S., R.14W., where they consist of interbedded, moderate- to dark-yellow-brown, to grayish-red, to grayish-red-purple, thin- to thick-bedded, fine- to medium-grained sandstone with ripple cross-stratification. Similar strata are exposed in lower Petrified Forest strata north of Quail Creek reservior and suggest a gradational contact there as well.

Petrified Forest Member (Trcp): Because of widespread deformation and extensive Quaternary cover, a complete section of the Petrified Forest Member is not exposed in the Harrisburg Junction quadrangle. Still, portions of the member are well exposed, including its base as described earlier. Perhaps the best exposures are found in an abandoned clay pit in the SESESE 1/4 section 5, T.42S., R.14W.; between the north- and south-bound lanes of Interstate 15, just south of Cottonwood Creek, in section 27, T.41S., R.14W.; and in scattered expsoures in the Harrisburg Flat area.

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. Petrified Forest strata commonly form rotational slumps, especially where exposed along steep hillsides. In the Harrisburg Junction quadrangle, such slumps are especially common along the southern reaches of Washington Black Ridge.

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. Montmorillonitic clays, those that swell conspicuously when wet, are common and give weathered surfaces a "popcorn" appearance. These swelling clays are also responsible for numerous foundation problems in the area. They are usually poorly exposed, but their bright colors commonly "bleed through" to the surface.

Sandstones of the Petrified Forest Member exhibit a wide variation in grain size and bedding characteristics. At the southern end of Washington Black Ridge, basal Petrified Forest mudstones are overlain by at least 42 feet (13 m) of fine- to very coarse-grained sandstone typical of the Shinarump Conglomerate. A 40-foot-thick (12 m), ledge-forming, very pale orange to pinkish-gray, medium- to coarse-grained, locally pebbly sandstone crops out north of Harrisburg Flat just west of Interstate 15. This thick channel sandstone can be traced to the northeast where it forms the northeast-plunging, tightly folded Leeds anticline at Leeds Reef. 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. Near the top of the member at Buckeye Reef, immediately east of the quadrangle in the NENENE 1/4 section 1, T.40S., R.14W., there is a very pale orange, massively bedded, coarse- to very coarse-grained pebbly sandstone about 10 feet (3 m) thick. This same sandstone crops out to the southwest below White Reef, in the NE 1/4 section 14, T.41S., R.14W.

As its name implies, petrified wood, commonly well silicified and brightly colored, is common in the Petrified Forest Member. Petrified wood appears to be more abundant in uppermost Petrified Forest strata and is commonly found in modern stream channels.

Even though the color change between Petrified Forest and Dinosaur Canyon strata is locally well developed below portions of White Reef and in the Harrisburg Flat area, their contact is nowhere well exposed. It corresponds to a slope forming interval of purplish swelling mudstones below that change upward to brown, very fine- to fine-grained sandstone, silty sandstone, and lesser siltstone and mudstone characteristic of overlying Dinosaur Canyon strata. The upper 30 feet (9 m) of the Petrified Forest Member commonly contains scattered selenite crystals, while the upper 15 feet (4.5 m) contains abundant light-gray to light-olive-gray limestone nodules. Just east of the quadrangle at Buckeye Reef, in the NENENE 1/4 section 12, T.40S., R.14W., there is a silicified bed up to one foot (0.3 m) thick near the top of the Petrified Forest Member. It is moderate red to moderate reddish orange, with streaks of light greenish gray. It appears similar to a silicified peat. Float, apparently from this same bed, is found sporadically in the White Reef and Harrisburg Flat areas. This is the same "agate bed" noted by Proctor (1953, p. 20) and included in the informally named "Fire Clay Hill bentonitic shales" unit. The upper contact is unconformable and represents a gap of about 10 million years.

In the Harrisburg Junction quadrangle, the Petrified Forest Member is everywhere deformed by folding and faulting making its local true thickness uncertain. It is probably 400 to 700 feet (121-212 m) thick in the Harrisburg Junction quadrangle. The member is reasonably well exposed though tightly folded immediately to the northeast in the Silver Reef Mining district, where Proctor and Brimhall (1986) reported Petrified Forest strata are 446 feet (135 m) thick. In the East Reef area of the adjacent Hurricane quadrangle, Stewart and others (1972) measured 408 feet (124 m) of Petrified Forest beds. The member is estimated to be about 700 feet (212 m) thick in the St. George quadrangle to the southwest (Higgins and Willis, 1995). The Petrified Forest Member was deposited in fluvial and floodplain environments (Dubiel, 1994); mottled, variegated mudstones probably represent paleosols.

Jurassic

Moenave Formation

The Moenave Formation forms a distinctive, three-part clastic sequence on the northwestern flank of the Virgin anticline, where it has been repeated by thrusting. Where not covered by basalt flows and younger alluvium, Moenave strata are also exposed on the anticline's southeastern flank. The Moenave Formation is divided into the Dinosaur Canyon Member, a brown, uniformly colored, slope-forming, very fine grained sandstone and interbedded siltstone; the Whitmore Point Member, which consists of a varicolored sequence of thin-bedded, slope-forming claystone, mudstone, siltstone, very fine grained sandstone, and lesser dolostone; and the ledge-forming, massive-weathering Springdale Sandstone Member, a varicolored, fine- to medium-grained sandstone that is host to the ore minerals of the Silver Reef mining district. The formation is 391 feet (119 m) thick at Harrisburg Flat, in the E ½ section 22, T.41S., R.14W. and the W ½ section 23, T.41S., R.14W. Proctor and Brimhall (1986) reported the Moenave Formation is just 261 feet (79 m) 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 (108 m) thick. On the northeast flank of the Virgin anticline about 2.5 miles (4 km) south-southeast of Leeds, Stewart and others (1972) reported 356 feet (108 m) of Moenave strata. Higgins and Willis (1995) measured a complete section of Moenave strata that totaled 420 feet (127 m) thick near the center of section 28, T.42S., R.15W., just east of Middleton Black Ridge.

Dinosaur Canyon Member (Jmd): The Dinosaur Canyon Member is exposed in a narrow belt from White Reef on the north to the quadrangle's southeastern corner; a small exposure is present along the Virgin River on the southeast flank of the Virgin anticline. It 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, low-angle, and ripple cross-stratification are common. Sandstone beds in the upper portion tend to be medium to thick bedded and are commonly ledge-forming. Dinosaur Canyon strata are uniformly colored moderate red brown to moderate reddish orange, although beds are locally mottled very pale orange. In aggregate, Dinosaur Canyon strata are distinctly browner than Kayenta beds, although isolated exposures are difficult to identify.

The contact with the overlying Whitmore Point Member is conformable and gradational and was placed at the base of a laterally persistent, thin-bedded, 6 to 18 inch (0.1-0.4 m) thick, light-gray dolomitic limestone with algal structures. 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 the nodules appear to fill burrows. In exposures north of Harrisburg Flat, this carbonate bed overlies about 3 feet (1 m) of ledge-forming, thin- to medium-bedded, yellowish-gray to light-greenish-gray, very fine- to fine-grained sandstone with common green copper carbonate stains. This carbonate and underlying sandstone are clearly visible on 1:24,000-scale color aerial photographs. About 25 feet (7.5 m) of brown sandstones, typical of underlying Dinosaur Canyon strata, overlie the dolomitic limestone and point to the conformable, intertonguing nature of the contact. The contact used here thus may differ slightly from that used by Willis and Higgins (1995) in the Washington quadrangle to the west. There, they placed the contact between the highest, reddish-brown sandstone of the Dinosaur Canyon Member and the purplish-gray-green claystone of the Whitmore Point Member.

The Dinosaur Canyon Member is 163 feet (49 m) thick in the E1/2 section 22, T.41S., R.14W. and the W1/2 section 23, T.41S., R.14W. Wilson and Stewart (1967) reported Dinosaur Canyon strata are about 200 feet (61 m) thick in the Leeds area, and Stewart and others (1972) reported an identical thickness at East Reef, on the northeast flank of the Virgin anticline. Dinosaur Canyon strata are 250 feet (76 m) thick east of Middleton Black Ridge, in the E1/2 SW1/4, section 28, T.42S., R.15W. (Higgins and Willis, 1995).

Whitmore Point Member (Jmw): The Whitmore Point Member weathers to poorly exposed slopes except where protected by resistant cliffs and ledges of the Springdale Sandstone Member. Even so, slopes developed on Whitmore Point strata are typically brightly colored and littered with a lag of resistant Whitmore Point lithologies, thus making the member an important marker horizon. Some of the best exposures are found in the State Highway 9 road cut at the common border of sections 4 and 5, T.42S., R.14W.; along Cottonwood Creek near the center of section 27, T.41S., R.14W.; along Quail Creek in the NW1/4 NW1/4 section 23, T.41S., R.14W.; and in numerous exposures along the southeastern flank of White Reef.

The Whitmore Point Member is a sequence of interbedded, varicolored mudstone and claystone, lesser moderate-reddish-brown, very fine- to fine-grained sandstone and siltstone, and several thin dolomitic limestone beds. A five-foot-thick (1.5 m) yellowish-gray to light-olive-gray, medium- to very coarse-grained sandstone is present in the upper part of the member at Cottonwood Creek. The mudstones and claystones vary from pale red purple, to greenish gray, to blackish red in color, in sharp contrast to enclosing map units. Dark-yellowish-orange micaceous siltstone and very fine- to fine-grained, very pale orange sandstone interbeds are present but not common. The dolomitic limestones range from 3 to 18 inches (0.1-0.4 m) thick and vary in color from light greenish gray, very light gray, to yellowish gray; they commonly weather to mottled colors of pale yellowish orange, white, yellowish gray, and pinkish gray, commonly with green copper carbonate stains. These carbonates appear bioturbated and contain grayish-orange-pink to moderate-reddish-brown chert nodules, sparse fossil fish scales of

Semionotus kanabensis (Hamilton, 1984), and poorly preserved and contorted algal structures. The lower 25 feet (7.5 m) of the member consists of brown sandstones similar to those of the Dinosaur Canyon Member. Along Cottonwood Creek near the center of section 27, T.41S., R.14W., these Dinosaur Canyon-like beds are overlain by about 35 feet (11 m) of poorly exposed, interbedded siltstone, mudstone, and very fine grained sandstone that weathers to pastel colors similiar to, but less striking than, overlying Whitmore Point strata.

The upper contact is generally conformable, although local channeling and mudstone ripup clasts are present at the base of the Springdale Sandstone Member. It was placed at the base of thick to massively bedded sandstones with planar and low-angle cross-stratification. The contact generally marks a pronounced break in slope, with the resistant Springdale Sandstone forming prominent ledges above gentle Whitmore Point slopes. The Whitmore Point Member is 64 feet (19 m) thick in the E1/2 section 22, T.41S., R.14W. and the W1/2 section 23, T.41S., R.14W. Just one mile (1.6 km) to the south, along Cottonwood Creek near the center of section 27, T.41S., R.14W., the member is about 125 feet (38 m) thick, apparently due in part to the transitional beds described above. Higgins and Willis (1995) reported the member is 55 feet (17 m) thick east of Middleton Black Ridge, in the NE1/4 NE1/4 SE1/4, section 28, T.42S., R.15W. Wilson and Stewart (1967) reported the member is about 60 feet (18 m) thick in the Leeds area. Stewart and others (1972) assigned 61 feet (18 m) to the Whitmore Point Member at East Reef, on the northeast flank of the Virgin anticline. The Whitmore Point Member was deposited in floodplain and lacustrine environments.

Springdale Sandstone Member (Jms): The Springdale Sandstone Member is well exposed in the west-dipping hogback of White Reef, and in numerous outcrops along strike to the south. Perhaps the best exposure south of White Reef is found along Cottonwood Creek, near the center of section 27, T.41S., R.14W. Although complicated by faulting, good exposures are also found southwest of Harrisburg Junction, in the SE 1/4 section 5 and the NW 1/4 section 8, T.41S., R.14W. The Springdale Sandstone Member is host to ore deposits of the Silver Reef mining district, near Leeds. There, the member was locally 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).

The Springdale Sandstone Member consists predominantly of medium to massively bedded, fine-grained or rarely medium-grained sandstone, with planar 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 red purple, pale yellowish orange, and dark yellowish orange, as opposed to moderate-reddish-brown hues that dominate Kayenta beds; common liesegang banding in Springdale beds; generally more massive bedding rather than thin- to medium-bedding typical of Kayenta strata; and the fact that Springdale sandstones are commonly characterized by small, resistant, 0.13-inch (2 mm) diameter concretions that give weathered surfaces a pimply appearance. Poorly cemented concretions up to 1 inch (25 mm) in diameter, which impart a pitted appearance to weathered surfaces, are also common in

Springdale sandstones. Poorly preserved, petrified and carbonized fossil plant remains are locally abundant. Springdale sandstones also commonly contain thin, discontinuous lenses of intraformational conglomerate, with mudstone and siltstone rip-up clasts. Thin interbeds of moderate-reddish-brown or greenish-gray mudstone and siltstone are present though not abundant.

The upper contact is conformable and locally gradational and corresponds to a pronounced color, topographic, and lithologic change. It marks a change from variously colored, ledge- and cliff-forming, thick to massively bedded, fine-grained sandstone of the Springdale Sandstone, to thin-bedded, very fine- to fine-grained silty sandstone of the Kayenta Formation. Wilson and Stewart (1967) noted that Springdale and Kayenta strata appear to intertongue in the Leeds area, apparently northeast of the quadrangle. The Springdale Sandstone Member attains a local maximum thickness of 164 feet (50 m) thick near Harrisburg Flat, in the E1/2 section 22 and W1/2 section 23, T.41S., R14W. It thins to the north where Proctor and Brimhall (1986) reported the member is about 105 feet (32 m) thick in the Silver Reef mining district; Stewart and Wilson (967) reported Springdale strata is about 95 feet (29 m) thick in this same area. Stewart and others (1972) reported 95 feet (29 m) of Springdale strata at East Reef, on the northeast flank of the Virgin anticline. One mile (1.6 km) south of Harrisburg Flat, along Cottonwood Creek near the center of section 27, T.41S., R.14W., Springdale strata are 120 feet (36 m) thick. Higgins and Willis (1995) reported the member is 115 feet (35 m) thick east of Middleton Black Ridge, in the SE1/4 SE1/4 NW1/4, section 28, T.42S., R.15W. The Springdale

Sandstone was probably deposited in braided stream and minor floodplain environments.

Kayenta Formation

The Kayenta Formation consists of a thick, monotonous sequence of interbedded, thin- to medium-bedded, moderate-reddish-brown siltstone, fine-grained sandstone, and mudstone. To the west in the Washington quadrangle, Willis and Higgins (1995) divided the Kayenta into three informal members, following the three-fold division of Hintze and others (1994) who mapped these strata in the Gunlock area. They later decided to map just two informal members and reassigned most of what was the upper member to the transition zone of the Navajo Sandstone (Willis and Higgins, 1996). Wilson and Stewart (1967) described the Kayenta in the Leeds-St. George area as consisting of two parts, but it is clear that much of their upper part included beds herein assigned to the Navajo Sandstone. In the Harrisburg Junction quadrangle, I did not find suitable horizons for subdividing the unit.

Kayenta strata generally weather to poorly exposed slopes, except in the upper part of the formation where ledges and small cliffs are common. However, the lower part of the formation is well exposed in Cottonwood Creek, in the SESENW 1/4 of section 27, T.41S., R.14W.

In the Harrisburg Junction quadrangle, Kayenta strata consist of interbedded, thin- to medium-bedded, moderate-reddish-brown siltstone, fine-grained sandstone, and mudstone. Kayenta sandstones are less commonly moderate reddish orange or yellowish gray. Kayenta strata are commonly mottled with small spherical and irregular reduction spots. Planar, low-angle, and ripple cross-stratification is common. East of Harrisburg Flat, approximately 100 feet (30m) above the base of the formation, there are several thin, light-olive-gray weathering, light-gray dolostones, each less than one inch (25 mm) thick; thin dolostones from 1 to 5 inches (25-125 mm) thick were also observed 427 (129 m) and 682 feet (207 m) above the base of the formation. Thin dolostones of the lower Kayenta were also observed elsewhere in the quadrangle, for example west of Washington Black Ridge in the NWSENW 1/4 section 7, T.42S., R.14W., but because intervening exposures are poor the lateral continuity of these dolostone beds is uncertain. The lower middle part of the formation commonly weathers to soft, punky, gypsiferous soils, although gypsum is rarely exposed.

In southwestern Utah, generally west of the Hurricane fault, the Kayenta/Navajo contact is marked by a transition zone up to several hundred feet (100 m) thick (Tuesink, 1989; Sansom, 1992). Previous workers have variously included these transition beds in the upper Kayenta or lower Navajo, as discussed below. I have chosen to place the Kayenta/Navajo contact at the base of the first cliff-forming sandstone, above which siltstone and mudstone interbeds are thin and volumetrically insignificant; transitional beds are thus included in the Navajo Sandstone. The contact corresponds to a slight color change, visible from a distance, with darker reddish brown Kayenta strata below and lighter, moderate-red-orange Navajo beds above. Northeast of

Washington Black Ridge, placement of the contact is facilitated by the presence of a thin, laterally continuous, limy dolostone about 80 feet (24 m) above the base of the Navajo Sandstone. Immediately west of the quadrangle boundary, the contact is marked by three thin dolostone beds that collectively total 6-8 inches (0.15-0.2 m) thick. The contact is the same as that of Sansom (1992), who noted that it generally corresponds to a break in slope, with cliff-forming sabkha deposits above and slope-forming fluvial deposits below.

The Kayenta Formation is 845 feet (258 m) thick west of Harrisburg Flat, in the NE 1/4 section 22, T.41S., R.14W. Willis and Higgins (1995) reported a composite thickness of the lower and middle members, which are roughly equivalent to the Kayenta of this report, in the greater St. George area of 787 feet (238 m). The Kayenta Formation is Early Jurassic in age.

Navajo Sandstone (Jn)

The Navajo Sandstone and correlative sandstones are reknown as one of the world's largest coastal and inland paleodune fields, which covered much of what is now Utah and portions of adjacent states in the Early Jurassic. Navajo strata are reknown too for their great thickness, locally exceeding 2,000 feet (66 m), and uniformity; except for the transitional zone described below, they consist almost entirely of massively cross-bedded, fine- to medium-grained quartz sandstone that weathers to bold, rounded cliffs.

In the Harrisburg Junction quadrangle, the Navajo Sandstone is widely exposed north and west of Interstate 15 where it forms bold cliffs, and southeast of the Virgin River where it is largely concealed by a thin cover of eolian sand deposits. Except for the transition beds described below, the Navajo Sandstone consists entirely of massively cross-bedded, fine- to medium-grained, well-rounded, frosted quartz sandstone that is poorly to moderately well cemented. Lower and middle Navajo strata are generally moderate reddish orange to moderate orange pink, although local, irregularly shaped areas are a very pale orange to yellowish-gray color. The upper part of the formation is commonly very pale orange to yellowish gray. Dark-brown to black iron and manganese oxides are locally common as thin coatings on fractures and as nodules. Navajo strata are also strongly jointed and locally brecciated. Navajo strata weather easily, liberating large amounts of sand that accumulates in channels and on broad, flat surfaces.

Along the southern flank of the Pine Valley Mountains, the upper Kayenta and lower Navajo is marked by a conformable and gradational interval that records the transition from distal fluvial, to sabkha, to erg-margin and finally erg-center depositional environments (Tuesink, 1989; Sansom, 1992) (figure 5). Cook (1957) was among the first to recognize this interval in Washington County, and in particular near Leeds, where he included about 100 feet (30 m) of these transition beds in his lower Navajo. Hintze and others (1994) included these transition beds in the upper Kayenta. Tuesink (1989) included these strata in what she informally called the "Transitional Navajo." Sansom (1992) referred to the "Transitional Navajo" as the "Transition Zone" but did not take a position as to which formation it belonged.

(Figure 5 near here)

Clearly, the decision as to which formation to lump the transition beds is an arbitrary one. Because the base of the interval generally corresponds to a break in slope and a slight color change, for mapping purposes the contact was placed at the base of the transitional interval. The contact choosen by Cook (1957, 1960) is probably the same as is used for this report. Sansom (1992) described lateral and vertical variations in the transition zone, and noted that it reached a maximum thickness of 305 feet (93 m) at the Red Cliffs Recreation Area in the NE 1/4 section 15, T.41S., R.14W. This interval is about 164 feet (50 m) thick at Snow Canyon, and 236 feet (72 m) thick in the Gunlock area. Tuesink (1989) assigned 312 feet (95 m) to this transitional interval near Leeds.

The transition zone beds are characterized by very fine- to fine-grained sandstone and silty fine-grained sandstone with thin mudstone interbeds, and less common but resistant cross-stratified sandstone. Bedding is thin to thick and planar, with common ripple and uncommon dune cross-stratification. Wavy bedding, dark flaser-like laminae, and soft sediment deformation features, including diapiric and load structures, and bioturbation are common. While the sandstones are generally very fine- to fine-grained, some beds have sparse medium-grained, rounded, frosted quartz sand. Most of these transition beds belong to the S6 facies (crinkly and wavily laminated fine-grained or silty sandstone), with lesser S1 facies (wind ripple sets) beds of

Sansom (1992). Unlike exposures near Moab, Sansom (1992) identified no super-surfaces or significant depositional hiatuses in the greater St. George area.

A thin, light gray limy dolostone bed, also noted by Tuesink (1989) and Sansom (1992), was found about 80 feet (24 m) above the base of the Navajo. This 3- to 8-inch-thick (0.08-0.2 m) dolostone weathers white and accumulates on slopes below, thus making a good marker that can be traced from the northeast corner of the quadrangle, southwest to the vicinity of the Interstate 15 and State Highway 9 interchange.

Sansom (1992) defined the top of the transition zone as the highest well-defined sabkha-aeolian cycle. Such cycles are generally 6 to 66 feet (2-20 m) thick and best developed in the St. George-Leeds area, on the southeastern flank of the Pine Valley Mountains. The idealized cycle has basal muddy and sandy sabkha deposits overlain by eolian deposits, but she noted wide variation and overall upward coarsening through the transition zone.

Sansom (1992) divided the Navajo Sandstone (exclusive of the basal transition beds) into a comparatively thin lower unit of interbedded dune and thin interdune deposits and an upper unit composed entirely of dune deposits. At the Red Cliffs Recreation Area, she noted the lower Navajo is 125 feet (38 m) thick, whereas the upper Navajo is in excess of 1,900 feet (600 m) thick. The upper Navajo is represented by a monotonous sequence of thick sets and cosets deposited by simple dunes and draas; planar interdune deposits are rare. The boundary between the lower and upper units is gradational and somewhat subjective.

Sansom (1992) also noted that the Navajo Sandstone was deposited by paleowinds that blew mostly from the north, except in the Red Cliffs Recreation Area where northeast winds appear to have been dominant. A northeast wind direction was also reported by Tuesink (1989) for transition zone strata near Leeds.

Because overlying Temple Cap strata form a slope on the broad bench of Navajo Sandstone, their mutual contact, termed the J-1 unconformity by Pipiringos and O'Sullivan, (1978), is nowhere well exposed in the Harrisburg Junction quadrangle. It is, however, marked by a prominent change in lithology, with moderate-reddish-brown, thin-bedded siltstone and grayish-orange-pink, very fine grained silty sandstone overlying the massively cross-bedded Navajo Sandstone. The lower Temple Cap Formation also contains several zones of white to pinkish-gray chert nodules, described below, that weather out and accumulate at the surface. The contrast on full-color aerial photographs is unmistakable. The Navajo Sandstone is estimated to be 2,300 feet (700 m) thick in the Harrisburg Junction quadrangle.

Temple Cap Formation (Jtc)

At its type locality in Zion National Park, the Temple Cap Formation, named for beds that cap the West Temple, consists of two members: the lower, thin Sinawava Member and the overlying, thicker, White Throne Member (Peterson and Pipiringos, 1979). The White Throne Member thins westward and pinches out near the Hurricane fault; only the Sinawava Member, which thickens westward, is present in the Harrisburg Junction quadrangle.

The Temple Cap Formation is exposed in the northwestern portion of the quadrangle, where it forms conspicuous bright red slopes, separated by a middle gray portion, atop a broad bench of Navajo Sandstone and below ledge-forming Carmel strata. Temple Cap beds typically weather to soft, gypsiferous soils and so exposures are poor except along the bottom of drainages. The best exposure, and only of the upper part of the formation, is found along the west side of Big Hollow, about 500 feet (155 m) north of the road crossing (at the north section line, NW 1/4, section 8, T.41S., R.14W.).

The Temple Cap Formation consists of interbedded, slope-forming, moderate-reddish-brown mudstone, siltstone, very fine grained silty sandstone, and lesser gypsum. Beds in the middle of the formation are commonly moderate reddish orange, white, and pinkish gray, tend to be gypsiferous, and consist of mostly fine- to medium-grained sandstone; they appear white on full-color aerial photographs. Temple Cap strata commonly have small reduction spots or irregular mottles. Soils developed on the formation tend to be soft and gypsiferous, especially in the middle part, although gypsum beds themselves are rarely exposed. The gypsum varies from white to gray to pink and is both bedded and nodular in beds up to about 10 feet (3 m) thick.

There are several small prospect pits for gypsum, and one gypsum claim (in the SE 1/4 section 12, T.41S., R.14W.), in the quadrangle. Thin, pale-greenish-gray mudstone beds with abundant biotite are common and represent altered volcanic ash layers.

A coarser facies is present in two beds approximately one-third the way up from the base of the formation near the center of section 7, T.41S., R.14W. It is exposed from 55 to 57 feet (17-17.5 m), and from 75 to 76.5 feet (23-23.5 m) above the base; intervening strata are covered. The lower bed consists of ledge-forming, pinkish-gray, locally mottled moderate-reddish-brown, calcareous, fine-grained sandstone with rounded medium- to coarse-grained quartz sand; locally the bed is entirely medium- to coarse-grained sandstone. The upper bed is coarser yet. It consists of ledge-forming, light-greenish-gray, non-calcareous, medium- to coarse-grained sandstone with lenses of rounded, very coarse sand to small pebble quartz sandstone. Moderate-reddish-brown mudstone is exposed at the base of this bed, so it is unlikely that the intervening covered slopes contain much, if any, similar coarse clastic sediments. The upper, coarse bed described above may correspond to the J-2 unconformity of Pipiringos and O'Sullivan (1978).

The lower Temple Cap Formation also contains several zones of white to pinkish-gray chert nodules that weather out and accumulate at the surface. The nodules are disc shaped, 0.25 inch to 1 inch (6-25 mm) thick and 1 to 3 inches (25-75 mm) in diameter, and appear to be composed of an aggregate of much smaller blebs and flakes. These nodules may be silicified bentonite.

The upper contact with the Co-op Creek Member of the Carmel Formation was placed at a color change from moderate reddish brown to yellowish gray, which occurs near the top of a clastic sequence. Red mudstone and siltstone, locally mottled yellowish gray, of the Temple Cap Formation is overlain by about 6 feet (2 m) of yellowish-gray to pale-olive calcareous siltstone, above which lies similarly colored yellowish-gray, thin-bedded limestone.

The Temple Cap Formation is 187 feet (57 m) thick near the center of section 7, T.41S., R.14W. Willis and Higgins (1995) measured 199 feet (61m) of Temple Cap strata at the western margin of the quadrangle. In a measured section about 1.5 miles (2.5 km) north of the quadrangle, Wright and others (1979) reported the Temple Cap Formation is 236 feet (72 m) thick. Based on correlation with strata of known age, the unfossiliferous Temple Cap Formation is assigned an early to middle Bajocian age (early Middle Jurassic) (Peterson and Pipiringos, 1979).

Carmel Formation

The Carmel Formation forms an eastward thickening wedge, preserved beneath a regional unconformity, across the southern flank of the Pine Valley Mountains. In the Harrisburg Junction quadrangle, it consists of two gray carbonate members - the lower Co-op Creek Member and the upper Paria River Member - separated by a sequence of mostly red mudstones, the Crystal Creek Member. The regional unconformity, termed the K-1 unconformity by Pipiringos and O'Sullivan (1978), truncates the Paria River Member at Big Hollow, so that only the lower two members are exposed at the quadrangle's western boundary. The Paria River Member has not previously been reported west of the Hurricane fault, presumably due to assumed truncation beneath the K-1 unconformity. The Carmel Formation is Bajocian to Bathonian (Middle Jurassic) in age (Imlay, 1980). It was deposited in a variety of shallow marine, shoreline, and sabhka environments (Blakey and others, 1983).

Co-op Creek Member (Jcco): When viewed from a distance, Co-op Creek strata are readily divisible into two units of approximately equal thickness, although they have not been mapped separately. The lower unit weathers to a pale yellowish gray, while the upper unit weathers to distinctly darker yellowish brown hues; both form steep ledgy slopes. Unlike exposures to the west, where Willis and Higgins (1995) reported that the lower part of the member was predominantly limestone and the upper part limestone with interbedded light-olive-brown sandstone and pale-greenish-brown mudstone, no such lithologic generalities were recognized in the Harrisburg Junction quadrangle. Collectively, these two unmapped units consist of a laterally variable sequence of interbedded, generally thin-bedded mudstone, siltstone, limestone, and, especially in the lower portion, lesser gypsum and very fine- to fine-grained sandstone. No sandstones were reported in the Danish Ranch measured section of Wright and others (1979), located in the NE 1/4 section 34, T.40S., R.14W.

The lower unit of the Co-op Creek Member is noted for its thin-bedded, yellowish-gray to very pale orange limy mudstone, and interbedded, similarly colored siltstone and limestone. Limestones in this part of the member are generally micritic and unfossiliferous, although thin, coarsely crystalline, fossiliferous beds are present. Several beds of ledge-forming, light-olive-gray to white or locally pink, parallel to wavy laminated and nodular gypsum beds up to 6 feet (2 m) thick are also present.

The upper portion of the Co-op Creek Member is noted for its generally thin-bedded, pale-yellowish-brown fossiliferous limestone, with abundant *Pentacrinus* sp. columnals, bivalves, and mollusks. Many of the limestones are oolitic and sedimentary structures, including ripple marks, ripple cross-stratification, and trace fossils on bedding planes, are common. Some limestones weather to a sacchroidal surface. In the northcentral portion of the quadrangle, a 3 to 12 foot-thick (1-4 m-), parallel to wavy laminated gypsum bed is present near the top of the member.

In the Harrisburg Junction quadrangle, the uppermost Co-op Creek Member is everywhere marked by a distinctive, yellowish-gray to greenish-gray, silicified mudstone with abundant moderate-reddish-brown blebby jasper and medium-sand-size biotite flakes. This resistant bed is about 6 inches (0.15 m) thick, and, in the western portion of the quadrangle, overlies nearly 30 feet (9 m) of yellowish-gray mudstone with a few thin interbeds of brown-weathering platey limestone. When traced eastward to the northcentral part of the quadrangle, the upper part of the mudstone is replaced by a 3-12 foot-thick (1-4 m), ledge-forming, planar to wavy laminated, greenish-gray-weathering gypsum. The lower portion of this mudstone locally contains a distinctive oyster coquina that weathers out as rounded, resistant cobbles and small boulders.

The upper contact corresponds to a prominent color change from various shades of pale yellowish and brownish gray below to moderate reddish brown above. It is marked by the distinctive, yellowish- to greenish-gray jasper-bearing silicified mudstone described earlier, above which lies slope-forming, pale- and moderate-reddish-brown mudstone and siltstone.

The Co-op Creek Member generally thickens eastward across the southern flank of the Pine Valley Mountains. Just west of the quadrangle boundary, in the SW 1/4 section 2, T.41S., R.15W., Willis and Higgins (1995) measured 285 feet (87 m) of Co-op Creek strata; Wright and others (1979) measured 258 feet (79 m) near the same location. In the SE 1/4 section 1, T.41S., R.15W., the Co-op Creek Member is 342 feet (104 m) thick. About 4 miles (6.5 km) to the northeast, in the northeast 1/4 section 34, T.40S., R.14W., Wright and others (1979) reported a nearly complete section of Co-op Creek strata is 448.5 feet thick (136 m).

Crystal Creek Member (Jccc): In the Harrisburg Junction quadrangle, Crystal Creek strata form a thin, pale- to moderate-reddish-brown and grayish-orange slope between the more resistant gray carbonates of the enclosing Co-op Creek and Paria River Members. Although poorly exposed, the Crystal Creek Member is readily distinguished from enclosing strata.

The lower part of the Crystal Creek Member consists of interbedded, generally thin-bedded, pale to moderate-reddish-brown mudstone, siltstone, very fine grained sandstone, and gypsum. Like the underlying Co-op Creek Member, Crystal Creek strata form a laterally variable sequence. The reddish-brown units contain thin interbeds of yellowish-gray to light-olive-gray mudstone with abundant fine- to coarse-sand-size biotite flakes. Moderate-reddish-brown blebby jasper, like that seen in the uppermost Co-op Creek bed, is common in the lower part of the member. The lower 10 to 20 feet (3-6 m) of the member is gypsiferous and, in section 5, T.41S., R.14W., contains a single bed of nodular gypsum up to 11 feet (3.4 m) thick.

In western exposures, uppermost Crystal Creek strata are marked by about 10 feet (3 m) of yellowish-gray to white, slope-forming, generally noncalcareous, very fine- to fine-grained quartz sandstone. To the east, in the vicinity of Big Hollow, upper Crystal Creek strata consist of 73 feet (22 m) of upward coarsening, grayish-orange-pink to light-brown to dark-yellowish-orange, slope-forming, calcareous, very fine- to medium-grained sandstone (with minor interbedded mudstone and siltstone) which is overlain by platey weathering Paria River limestone. These light colored sandstones overlie interbedded, pale- to moderate-reddish-brown mudstone, siltstone, and lesser very fine grained sandstone typical of underlying Crystal Creek beds.

The Crystal Creek Member is unconformably overlain by Cretaceous bentonitic beds in western exposures. East of Big Hollow, Crystal Creek strata appear to be conformably overlain by limestones of the Paria River Member.

In the Harrisburg Junction quadrangle, an incomplete, eastward thickening wedge of Crystal Creek strata is preserved below the regional K-1 unconformity of Pipiringos and O'Sullivan (1978). Just west of the quadrangle, in the SW 1/4 section 2, T.41S., R.15W., Willis and Higgins (1995) measured 48 feet (14.6 m) of Crystal Creek beds; Wright and others (1979) measured 50 feet (15 m) in about the same location. In the SE 1/4 section 1, T.41S., R.15W., the Crystal Creek Member is 69 feet (21 m) thick, and in the SW 1/4 section 5, T.41S., R.14W., the member is 144 feet (44 m) thick.

Paria River Member (Jcpr): In section 5, T.41S., R.14W., in the northcentral portion of the quadrangle, the uppermost Carmel Formation is capped by 28 feet (8.5 m) of yellowish-gray to light-olive-gray, thin- to medium-bedded, platey weathering, ledge-forming limestone and lithographic limestone that contains sparse bivalve fossils. West of Big Hollow, this limestone is truncated under the K-1 unconformity, although underlying similarly colored sandstone assigned to the Crystal Creek Member is present. These limestone strata are herein assigned to the Paria River Member.

The Paria River Member has not previously been reported west of the Hurricane fault, presumably due to assumed truncation beneath the K-1 unconformity. However, in a measured section at Danish Ranch, just north of the Harrisburg Junction quadrangle in the NE 1/4 section 34, T.40S., R.14W., Wright and others (1979) reported similar limestones at the top of the Carmel Formation. Blakey and others (1983) noted that west of the East Kaibab monocline, the basal Paria River Member is composed of a sandstone-dolomite-gypsum sequence characteristic of a regressive sabkha depositional environment. Gypsum is lacking in these exposures, but if once present, it may have been removed by erosion associated with the K-1 unconformity.

The Paria River Member is unconformably overlain by Cretaceous bentonitic beds that weather to readily recognizable, soft, "popcorn" soils. The contact, however, is everywhere concealed by slumping and colluvium. Farther east, in the Signal Peak quadrangle in the NE 1/4 section 34, T.40S., R.14W., Paria River limestones are unconformably overlain by pebbly and cobbly conglomerate believed to represent the Dakota Conglomerate.

Cretaceous

Bentonitic Bed (Kb)

A thin bentonitic interval overlies the K-1 unconformity along the southern flank of the Pine Valley Mountains. To the west, in the Washington quadrangle, Willis and Higgins (1995) tentatively correlated this interval with a bentonitic bed mapped by Hintze and others (1994) in the Gunlock area. The bed occupies the same stratigraphic interval and is of similar thickness as the Gunlock bentonitic bed, although it weathers to light brownish gray rather than moderate red, and apparently lacks barite nodules that are common in the Gunlock area, facts also noted by Willis and Higgins (1995).

The bentonitic bed weathers to soft, "popcorn" soils and so is poorly exposed. Fresh samples are brownish gray and have common limonite stains. Willis and Higgins (1995) reported quartz crystals in the bentonitic soils that give slopes a sparkly sheen, but these were not observed in the Harrisburg Junction quadrangle. In the western part of the quadrangle, however, the bentonitic bed is enclosed by white to very pale orange, very fine- to fine-grained quartz sandstone. To the east near Big Hollow, in section 5, T.41S., R.14W., the bentonitic bed overlies yellowish gray limestone of the Paria River Member.

The bentonitic bed is about 20 to 25 feet (6-7.5 m) thick throughout the Harrisburg Junction quadrangle, although the upper contact is everywhere obscurred by a thin mantle of colluvium and thicknesses are difficult to determine. Willis and Higgins (1995) measured a maximum thickness of about 90 feet (27 m) near Diamond Valley, in the northwestern part of the Washington quadrangle. Hintze and others (1994) reported a fission-track age of 80.0 +/-5 Ma (Campanian) obtained from zircon from the bentonitic beds in the Gunlock area.

Iron Springs Formation (Ki)

The Iron Springs Formation forms steep ledgy slopes in the northwestern part of the quadrangle. Only about the lower 250 feet (76 m) of the formation is present in the quadrangle, but the formation is about 3,500 to 4,000 feet (1,067 - 1,220 m) thick in the area (Cook, 1960; Hintze and others, 1994). It consists of interbedded, ledge-forming, mildly calcareous, cross-bedded, fine- to medium-grained sandstone and less resistant, poorly exposed sandstone, siltstone, and mudstone. The formation is variously colored grayish orange, pale yellowish orange, dark yellowish orange, white, and pale reddish brown, and is locally heavily stained by iron-manganese oxides; liesegang banding is common. In the SE 1/4 section 1, T.41S., R.15W., the base of the formation is marked by a slope-forming, white to very pale orange, noncalcareous, fine-grained quartz sandstone, above which lies a 30-foot-thick (9 m-) sequence of brownish-gray slightly swelling mudstones. Hintze and others (1994) reported a palynomorph assemblage from the formation in the Gunlock area that suggested a Turonian to Cenomanian (90 - 100 Ma) age, slightly older than the Campanian age determined for the underlying bentonitic bed. The Iron Springs Formation is thus bracketed only as early Late Cretaceous. In a study of the formation in the Gunlock area to the west, Johnson (1984) suggested that Iron Springs strata were deposited in braided stream and floodplain environments.

Quaternary/Tertiary

Basaltic rocks from two distinct vents, one of which is present in the quadrangle, are exposed in the Harrisburg Junction quadrangle, on either side of the Virgin anticline. These rocks 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 regions in the western United States, these flows provide important constraints on local tectonic and geomorphic development. The region is known for its inverted valleys and isolated, basalt capped buttes and mesas. Based on the degree of erosion and weathering of individual flows, Hamblin (1963, 1970, 1987) identified four major periods, or stages, of mafic volcanism in the western Grand Canyon region. Stage I flows are high, isolated remanents that bear little or no relation to modern drainages, whereas stage IV flows were deposited in modern drainages and show little evidence of erosion or alteration. Hamblin also identified substages based on local geomorphic relations.

Best and Brimhall (1974) noted that the dominant lavas in the western Grand Canyon region - basinite, alkali olivine basalt, hawaiite, and quartz-bearing basaltic andesite - display a chemical continuum that cannot be accounted for by simple crystal fractionation of a single melt. They suggested that they originated as distinct partial melts of mantle periodite over a range of depths, followed by independent fractionation within each magma. They also noted that the inception of hawaiite (sodium-rich trachybasalt) volcanism migrated eastward at a rate of about 0.4 inch per year (1 cm/yr).

Washington flow and cinder cone (QTbw, QTbwc)

The Washington flow, which forms a prominent inverted valley called Washington Black Ridge, has its source at a deeply dissected cinder cone at the common border of sections 25 and 36, T.41S., R.15W. (figure 6). The flow is about 5.5 miles (8.8 km) long and maintains a relatively constant thickness of about 25 to 35 feet (7.5-10.5 m) thick along its length, except near its source. There, where Grapevine Wash plunges over the flow in the NENE 1/4 section 36, T.41S., R.15W., the flow is about 100 feet (30 m) thick. The Washington flow is inverted up to about 360 feet (110 m) at its southern end; incision decreases upstream to about 60 feet (18 m) at a nick point in the extreme NW 1/4 section 6, T.41S., R14W. Farther upstream, incision varies from zero to a few tens of feet (0-several meters). It has an average gradient of about 150 feet per mile (27 m/km). The flow trends south-southeast from the vent, apparently along the course of the ancestral Grapevine Wash. It is deflected to the southwest and west by the resistant Shinarump hogback on the west flank of the Virgin anticline. The west-trending portion of Washington Black Ridge locally overlies well-cemented gravels that may be deposits of the ancestral Virgin River. Extensive mass movements characterize the lower portions of the flow that overlie swelling mudstones of the Petrified Forest Member. The extreme western end of the flow crosses the Washington fault zone and is cut by a series of small normal faults with both down-to-the-east and down-to-the-west displacement.

(Figure 6 near here)

The Washington flow itself is made up of at least three cooling units (the term cooling unit is used in the same sense as Willis and Higgins (1995) who noted that cooling units are lava pulses from the same eruption separated by short time intervals, whereas flows are from different eruptions and are separated by enough time for weathering to occur). At the southern end of Washington Black Ridge, in the SWSW 1/4 section 18, T.42S., R14W. and the SE 1/4 section 13, T.42S., R15W., three cooling units are exposed that total about 40 feet (12 m) thick. Two cooling units are exposed in the unusually thick section in the NENE 1/4 section 36, T41S., R.15W.

The margins of the Washington flow have been eroded and the flow is largely concealed by mixed eolian and alluvial deposits. The flow displays well developed columnal jointing. The upper portion of the flow is highly vesicular and has local Stage IV-V (Birkeland and others, 1991) pedogenic calcium carbonate deposits. Perhaps the best exposure of these pedogenic calcium carbonate deposits is found in a road cut on the west side of the ridge, in the SWNENW 1/4 section 7, T.42S., R.14W.

The source vent for the Washington flow is a highly dissected cinder cone (QTbwc) located at the common border of sections 25 and 36, T.41S., R.15W. The cone itself is upheld by a core of volcanic breccia, welded spatter or agglutinate, and small, highly vesicular flows, which are also exposed on the cone's southeastern flank. Volcanic cinders and bombs form the remainder of the cone.

Geochemical analyses show that the Washington flow plots in the tephrite basinite field on the LeBas diagram (figure 7; table 1). Petrographically, it is classified as an ankaramite, indicating that it contains abundant clinopyroxene and olivine phenocrysts. Best and Brimhall (1974) suggested that it originated by accumulation of olivine and clinopyroxene in a fractionating, high-pressure basinite magma chamber. Best and Brimhall (1970) described five main basalt types in the western Grand Canyon basaltic field, the volumetrically least significant of which is the Washington basalt type, which takes its name from the Washington flow. They noted that it is the most mafic of the five types and that, interestingly, it lies next to the essentially contemporaneous Middleton basalts, which are the most siliceous and feldspathic. Abundant phenocrysts of olivine and pyroxene up to about 0.1 inch (3 mm) across are the only recognizable minerals in hand samples. They are set in a medium to dark-gray, very fine grained groundmass of plagioclase and titaniferous magnetite (Best and Brimhall, 1974). Near the source vent, in the SENENE 1/4 section 36, T.41S., R.15W., the upper cooling unit contains conspicuously more olivine, much of which is brownish in color, probably due to an alteration rind of "iddingsite." This cooling unit is apparently not present at the southern end of Washington Black Ridge, where each of the three cooling units are similar to the lower cooling unit exposed near the vent.

(Figure 7 near here)

The Washington flow is classified as stage IIb, indicating that it was deposited on a surface that has a similar slope and gradient to the present drainage but that now lies 200-500 feet (60-150 m) above the modern stream. A sample from the Washington flow (near the center of section 7, T.42S., R14W.) was dated at 1.7 ± 0.1 m.y. by Best and others (1980).

Alluvial gravel associated with the Washington flow (QTag)

Moderately sorted, moderately to well cemented pebble to cobble gravel, with rounded clasts of quartzite, limestone, and basalt, is exposed both above and below the Washington flow in the SW 1/4 section 13, T.42S., R.15W. Gravels under the flow are probably less than 15 feet (4-5 m) thick, although the lower contact is concealed by colluvium and thickness are difficult to determine. Overlying gravels are about 5 feet (1.5 m) thick. These gravels are probably channel lag deposits of the ancestral Virgin River.

Quaternary

Unnamed basalt flows (Qbi_1, Qbi_2)

Two flows are present in the southeast corner of the quadrangle, south of the Virgin River. They are well exposed only in vertical cliffs along the Virgin River, and in the vicinity of Berry Springs, especially in the State Highway 9 roadcut at the common border of section 1 and

2, T.42S, R.14W. Elsewhere, the flows are largely concealed by eolian and other sediments. The contact between these flows is also concealed. Both flows locally overlie well-cemented gravels of the ancestral Virgin River.

Hamblin (1970) classified the southwestern portion of these flows, roughly that part exposed in the Harrisburg Junction quadrangle, as stage III. To the east, other flows at and near Ivan's Knoll, Volcano Mountain, and Cinder Pits were classified as stages II and IV. Sanchez (1995) refined this classification and suggested that flows in the Harrisburg Junction quadrangle be classified as stage IIb and stage III, both of which may have been sourced at Ivan's Knoll, just south of Volcano Mountain. The lower flow (Qb_1), however, crops out at current base level along the Virgin River and so may be better classified as a stage IV flow. Regardless, the two flows are differentiated on the basis of elevation. The subscript denotes relative elevation, with Qb_1 lower and Qb_2 higher, although ages are uncertain. The flows remain unnamed pending further work in the adjacent Hurricane quadrangle, their likely source area.

Whole rock chemical analyses on two samples - one each from the upper flow (Qb_2) (taken at the State Highway 9 roadcut near the common border of sections 1 and 2, T.42S., R.14W.) and the lower flow (Qb_1) (taken immediately south of Highway 9, along the east bank of the Virgin River) - show that both flows are chemically similar and are classified as alkali basalt or borderline trachybasalt (figure 7; table 1), similar to findings reported in Sanchez (1995). Both look similar in hand sample and both contain sparse, unaltered, millimeter-size olivine phenocrysts set in a grayish-black, very fine grained groundmass; the stage III flow may contain slightly more abundant olivine phenocrysts. Best and Brimhall (1974) suggested that these flows originated at shallow lower mantle depths and experienced extensive fractionation of olivine and perhaps limited accumulation of plagioclase. They classified them as hawaiite (Grand Wash basalt of earlier reports), the most voluminous of the five main types of basalt in the western Grand Canyon region. In hand specimens, these flows are distinguished from the Washington flow by their finer grained groundmass and less abundant olivine phenocrysts.

Alluvial gravel associated with unnamed basalt flows (Qag)

Ancestral Virgin River gravels are well exposed in several areas both under and over the lower unnamed basalt flow (Qb_l). These gravels are similar to those associated with the Washington flow. They consist of moderately sorted, moderately to well cemented pebble to cobble gravel, with rounded clasts of quartzite, limestone, and basalt. In two areas - in the NESW 1/4 section 2, T.42S., R.14W. and in the NESE 1/4 section 16, T.42S., R.14W. - these gravels enclose thin tongues of basalt, suggesting that the river reoccupied its channel soon after the lower flow was deposited. The gravels reach up to 20 feet (6 m) thick.

Alluvial Deposits

Alluvial boulder deposits (Qab, Qabo): Two levels of coarse boulder gravel deposits are found on the flanks of the Pine Valley Mountains, in the northwestern portion of the quadrangle. They consist of very poorly sorted sand to boulder deposits with clasts in excess of 10 feet (3 m) in diameter. Most clasts, and all of the larger clasts, are from the Pine Valley intrusive complex. The Pine Valley clasts are highly weathered such that the outer rind easily disaggregates into its constituent grains, forming a granular soil. The basal portion of many of the deposits contains a more varied suite of clasts, including sandstone, limestone, and reworked quartzite and pebbly conglomerate cobbles derived from Cretaceous strata exposed on the flanks of the mountain.

These deposits were probably formed by alluvial and debris flow processes. They form narrow, elongate ridges that trend radially away from the Pine Valley Mountains. Qab deposits are found up to about 200 feet (60 m) above nearby modern drainages; Qabo deposits lie up to about 400 feet (120 m) above nearby drainages. The deposits vary from 0 to about 160 feet (0-50m) thick. The age of these deposits is uncertain. They are probably early to middle Pleistocene, but the older deposits may be in part latest Tertiary in age.

Older stream terrace deposits (Qao_5, Qao_6): Older stream terrace deposits are found along the west flank of the Virgin anticline where they form extensive, locally deeply dissected terraces. Similar, small, isolated deposits have been mapped along Cottonwood Creek and Heath Wash. Although these deposits appear to be virtually identical in composition, clast size, and other characteristics to the alluvial boulder deposits (Qab, Qabo) described earlier, they are not wellgraded to major drainages and it is not known whether they are in part correlative. The deposits appear to have their principal source in the Leeds Creek drainage just north of the quadrangle, and in the Cottonwood Canyon and Heath Wash areas. The younger, level 1 deposits are generally 40 to 100 feet (12-30 m) above nearby drainages. Level 2 deposits are 120 to 200 feet (36-60 m) above nearby drainages. Both deposits range from 0 to about 30 feet (0-9 m) thick.

Stream terrace deposits (Qal_2, Qal_3, Qal_4): Three levels of inactive stream terrace deposits have been mapped in the Harrisburg Junction quadrangle. These terrace deposits are restricted to modern drainages and truncate the older stream terrace deposits described above. They consist of poorly to moderately sorted, poorly cemented sand, silt, clay, and pebble to boulder gravel. Each forms isolated, level to gently sloping surfaces above modern drainages (figure 8). Level 2 deposits are generally 20 to 40 feet (9-12 m) above modern drainages, level 3 deposits range from 40 to 60 feet (12-18 m), and level 4 deposits are from about 60 to 80 feet (18-24 m) above modern drainages. Each of these deposits varies from 0 to 20 feet (0-6 m) thick. Level 2 and 3 deposits are likely Holocene in age; level 4 deposits may be late Pleistocene in age.

(Figure 8 near here)

Modern alluvial deposits (Qal_1):

Modern alluvial deposits have been mapped along the Virgin River and other principal drainages in the quadrangle. Modern alluvial deposits include river channel and floodplain sediments and minor terraces up to about 20 feet (6 m) above current stream levels. They consist of moderately to well sorted sand, silt, clay, and local pebble to boulder gravel normally less than about 10 feet (3 m) thick; deposits along the Virgin River are likely about 20 to 40 feet (6-12 m) thick. These deposits are gradational with mixed alluvial and colluvial deposits. Where not constrained by topography, deposits along the Virgin River are marked by numerous meander scars.

Colluvial deposits (Qc, Qco)

Colluvial deposits consist of poorly to moderately sorted, angular, clay to boulder size, locally derived material deposited by slopewash, soil creep, and debris flow processes on moderate slopes. Colluvium is common on most slopes in the quadrangle but has only been mapped where it conceals large areas of bedrock. These deposits locally include talus, mixed alluvial and colluvial, and eolian deposits that are too small to be mapped separately. Two levels of colluvium, in part gradational with one another, have been mapped. Older colluvial deposits form incised, largely inactive surfaces; modern deposits are only locally incised along their lower margins. Older colluvial deposits (Qco) are probably Pleistocene to Holocene in age. Both deposits vary from 0-30 feet (0-9 m) thick.

Eolian deposits

<u>Eolian sand and caliche deposits (Qecl):</u> These deposits form planar surfaces covered with abundant pedogenic calcium carbonate (caliche) (Stage IV of Birkeland and others, 1991) and sparse eolian sand. These deposits are equivalent to the lower part of the eolian sand deposits described below; most of the overlying unconsolidated sand has been removed by erosion. They have been mapped principally along the central portion of Washington Black Ridge, and atop planated bedrock surfaces in the southeast corner of the quadrangle. These deposits generally range from 0 to 10 feet (0-3 m) thick.

Caliche deposits (Qec): Three small deposits of pale red, stage IV-V (Birkeland and others, 1991) caliche have been mapped on Shinarump strata on the east limb of the Virgin anticline, immediately south of State Highway 9. The deposits are very rough weathering and vary from 2 to 5 feet (0.6-1.5 m) thick. The origin and age of the deposits is uncertain.

Eolian sand and dune sand deposits (Qe, Qed): Eolian sand covers broad, irregular areas on the Navajo Sandstone and adjacent bedrock formations. The sand is well rounded, well to very well sorted, fine- to very fine-grained quartz sand derived from Navajo and upper Kayenta strata. It forms an irregular blanket, stabilized in part by sparse vegetation, that varies from 0 to about 30 feet (0-9 m) thick. Local, small, active dune deposits have been mapped separately. In most areas, this sand likely overlies a thick pedogenic calcium carbonate (Stage IV of Birkeland and others, 1991), which is rarely exposed in washes and as isolated nodules at the surface. Large exposures of pedogenic calcium carbonate (Qecl) are mapped separately.

Human-made deposits

Artificial fill (Qf): Artificial fill - used for road construction, dams and retaining ponds, to provide level building surfaces, and waste rock from mining - has been mapped thoughout the quadrangle. These deposits consist of engineered fill and general borrow material and vary greatly in thickness. Fill along Interstate 15 was only mapped where it forms thick deposits that fill cross-cutting drainages. Fill in the Silver Reef mining district includes both piles of waste rock and a reclaimed tailings pile. Although only a few areas of fill have been mapped, fill should be anticipated in all built-up areas, many of which are shown on the topographic base map.

Landfill deposits (Qfl): Three landfill deposits have been mapped along the western flank of Harrisburg Dome. The landfills contain common trash and general borrow material and are currently operated by Washington County.

Mine dump deposits (Qfm): Waste rock from mining is present along White Reef in the northeastern corner of the quadrangle. Only the larger deposits, which consist principally of angular blocks of Springdale strata, were mapped.

Mass-movement deposits

Landslide deposits (Qms): Several large landslide deposits have been mapped in the quadrangle. With the exception of three deposits near Quail Creek reservoir and the Carmel Formation landslides in the northwest corner of the quadrangle, which are all deeply dissected by erosion, all of the landslides are characterized by moderately subdued hummocky surfaces and internal scarps, indicative of middle to late Holocene movement, and so should be considered capable of renewed movement. Basal detachments occur most commonly in the Petrified Forest Member of the Chinle Formation, the upper red member of the Moenkopi Formation, and the Carmel Formation. The slides themselves incorporate these units and overlying formations.

The largest landslides occur in the Petrified Forest Member of the Chinle Formation where these strata form steep slopes along the flanks of Washington Black Ridge. They are characterized by hummocky topography, numerous internal scarps, and chaotic bedding attitudes, and are covered in part by blocks of basalt derived from the Washington flow.

A block glide detachment, with failure at or near the top of the upper red member of the Moenkopi Formation, has been mapped in the NE 1/4 section 10, T.42S., R.14W. There, large blocks of Shinarump strata have slid part way down a dip slope where Shinarump strata have been under cut by the Virgin River. An older, deeply dissected rotational landslide that involved strata of the Shnabkaib and upper red members of the Moenkopi Formation is found immediately north of Quail Creek Reservoir.

Talus deposits (Qmt): Talus has only locally been mapped at the base of steep slopes of the

Navajo Sandstone. It consists of locally derived, very poorly sorted, angular boulders and lesser fine-grained interstitial sediments deposited by rock fall processes. These deposits are gradational with colluvial deposits and vary from 0 to about 20 feet (0-6 m) thick.

Mixed-environment deposits

Older alluvial and colluvial deposits (Qaco): Older mixed alluvial and colluvial deposits were mapped only near the southern end of Harrisburg Dome. They are similar to modern deposits, except that they form incised, inactive surfaces up to about 20 feet (6 m) above modern drainages. They consist principally of poorly to moderately sorted, locally derived or reworked sediments. Most deposits are less than about 20 feet (6 m) thick.

Alluvial and colluvial deposits (Qac): Mixed alluvial and colluvial deposits have been mapped throughout the quadrangle. They consist principally of poorly to moderately sorted, locally derived or reworked sediments. These deposits generally occur in small, nearly enclosed depressions that receive diffuse, locally derived, clastic input from surrounding slopes, unlike alluvial deposits which have a definite unidirectional source and transport. Some deposits occur in narrow washes that receive significant slopewash sediment from adjacent slopes. Mixed alluvial and colluvial deposits are gradational and correlative with modern alluvial and colluvial deposits. Most deposits are less than about 20 feet (6 m) thick.

Older alluvial and eolian deposits (Qaeo): Older mixed alluvial and eolian deposits are similar to modern such deposits, except that they generally form incised, inactive, gently sloping surfaces about 20 feet (6 m) above modern drainages. They consist of poorly to moderately sorted clay- to boulder-size sediments with well sorted eolian sand and reworked eolian sand, commonly with well-developed pedogenic calcium carbonate. The deposits west of Harrisburg Flat are gypsiferous. These deposits have been mapped principally along the Kayenta outcrop on the west side of the Virgin anticline. Older mixed alluvial and eolian deposits are correlative with level 2 and level 3 alluvial deposits. Most deposits are less than about 30 feet (9 m) thick.

Alluvial and eolian deposits (Qae): Mixed alluvial and eolian deposits consist of poorly to moderately sorted clay- to boulder-size sediments with well sorted eolian sand and reworked eolian sand. These deposits have been mapped in modern channels and over broad, gently sloping depressions. Mixed alluvial and eolian deposits are gradational and correlative with modern alluvial and eolian deposits, and with mixed eolian and alluvial deposits. They are differentiated from the later by their preponderance of alluvial sediments and sedimentary structures over eolian sediments and features. Most deposits are less than about 20 feet (6 m) thick.

Eolian and alluvial deposits (Qea): Mixed eolian and alluvial deposits are mapped north of Washington City. They consist of well sorted eolian sand and reworked eolian sand and lesser clay- to pebble-size alluvial sediments, normally with thick pedogenic calcium carbonate.

Eolian and alluvial deposits are correlative and gradational with mixed alluvial and eolian deposits. They are generally less than about 20 feet (6 m) thick.

Alluvial, eolian, and colluvial deposits (Qaec): Mixed alluvial, eolian, and colluvial deposits have been mapped in several areas between Washington and Harrisburg Junction, and in the middle reaches of Cottonwood Wash. These deposits consist principally of poorly to moderately sorted, clay- to small boulder-size sediments with well sorted eolian sand and reworked eoilan sand, but with a significant component of colluvial or slopewash material. The deposits on the southern flank of the cinder cone in section 36, T.41S., R.15W., however, contain a greater proportion of colluvial debris shed off the cone itself. These deposits are generally less than about 20 feet (6 m) thick.

Residual deposits (Qr)

Angular cobble- to boulder-size basalt clasts that form a blocky surface that drapes over and mostly conceals Springdale Sandstone (Qr/Jms) and Kayenta (Qr/Jk) strata west of Washington Black Ridge has been mapped as residual deposits. The basalt clasts apparently represent a lag deposit derived from the Washington flow. They vary from 0 to 2 feet (0-0.6 m) thick.

Spring deposits (Qst)

Calcareous spring tufa is exposed in two areas in the southwestern corner of the quadrangle. One outcrop, of uncertain thickness, is exposed in a trench in the NWNWNW 1/4 section 13, T.42S., R.15W. The other outcrop forms a veneer at the base of the Shinarump Conglomerate on the southern side of Washington Black Ridge. Both deposits are light gray to brownish gray, porous, and contain a sponge-like network of vesicles. Both appear to be actively forming.

STRUCTURE

Regional Setting

The Harrisburg Junction quadrangle lies within the north-trending transition zone between the Basin and Range and Colorado Plateau physiographic provinces. The Basin and Range province is characterized by roughly east-west extensional tectonics, including block faulting and widespread igneous activity. The Colorado Plateau province is a relatively coherent and tectonically stable region underlain by generally horizontal sedimentary strata that are locally disrupted by early Tertiary Laramide basement-block uplifts, Oligocene/Miocene igneous intrusions, and Late Tertiary to Quaternary basalt flows. Both provinces have experienced broad, epeirogenic uplift. The transition zone is characterized by sedimentary strata and structures common to both physiographic provinces. In southwestern Utah, it includes two major down-to-the-west normal fault zones that step down from the Colorado Plateau to the Basin and Range. The greater St. George area, including the Harrisburg Junction quadrangle, lies on the intermediate structural block thus created, bounded on the east by the Hurricane fault and on the west by the Gunlock-Grand Wash faults (figure 1).

The transition zone also roughly coincides with the leading edge of the Sevier orogenic belt, and it is this Late Cretaceous compressional event that gives the quadrangle its most prominent structural feature - the Virgin anticline. The Virgin anticline trends northeast through the quadrangle. A number of low-angle, comparatively shallow, eastward-directed reverse faults repeat Triassic strata on the northwest flank of the anticline. Aeromagnetic anomalies suggest that the Virgin anticline is detached from basement rocks.

Folds

Virgin Anticline

The Virgin anticline - the dominant structural feature of the Harrisburg Junction quadrangle - is a 30-mile (48 km) long, northeast trending, generally symmetrical fold that is co-linear with the Kanarra anticline to the north. The Virgin anticline is neatly outlined by the resistant Shinarump Conglomerate Member of the Chinle Formation, which forms a hogback around a central core of Moenkopi and Kaibab strata (see figure 4). The anticline has three similar structural domes along its length. From south to north these are the Bloomington Dome, Washington Dome, and, in the Harrisburg Junction quadrangle, the Harrisburg Dome. The Permian Kaibab Formation forms the exposed core of each dome.

Most reports indicate that the Virgin anticline is asymetrical, with steeper dips on its northwest flank. In the Harrisburg Junction quadrangle, the fold appears generally symmetrical, with dips of 20 to 35 degrees common on the flanks of the fold, and steeper dips of 30 to 50 degrees at the more tightly folded Harrisburg Dome.

Several minor subsidiary folds, with axes generally parallel to the main axis of the Virgin anticline, have been mapped in the quadrangle. Most are related to folding associated with west-dipping low-angle faults west and south of Harrisburg Junction and north of old Harrisburg. The Shnabkaib Member of the Moenkopi Formation is tightly folded along the northwest flank of Harrisburg Dome, and immediately north of the Quail Creek south dam; these folds, too, appear to be associated with west-dipping, low-angle faults.

Harrisburg Dome: Harrisburg Dome lends its name to the Harrisburg Member of the Kaibab Formation, which forms the core of this elongate dome. Only the upper portion of the Harrisburg Member, above and including the medial limestone, is exposed at the dome. All but the southern end of the dome is neatly outlined by a thin, low, resistant hogback of Virgin Limestone. Based on dips of the Virgin Limestone, the northern end of the dome's axis plunges northeast at about 8 degrees. The south part appears to plunge gently southwest as well, based on exposures of Harrisburg strata at Harrisburg and Washington Domes. An axial backthrust, described below, has served to accomodate tight folding in the core of the dome.

Leeds Anticline and Leeds Syncline

The northwestern flank of the Virgin anticline is marked by parallel, 2 to 3 mile (3-5 km) long subsidiary folds of the Leeds anticline and Leeds syncline (Proctor, 1953). The Leeds anticline is best exposed at Tecumseh Hill, northwest of Leeds, immediately east of the quadrangle boundary. There the Springdale Sandstone forms the crest of this fold, which plunges about 15 degrees north. South of Buckeye Reef, which forms the western flank of this fold, the anticlinal axis bends abruptly to the southwest along Leeds Reef. The Leeds anticline is bounded on the east by a west-dipping, low-angle fault, which truncates the southern portion of the anticline. Only this southern part is contained with the Harrisburg Junction quadrangle.

Leeds Reef, along the core of the Leeds anticline, is formed of folded beds previously mapped as the the Shinarump Conglomerate Member of the Chinle Formation (Proctor, 1953; Proctor and Brimhall, 1986). Exposures in the SE 1/4 section 14, T.41S., R.14W., however, show that these beds are underlain by brightly colored swelling mudstones characteristic of the Petrified Forest Member. I reinterpret these Shinarump-like strata as thick channel sandstones of the basal Petrified Forest Member, similar to those exposed at the southern end of Washington Black Ridge.

The Leeds syncline, which lies between and roughly parallel to the Leeds and Virgin anticlines, plunges gently northeast beneath the town of Leeds, immediately east of the Harrisburg Junction quadrangle. The syncline is cored by the Petrified Forest Member of the Chinle Formation, while its flanks are upheld by the Shinarump Conglomerate and basal sandstones of the Petrified Forest Member. The syncline is mostly concealed by Quaternary deposits under the town of Leeds and along the Interstate 15 corridor. It is poorly defined in the Harrisburg Junction quadrangle due to low-angle faulting and minor folds along the eastern side of Leeds Reef; thus, the axial trace of the syncline has not been mapped.

St. George Syncline

Along the southern flank of the Pine Valley Mountains, strata between the Virgin anticline and Gunlock Fault form a broad, shallow fold that Cordova (1978) called the St. George syncline. Strata in the northwestern portion of the Harrisburg Junction quadrangle and adjacent areas to the west and north are interpreted to form the ill-defined eastern limb of this fold. Willis and Higgins (1995) noted that this fold may die out near the middle of the Washington quadrangle, immediately west of the Harrisburg Junction quadrangle.

Faults

Low-angle Reverse Faults

Several west-dipping, low-angle reverse faults are found along the west flank of the Virgin anticline. The largest and westernmost such fault was first recognized by Proctor (1948, 1953) amid considerable controversy over structural interpretations of the Silver Reef mining district. This fault separates Buckeye Reef and White Reef and can be traced at least 7 miles (11 km) to the southwest. The fault repeats the Moenave Formation in the reefs, and 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 that it undulates between upper Petrified Forest and lower Kayenta strata. The fault plane is visible in the SW 1/4 section 12, T.41S., R.14W., about 300 feet (91 m) from the west section line and 700 feet (213 m) from the south section line; and in the NW 1/4 section 12, T.41S., R.14W., about 1,900 feet (579 m) from the west section line and 2,400 feet (732 m) from the north section line. In the State Highway 9 roadcut at the common border of sections 4 and 5, T.42S., R.14W., a prominent drag fold is exposed below the fault zone (figure 9). Based on surface and subsurface data, the fault dips about 30 degrees west-northwest. Proctor and Brimhall (1986) estimated that, in the Silver Reef mining district, the Springdale Sandstone Member has been displaced eastward at least 2,000 feet (610 m) on this fault.

(Figure 9 near here)

Proctor and Brimhall (1986) also described a smaller thrust fault between Buckeye and Butte Reefs, in the adjacent Hurricane quadrangle. This low-angle reverse fault can be traced southwest into the Harrisburg Junction quadrangle, where it truncates the Leeds anticline at Leeds Reef and may account for steeper dips on that fold's eastern flank.

Two minor low-angle reverse faults cut the resistant hogback of Shinarump strata on the west flank of the Virgin anticline. Near the Washington County landfill, Shinarump strata reveal a stratigraphic separation of about 200 feet (61 m). Except for minor folding of the Shnabkaib Member, Moenkopi strata below the upper part of the upper red member are unaffected by this faulting. Outcrop patterns suggest that the fault dips northwest parallel to bedding in the upper red member, but that at its southern terminous, it bends abruptly to merge with a northwest-trending, steeply northeast-dipping fault that may represent a tear fault. Shinarump strata in the hanging wall of this fault block are tightly folded into a series of poorly expressed, northeast-trending folds.

Farther north, at Quail Creek Reservoir, a similar low-angle, west-dipping, reverse fault offsets Shinarump beds. The stratigraphic separation is only a few tens of feet but is readily visible where the lower, yellow, cliff-forming sandstone (the "Purgatory Sandstone") of the upper red member has been offset. The fault is traced with difficulty into Shnabkaib strata, where it appears to die out. Kink folds and a small back thrust associated with this low-angle fault are exposed in a wash in the SW 1/4 section 26, T.41S., R.14E., about 400 feet (121 m) north of the south section line and 2,200 feet (670 m) east of the west section line. A series of east-northeast-trending anticlines and synclines, now inundated by Quail Creek reservoir, are found immediately north of Quail Creek south dam. They, too, appear to be related to this west-dipping low-angle fault. Upper red member strata in the footwall of this block are deformed by at least one secondary low-angle fault near the center of section 26, T.41S., R.14W..

Axial Thrust Fault

Harrisburg Dome is cut by a steeply east-dipping backthrust that repeats Harrisburg Member strata along the dome's southeast flank. The cuesta immediately east of the main axis of the dome consists of east-dipping strata of the lower red member of the Moenkopi Formation that is overlain in fault contact with east-dipping strata of the Harrisburg Member of the Kaibab Formation (figures 2 and 3). Exposures of Harrisburg strata suggest that the fault cuts gradually up through Harrisburg beds when traced from north to south, but that it is otherwise substantially parallel to bedding. An apparent maximum lateral displacement of about 1,000 feet (305 m) is found near the center of the dome, with displacement decreasing both to the north and south; the maximum stratigraphic separation is about 400 feet (122 m). Noweir (1990) interpreted this as an axial thrust fault that developed to accomodate tight folding in the core of the Virgin anticline. Noweir (1990) further suggested that the shape of the fold is due to a basal detachment at the

Cambrian/Precambrian boundary.

High-angle Normal Faults

The Washington fault zone is a 42-mile-long (68 km), down-to-the-west normal fault that extends from northern Arizona into southern Utah. Displacement decreases northward from an estimated maiximum of 2,460 feet (750 m) in Arizona (Anderson and Christenson, 1989). The fault apparently splays and dies out in the adjacent Washington quadrangle to the west (Willis and Higgins, 1995). Willis and Higgins (1995) suggested that the Washington fault zone may have about 700 feet (213 m) of offset in the Washington area based on tenuous projections of widely separated bedrock units.

In the extreme southwest corner of the Harrisburg Junction quadrangle, the Washington basalt flow is offset by several down-to-the-west and down-to-the-east splays of the Washington fault zone. In the adjacent Washington Dome quadrangle to the south, Shinarump and upper red member strata are offset as well. The shallow horsts and grabens thus formed show up to about 15 feet (4.5 m) of offset on the basalt flow itself, which has a K-Ar date of 1.7 +/- 0.1 Ma reported in Best and others (1980). The fault zone also offsets late Pleistocene sediments south of the quadrangle (Anderson and Christenson, 1989; Hecker, 1993).

Joints

Joints are common in all bedrock units in the Harrisburg Junction quadrangle, but they are best developed in the Navajo Sandstone and the Shinarump Conglomerate Member of the Chinle Formation. Joints in the latter are generally widely spaced (from a few tens of feet to several tens of feet) and form a conjugate set subparallel to the strike and dip of bedding. The joints and adjacent rock are heavily stained by iron-manganese oxides, forming "picture stone."

The Navajo Sandstone itself is nearly everywhere pervasively jointed. As a result, the Navajo is more easily eroded and forms fewer massive, high cliffs than is typical of exposures a few tens of miles to the east. The most prominent are high-angle, open joints that trend roughly parallel to the Navajo outcrop belt, swinging from northeast to more northerly trends when traced northward through the quadrangle. They form a conjugate set with similar but less well developed, generally northwest-trending joints. Hurlow (in preparation) reported similar joint orientation maxima in his larger study of the region's ground water conditions. These joints tend to form long, straight, deep, narrow cracks in the rock; evidence of brecciation or recementation is uncommon. Some of the larger, more prominent joints have been mapped individually.

Similar, though shorter and more closely spaced joints are also common throughout the Navajo Sandstone. These joints exhibit wide variation in orientation, and commonly appear curvilinear in many exposures, suggesting that they may be related in part to unloading and exfoliation. Where well developed, these are shown on the map by a joint symbol.

ECONOMIC GEOLOGY

Sand and Gravel

Sand and gravel is currently being mined at the southeast end of Harrisburg Dome, in deposits mapped as Qal_3. Abandoned sand and gravel pits are common throughout the lower elevations of the quadrangle, and are shown with a symbol. Most are found in deposits mapped as Qao_1, Qao_2, Qal_1, and Qal_3. Trenches in many deposits - for example in Qal_4 deposits at the common corner of sections 15, 16, 21, and 22, T.42S., R.14W., and in Qao_2 deposits northwest of Harrisburg Junction - indicate that some sand and gravel deposits in the quadrangle have been evaluated but not developed. Deposits mapped as Qao_1 along the west flank of the Virgin anticline, although not as well sorted as Virgin River gravels, may provide a significant source of coarse sand and gravel.

Moderately sorted sand and silt is being mined for use as a road base and general borrow material from Qal_1 deposits in the NE 1/4 section 18, T.42S., R.14W. Similar deposits, mapped as Qae and Qaeo, are found in section 13, T.42S., R.15W.

Well sorted eolian sand (Qe) is found throughout the quadrangle in generally thin, widely scattered exposures. The most extensive deposits are found south of the Virgin River where they largely conceal the Navajo Sandstone from which they are mostly derived.

Gypsum

Two small gypsum quarries are present in Temple Cap strata in the northwest portion of the quadrangle. One, still active, is located in the SE 1/4 section 12, T.41S., R.14W. It provides small blocks of white, gray or pink massive gypsum that is sold for use in sculpting. A similar quarry, now abandoned, is located in the SW 1/4 section 4, T.41S., R.14W. Massive gypsum, suitable for sculpting, is found elsewhere in Temple Cap strata within the quadrangle, and it is also common in the overlying Co-op Creek and Crystal Creek Members of the Carmel Formation. These bedded and nodular gypsum deposits reach up to 12 feet (4 m) in thickness.

A gypsum prospect in the Harrisburg Member of the Kaibab Formation is located on the southeast flank of Harrisburg Dome, in the SE 1/4 section 17, T.42S., R.14W. The upper part of the Harrisburg Member at Harrisburg Dome is very gypsiferous, but the gypsum occurs principally as impure beds and gypsiferous mudstone. The Shnabkaib Member of the Moenkopi Formation is similarly gypsiferous, but no prospects are known in the quadrangle.

Building and Ornamental Stone

The Shinarump Conglomerate, Springdale Sandstone, Navajo Sandstone, Temple Cap Formation, and Washington basalt flow have each been quarried for building or ornamental stone in the Harrisburg Junction quadrangle. Each of the quarries is small, having produced rough blocks for building and landscaping. A recently worked quarry in the Navajo Sandstone is located in the east-central portion of section 11, T.41S., R.15W. A smaller, apparently abandoned quarry is located in the south-central portion of section 7, T.41S., R.14W. Lower Temple Cap sandstone has been quarried in the SW 1/4 section 4, T.41S., R.14W. and the NW 1/4 section 9, T.41S., R.14W. Several historic buildings at and near the old Harrisburg site, and in the Silver Reef mining district, are made of what appears to be Springdale Sandstone.

Basalt columns and blocks from the southern end of Washington Black Ridge have been quarried in the past, probably principally for use in small retaining walls, landscaping, and for building foundations. Similar columns are present and accessible elsewhere along the flow.

The Shinarump Conglomerate has been widely quarried for use as decorative stone and, when thinly cut, for use as "picture stone" that is made into tiles and coasters. The Shinarump Conglomerate contains prominent but widely spaced joints. Staining by iron-manganese oxides is controlled by these joints, such that large blocks become concentrically zoned in a variety of interesting patterns. The largest quarries, currently active, are located along the lower reaches of Cottonwood Wash, in the SW 1/4 section 18, T.42S., R.14W. Other, inactive quarries, identified by symbols, are located to the north along the northwest flank of the Virgin anticline. Numerous small workings, made largely by hand, have not been mapped. "Picture stone" is also common in the Iron Springs Formation, although no workings are known in the quadrangle.

Clay

A single abandoned clay pit - incorrectly labeled a gravel pit on the topographic base map in the SE 1/4 section 5, T.42S., R.14W. - was found in upper Petrified Forest Member strata. The pit measures about 500 feet (152 m) long by about 35 feet (11 m) deep. The clays are brightly colored swelling clays typical of the Petrified Forest Member. They may have been used to line retaining ponds.

Metals

Silver Reef mining district

The Silver Reef mining district is noted for its uncommon occurrence of ore-grade silver chloride (cerargyrite or horn silver) in sandstone, unaccompanied by obvious alteration or substantial base metal ores. High-grade silver chloride float was first discovered near Harrisburg in 1866, but it wasn't until 1876 that the silver rush was underway in earnest (Proctor, 1953; Proctor and Brimhall, 1986). Proctor and Shirts (1991) provide a fascinating account of the discovery, disbelief, and re-discovery of this unusual mineral occurrence.

The Silver Reef mining district consists of four "reefs" located along the northern flanks of the Virgin anticline; White, Buckeye, and Butte Reefs are located on the anticline's northwest flank, while East Reef is located on the anticline's northeastern flank (figure 10). The ore horizons are contained within the Springdale Sandstone Member of the Moenave Formation, 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 southern part of White Reef and the extreme southern portion of Buckeye Reef are present in the Harrisburg Junction quadrangle.

(Figure 10 near here)

The principal mining activity in the district lasted only through 1888, with lessee operations through 1909, after which operations essentially ceased. Approximately 8 million ounces (226,800,000 gm) of silver were produced prior to 1910, nearly 70 percent of which came from the prolific Buckeye Reef immediately east of the quadrangle. Sporadic production between 1949 and 1968 amounted to about 30 oz (850 gm) of gold, 166,000 oz (4,706,100 gm) of silver, 60 short tons (54,000 kg) of copper, and at least 2,500 pounds (1,125 kg) of uranium oxide (Houser and others, 1988). The mines were shallow, less than 350 feet (107 m) deep, and most ore bodies were lens shaped, averaging 200-300 feet (61-91 m) long by about half as wide. The ore averaged 20 to 50 oz (567-1,417 gm) silver per ton, but varied from only a few ounces to about 500 ounces (14,175 gm) per ton. (Proctor and Brimhall, 1986; Eppinger and others, 1990).

The genesis of these deposits has been the subject of considerable debate ever since their discovery, and it remains equivocal. Proctor (1953), Wyman (1960), Cornwall and others

(1967), Heyl (1978), James and Newman (1986), Proctor and Brimhall (1986), and Eppinger and others (1990) discuss mineral ocurrences and proposed models for the Silver Reef mining district. Several of these models are summarized by Houser and others (1988).

In the early 1950's, the U.S. Atomic Energy Commission initiated a drilling program to evaluate uranium resources in the Silver Reef mining district (Stugard, 1951, Poehlmann and King, 1953). Over 350 holes were drilled at Buckeye Reef, immediately east of the quadrangle boundary. They noted that uranium mineralization was controlled by lithology and structure, with faults and joints serving as conduits for transporting mineralized solutions to the favorable beds. Several hundred tons of uranium ore was mined in the Silver Reef mining district, beginning with an initial shipment in 1950. Carnotite is the predominant uranium and vanadium mineral. It occurs as a cementing agent, and, more commonly, as a fracture filling and in association with carbonized wood fragments.

As recently as 1979, a leach pad operation was established between White and Buckeye Reefs to process tailings, but this venture closed with the collapse of silver prices (C. Rohrer, Utah Abandoned Mine Land Reclamation Program, verbal communication, April 7, 1997).

Other prospects

There are numerous prospect pits and a few short adits and shafts outside the Silver Reef mining district. Most are located in Moenave strata to the south, along the west flank of the Virgin anticlne. Numerous prospect pits and minor shafts are present in Dinosaur Canyon strata in the NW 1/4 section 8, T.42S., R.14W., and two vertical shafts in excess of 20 feet (6 m) deep are found in Dinosaur Canyon strata in the SE 1/4 section 12, T.42S., R.15W. Prospects and minor inclined shafts are found in Springdale Sandstone in the NW 1/4 section 8, T.42S., R.14W.; in the SW 1/4 section 27, T.41S., R.14W.; and in the SE 1/4 section 22, T.41S., R.14W. A propsect is located in Whitmore Point strata in the SE 1/4 section 5, T.41S., R.14W. Each of these prospects reveals malachite and minor azurite mineralization.

Three prospect pits are also found at the north end of Harrisburg Dome. They are located in white, highly fractured chert of the Harrisburg Member of the Kaibab Formation. The chert is thin-bedded with poorly preserved low-angle cross stratification and has minor fracture-controlled malachite staining.

Oil and Natural Gas

Two unsuccessful wildcat wells, now abandoned, were drilled in the Harrisburg Junction quadrangle. According to records at the Utah Division of Oil, Gas and Mining, the Harry T. Cypher Co. #1 well (formerly the Virgin Dome Oil Co.) (API #43-053-20516) was drilled to a depth of 3,400 feet (1,037 m) before 1923. The hole was later re-entered and abandoned in 1941 at a total depth of 3,508 feet (1,070 m). This was the first wildcat well drilled on the Virgin anticline following the discovery of oil at the Virgin Oil Field, about 10 miles (16 km) to the east. (These records conflict slightly with that reported by Boshard (1952) who stated that the well was begun in 1919 and after intermittent drilling reached a total depth of 3,400 feet (1,037 m) in 1934. Cook (1960, p. 111) reported that the hole was begun in 1918 and implied that a second well was drilled between 1929 and 1936 to a depth of 2,540 feet (774 m), however, no other reports of such a well have been found.) No oil shows were reported in DOGM records or in Boshard (1952), but Bassler and Reeside (1921, p. 101) stated that a light showing of oil was reported at a depth of about 1,000 feet (305m), near the top of what was then called the Coconino-Supai sandstone. The well, shown on the topographic base map by the symbol *DH*, is located in the NENWNW 1/4 section 16, T.42S., R.14W. Reeside and Bassler (1921) summarized a stratigraphic section from this well, although no log is currently available. A second wildcat well (API #43-053-20500), abandoned in 1938 at a total depth of just 47 feet (14 m), is located in the SWSW 1/4 section 24, T.41S., R.14W.

The Virgin oil field, the oldest oil field in Utah, was first developed in 1907 following the discovery of oil and asphalt seeps about 10 miles (16 km) east of the Harrisburg Junction quadrangle near the town of Virgin. The primary productive interval at the Virgin oil field is the uppermost part of the Timpoweap Member of the Moenkopi Formation. This interval is not present at Harrisburg Dome, probably due to depositional patterns that were influenced by paleotopography. Timpoweap strata are exposed at Bloomington Dome, although no shows of oil or asphaltic material have been found there. Timpoweap strata may be present in the

Harrisburg Junction quadrangle in the subsurface. Significant shows of oil at the Virgin oil field are also reported from the Kaibab and Pakoon Formations, and the Callville Limestone, the latter two of which have apparently not been drilled at Harrisburg Dome (although they were penetrated in the California Oil Company No. 1 St. George Unit well on Bloomington Dome) (Heylmun, 1993). Possible structural traps are present along the western flank of the Virgin anticline, as well as along the anticlinal axis itself.

The lower part of the upper red member of the Moenkopi Formation is marked by a 100-foot-thick (30 m), light yellowish brown, cliff-forming sandstone (the "Purgatory Sandstone") that stands in marked contrast to the enclosing red beds. No evidence of oil has been found at this horizon, but the yellowish color o fthe bed may have been caused by reducing hydrocarbon brines trapped in the core of the Virgin anticline prior to erosion along the anticlinal axis.

Geothermal Resources

Budding and Sommer (1986) conducted an assessment of low-temperature geothermal resources in the St. George basin. They found the highest recorded spring water temperature to be 108^{0}F (42^{0}C) at the Pah Tempe Hot Springs, located 6 miles (10 km) east of the Harrisburg Junction quadrangle between LaVerkin and Hurricane. They also identified an area of possible low-temperature geothermal potential, with warm well water (> 76^{0}F (24.5^{0}C)), in the area north of Washington and St. George. Low-temperature geothermal resources in this region appear to be related to structure, rather than to recent volcanic activity. Basalts in the region are believed to have originated at considerable depth, rising to the surface though narrow conduits, thus obviating the basalt as a significant heat source (Budding and Sommer, 1986). The Washington fault zone may provide a conduit for warm ground water north of Washington.

WATER RESOURCES

With an average annual precipitation of just 10 to 12 inches (254-305 mm) (Cordova and others, 1972), and the recent surge in popularity of the greater St. George area as a retirement and vacation center, water is a major issue in the future development of the area. The 1993 State Water Plan for the Kanab Creek/Virgin River Basin summarizes water availability and use for the basin, as well as development, regulatory, and other issues that relate to water management. Several other studies of water use and availability, cited below, have been undertaken in the St. George basin.

Surface Water

The Virgin River, the trunk river of the Virgin River basin, bisects the southeastern corner of the Harrisburg Junction quadrangle. Just upstream at Virgin, it has an average annual flow of about 145,000 acre-feet (189,486,000 m^3) (Cordova and others, 1972). Leeds Creek, the only perennial tributary stream in the quadrangle, has an average annual flow of about 5,000 acre feet (6,534,000 m^3) (Cordova and others, 1972). Water Canyon, Big Hollow, Heath Wash, Bitter Creek, and Cottonwood Canyon often carry streams in their upper reaches but are normally dry in their middle and lower reaches. Heath Wash, in the SE 1/4 section 5, T.41S., R.124W., had a fairly consistent flow of 20 to 30 gpm (76-114 liters per minute) during the course of this mapping project.

Quail Creek Reservoir, operated as an off-line reservoir by the Washington County Water Conservancy District, is located in the eroded core of the Virgin anticline, north of State Highway 9. Two zoned-earth embankments, completed in 1984 and 1985, originally impounded the reservoir. The south dike failed catastrophically in 1989 and was rebuilt in 1990 as a concrete gravity dam. At its maximum pool elevation of 2,985 feet (910 m), the lake covers 640 acres (256 hectares) and stores 40,325 acre-feet (49,745,694 m^3) of water. Most of the water is diverted from the Virgin River northeast of Hurricane and piped to the reservoir; a small amount comes from Quail and Leeds Creeks. The City of St. George recently purchased 10,000 acre-feet (13,068,000 m^3) per year from the Washington County Water Conservancy District, almost half of the reservoir's annual yield. (Horrocks-Carollo Engineers, 1993).

Herbert (1995) conducted a seepage study of selected reaches of the Virgin River between Ash Creek and Harrisburg Dome, and noted that the downstream reaches of his study area, including that segment of the river in the Harrisburg Junction quadrangle, had no substantial gain or loss from seepage.

The western abutment of the proposed Sand Hollow dam will be located in the extreme southeast corner of the Harrisburg Junction quadrangle (Dan Aubrey, Utah Division of Water Rights, June 10, 1997). It will be operated as an offline reservoir. Anticipated seepage into the underlying Navajo Sandstone will replenish local ground water and effectively serve to increase the reservoir's capacity.

Ground Water

The principal aquifers in the St. George basin are found in Moenkopi, Chinle, Moenave, Kayenta, Navajo, and overlying unconsolidated strata. In the Harrisburg Junction quadrangle, most wells tap Navajo and Kayenta strata, and Quaternary alluvial deposits.

Several large wells in the Navajo Sandstone provide much of the drinking water for Washington and St. George (Horrocks and Carollo Engineers, 1993). The City of Washington recently completed a 950-foot-deep (290 m) well in the upper reaches of Grapevine Wash. This well penetrates Navajo/Kayenta transition strata but is a relatively poor producer. A 24-hour aquifer test of this well yielded an average production of just 180 gpm (684 liters per minute) (Heilweil, 1997).

The principal recharge to the Navajo aquifer, which is unconfined, comes from precipitation over the Navajo outcrop belt and from streams that cross and seep into the formation; joints in the Navajo act as major conduits for infiltrating ground water (Cordova, 1978; Freethey, 1993; Hurlow, in preparation). Ground water in the Navajo aquifer generally moves southward, against the gentle northward dip of bedrock strata and radially away from the Pine Valley Mountains, towards the Virgin River Valley. The Virgin River forms the major base level in the area.

Hurlow (in preparation) reported on the geology and groundwater conditions of the central Virgin River basin, which includes the Harrisburg Junction quadrangle. He noted that joint zones - discrete, linear zones of high joint density - should be the primary targets for future water wells because the permeability of these zones is up to 35 times that of adjacent, less densely jointed rock.

A number of springs issue from lower Navajo and upper Kayenta strata between St. George and Washington. Several are shown on the topographic base map; others are listed in Cordova and others (1972), Cordova (1978), Clyde (1987), and Freethey (1993). These springs issue out of the base of the aquifer, above impermeable Kayenta beds, and represent water that is spilling over the lip of the gently north-dipping aquifer.

Ground water quality in the St. George basin was reported in Cordova and others (1972), Cordova (1978), Clyde (1987), and summarized in Freethey (1993). Water in the Navajo aquifer generally contains less than 1,500 mg/L, and commonly less than 500 mg/L, dissolved solids and is therefore of generally high quality. Total dissolved solids are generally greater in deeper aquifers, and down-gradient within an individual aquifer.

GEOLOGIC HAZARDS

Earthquakes

The Harrisburg Junction quadrangle lies near the southern end of the Intermountain seismic belt, a north-trending zone of pronounced, shallow seismicity approximately encompasing the transition zone between the Basin and Range and Colorado Plateau physiographic provinces. Three major faults - the Gunlock, Washington, and Hurricane - are known to have Quaternary offset in southwestern Utah (Anderson and Christensen, 1989; Christensen, 1992; Hecker, 1993). The Washington and Hurricane faults in particular apparently have relatively high long-term slip rates, yet a general lack of evidence of recurrent Holocene movement, making it difficult to determine average recurrence intervals of surface faulting events. The region is generally considered capable of producing earthquakes of magnitude 7-7.5 (Arabasz and others, 1992), comparable to those known to have occurred prehistorically on the Wasatch fault zone in northern Utah.

Christensen and Deen (1983) compiled a record of 23 historical earthquakes of Richter magnitude 2.0 and greater within a 22-mile (35 km) radius of St. George that occurred during the period from 1850 to 1981; Anderson and Christensen (1989) updated that record though 1988. The largest such event, with an estimated magnitude of 6.3, occurred in 1902 and had an epicenter in Pine Valley, about 20 miles (32 km) north of St. George.

The most recent large earthquake in the greater St. George area occurred on September 2, 1992 (Black and Christensen, 1993; Pechmann and others, 1995). It had a Richter magnitude (M_L) of 5.8 and an epicenter about 6 miles (9 km) east of St. George. The estimated focal depth of the earthquake was about 9 miles (15 km). Arabasz and others (1992) suggested that the earthquake may have been generated by normal dip-slip movement on the west-dipping subsurface projection of the Hurricane fault. Olig (1995) prepared a preliminary isoseismal map that shows the relative intensity of ground shaking in southwestern Utah and adjacent areas from this event. The maximum Modified Mercalli intensity was VII in the Hurricane-Toquerville area. Although there was no evidence of surface fault rupture (Black and others, 1995), the earthquake caused damage up to 95 miles (153 km) from the epicenter (Carey, 1995; Olig, 1995). Borgione (1995) reported significant water level fluctuations in the main Quail Creek dam, although design parameters were not exceeded and the dam was considered safe. Black and others (1995) discussed other geologic effects of the St. George earthquake.

In the extreme southwest corner of the Harrisburg Junction quadrangle, the Washington basalt flow is offset by several down-to-the-west and down-to-the-east splays of the Washington fault zone. The flow, dated at 1.7 +/- 0.1 Ma (Best and others, 1980), is offset up to 15 feet (4.5m). The fault zone also offsets late Pleistocene sediments south of the quadrangle (Anderson and Christenson, 1989; Hecker, 1993). Anderson and Christensen (1989) interpreted the age of the last scarp-forming movement on the northern part of the Washington fault zone as middle to late Pleistocene in age (10-750 ka).

As the 1992 St. George earthquake demonstrated, hazards associated with earthquake activity include ground shaking, liquifaction, flooding, and rock falls and other seismically induced slope failures (Christensen, 1992; Black and Christensen, 1993; Black and others, 1995). Although not triggered by the St. George earthquake, surface fault rupture is also a potential hazard for large magnitude events. Old, unreinforced masonry structures present a serious potential for personal injury and property damage in the event of an earthquake. Ground shaking can be amplified in poorly consolidated alluvial and eolian deposits, further damaging structures, and may lead to hydrocompaction or liquifaction. Rock falls are of increasing concern as development encroaches on steep slopes. The Harrisburg Junction quadrangle is located in the Uniform Building Code seismic zone 2B, an area of moderate seismic risk with expected peak horizontal ground acceleration of 0.1 to 0.2 g (International Conference of Building Officials, 1997; Christensen and Nava, 1992).

Mass Movements

Landslides

In the Harrisburg Junction quadrangle, stratigraphic units especially susceptible to landslides include the Petrified Forest Member of the Chinle Formation, the Shnabkaib and upper red members of the Moenkopi Formation, and the Carmel Formation. Several large landslide complexes that involve these and adjacent overlying strata were mapped. Although most of the movement in these slides apparently took place in the Pleistocene when conditions were wetter than at present (Christensen and Deen, 1983; Christensen, 1992), they should be considered capable of renewed movement, especially if disturbed by construction activities.

Perhaps the most prominent landslides occur in the Petrified Forest Member of the Chinle Formation along the southern portion of Washington Black Ridge. These strata normally weather to gentle slopes, but where protected by a resistant unit such as the Washington basalt flow, they form steep, unstable slopes. At Washington Black Ridge, these slopes are characterized by rotational slumps with a hummocky surface and numerous internal scarps, and are littered with blocks of basalt. Petrified Forest strata, especially those that contain brightly colored swelling clays, are notoriously unstable even where exposed in areas of low relief.

Landslides that formed by translational rather than rotational movement are present on the southeast flank of the Virgin anticline. There, in the NE 1/4 section 10, T.42S., R.14W., the Virgin River has undercut steeply dipping Shinarump strata, exposing an unsupported dip slope.

Shinarump strata, already jointed from folding associated with the formation of the Virgin anticline, have slid downslope as coherent blocks above a failure plane in the upper red member of the Moenkopi Formation.

Rock falls

Evidence of rock falls are found throughout the quadrangle as an accumulation of large boulders at the base of steep slopes. Rock falls are a natural part of the erosion process and occur where resistant, fractured or jointed strata break apart and tumble downslope. They are commonly associated with heavy rainfall events or earthquakes, but many probably occur as isolated random events after prolonged weathering. Slopes that are oversteepened by construction activities may present additional rockfall hazards.

Many map units within the quadrangle are capable of producing rockfalls, but perhaps the most prolific are the upper red member of the Moenkopi Formation, the Shinarump Conglomerate Member of the Chinle Formation, the upper Kayenta Formation, and the Washington basalt flow. Particularly large blocks of Shinarump strata are found along the interior of the Virgin anticline, attesting to that unit's proclivity for producing rock falls.

Rock fall hazards becomes ever more insidious as an expanding population encroaches upon steeper slopes. The extent of the hazard can be assessed by the relative abundance of rockfall debris at the base of a slope. The relative hazard itself varies locally and depends upon the distance from the base of the slope, nature and stability of slope debris, and local topography (Christensen, 1992).

Problem Soil and Rock

Expansive soil and rock

Expansive soil or rock contains clay minerals that swell conspicuously when wet and shrink as they dry. This swelling and shrinking can cause significant foundation problems and can damage roads and underground utilities. The Petrified Forest Member of the Chinle Formation contains swelling bentonitic clays that are responsible for numerous foundation problems in the greater St. George area (Christensen and Deen, 1983; Christensen, 1992). Locally known as "blue clay," these clays are commonly brightly colored and "bleed" through to the surface; they typically weather to a cracked, popcorn-like surface. Mulvey (1992) noted that common problems associated with swelling soils include cracked foundations, heaving and cracking of floor slabs and walls, and failure of septic systems. Special foundation design and drainage control are necessary for construction in such areas (Christensen, 1992).

Although no mention of expansive clays was made in engineering reports of the Quail Creek dam and underlying Shnabkaib strata (Gourley, 1992; Payton, 1992), such clays are known to occur in the Shnabkaib Member, and, to a lesser extent, in the lower, middle, and upper red members of the Moenkopi Formation (Christensen, 1992). Expansive clays may also be present in the Whitmore Point Member of the Moenave Formation, the Temple Cap and Carmel Formations, and Cretaceous strata. Fine-grained alluvial sediments derived from these strata may also have a moderate swell potential (Christensen and Deen, 1983).

Gypsiferous soil and rock

Dissolution of gypsum can lead to a loss of internal strength within a deposit, resulting in collapse of overlying strata; the resulting subsidence and sinkholes are similar to those found in limestone terrain. Gypsum dissolution is accelerated by increased amounts of water, such as may occur in proximity to a reservoir, leach fields, or irrigated areas. Gypsum is an important component of the Shanabkaib Member of the Moenkopi Formation and the Harrisburg Member of the Kaibab Formation. Gypsum is also common in the lower, middle, and upper red members of the Moenkopi Formation; in the Kayenta, Temple Cap, and Carmel Formations; and in fine-grained alluvial and eolian deposits derived from these units.

Dissolution of gypsum may lead to local foundation problems and may affect roads, dikes, and underground utilities. Gypsum dissolution was an important factor in the January 1, 1989 failure of the Quail Creek dike (Gourley, 1992). Mulvey (1992) also noted that gypsum is a structurally weak material that has a low bearing strength, unsuitable for typical foundations.

Sulfuric acid and sulphate derived from gypsum dissolution can react with certain types of cement, weakening foundations.

Collapsible and compressible soil

Collapse-prone soils are known to occur in the Hurricane and Cedar City areas, and they may be present in the greater St. George area (Christensen and Deen, 1983; Mulvey, 1992). Collapsible soils have considerable strength and stiffness when dry, but can settle dramatically when wet, causing significant damage to structures and roads (Rollins and others, 1992). Such soils typically occur in geologically young, loose, dry, low-density deposits such as are common in Holocene-age alluvial fan and colluvial depositional environments. Hydrocompaction, or collapse, can occur when susceptible soils are wetted below the level normally reached by rainfall, destroying the clay bonds between grains (Mulvey, 1992). Irrigation water, lawn watering, or water from leach fields can initiate hydrocompaction. Some wind-blown deposits are also susceptible to hydrocompaction.

Flooding

In the Harrisburg Junction quadrangle, the Virgin River and its floodplain are contained within a relatively narrow, mostly undeveloped corridor bounded by resistant Shinarump strata and basalt flows. Major riverine floods would thus have comparatively little impact within the quadrangle. The potential hazard associated with flash floods and debris flows in tributary drainages, however, is much more serious.

Although most streams in the quadrangle carry water only intermittantly, they have large catchment basins on the flanks of the Pine Valley Mountains. Flash floods from rapid snowmelt or thunderstorm cloudbursts can turn these normally dry washes into raging torrents. In contrast to major riverine floods, flash floods are highly localized and unpredictable; they quickly reach a maximum flow and then quickly diminish. Flash floods commonly contain high sediment or debris loads and commonly begin or end as debris floods or flows (Lund, 1992), further adding to the destructiveness of such events.

The most recent major flood to scour the Virgin River channel was that which occured on January 1, 1989 following the catastrophic failure of the Quail Creek dike. O'Neill and Gourley (1991), Gourley (1992), and Payton (1992) summarized the events and conditions that led to the dike's failure as well as geotechnical aspects of its reconstruction. Evidence of the flood is still visible downstream of the dike where Shnabkaib strata were scoured clean of loose overlying sediment, and atop the basalt flow immediately south of the State Highway 9 bridge over the Virgin River, where well-cemented gravels overlying the basalt were scoured clean.

Abandoned mines

The Abandoned Mine Land Reclamation Program (AMLRP), a part of the Utah Division of Oil, Gas and Mining, recently completed reclamation of the western portion of the Silver Reef mining district. Wright (1992) discussed early reclamation efforts at Silver Reef, which began in 1988. A variety of methods were used to seal over 500 adits and shafts in the district. Detailed maps and information on mine openings are available from AMLRP. Some adits are shown on the topographic base map. Reclamation work at East Reef, in the adjacent Hurricane quadrangle, is scheduled to begin in 1997.

Additional, as yet unsealed and potentially hazardous adits and shafts are present in Moenave strata southwest of the mining district. Their locations are shown on the map by a symbol and are also given in the economic geology section of this report.

Radon

Radon is an odorless, tasteless, colorless radioactive gas that is found in small concentrations in nearly all rocks and soil. Radon can become a health hazard when it accumulates in sufficient concentrations in enclosed spaces such as buildings. A variety of geologic and non-geologic factors combine to influence indoor radon concentrations, including soils or rocks with naturally elevated levels of uranium, soil permeability, ground water levels, atmospheric pressure, building materials and design, and other factors. Indoor radon concentrations can vary dramatically within short distances due to both geologic and non-geologic factors. Still, geologic factors can be assessed to create generalized maps that show areas where elevated indoor radon levels are more likely to occur.

Solomon (1922a, 1992b, 1995) evaluated the radon hazard potential of the greater St. George area, including the southwestern corner of the Harrisburg Junction quadrangle; the rest of the quadrangle was not evaluated. The part of the area evaluated was assigned a low to moderate indoor radon hazard potential, suggesting that indoor radon concentrations are likely to be below 4 pico curies per liter (pCi/L), the current EPA action level. It is important to note, however, that a quantative relationship between geologic factors and indoor radon levels does not exist, and that localized areas of higher or lower radon potential are likely to occur in any given area. Actual indoor radon levels can vary widely over short distances, even between buildings on a single lot.

Soloman's work also suggests that the Petrified Forest Member of the Chinle Formation, and clasts from the Pine Valley intrusive complex, are a local primary source of uranium. Uranium has been mined from the Springdale Sandstone Member of the Moenave Formation in the Silver Reef mining district. The indoor radon hazard may be greater in structures built on these formations or sediments or tailings derived from them.

Volcanism

Flood basalts and basaltic cinder cones show that the St. George basin has been the site of numerous volcanic eruptions during the past two million years. The most recent flow in the area is the Santa Clara flow, which, based on geomorphic considerations, Willis and Higgins (1995) estimate is about 10,000 to 20,000 years old. Such relatively young flows and anomalous geothermal activity suggest that additional eruptions will occur. Future eruptions can be expected to follow a similar pattern, producing relatively small cinder cones and slow-moving flows that follow topographic lows. Such eruptions are likely to be preceeded by anomalous earthquake activity that may provide considerable warning of an impending eruption. Bugden (1992) discussed possible effects of volcanic hazards in southwestern Utah, including those associated with distant volcanoes.

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REFERENCES CITED

Anonymous, 1993, State Water Plan, Kanab Creek/Virgin River basin: Salt Lake City, Utah Board of Water Resources, unnumbered, variously paginated.

Anderson, R.E., and Christensen, G.E., 1989, Quaternary faults, folds, and selected volcanic features in the Cedar City $1^0 \times 2^0$ quadrangle, Utah: Utah Geological and Mineral Survey Miscellaneous Publication 89-6, 29 p., scale 1:250,000.

Arabasz, W.J., Pechmann, J.C., and Nava, S.J., 1992, The St. George (Washington County), Utah, earthquake of September 2, 1992: University of Utah Seismograph Stations Preliminary Earthquake Report, 12:00 MDT, September 6, 1992, 6 p.

Bassler, Harvey, and Reeside, J.B., Jr., 1921, Oil prospects in Washington County, Utah: U.S. Geological Survey Bulletin 726, p. 87-107.

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

Best, M.G., and Brimhall, W.H., 1974, Late Cenozoic alkalic basaltic magmas in the western Colorado Plateaus and the Basin and Range transition zone, U.S.A., and their bearing on mantle dynamics: Geological Society of America Bulletin, v. 85, no. 11, p. 1,677-1,690.

Best, M.G., McKee, E.H., and Damon, P.E., 1980, Space-time-composition patterns of late Cenozoic mafic volcanism, southwestern Utah and adjoining areas: American Journal of Science, v. 280, p. 1,035-1,050.

Birkeland, P.W., Machette, M.N., and Haller, K.M., 1991, Soils as a tool for applied Quaternary geology: Utah Geological and Mineral Survey Miscellaneous Publication 91-3, 63 p.

Black, B.D., and Christensen, G.E., 1993, M_L 5.8 St. George earthquake: Utah Geological Survey, Survey Notes, v. 25, nos. 3-4, p. 25-29.

Black, B.D., Mulvey, W.E., Lowe, M., and Solomon, B.J., 1995, Geologic effects, *in* Christensen, G.E., editor, The September 2, 1992 M_L 5.8 St. George earthquake, Washington County, Utah: Utah Geological Survey Circular no. 88, p. 2-11.

Blakey, R.C., Peterson, Fred, Caputo, M.V., Geesman, R.C., and Voorhees, B.J., 1983, Paleogeography of Middle Jurassic continental, shoreline, and shallow marine sedimentation, southern Utah, *in* Reynolds, M.W. and Dolly, E.D., editors, Mesozoic paleogeography of west-central United States: Rocky Mountain Section of Society of

Economic Paleontologists and Mineralogists, p. 77-100.

Borgione, Joe, 1995, Impact on dams, *in* Christensen, G.E., editor, The September 2, 1992 M_L 5.8 St. George earthquake, Washington County, Utah: Utah Geological Survey Circular no. 88, p. 31-34.

Boshard, J.R., 1952, Summary of the history of exploratory drilling of Virgin anticline, Washington County, Utah: Intermountain Association of Petroleum Geologists Guidebook to the Geology of Utah, no. 7, p. 84-85.

Budding, K.E., and Sommer, S.N., 1986, Low-temperature geothermal assessment of the Santa Clara and Virgin River Valleys, Washington County, Utah: Utah Geological and Mineral Survey Special Studies 67, 34 p.

Bugden, Miriam, 1992, Volcanic hazards of southwestern Utah, *in* Harty, K.M., editor, Engineering and environmental geology of southwestern Utah: Utah Geological Association Publication 21, p. 193-200.

Carey, Robert, 1995, Estimated economic losses, *in* Christensen, G.E., editor, The September 2, 1992 M_L 5.8 St. George earthquake, Washington County: Utah Geological Survey Circular no. 88, Utah, p. 40.

Christensen, G.E., and Deen, R.D., 1983, Engineering geology of the St. George area, Washington County, Utah: Utah Geological and Mineral Survey Special Studies 58, 32 p., scales 1:63,360 and 1:31,250.

Christensen, G.E., 1992, Geologic hazards of the St. George area, Washington County, Utah, *in* Harty, K.M., editor, Engineering and environmental geology of southwestern Utah: Utah Geological Association Publication 21, p. 99-107.

Christensen, G.E., and Nava, S.J., 1992, Earthquake hazards of southwestern Utah, *in* Harty, K.M., editor, Engineering and environmental geology of southwestern Utah: Utah Geological Association Publication 21, p. 123-137.

Clyde, C.G., 1987, Groundwater resources of the Virgin River basin in Utah: Logan, Utah State University, Utah Water Resource Laboratory, unnumbered, 104 p.

Cook, E.F., 1957, Geology of the Pine Valley Mountains, Utah: Utah Geological and Mineral Survey Bulletin 58, 111 p., scale 1:125,000.

Cook, E.F., 1960, Geologic atlas of Utah - Washington County: Utah Geological and Mineral Survey Bulletin 70, 119 p., scale 1:125,000.

Cordova, R.M., 1978, Ground-water conditions in the Navajo Sandstone in the central Virgin River basin, Utah: Utah Department of Natural Resources, Division of Water Rights, Technical Publication No. 61, 66 p., 3 pl., scale 1:250,000.

Cordova, R.M., Sandberg, G.W., and McConkie, Wilson, 1972, Ground-water conditions in the central Virgin River basin, Utah: Utah Department of Natural Resources, Division of Water Rights, Technical Publication no. 40, 64 p., 3 pl., scales 1:250,000, 1:125,000, and 1:63,360.

Cornwall, H.R., Lakin, H.W., Nakagawa, H.M., and Stager, H.K., 1967, Silver and mercury geochemical anomalies in the Comstock, Tonopah, and Silver Reef Districts, Nevada-Utah: U.S. Geological Survey Professional Paper 575-B, p. B10-B20.

Dobbin, C.E., 1939, Geologic structure of St. George district, Washington County, Utah: American Association of Geologists Bulletin, v. 23, no. 2, p. 121-144.

Dubiel, R.F., 1994, Triassic deposystems, paleogeography, and paleoclimate of the Western Interior, *in* Caputo, M.V., Peterson, J.A., and Franczyk, K.J., editors, Mesozoic systems of the Rocky Mountain region, USA: Rocky Mountain Section of Society of Economic Paleontologists and Mineralogists, p. 133-168.

Eppinger, R.G., Winkler, G.R., Cookro, T.M., Shubat, M.A., Blank, H.R., Crowley, J.K., Kucks, R.P., and Jones, J.L., 1990, Preliminary assessment of the mineral resources of the Cedar City 1^0 x 2^0 quadrangle, Utah: U.S. Geological Survey Open-File Report 90-34, 142 p., scale 1:250,000.

Freethey, G.W., 1993, Maps showing recharge areas and quality of ground water for the Navajo aquifer, western Washington County, Utah: U.S. Geological Survey Water Resources Division Map WRIR 92-4160, scale approximately 1:250,000.

Gourley, Chad, 1992, Geological aspects of the Quail Creek dike failure, *in* Harty, K.M., ed., Engineering and environmental geology of southwestern Utah: Utah Geological Association Publication 21, p. 17-38.

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

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

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

Hamblin, W.K., 1987, Late Cenozoic volcanism in the St. George basin, Utah, *in* Beus, S.S., editor, Geological Society of America Centennial Field Guide - Volume 2, Rocky Mountain Section: Geological Society of America, p. 291-294.

Hamiliton, W.L., 1984, The sculpturing of Zion: Springdale, Utah, Zion Natural History Association, 131 p.

Haynes, S.A., 1983, Geomorphic development of the Virgin River near Hurricane, Utah: Salt Lake City, University of Utah, M.S. thesis, 189 p., scale 1:31,680.

Hecker, Suzanne, 1993, Quaternary tectonics of Utah with emphasis on earthquake-hazard characterization: Utah Geological Survey Bulletin 127, 157 p., scale 1:500,000.

Heilweil, V.M., 1997, Unpublished U.S. Geological Survey memorandum regarding re-submission of aquifer test analysis for a single-well aquifer test at Grapevine Pass, Washington County, Utah, dated January 23, 1997.

Herbert, L.R., 1995, Seepage study of the Virgin River from Ash Creek to Harrisburg Dome, Washington County, Utah: Division of Water Rights Technical Publication no. 106, 8 p.

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

Heylmun, E.B., 1993, Virgin Field, *in* Hill, B.G. and Bereskin, S.R., editors, Oil and gas fields of Utah: Utah Geological Association Publication 22, unpaginated.

Higgins, J.M., 1977, Interim geologic map of the White Hills quadrangle, Washington County, Utah: Utah Geological Survey Open-File Report xxx, xxx p., scale 1:24,000.

Higgins, J.M., and Willis, G.C., 1995, Interim geologic map of the St. George quadrangle, Washington County, Utah: Utah Geological Survey Open-File Report 323, 114 p., scale 1:24,000.

Hintze, L.F., Anderson, R.E., and Embree, G.F., 1994, Geologic map of the Motoqua and Gunlock quadrangles, Washington County, Utah: U.S. Geologic Survey Miscellaneous Investigations Series Map I-2427, 7 p., scale 1:24,000.

Horrocks-Carollo Engineers, 1993, Culinary water resources study: St. George City Water and

Power Department, June 1993, 128 p.

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

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

International Conference of Building Officials, 1997, Uniform Building Code: Whittier, California, International Conference of Building Officials, ~~1,471~~ p. variously paginated

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

Johnson, B.T., 1984, Depositional environments of the Iron Springs Formation, Gunlock, Utah: Brigham Young University Geology Studies, v. 31, pt. 1, p. 29-46.

Lambert, R.E., 1984, Shnabkaib Member of the Moenkopi Formation: Depositional environment and stratigraphy near Virgin, Washington County, Utah: Brigham Young University Geology Studies, v. 31, pt. 1, p. 47-65.

LeBas, M.J., LeMaitre, R.W., Streckeisen, A., and Zanettin, B., 1986, A chemical classification of volcanic rocks based on the total alkali-silica diagram: Journal of Petrology, v. 27, p. 745-750.

Lund, W.R., 1992, Flooding in southwestern Utah, *in* Harty, K.M., editor, Engineering and environmental geology of southwestern Utah: Utah Geological Association Publication 21, p. 159-163.

Mulvey, W.E., 1992, Engineering geologic problems caused by soil and rock in southwestern Utah, *in* Harty, K.M., editor, Engineering and environmental geology of southwestern Utah: Utah Geological Association Publication 21, p. 139-144.

Nielson, R.L., 1981, Depositional environment of the Toroweap and Kaibab Formations of southwestern Utah: Salt Lake City, University of Utah, Ph.D. dissertation, 495 p.

Nielson, R.L., 1986, The Toroweap and Kaibab Formations, southwestern Utah, *in* Griffen, D.T. and Phillips, W.R., editors, Thrusting and extensional structures and mineralization in the Beaver Dam Mountains, southwestern Utah: Utah Geological Association Publication 15,

p. 37-53.

Noweir, M. A., 1990, Structural analysis of the overthrust belt (OTB) of southwest Utah: Rolla, University of Missouri - Rolla, Ph.D. dissertation, 129 p.

Olig, S.S., 1995, Ground shaking and Modified Mercalli intensities, *in* Christensen, G.E., editor, The September 2, 1992 M_L 5.8 St. George earthquake, Washington County, Utah: Utah Geological Survey Circular no. 88, p. 12-20.

O'Neill, A.L., and Gourley, Chad, 1991, Geologic perspectives and cause of the Quail Creek dike failure: Bulletin of the Association of Engineering Geologists, v. 28, no. 2, p. 127-145.

Payton, C.C., 1992, Geotechnical investigation and foundation design for the reconstruction of Quail Creek dike, *in* Harty, K.M., editor, Engineering and environmental geology of southwestern Utah: Utah Geological Association Publication 21, p. 39-51.

Pechmann, J.C., Arabasz, W.J., and Nava, S.J., 1995, Seismology, *in* Christensen, G.E., editor, The September 2, 1992 M_L 5.8 St. George earthquake, Washington County, Utah: Utah Geological Survey Circular no. 88, p. 1.

Peterson, Fred, and Pipiringos, G.N., 1979, Stratigraphic relations of the Navajo Sandstone to Middle Jurassic formations, southern Utah and northern Arizona: U.S. Geological Survey Professional Paper 1035-B, 43 p.

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

Poborski, S.J., 1954, Virgin Formation (Triassic) of the St. George, Utah, area: Geological Society of America Bulletin, v. 66, no. 10, p. 971-1,006.

Poehlmann, E.J., and King, E.N., 1953, Report on wagon drilling for uranium in the Silver Reef (Harrisburg) district, Washington County, Utah: U.S. Atomic Energy Commission RME-2004 (pt. 1), 24 p.

Proctor, P.D., 1948, Geologic map and sections of the Silver Reef mining area, *in* Stugard, F., 1951, Uranium resources in the Silver Reef (Harrisburg) district, Washington County, Utah: U.S. Geological Survey Trace Elements Memorandum Report 214, scales 1:31,360 and 1:4,560.

Proctor, P.D., 1953, Geology of the Silver Reef (Harrisburg) mining district, Washington

County, Utah: Utah Geological and Mineral Survey Bulletin 44, 169 p.

Proctor, P.D., and Brimhall, W.H., 1986, Silver Reef mining district, revisited, Washington County, Utah, *in* Griffen, D.T. and Phillips, W.R., editors, Thrusting and extensional structures and mineralization in the Beaver Dam Mountains, southwestern Utah: Utah Geological Association Publication 15, p. 159-177.

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

Reeside, J.B., Jr., and Bassler, H., 1921, Stratigraphic sections in southwestern Utah and northwestern Arizona: U.S. Geological Survey Professional Paper 129-D, p. 53-77.

Rollins, K.M., Williams, T., Bleazard, R., and Owens, R.L., 1992, Identification, characterization, and mapping of collapsible soils in southwestern Utah, *in* Harty, K.M., editor, Engineering and environmental geology of southwestern Utah: Utah Geological Association Publication 21, p. 145-158.

Sanchez, Alexander, 1995, Mafic volcanism in the Colorado Plateau/Basin-and-Range transition zone, Hurricane, Utah: Las Vegas, Nevada, University of Nevada, M.S. thesis, 92 p., scale 1:52,000.

Sansom, P.J., 1992, Sedimentology of the Navajo Sandstone, southern Utah, USA: Oxford, England, Department of Earth Sciences and Wolfson College, Ph.D. dissertation, 291 p.

Solomon, B.J., 1992a, Geology and the indoor-radon hazard in southwestern Utah, *in* Harty, K.M., editor, Engineering and environmental geology of southwestern Utah: Utah Geological Association Publication 21, p. 165-172.

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

Solomon, B.J., 1995, Radon-hazard potential of the southern St. George basin, Washington County, and Ogden Valley, Weber County, Utah: Utah Geological Survey Special Study 87, 42 p.

Sorauf, J.E., 1962, Structural geology and stratigraphy of Whitmore area, Mohave County, Arizona: Lawrence, Kansas, University of Kansas, Ph.D. dissertation, 361 p.

Stewart, J.H., Poole, F.G., and Wilson, R.F., 1972, Stratigraphy and origin of the Triassic

Moenkopi Formation and related strata in the Colorado Plataeu region, with a section on sedimentary petrology by R.A. Cadigan: U.S. Geological Survey Professional Paper 691, 195 p., scale 1:2,500,000.

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

Willis, G.C., and Higgins, J.M., 1995, Interim geologic map of the Washington quadrangle, Washington County, Utah: Utah Geological Survey Open-File Report 324, 108 p., scale 1:24,000.

Willis, G.C., and Higgins, J.M., 1996, Interim geologic map of the Santa Clara quadrangle, Washington County, Utah: Utah Geological Survey Open-File Report 339, 87 p., scale 1:24,000.

Wilson, R.F., and Stewart, J.H., 1967, Correlation of Upper Triassic and Triassic(?) formations between southwestern Utah and southern Nevada: U.S. Geological Survey Bulletin 1244-D, 20 p.

Wright, J.C., Snyder, R.P., and Dickey, D.D., 1979, Stratigraphic sections of Jurassic San Rafael Group and adjacent rocks in Iron and Washington Counties, Utah: U.S. Geological Survey Open-File Report 79-1318, 53 p.

Wright, M.A., 1992, Abandoned mine reclamation and mining history in southwestern Utah, *in* Harty, K.M., editor, Engineering and environmental geology of southwestern Utah: Utah Geological Association Publication 21, p. 281-285.

Wyman, R.V., 1960, Comments regarding ore genesis at Silver Reef, Utah: Economic Geology, v. 55, p. 835-839.

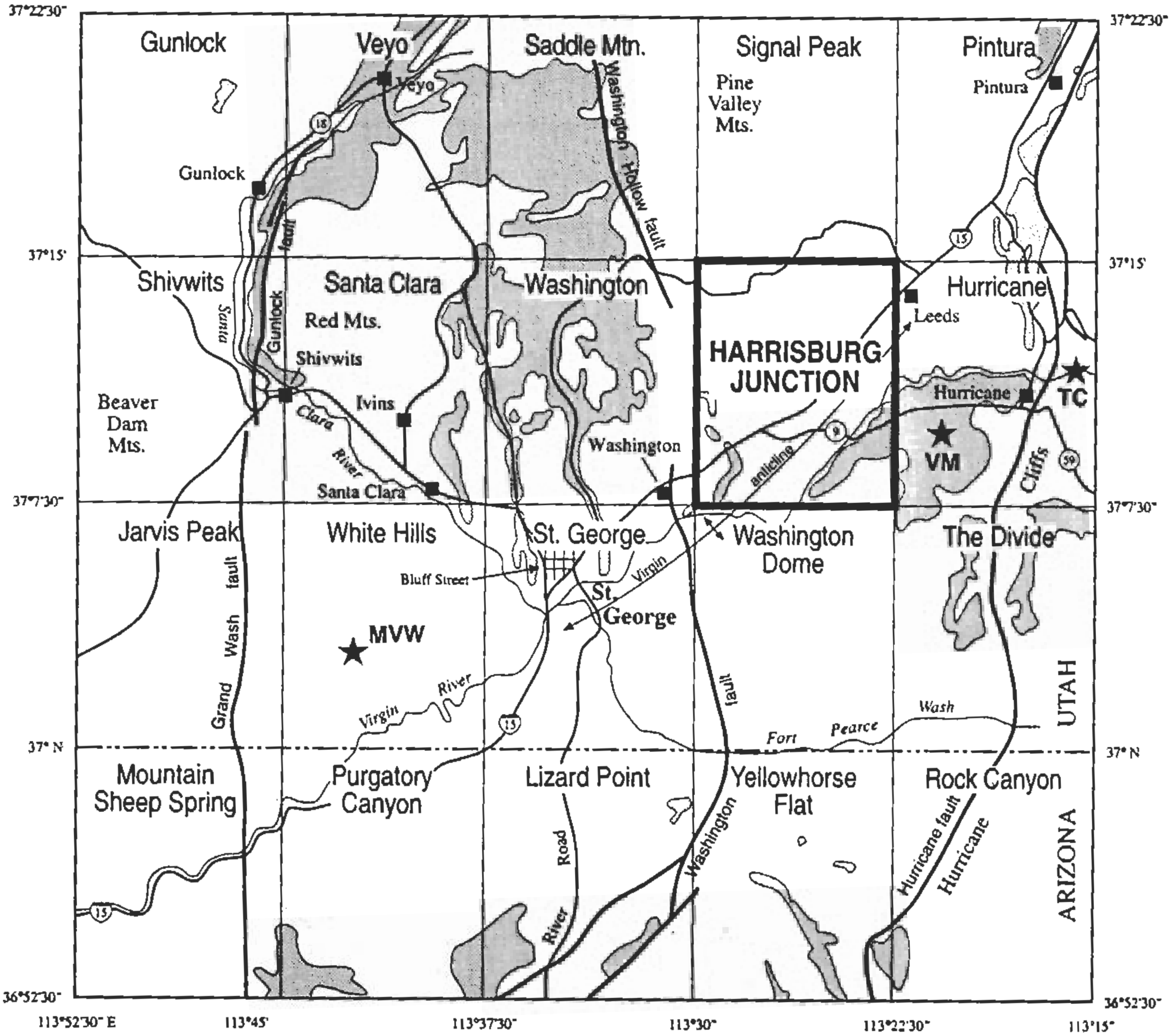


Figure 1 Location of the Harrisburg Junction and surrounding quadrangles, with major geographic and geologic features; basalt flows are shaded. This quadrangle is one of several 7.5' quadrangles recently mapped as part of the UGS effort to map the rapidly growing St. George basin. Additional geologic maps and reports are available for the Santa Clara quadrangle (Willis and Higgins, 1996), St. George quadrangle (Higgins and Willis, 1995), Washington quadrangle (Willis and Higgins, 1995), and the White Hills quadrangle (Higgins, 1997). The Hurricane and Washington Dome quadrangles are scheduled for completion in 1998. VM = Volcano Mountain and Ivan's Knoll; MVW = Mountain Valley Wash; TC = Timpoweap Canyon.

Figure 2 Looking northeast towards Harrisburg Dome, in the core of the Virgin anticline; photo taken from the NW 1/4 section 19, T.42S., R.14W. The lower red member of the Moenkopi Formation is exposed in the east-dipping cuesta immediately east of the dome's axis. The cuesta itself is capped by Harrisburg Member strata that are in fault contact with the lower red member.

Figure 3 Looking northeast at the east-dipping cuesta immediately east of the main axis of Harrisburg Dome; photo taken from the SW 1/4 section 17, T.42S., R.14W. An east-dipping axial backthrust separates the lower red member of the Moenkopi Formation (exposed along the lower slopes of the cuesta) from the Harrisburg Member of the Kaibab Formation (which caps the cuesta, forming the skyline in this photo).

Figure 4 Looking northeast toward Quail Creek reservoir, along the axis of the Virgin anticline; photo taken from the SE 1/4 section 3, T.42S., R.14W. Resistant Shinarump Conglomerate strata form the flanks and crest of the anticline, below which are ledgy slopes of the upper red member of the Moenkopi Fomation. The light band near the base of the upper red member is informally known as the "Purgatory Sandstone." Red-and-white banded strata of the Shnabkaib Member forms the eroded floor of the anticline. Note bright white beds below Quail Creek dike, which were scoured clean from the catastrophic dike failure of January 1, 1989. Note also the deeply dissected landslide deposit north of Quail Creek reservoir. State Highway 9 cuts across center of photograph.

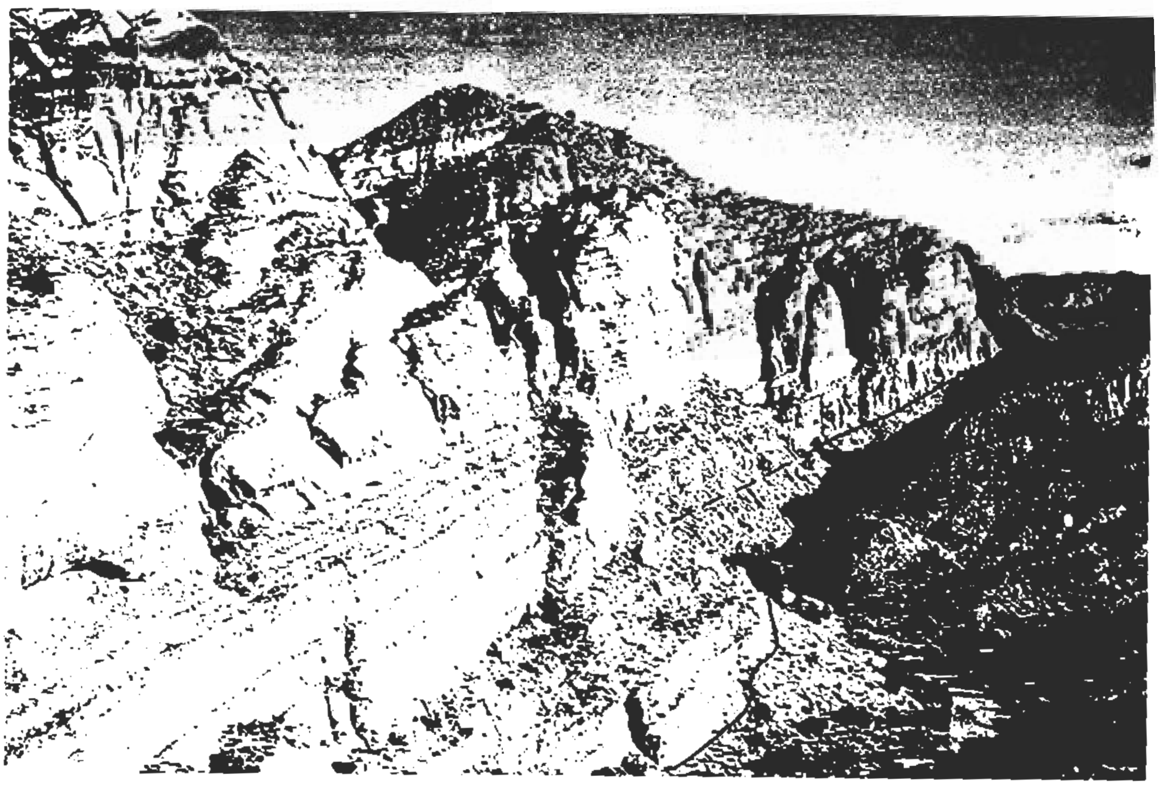


Figure 5 Looking north at the transition zone of the basal Navajo Sandstone; photo taken from the Red Cliffs Recreation Area overlook, NENE 1/4 section 15, T.41S., R.14W. Note planar bedded strata and thin, slope-forming mudstone intervals in lower part of transition zone. The contact with the underlying Kayenta Formation (shown) is at the base of the lowest cliff-forming sandstone; the hill on the right is capped by Navajo Sandstone.

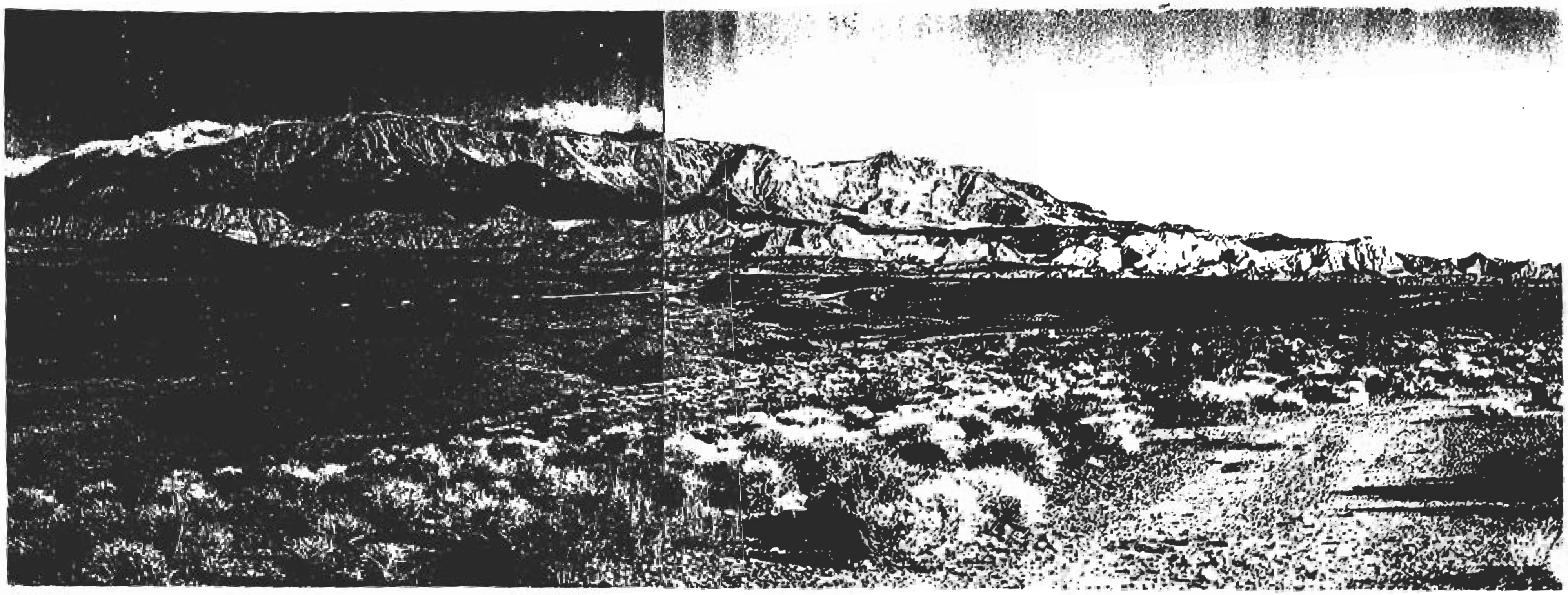


Figure 6 Looking north at the Washington basalt flow and, at extreme left, cinder cone; photo taken from the southern end of Washington Black Ridge, in the SE 1/4 section 13, T.42S., R.15W. The Washington flow forms a prominent inverted valley along its middle and lower portions, where it maintains a uniform thickness of 25 to 35 feet. Interstate 15 passes through Grapevine Wash near the center of the photograph. The Navajo Sandstone forms the light-colored hills in the middle distance, above which rises the Pine Valley Mountains, a Miocene-age laccolith.

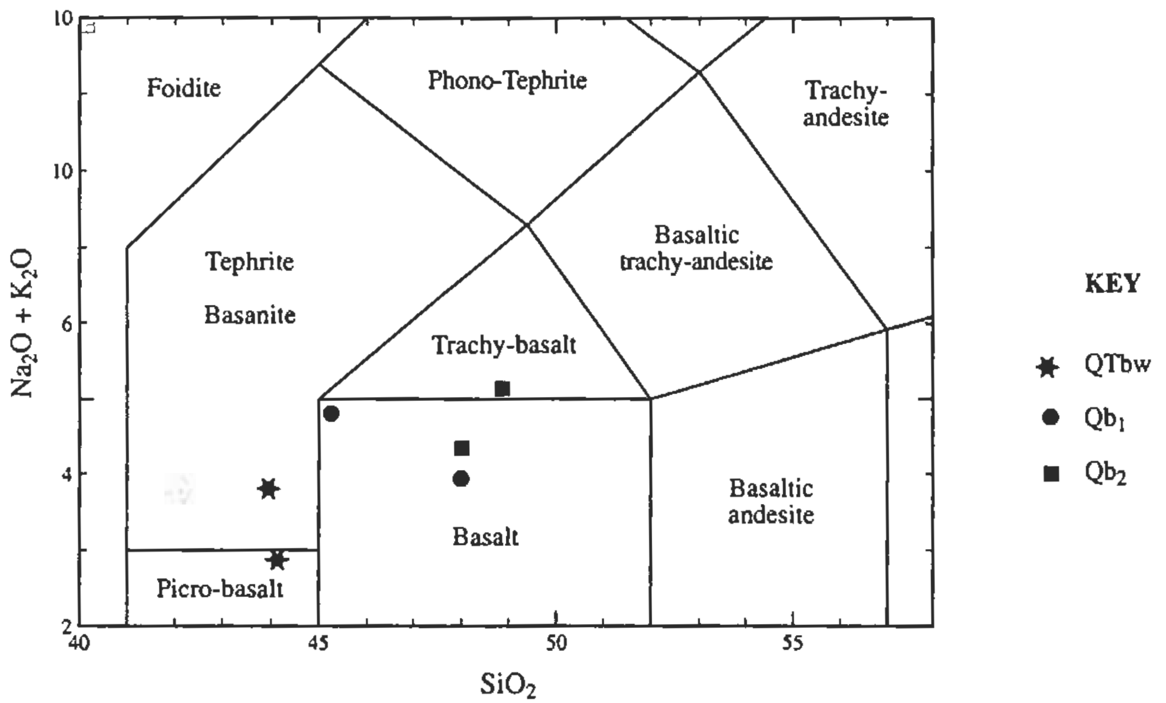
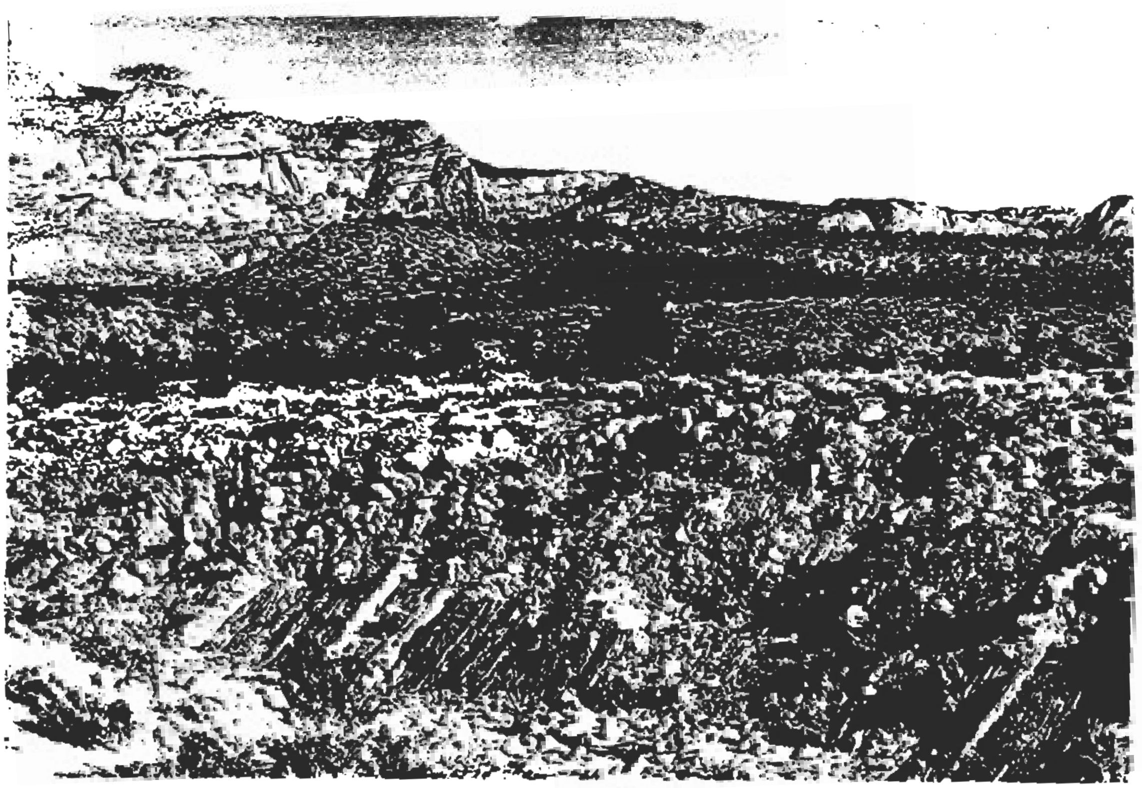


Figure 7 Geochemical classification of basaltic rocks in the Harrisburg Junction quadrangle using scheme of LeBas and others (1986). See Table I for analytical results. The QTbw analysis that plots in the picro-basalt field is sample no. 23 from Best and others (1980).



:gure 8 Looking north across Cottonwood Creek at terrace gravels overlying steeply dipping Kayenta strata; photo taken from the SENW 1/4 section 27, T.41S., R.14W. Terrace deposits in the foreground are mapped as Qal_3, those in the middle distance, beyond the small tree, as Qal_4, while the highest terrace level is mapped as Qao_5. The Navajo Sandstone forms cliffs in the background.

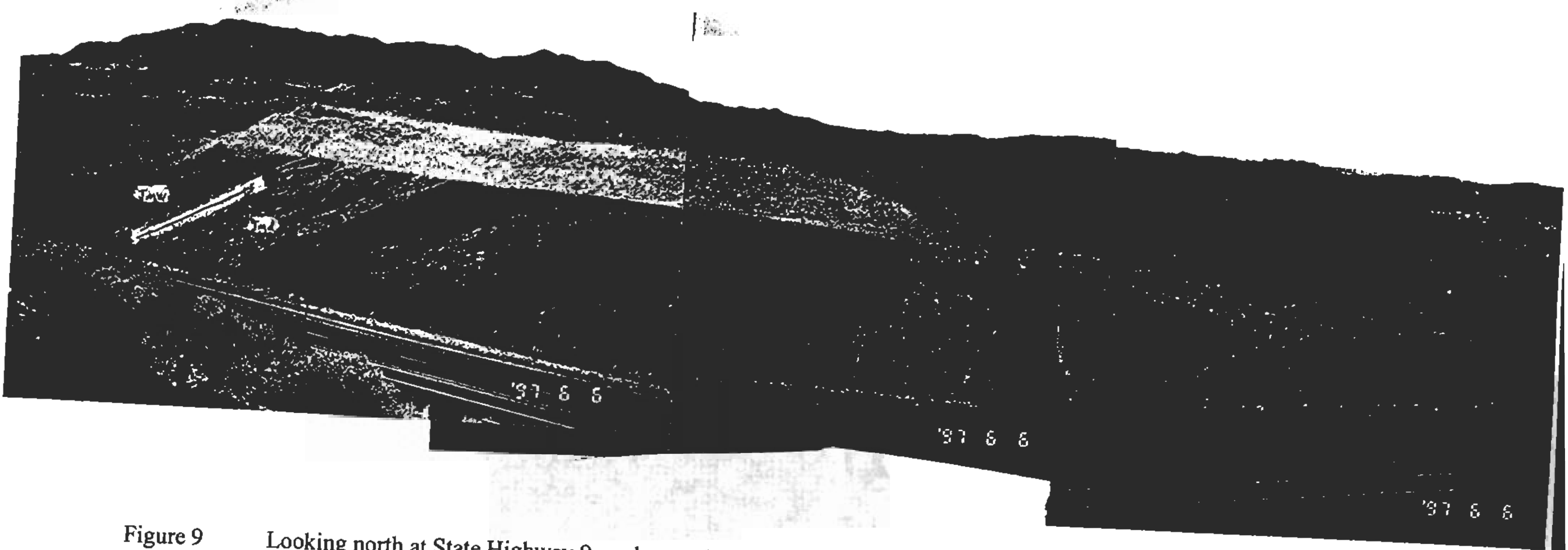


Figure 9 Looking north at State Highway 9 roadcut at the common border of sections 4 and 5, T.42S., R.14W. Here, west-dipping Moenave strata are thrust eastward over tightly folded Kayenta strata, causing a repetition of Moenave beds that are exposed in normal stratigraphic sequence about 1,000 feet (305 m) to the east. The west-dipping, low-angle fault zone is marked by a block of highly deformed sandstone immediately west of the steeply dipping Kayenta beds. Dinosaur Canyon strata form the bulk of the exposure. An algal limestone marks the contact with the overlying Whitmore Point Member near the west end of the roadcut, while Springdale beds occur along the west side of the ridge. The ridge itself is capped by Qao_6 deposits.

Figure 10 Looking northeast to the Silver Reef mining district; photo taken from the SW 1/4 section 27, T.41S., R.14W. The west-dipping Springdale Sandstone forms the crest of White Reef, in the west half of the photograph, and the nose of the Leeds anticline (Buckeye Reef) in the east half of the photograph. West-dipping Shinarump-like beds in the Petrified Forest Member of the Chinle Formation form Leeds Reef in the right-center of the photograph, immediately west of Interstate 15. Note extensive planar surfaces of Qao_5 on either side of White Reef. Cottonwood Creek is in the foreground.

Table I

Sample	VR4007	VR4008	VR4009	7-20	1-1
Map Unit	QTbw	Qb_1	Qb_2	Qb_1	Qb_2
Latitude	113.472	113.340	113.384	113.395	113.385
Longitude	37.138	37.161	37.164	37.069	37.164
SiO_2	42.64	45.30	48.78	48.4	48.4
TiO_2	1.56	2.09	1.67	2.26	1.85
Al_2O_3	12.13	12.76	14.61	13.8	15.2
Fe_2O_3	12.37	12.11	11.11	12.5	11.3
MnO	0.20	0.17	0.16	0.19	0.16
MgO	12.70	9.90	7.74	10.35	7.15
CaO	12.09	10.38	8.35	11.0	8.9
Na_2O	2.45	2.91	3.07	2.64	2.86
K_2O	1.33	1.87	2.05	1.38	1.33
P_2O_5	0.78	0.66	0.51	0.59	0.52
LOI	0.01	0.01	0.01		
Total	98.34	98.19	98.08	103.13	97.79
Ba				1024	1072
Cs	1	1	1		
Hf	3	4	5		
La	69	52	40		
Nb	60	47	32	41.9	29.7
Rb	12	15	17	14.5	16.9
Sr	937	928	666	929	746
Ta	4	4	3		
Y	27	23	23	24.1	27.8
Zr	167	164	164		

Samples VR4007 to VR4009 are from this project. Samples 7-20 and 1-1 are from Sanchez (1995).