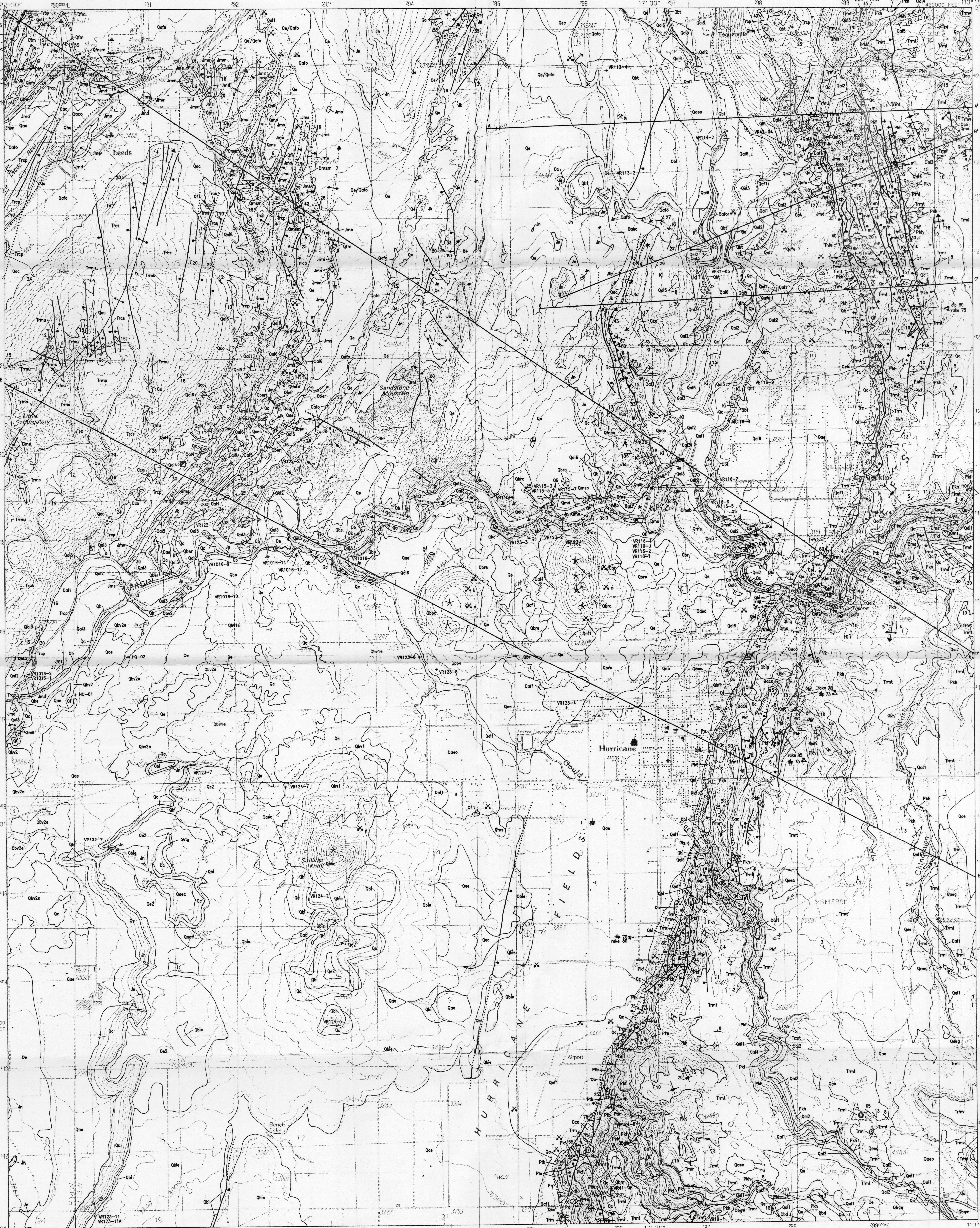
UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

HURRICANE QUADRANGLE
UTAH-WASHINGTON CO.
7.5 MINUTE SERIES (TOPOGRAPHIC)



PRODUCED BY THE UNITED STATES GEOLOGICAL SURVEY
CONTROL BY .... USGS, NOS/NOAA
COMPILED FROM AERIAL PHOTOGRAPHS TAKEN 1978
FIELD CHECKED .... 1979 MAP EDITED 1986
PROJECTION .... LAMBERT CONFORMAL CONIC
GRID: 1000-METER UNIVERSAL TRANSVERSE MERCATOR .... ZONE 12
10,000-FOOT STATE GRID TICKS .... UTAH, SOUTH ZONE
UTM GRID DECLINATION .... 1°24' WEST
1986 MAGNETIC NORTH DECLINATION .... 14° EAST
VERTICAL DATUM .... NATIONAL GEODETIC VERTICAL DATUM OF 1929
HORIZONTAL DATUM .... 1927 NORTH AMERICAN DATUM

To place on the predicted North American Datum of 1983, move the projection lines as shown by dashed corner ticks (6 meters north and 69 meters east)

There may be private inholdings within the boundaries of any Federal and State Reservations shown on this map

All marginal data and lettering generated and positioned by automated type placement procedures

NORTH

PROVISIONAL MAP
Produced from original manuscript drawings. Information shown as of date of field check. 2

SCALE 1:24 000

1 .5 0 1 MILES
1000 0 1000 2000 3000 4000 5000 6000 7000 8000 9000 10 000 FEET
1 .5 0 1 2 KILOMETERS
1000 0 1000 2000 METERS

CONTOUR INTERVAL 40 FEET
SUPPLEMENTAL CONTOUR INTERVAL 20 FEET

THIS MAP COMPLIES WITH NATIONAL MAP ACCURACY STANDARDS
FOR SALE BY U.S. GEOLOGICAL SURVEY, DENVER, COLORADO 80225
OR RESTON, VIRGINIA 22092

UTAH

QUADRANGLE LOCATION

1	2	3
4		5
6	7	8

1 Signal Peak
2 Pintura
3 Smith Mesa
4 Harrisburg Junction
5 Virgin
6 Washington Dome
7 The Divide
8 Little Creek Mountain

ADJOINING 7.5' QUADRANGLE NAMES

INTERIOR-GEOLOGICAL SURVEY, RESTON, VIRGINIA-1987

ROAD LEGEND

Improved Road ....
Unimproved Road ....
Trail ....
Interstate Route U.S. Route State Route

HURRICANE, UTAH
PROVISIONAL EDITION 1986

37113-B3-TF-024

PLATE 1
Interim Geologic Map of the Hurricane Quadrangle
Washington County, Utah

Open-File Report 361 October 1998
UTAH GEOLOGICAL SURVEY
a division of
Utah Department of Natural Resources

PLATE 2
Interim Geologic Map of the Hurricane Quadrangle
Washington County, Utah
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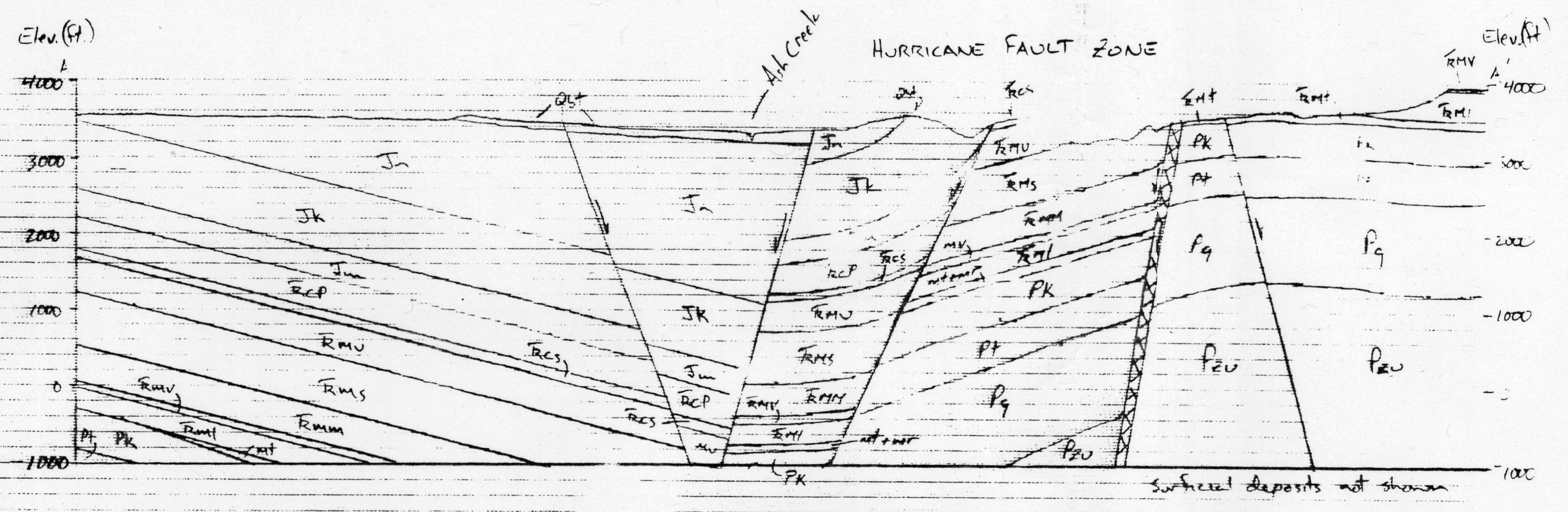
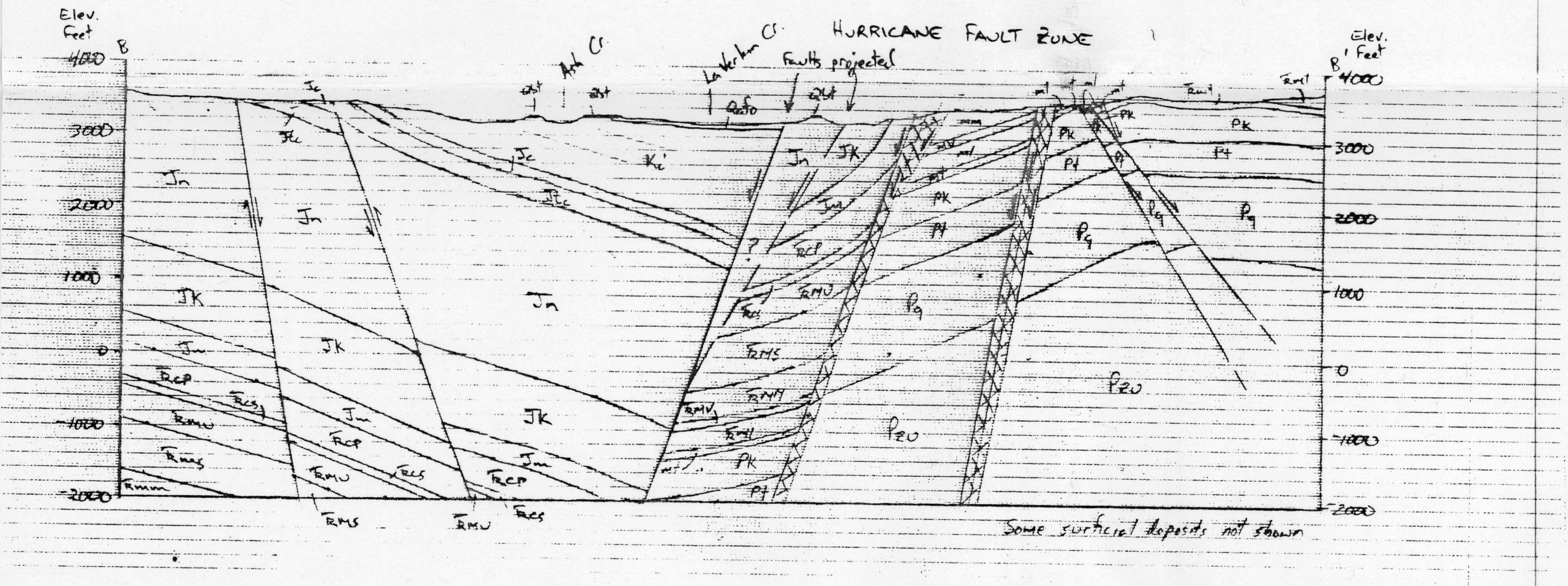
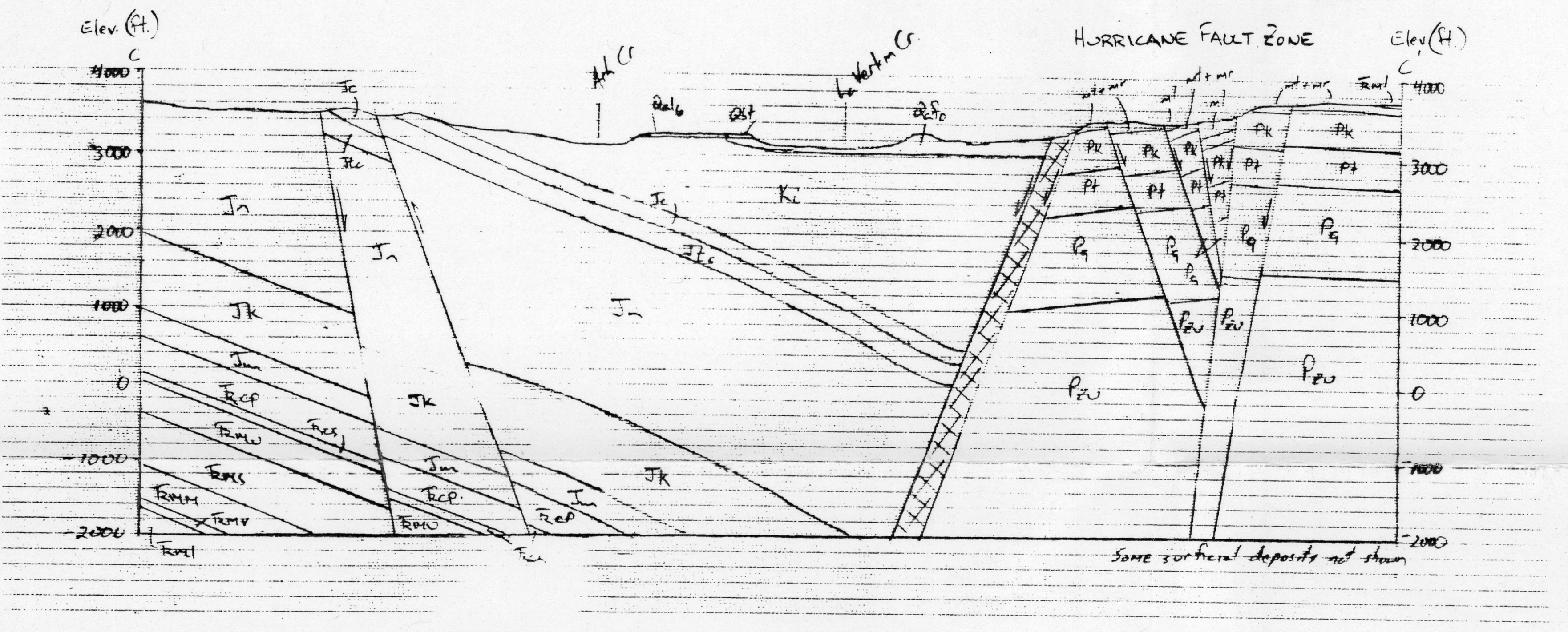
Utah Department of Natural Resources
in cooperation with
U.S. Geological Survey

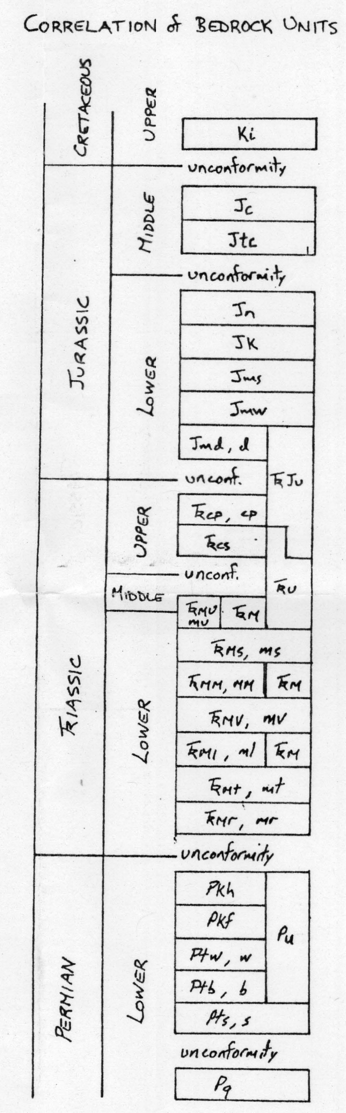


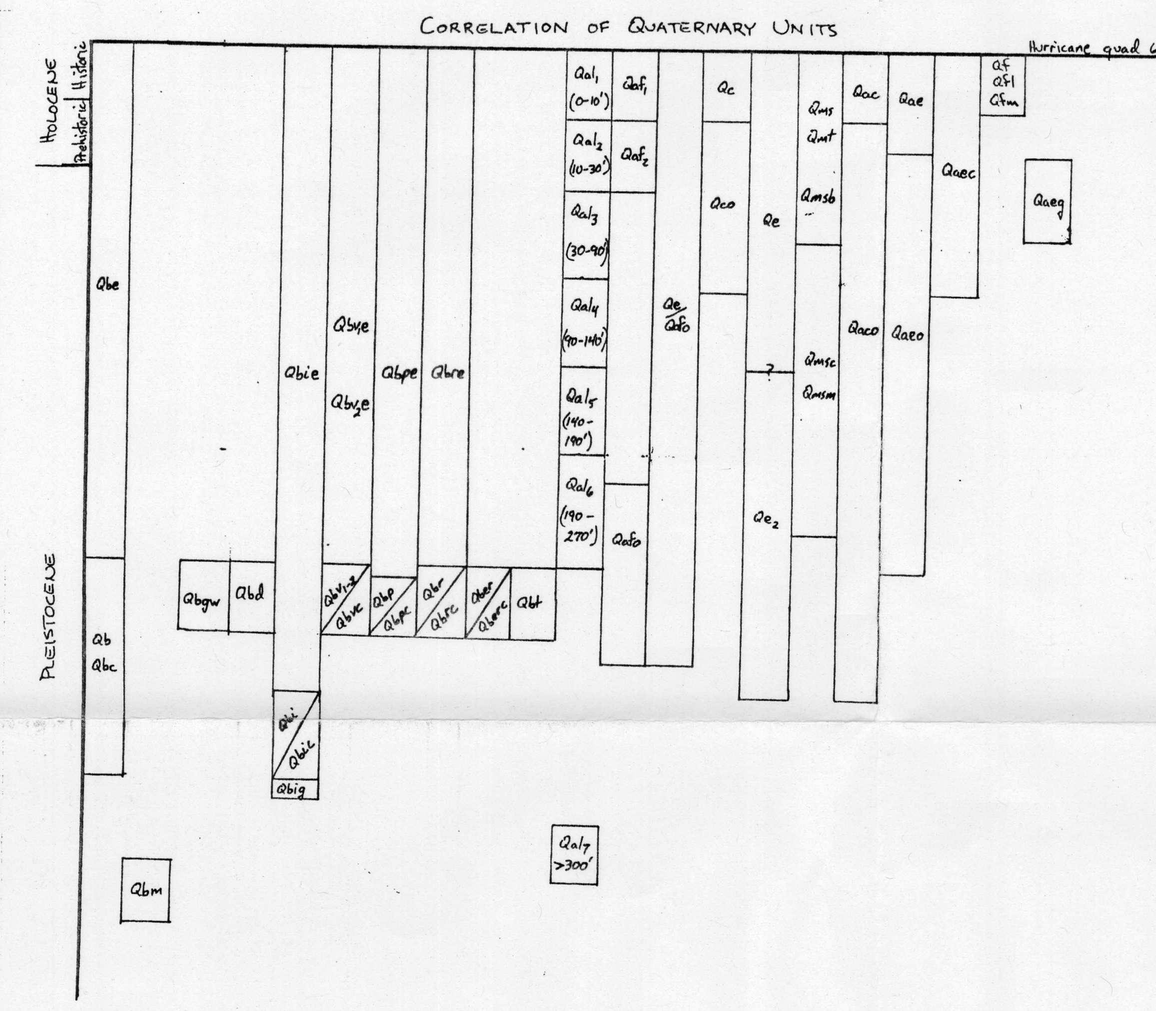


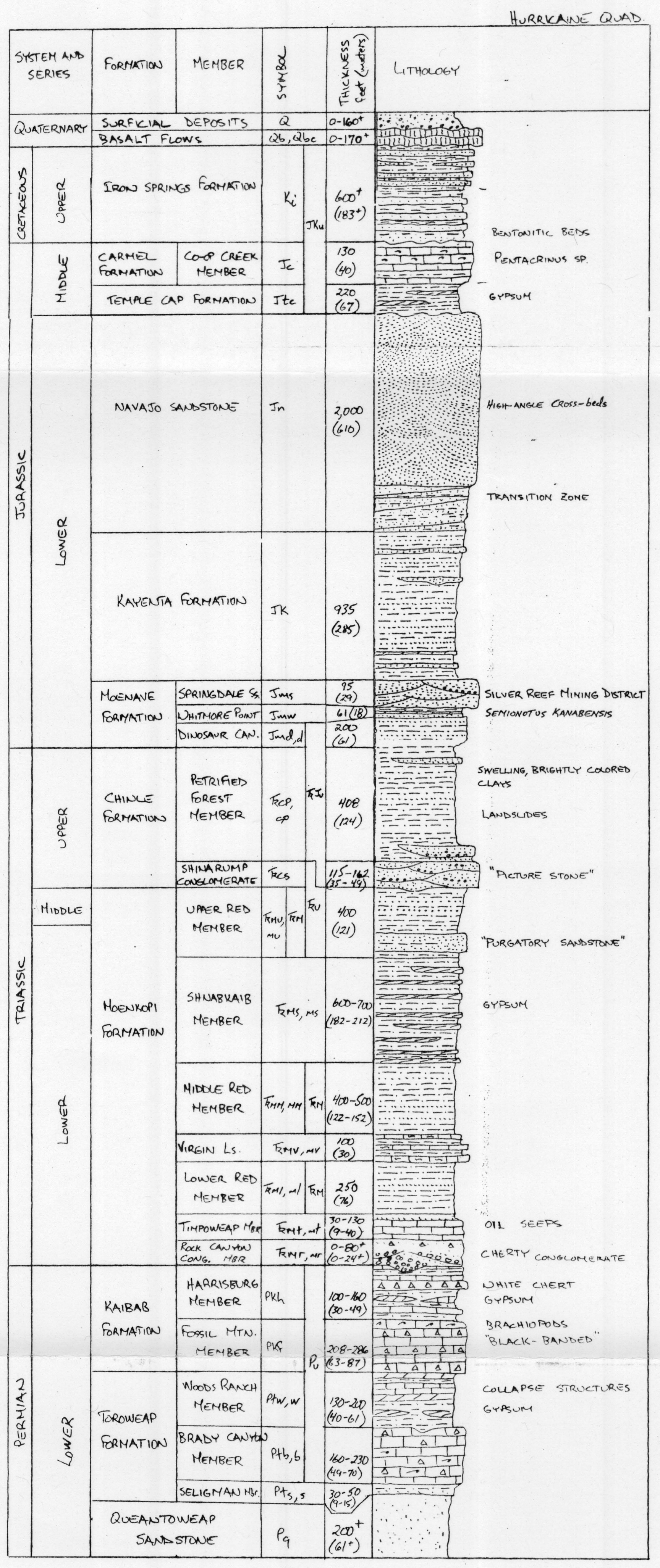


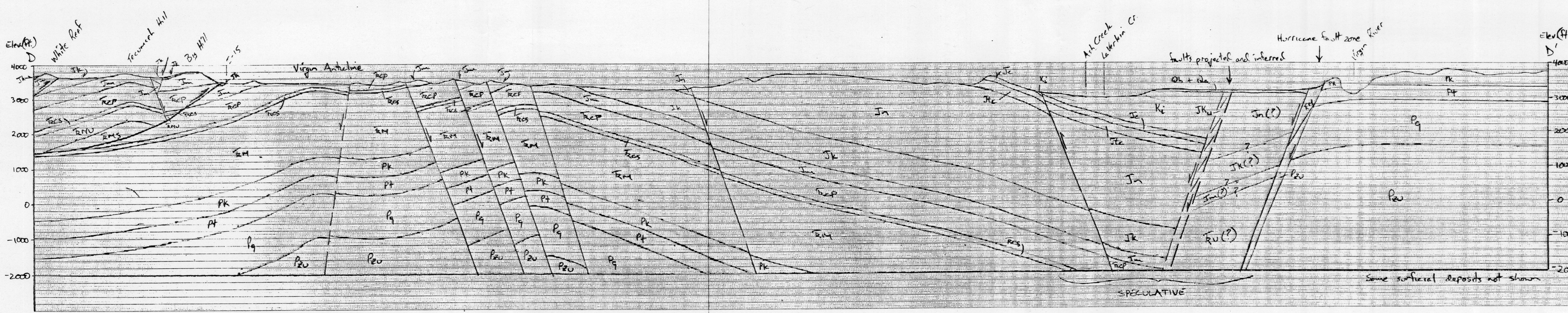
Map Symbols

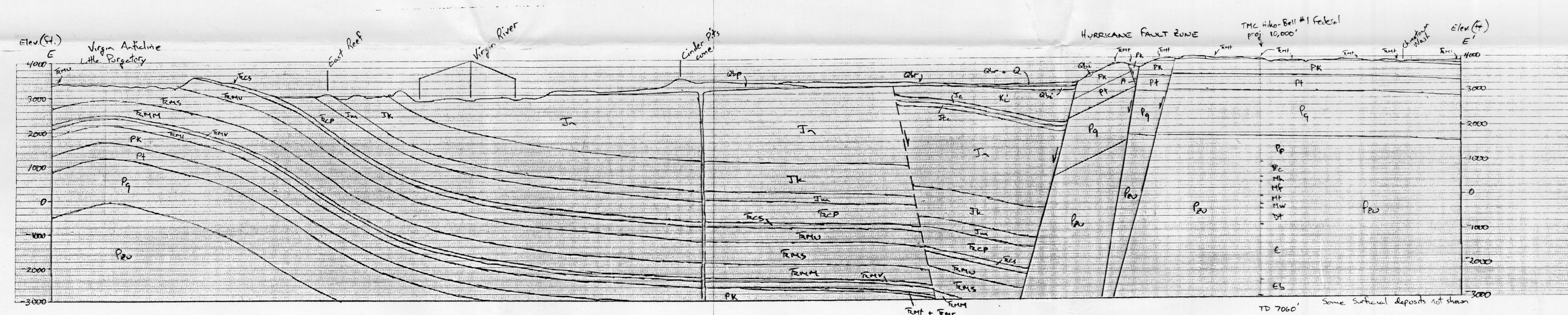
- Contact
- High-angle normal fault, dotted where concealed; bar and ball, or arrows showing dip and rake, on down-thrown side
- Thrust fault, dotted where concealed; teeth on upper plate
- Reverse fault, dotted where concealed; teeth on upper plate; arrows show dip and rake
- Prominent vertical joint
- Anticline, with direction and degree of plunge; dotted where concealed
- Syncline, with direction of plunge; dotted where concealed
- Landslide scarp, teeth on down-dropped side
- Strike and dip of inclined bedding
- Approximate strike and dip of inclined bedding determined from stereoplotter
- Approximate strike and dip of inclined bedding
- Horizontal bedding
- Strike of vertical joint
- Strike and dip of joint
- Pit - sand and gravel (no letter), cinders (c)
- Quarry - basalt (b)
- Prospect - gypsum (g), metals (no letter)
- Mine shaft
- Collapse feature
- Spring
- Oil seep
- Oil well test hole, plugged and abandoned
- Volcanic vent
- Sample location











INTERIM GEOLOGIC MAP OF THE HURRICANE QUADRANGLE, WASHINGTON COUNTY, UTAH

by
Robert F. Biek
Utah Geological Survey

OPEN-FILE REPORT 361 October 1998
UTAH GEOLOGICAL SURVEY
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in cooperation with U.S. Geological Survey
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ABSTRACT

The Hurricane 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 Early Permian Queantoweap Sandstone to the Late Cretaceous Iron Springs Formation are exposed in the quadrangle. Ten Quaternary basaltic flows, five cinder cone complexes, and a variety of Quaternary deposits are also mapped. The Permian-Triassic unconformity is well-exposed in the Hurricane Cliffs and locally shows at least 80 feet (24 m) of erosional relief.

The Virgin anticline, an open, upright, symmetrical, Sevier-age fold with flank dips of 25 to 35 degrees, plunges gently northeast in the northwest corner of the quadrangle. Two west-dipping thrust faults repeat Moenave strata on the northwest flank of the anticline, forming White, Buckeye, and Butte Reefs of the Silver Reef mining district. The presence of northeast-plunging subsidiary folds on the nose of the anticline suggests that while the Virgin and Kanarra anticlines are colinear and likely genetically related, they are individual structural units. The nose of the anticline is also marked by a series of down-to-the-west and down-to-the-east normal faults that serve to accommodate tight folding at the core of the anticline.

The Anderson Junction segment of the Hurricane fault zone is itself composed of three straightline segments in the quadrangle that trend due north, N.20°E., and N.15°W. Each of these short segments is characterized by down-to-the-west normal faults that bound blocks of west-dipping Permian, Triassic, and Jurassic strata; numerous slickenlines demonstrate a slight

component of right-lateral slip on these faults. The footwall is marked by particularly complex faulting at the intersection of these segments. A basaltic flow at the entrance to Timpoweap Canyon was dated at 353,000 +/- 45 ka (Sanchez, 1995) and shows about 240 feet (73 m) of offset on the Hurricane fault zone, yielding a rate of stratigraphic displacement of about 0.75 inches/100 years (2 cm/100 years) for this portion of the fault. Stratigraphic separation on the Hurricane fault zone may approach 9,000 feet (2,744 m) immediately north of LaVerkin and decrease both to the north and south to about 6,000 to 7,000 feet (1,829-2,134 m), respectively. Tectonic displacement on the fault zone is probably about 3,600 feet (1,098 m) in the Hurricane quadrangle. Basaltic flows that cross and are offset by the Hurricane fault zone demonstrate that the amount of erosional down-cutting is largely a function of the amount and rate of uplift.

Primary economic resources in the quadrangle include sand and gravel, cinders, building and ornamental stone, clay, and silver. The Silver Reef mining district, in the northwest 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 district is currently being re-evaluated northwest of Leeds. The Navajo Sandstone 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 Hurricane quadrangle covers an area of about 60 square miles (156 square km) in the greater Hurricane area in south-central Washington County (figure 1). This area is part of the burgeoning retirement, retail, and vacation center of southwestern Utah, affectionately known as "Utah's Dixie." Once populated by a few hardy pioneers sent south from Salt Lake City to grow cotton, the region's population grew by 140 percent from 1980 to 1995 and it continues to be among the fastest growing areas in the state. One of many important concerns is that this new development will encroach into geologically hazardous areas. Geological hazards associated with earthquakes, landslides and rock falls, expansive and collapsible soil and rock, and other factors are known in the Hurricane quadrangle and surrounding area. Another major concern involves development pressure on the region's natural resources - especially scarce gravel and water resources; silver and other metals; and even open space. This geologic map and report contains much of the basic geologic information needed to address these and other issues.

(Figure 1 near here)

The Hurricane quadrangle lies in the transition zone between the Colorado Plateau and Basin and Range physiographic provinces. Strata in the Hurricane quadrangle are characteristic of the generally flat-lying rocks of the Colorado Plateau physiographic province, but they were folded into the Virgin anticline and subsidiary folds and thrust faults during the Late Cretaceous

Servier orogeny, cut by the Late Tertiary-Quaternary Hurricane fault zone, and partially covered by Quaternary basaltic flows and cinder cones. In southwestern Utah, the transition zone encompasses the area between two major down-to-the-west normal fault zones - the Gunlock-Grand Wash faults to the west and the Hurricane fault zone to the east - that step down from the Colorado Plateau to the Basin and Range (figure 1). The Hurricane quadrangle straddles the eastern edge of the intermediate structural block thus created. The Hurricane fault zone shows about 6,000 to 9,000 feet (1,829-2,744 m) of stratigraphic offset - or about 3,600 feet (1,098 m) of tectonic displacement - in the quadrangle.

The greater St. George area, including the Hurricane quadrangle, has been the focus of numerous topical geological investigations, many of which are cited under other sections of this report. Dobbin (1939) prepared a small-scale geologic map for his study of the structural geology of the greater St. George area. Gardner (1941) included a 1:320,000-scale geologic map with his report of the Hurricane fault zone in southwestern Utah and northwestern Arizona. Proctor (1948, 1953) made detailed geologic maps of the Silver Reef mining district. Gregory (1950) produced a 1:125,000-scale geologic map of the area east of the Hurricane fault zone in his report on the geology of the Zion National Park region. Marshall (1956a, 1956b) made photogeologic maps of the Little Creek Mountain and Virgin quadrangles. 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). Nielson and Johnson (1979) mapped the lower part of Timpoweap Canyon east of Pah Tempe Hot Springs at 1:35,000 as part of their study of the

Timpoweap Member of the Moenkopi Formation. Haynes (1983) mapped geomorphic features of a portion of the Virgin River basin between Hurricane and Washington. 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. Eppinger and others (1990) produced a 1:250,000-scale geologic map of the Cedar City 1^0x2^0 quadrangle, which includes the Hurricane quadrangle. Schramm (1994) mapped the Hurricane fault zone north of LaVerkin at 1:12,000. Sanchez (1995) studied the eruptive history and geochemistry of the Hurricane basalt field and included a simplified map of volcanic rocks south of the Virgin River at 1:52,000. Biek (1997) and Higgins (1998) completed 1:24,000-scale geologic maps of the adjacent Harrisburg Junction and Washington Dome quadrangles, respectively, 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

(Note: an abbreviated one- or two-letter symbol is used in congested parts of the map.)

The oldest strata in the quadrangle, the Permian Queantoweap Sandstone, are exposed at the base of the Hurricane cliffs, west of Mollies Nipple, at the southern boundary of the quadrangle. South of LaVerkin, the Hurricane cliffs themselves represent a partly eroded fault scarp developed principally in Permian Toroweap and Kaibab strata, with slivers of west-dipping Moenkopi beds caught up in the fault zone. North of LaVerkin, south of a fault segment boundary (Stewart and Taylor, 1996), the fault zone is marked by a complexly faulted, but nearly complete section of the Moenkopi Formation and portions of the Chinle, Moenave, Kayenta, and Navajo formations. The broad bench east of the Hurricane fault zone is held up principally by gently undulating beds of the Timpoweap Member of the Moenkopi Formation. The Virgin anticline bisects the northwest portion of the quadrangle, where the Shnabkaib Member of the Moenkopi Formation is exposed at Little Purgatory. Strata become progressively younger across the limbs of the anticline and eastward into the Ash Creek and LaVerkin Creek drainages, where the youngest bedrock strata in the quadrangle, the Upper Cretaceous Iron Springs Formation, are exposed. About 8,200 feet (2,500 m) of Permian to Upper Cretaceous sedimentary strata are exposed in the quadrangle. Ten basaltic lava flows or groups of flows, which came from five cinder cone complexes within the Hurricane quadrangle and from at least three additional cinder cone complexes located outside the quadrangle, are mapped. A variety of Quaternary deposits are also mapped.

Permian

Queantoweap Sandstone (Pq)

In southwestern Utah, clastic rocks that lie between the dominantly carbonate intervals represented by the Pakoon Dolomite and Toroweap Formation are assigned to the Queantoweap Sandstone (Hintze, 1986; Billingsley, 1997; Higgins, 1997). South of the Virgin River Gorge in Arizona, the lower part of this clastci interval is the Queantoweap Sandstone and the upper part is the Sandstone facies of the Hermit Shale (Billingsley, 1997). In southwestern Utah, strata correlative with the Hermit Shale are a white to tan, low-angle, cross-bedded sandstone that are indistinguishable from underlying Queantoweap strata, thus making subdivision of these beds impractical.

In the Hurricane quadrangle, the Queantoweap Sandstone is only exposed along the Hurricane Cliffs west of Mollies Nipple. There, it consists of yellowish-brown, massively bedded to cross-bedded, very fine- to fine-grained noncalcareous sandstone that forms steep slopes. Queantoweap strata are highly fractured owing to proximity to the Hurricane fault zone, and are commonly stained by iron-manganese oxides. The upper contact is poorly exposed in the Hurricane quadrangle, but was chosen to correspond to a break in slope at the base of similarly colored, locally gypsiferous siltstone and fine-grained sandstone of the Seligman Member of the Toroweap Formation; regionally, the contact is unconformable (Billingsley, 1997). Only about the upper 200 feet (61 m) of the formation are exposed in the Hurricane quadrangle, but Queantoweap strata are estimated to be 1,500 to 2,000 feet (460-610 m) thick to the west, in the Beaver Dam Mountains (Hintze, 1986). Billingsley (1997) measured 1,020 feet (311 m) of beds in the Hurricane Cliffs, just south of the Utah-Arizona border, that are equivalent to the

Queantoweap Sandstone of southwestern Utah. The Queantoweap Sandstone is Early Permian (Wolfcampanian) in age and was deposited in a shallow-marine environment (Billingsley, 1997).

Toroweap Formation

In ascending order, the Early Permian Toroweap Formation consists of the Seligman, Brady Canyon, and Woods Ranch Members that record a major west to east trangresssion, followed by a regression (McKee, 1938; Rawson and Turner-Peterson, 1979; Nielson, 1981, 1986; Sorauf and Billingsley, 1991).

Seligman Member (Pts, s): The Seligman Member forms a poorly exposed slope between the overlying, cliff-forming, cherty limestone of the Brady Canyon Member and the uppermost, ledge- and cliff-forming Queantoweap Sandstone. Seligman strata are incompletely exposed at the entrance to Timpoweap Canyon, which forms a recess at the base of the Brady Canyon Member along the north side of the canyon, and at the south side of the entrance to Gould Wash. A complete section is exposed near the base of the Hurricane Cliffs west of Mollies Nipple. The Seligman Member consists of yellowish-brown, planar bedded, locally gypsiferous, very fine-grained sandstone and siltstone. The conformable upper contact with the Brady Canyon Member is placed at the base of a massive cliff of light-gray, cherty dolostone.

The Seligman Member changes from interbedded sandy siltstone, gypsum, sandstone, and dolomitic limestone in southern and western exposures (appoximately near the Utah-Arizona border and in the Beaver Dam Mountains, respectively), to sandstone in northern exposures near Kanarraville (Nielson, 1986). The Seligman Member varies from 50 to 200 feet (15-61 m) thick in the Beaver Dam Mountains (Hintze, 1986). Higgins (1997) reported that the Seligman Member is 100 feet (31 m) thick to the southwest, in the Virgin River Gorge in the White Hills quadrangle. Seligman strata thin to the north and east, and in the Hurricane quadrangle the Seligman Member is about 30 to 50 feet (9-15 m) thick. Nielson (1986) suggested that the Seligman Member in southern and western exposures was deposited in sabhka and tidal-flat environments that developed after regression of the Permian sea. The restricted lithologies found in the Hurricane quadrangle also suggest deposition in sabhka and nearshore environments. The Early Permian age of the Seligman Member is bracketed between the underlying Wolfcampian-age Queantoweap Sandstone and the overlying Leonardian-age Brady Canyon Member of the Toroweap Formation (Sorauf and Billingsley, 1991; Billingsley, 1997).

Brady Canyon Member (Ptb, b): The Brady Canyon Member is the middle, cliff-forming, carbonate unit of the Toroweap Formation. Brady Canyon strata are well exposed in the lower reaches of Timpoweap Canyon, Gould Wash, and Frog Hollow, and in complexly faulted exposures along the Hurricane Cliffs south of Gould Wash. The Brady Canyon Member consists of light- to medium-gray, medium- to coarse-grained, thick- to very thick-bedded, even-bedded, limestone and cherty limestone; it is dolomitic and locally sandy near the base. It contains common disarticulated brachipods, and crinoid, coral, and sponge fragments. Chert occurs as large, light-grayish-brown nodules that are commonly concentrically zoned. These nodules are commonly about one foot (0.3 m) long in their long dimension, occur along bedding planes, and commonly form irregular masses. Brady Canyon strata are commonly riddled with small caves. While both Brady Canyon and Fossil Mountain strata form prominent cliffs and appear similar in many respects, Brady Canyon strata are distinguished from Fossil Mountain strata based on stratigraphic position and by the fact that chert in the Fossil Mountain Member weathers black, thus creating a distinctive black-banded outcrop.

The unconformable contact between Brady Canyon and overlying Woods Ranch strata marks a prominent break in slope, with cliff-forming cherty limestone below and slope-forming, gypsiferous siltstone, gypsum, and minor thin limestone beds above. In the lower reaches of Frog Hollow, about 1,000 feet (305 m) east of the canyon entrance, there is about 80 feet (24 m) of relief on the contact, suggesting channel development or a collapse feature as described below.

The Brady Canyon Member is about 160 to 230 feet (49-70 m) thick in the Hurricane quadrangle (this report; Nielson, 1981). Reeside and Bassler (1921) measured 200 feet (61 m) of what are now known as Brady Canyon strata near Pah Tempe Hot Springs, at the entrance to Timpoweap Canyon. Brady Canyon strata are 250 feet (76 m) thick in the Virgin River Gorge to the southwest (Higgins, 1997). The Brady Canyon Member is Early Permian (Leonardian) in age and was deposited in a shallow-marine environment (McKee, 1938; Rawson and Turner-

Peterson, 1979).

Woods Ranch Member (Ptw, w): The Woods Ranch Member is a lithologically variable, slope-forming interval sandwiched between the similar, cliff-forming carbonates of the Brady Canyon Member of the Toroweap Formation and the Fossil Mountain Member of the Kaibab Formation. Woods Ranch strata are widely exposed along the Hurricane Cliffs south of LaVerkin, but the best exposures are found in the lower reaches of Timpoweap Canyon, Gould Wash, and Frog Hollow.

The Woods Ranch Member consists of a laterally variable sequence of interbedded, yellowish-gray to light-gray, laminated to thin-bedded dolostone and similarly bedded black chert, massive gypsum and gypsiferous mudstone, limestone, and collapse breccia. Generally, the lower, thicker part is composed of gypsum and gypsiferous mudstone; the middle part locally consists of a limestone interval informally named the Hurricane Cliffs tongue by Altany (1979) and also known as the *Schizodus* zone; and the thin upper part is composed of gypsiferous mudstone, dolostone, and chert. The middle limestone interval thickens northward from the Utah-Arizona border to Kanarraville, where it may constitute up to half of the member, but is missing in areas of exceptional gypsum accumulation (Nielson, 1986). It is not mapped here due to problems of scale.

Collapse breccias, probably formed as a result of gypsum dissolution, are well exposed in

Gould Wash, especially at the head of the box canyon in the NE1/4NW1/4NE1/4 section 11, T.42 S., R. 13 W. There, the upper Woods Ranch Member consists of laminated to thin-bedded, planar bedded, yellowish-gray, light-gray, and greenish-gray dolostone, limy dolostone, and black nodular and ribbon chert. These beds are locally deformed along the edges of collapse structures and chaotically jumbled within the collapse structures themselves.

The base of the Woods Ranch Member is locally marked by a yellowish-brown intraformational conglomerate or breccia. This unit is best exposed in the lower reaches of Frog Hollow (about 1,100 feet [335 m] east of the canyon entrance), and in an unnamed wash in the NE1/4SE1/3SE1/4 section 10, T. 42 S., R. 13 W. Both of these areas are overlain by gypsum and gypsiferous mudstone about 200 feet (61 m) thick and lack the limestone of the Hurricane Cliffs tongue.

The contact with the overlying Fossil Mountain Member of the Kaibab Formations appears to be conformable and gradational and was chosen to correspond to the first appearance of light-gray, thick-bedded, fossiliferous, cherty limestone that weathers to a characteristic "black-banded" cliff. The contact normally corresponds to a prominent break in slope, although thin-bedded Woods Ranch dolostones are locally cliff-forming in cross-cutting drainages where protected by vertical walls of Fossil Mountain strata. Nielson (1986) and Higgins (1997) noted minor erosional relief on top of Woods Ranch strata in southwestern Utah.

The Woods Ranch Member is normally about 130 to 200 feet (40-61 m) thick in the Hurricane quadrangle, except in a possible paleochannel or collapse feature in the lower reaches of Frog Hollow, where it is about 300 feet (91 m) thick. Nielson (1981) measured several sections of Woods Ranch strata in the Hurricane quadrangle that varied from 130 to 172 feet (40-52 m) thick. Woods Ranch strata are about 200 feet (61 m) thick in the Virgin River Gorge of southwestern Utah (Higgins, 1997). In their measured section near Pah Tempe Hot Springs, Reeside and Bassler (1921) inexplicably reported only 100 feet (30 m) of strata now known as Woods Ranch, about half of the true thickness at this location. The Woods Ranch Member is Early Permian (Leonardian) in age based on its stratigraphic position between the Leonardian-age carbonates of the Brady Canyon Member and Fossil Mountain Member. Woods Ranch strata were probably deposited in coastal sabhka and supratidal environments; the Hurricane Cliffs limestone tongue was deposited in a shallow-marine environment representing a minor transgression of the Permian sea (Rawson and Turner-Peterson, 1979; Nielson, 1986).

Kaibab Formation

The Kaibab Formation consists of two members, the upper Harrisburg Member and the lower Fossil Mountain Member (Nielson, 1981; Sorauf and Billingsly, 1991). These units are exposed in the Hurricane cliffs and in deep drainages that cut across the Hurricane bench. The Kaibab Formation is late Early Permian in age (McKee, 1938; Rawson and Turner-Peterson, 1979, Sorauf and Billingsley, 1991).

Fossil Mountain Member (Pkf): The Fossil Mountain Member crops out extensively along the Hurricane Cliffs south of Highway 9, where it forms a prominent cliff and the sheer walls of many box canyons; it is also exposed in several cross-cutting drainages north of Highway 9. Fossil Mountain strata consist of a lithologically uniform sequence of light-gray, thick- to very thick-bedded, even-bedded, fossiliferous limestone and cherty limestone sandwiched between the lithologically variable, slope-forming units of the Woods Ranch Member of the Toroweap Formation and the Harrisburg Member of the Kaibab Formation.

The Fossil Mountain Member is conspicuously "black-banded" due to the presence of abundant reddish-brown, brown, and black chert; chert may make 30 percent or more of the member. Fossil Mountain limestones are very rough weathering due to the presence of disseminated chert. Whole silicified brachipods are characteristic of the member and are most abundant in the uppermost beds. Silicified sponges and disarticulated corals, crinoids, and bryozoans are also common.

The contact of the Fossil Mountain and Harrisburg Members is conformable and corresponds to a pronounced break in slope (figure 2). It is placed at the top of the cliff-forming, thick-bedded, fossiliferous, cherty limestone, which is overlain by slope-forming, gypsiferous mudstone and gypsum of the Harrisburg Member.

(Figure 2 near here)

The Fossil Mountain Member is 208 to 286 feet (63-87 m) thick in the Hurricane quadrangle (Nielson, 1981). Reeside and Bassler (1921) measured beds near Pah Tempe Hot Springs, likely equivalent to the Fossil Mountain Member, that totaled 280 feet (85 m) thick. Fossil Mountain strata are about 300 feet (91 m) thick in the Virgin River Gorge of southwestern Utah (Higgins, 1997) and 250 to 300 feet (76-91 m) thick in the Beaver Dam Mountains (Hintze, 1986). The Fossil Mountain Member was deposited in a shallow-marine environment and records the last major Permian transgression in what is now southwestern Utah (Nielson, 1986). The Fossil Mountain Member is Early Permian (Leonardian) in age (McKee, 1938; Rawson and Turner-Peterson, 1979).

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, immediately east of the Hurricane quadrangle (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 rapid east-west facies changes characteristic of the Harrisburg Member.

The Harrisburg Member consists of slope- and ledge-forming, interbedded gypsum, gypsiferous mudstone, and thin-bedded limestone and cherty limestone. Nielson (1981, 1986) recognized eleven lithologic units in the Harrisburg Member, which can be grouped into a lower slope-forming interval, a middle limestone, cherty limestone, and chert that forms a low cliff, and an upper slope-forming interval. Both the lower and upper slope-forming intervals are characterized by interbedded, irregularly bedded, gray- to yellowish-brown, gypsiferous mudstone, gypsum, and thin limestone, cherty limestone, and dolostone; intraformational breccias and minor intraformational pebbly conglomerates, probably formed as a result of gypsum dissolution, are also found.

The middle limestone and chert interval (unit 5 of Nielson, 1986) is an important marker in the Harrisburg Member (figure 2). It consists of thick- to very thick-bedded limestone and cherty limestone that is overlain by white chert. Cherty limestones are characterized by very coarse sand- to pebble-size angular chert clasts that form both clast- and matrix-supported limestone breccias. The chert contained within the limestone 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. The overlying white, structureless chert occurs as highly fractured nodules and lenticular beds. Nielson (1986) interpreted this distinctive white chert as a weathering horizon.

The upper contact of the Harrisburg Member marks an erosional unconformity that spans 10 to 20 million years during Late Permian and Early Triassic time (Nielson, 1981; Sorauf and Billingsley, 1991). In the Hurricane quadrangle, erosion has incised the down to, and rarely into, the middle limestone and chert unit of the Harrisburg Member. Locally, in excess of 80 feet (24 m) of upper, slope-forming Harrisburg strata are eroded. As a result, the upper contact with the Rock Canyon Conglomerate Member, or where not present, the Timpoweap Member of the Moenkopi Formation commonly occurs in a ledgy or cliff-forming interval and so is difficult to pick from a distance. Close inspection reveals distinctive lithologies for each of these units, as discussed later, but in aggregate and from even a short distance, medial Harrisburg, Rock Canyon, and Timpoweap strata look remarkably similar (figure 2). In order to be accurately mapped, these contacts must be walked out in their entirety, even across drainages a few hundred feet wide. In a general sense, Harrisburg strata tend to weather to grayer hues, are irregularly bedded, and are blocky weathering; Timpoweap strata weather to browner hues, are characterized by gently undulating, thin, laterally continuous beds, and are platy weathering.

The Harrisburg Member varies from about 100 to 160 feet (30-49 m) thick in the Hurricane quadrangle as a result of pre-Moenkopi erosion (Nielson, 1981). Reeside and Bassler (1921) assigned 150 feet (46 m) of strata near Pah Tempe Hot Springs to their newly named Harrisburg gypsiferous member. The Harrisburg Member varies from 0 to about 300 feet (0-91 m) thick in the St. George and White Hills quadrangles to the southwest, again as a result of pre-Moenkopi erosion (Nielson, 1981; Higgins and Willis, 1995; Higgins, 1997). The Harrisburg

Member was deposited in a complex sequence of shallow-marine and sabhka environments (Nielson, 1981; 1986), and is considered to be Early Permian (Leonardian) in age (Sorauf and Billingsly, 1991).

Toroweap and Kaibab Formations, undifferentiated (Pu)

Due to structural complications and alteration along the Hurricane fault zone, four areas are mapped as undifferentiated Toroweap and Kaibab strata. East of LaVerkin this map unit consists of highly fractured and brecciated, generally west-dipping Fossil Mountain and Harrisburg strata; Woods Ranch strata may be locally present near the base of this exposure. Fossil Mountain strata are locally "bleached" white, especially near the northern end of this undifferentiated exposure.

Two small areas east of Hurricane are also mapped as undifferentiated Toroweap and Kaibab strata; they likely consist of Fossil Mountain and Woods Ranch strata. Just south of Gould Wash, undifferentiated Toroweap and Kaibab strata consist of Fossil Mountain, Woods Ranch, and Brady Canyon beds.

Triassic

Moenkopi Formation

The Moenkopi Formation of southwestern Utah consists of three transgressive members (the Timpoweap, Virgin Limestone, and Shnabkaib Members) each of which is overlain by an informally named red-bed member (the lower, middle, and upper red members, respectively); the Rock Canyon Conglomerate Member locally forms the base of the Moenkopi Formation (Reeside and Bassler, 1921; Stewart and others, 1972; Dubiel, 1994). The Moenkopi Formation (late Early Triassic) records a complicated series of marine transgressions and regressions on a very gently sloping continental shelf, where sea level changes of several feet translated into shoreline changes of many miles (Dubiel, 1994). The transgressive members generally thicken, and the red bed members thin, from east to west across southwestern Utah.

The Permian-Triassic boundary in southwestern Utah is marked by a major disconformity that represents about 10 to 20 million years of erosion (Nielson, 1981; Sorauf and Billingsley, 1991); it corresponds to the Tr-1 unconformity of Pipiringos and O'Sullivan (1978). Erosion produced an irregular surface with several hundred feet of relief upon which conglomerates and breccias of the Rock Canyon Conglomerate Member were locally deposited in paleo-canyons, karst depressions, and as regolith (Nielson, 1991). The overlying Timpoweap Member was deposited in broader paleo-valleys.

A complete, though highly faulted section of Moenkopi strata is present in the Hurricane

Cliffs north of Highway 9. At Hurricane Mesa immediately east of the Hurricane quadrangle, Moenkopi strata total about 1,500 feet (457 m) thick. The upper five members present in the Harrisburg Junction quadrangle total about 1,600 to 1,800 feet (494-569 m) thick (Biek, 1997), significantly less than the 2,035 feet (620 m) reported by Reeside and Bassler (1921) on the south side of Harrisburg Dome. 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. Only the five upper members of the Moenkopi Formation are present in the Washington Dome quadrangle to the south, where they total about 1,900 feet (575 m) thick (Higgins, 1998).

Rock Canyon Conglomerate Member (Trmr, mr): The Rock Canyon Conglomerate Member consists of two main rock types: a rounded pebble and cobble conglomerate found in paleovalleys, and a widespread, but thin, angular breccia. The Rock Canyon Conglomerate Member is here used in the sense of Nielson (1991), except that, in accord with recent usage in the St. George basin (Hintze, 1993; Higgins, 1997), it is placed as the lowest member of the Moenkopi Formation, rather than elevated to formational rank as suggested by Nielson (1991).

The best exposures of channel-form conglomerates are found in Frog Hollow, in the SW1/4SE1/4 section 14 and the SE1/4SE1/4SW1/4 section 14, T. 42 S., R. 13 W.; in the upper reaches of Gould Wash, section 11, T. 42 S., R. 13 W.; and northeast of LaVerkin, in the NE1/4NE1/4SE1/4 section 13 and the NW1/4SE1/4NE1/4 section 13, T. 41 S., R. 13 W. and in exposures to the west along the base of the Hurricane Cliffs. The best exposures of thin breccias are found on the south side of Frog Hollow, in the vicinity of Mollies Nipple.

The most conspicuous Rock Canyon lithology is a pebble to cobble, clast-supported conglomerate that contains subrounded to rounded chert clasts set in a pinkish-gray to very pale-orange, calcareous, medium- to coarse-sand matrix; small boulder-size clasts are locally common at the base of the deposits. The clasts are predominantly chert and minor limestone that appear to be derived exclusively from Harrisburg Member strata. These deposits are restricted to channels that are locally in excess of 80 feet (24 m) deep and are characterized by low-angle cross-stratification (figure 3). These ledge- and cliff-forming deposits are normally well-cemented, such that fractures break through clasts; they weather to more rounded outcrops than overlying, cliff-forming but platy-weathering Timpoweap strata. Cross-stratification generally dips to the north in the Hurricane quadrangle, in accord with paleocurrent data in Nielson (1991) who showed that the Rock Canyon Congomerate Member was deposited in part by streams that flowed toward the northeast in southwestern Utah.

(Figure 3 near here)

Rock Canyon Conglomerate breccia deposits are found over positive areas between channel-form conglomerates. These deposits consist of both clast- and matrix-supported breccias that contain well-cemented, angular, pebble- to cobble-size, chert and limestone clasts derived from the underlying Harrisburg Member of the Kaibab Formation. Breccia deposits vary from 0 to about 10 feet (0-3 m) thick and, due to problems of scale, are mapped only where well-developed. The contact between Harrisburg and Timpoweap strata is nearly everywhere marked by unmapped Rock Canyon breccia deposits that vary from less than one foot to about 2 feet (0.2-0.6 m) thick.

The upper contact with the Timpoweap Member is gradational; Nielson (1991) noted that Rock Canyon strata locally interfingers with Timpoweap and lower red beds in southwestern Utah. In the Hurricane quadrangle, the contact was placed at the base of the first yellowish-brown-weathering, thin-bedded, even-bedded, laterally extensive limestone of the Timpoweap Member.

The Rock Canyon Conglomerate varies from 0 to at least 80 feet (0-24 m) thick in the Hurricane quadrangle. Higgins (1997) reported Rock Canyon Conglomerate thicknesses that varied from 0 to 200 feet (0-61 m) in the White Hills quadrangle to the southwest. The Rock Canyon Conglomerate was deposited in fluvial channels, alluvial fans, and fan deltas in southwestern Utah (Nielson, 1991), but most of the rounded, conglomeratic deposits in the Hurricane quadrangle appear to be fluvial channel deposits. Comparatively thin breccia deposits are believed to have formed as a regoltih (Nielson, 1991).

Timpoweap Member (Trmt, mt): The Timpoweap Member was named by Gregory (1950) for exposures in the lower reaches of Timpoweap Canyon, although he failed to designate a type section or locality. Nielson and Johnson (1979) subsequently designated four reference sections in Timpoweap Canyon, immediately east of the Hurricane quadrangle. The Timpoweap Member is widely exposed as a caprock along the Hurricane Cliffs.

The lower part of the Timpoweap Member consists of light-brown-weathering, light-gray to grayish-orange, thin- to thick-bedded, even-bedded limestone and cherty limestone. Chert occurs principally as dissemniated blebs and grains, thus giving the limestones a very rough weathering appearance. Locally, the upper part of this limestone sequence contains euhedral pyrite crystals up to 1/3 inch (1 cm) in diameter. A few poorly preserved ammonites were also recovered from these beds in the Frog Hollow and Gould Wash areas. The upper part of the Timpoweap Member typically consists of grayish-orange, thin- to thick-bedded, even-bedded, slightly calcareous, very fine-grained sandstone with both planar and ripple cross-stratification, and similarly colored, thin-bedded siltstone and mudstone. These upper sandstone beds are best exposed between Gould Wash and Frog Hollow. An oil seep in upper Timpoweap strata is mapped in Chinatown Wash, immediately east of Highway 69, and additional seeps are found upstream; still other oil seeps are known in the Virgin quadrangle to the east.

The upper contact with the lower red member corresponds to a color and lithologic change from yellowish-brown siltstone, mudstone, and local limestone to reddish-brown siltstone and mudstone. Based on stratigraphic studies in Timpoweap Canyon, Nielson and Johnson

(1979) recommended that the contact be placed at the top of the highest, thick Timpoweap limestone bed, thereby including yellowish-brown clastic strata in the lower red member. While yellowish-brown clastic strata appear to locally intertongue with red beds of the lower red member, the entire Timpoweap-lower red member succession appears to be gradational and conformable in the Hurricane quadrangle; it would be impractical to differentiate yellowish-brown, similarly colored and similarly weathering clastic and carbonate strata of the upper Timpoweap Member.

The Timpoweap Member forms a consistent low cliff or ledgy interval at the top of the Harrisburg Member and locally above channel-form deposits of the Rock Canyon Conglomerate. Timpoweap strata form a gently undulating surface on top of the Permian-Triassic unconformity. Because of this undulating bedding and the broad bench across which the Timpoweap Member must normally be measured, the thickness of the Timpoweap Member is imprecisely known. Nielson (1981) measured two complete sections of Timpoweap strata in the Hurricane quadrangle - at Mollies Nipple and at the quadrangle's eastern boundary just south of the Virgin River - that totaled 132 feet (40 m) and 79 feet (24 m) thick, respectively. Timpoweap strata probably vary between about 30 to 130 feet (9-40 m) thick in the Hurricane quadrangle. The Timpoweap Member is absent along the central portion of the Virgin anticline (Nielson, 1981; Biek, 1997; Higgins, 1998), but is 75 to 110 feet (23-34 m) thick at Bloomington Dome (Higgins and Willis, 1995). Timpoweap strata vary from 0 to 100 feet (0-30 m) thick in the White Hills quadrangle due to pinch outs against paleotopography (Higgins, 1997). The Timpoweap

Member was deposited in a shallow, north-trending marine trough in southwestern Utah, filling the topographic unconformity at the top of the Kaibab Formation (Nielson and Johnson, 1979; Nielson, 1981).

Lower red member (Trml, ml): The lower red member crops out along the base of Hurricane and Gooseberry Mesas, in the northeast and southeast corners of the quadrangle, respectively; erosional outliers are also found at Mollies Nipple and on the south side of Timpoweap Canyon, and in fault-bounded blocks along the Hurricane fault zone.

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 lower part of the member is locally irregularly colored yellowish orange. The upper contact of the lower red member was placed at the base of the lowest Virgin Member limestone bed.

Based on map patterns, the lower red member is about 250 feet (76 m) thick in the Hurricane quadrangle. Gregory (1950) reported a thickness of 220 to 310 feet (67-95 m) in the Zion National Park region. Higgins (1998) reported thickness variations from 25 to 200 feet (8-60 m) at Washington Dome to the southwest, probably due to attenuation faulting. Along the flanks of the Bloomington Dome to the southwest, lower red strata vary in thickness from 25 to 300 feet (8-91 m), probably due to attenuation faulting (Higgins and Willis, 1995). In the White

Hills quadrangle, Higgins (1997) reported lower red thicknesses that varied from 0 to 200 feet (0-61 m) due to paleotopography. The lower red member is unconformably overlain by the Virgin Limestone Member throughout southwestern Utah and was probably deposited in a tidal-flat environment (Stewart and others, 1972; Nielson and Johnson, 1979).

Virgin Limestone Member (Trmv, mv): The Virgin Limestone Member forms a prominent bench along the flanks of Hurricane and Gooseberry Mesas, in the northeast and southeast corners of the quadrangle, respectively; it is also exposed in numerous fault blocks along the Hurricane fault zone. The member weathers to well-exposed limestone ledges and poorly exposed siltstone and mudstone slopes.

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. Three prominent limestone ledges are present in Hurricane Mesa, immediately east of the Hurricane quadrangle.

A complete, unfaulted section of Virgin Limestone strata is not exposed in the Hurricane quadrangle, but it is estimated to be about 100 feet (30 m) thick in this area. The member varies from 8 to 116 feet (2.5-35 m) thick in the Zion National Park region (Gregory, 1950). Along the southwestern flank of Harrisburg Dome, the Virgin Limestone Member is about 85 feet (26 m) thick (Biek, 1997). To the south, in the Washington Dome quadrangle, Higgins (1998) reported that undisturbed Virgin strata are 115 feet (35 m) thick. In the St. George quadrangle to the southwest, Higgins and Willis (1995) reported the Virgin Limestone Member is 134 feet (41 m) thick. The member varies considerably in thickness along the flanks of 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. The Virgin Limestone is conformably overlain by the middle red member (Poborski, 1954; Stewart and others, 1972). The upper contact was placed at the top of the uppermost limestone bed. The Virgin Limestone Member is early to middle Spathian in age and was deposited in a shallow-marine environment (Dubiel, 1994).

Middle red member (Trmm, mm): The middle red member is only exposed in a complexly faulted section along the Hurricane Cliffs north of Highway 9. The middle red member 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. The lower part of the member contains several thick, ledge-forming gypsum beds that are well exposed along Hurricane Mesa, east of the quadrangle.

The upper contact is placed at the base of the first thick gypsum bed of the Shnabkaib Member. The upper contact 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) noted that in many places this contact corresponds to a transition zone that is about 100 to 300 feet (30-91 m) thick, although here the contact appears relatively straightforward.

A complete, unfaulted section of the middle red member is not exposed in the Hurricane quadrangle. Gregory (1950) reported the member varies from 436 to 520 feet (133-159 m) thick in the Zion National Park region. The middle red member is about 400 to 500 feet (122-152 m) thick along the southeastern flank of Harrisburg Dome (Biek, 1997). 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 south in the Washington Dome quadrangle, Higgins (1998) reported the member is 400 feet (122 m) thick. 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). The middle red member was probably deposited in a tidal-flat environment.

<u>Shnabkaib Member (Trms, ms):</u> The Shnabkaib Member is incompletely but well exposed at Little Purgatory in the core of the Virgin anticline, and along the Hurricane Cliffs in a large fault-bounded block south of LaVerkin Creek; steeply west-dipping Shnabkaib strata are also exposed at the entrance to Timpoweap Canyon. Shnabkaib strata form 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.

The mudstones and siltstones of the Shnabkaib Member 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 secondary cavity fillings and cross-cutting veins. The gypsum beds vary from less than one inch to about 9 feet (0.01-3 m) thick. The Shnabkaib Member also contains thin, laminated, light-gray dolostone beds that, being more resistant than enclosing rocks, weather out, with dolostone debris accumulating at the surface. Shnabkaib strata weather to soft, punky, gypsiferous soils.

The upper contact of the Shnabkaib Member 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.

The Shnabkaib Member is estimated to be 600 to 700 feet (182-212 m) thick in the Harrisburg Junction quadrangle (Biek, 1997). Higgins (1998) reported that Shnabkaib strata total about 750 feet (229 m) thick in the Washington Dome quadrangle. Lambert (1984), however, reported the Shnabkaib Member is only about 426 feet (130 m) thick on the east flank of the Washington Dome, and is comparably thick east of Hurricane, at Hurricane Mesa and Little

Creek Mountain. Gregory (1950) inexplicably assigned just 216 to 376 feet (66-115 m) of strata to the Shnabkaib Member in the Zion National Park region. Higgins and Willis (1995) reported the Shnabkaib Member is 996 feet (304 m) thick in the St. George quadrangle to the southwest. Proctor and Brimhall (1986) estimated Shnabkaib 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. The intricate interbedding of evaporites and red beds suggests complex water table fluctuations, probably associated with minor sea level fluctuations (Dubiel, 1994).

Upper red member (Trmu, mu): The upper red member is well exposed below cliffs of Shinarump Conglomerate at Little Purgatory, in the core of the Virgin anticline. Upper red strata are also exposed along the Hurricane fault zone north of LaVerkin Creek, and at the entrance to Timpoweap Canyon. With the exception of a lower, cliff-forming yellowish 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, yellowish sandstone, described below, is present near the base of the member. Planar, low-angle, and ripple cross-stratification, and well-preserved ripple marks, are common.

A prominent, normally cliff-forming, pale-yellowish-orange to grayish-orange, fine-grained sandstone with liesegang banding occurs about 50 feet (15 m) above the base of the member; this yellowish sandstone is informally known as the "Purgatory Sandstone". 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 sandstone unit is 108 feet (33 m) thick southeast of Quail Creek reservoir, in the NE1/4 section 35, T. 41 S., R. 14 W. (Biek, 1997), and is comparably thick in the Hurricane quadrangle.

The upper red member is about 400 feet (121 m) thick in the Hurricane quadrangle; it is 397 feet (120 m) thick southwest of Quail Creek reservoir (Biek, 1997). To the south in the Washington Dome quadrangle, Higgins (1998) reported that upper red strata are 475 feet (145 m) thick. Higgins and Willis (1995) reported the upper red member is 363 feet (111 m) thick south of St. George, on the northwest flank of the Virgin anticline. Proctor (1953) measured 376 feet (115 m) of what are now called upper red strata north of Highway 9. Reeside and Bassler (1921) assigned 475 feet (145 m) to this member near Harrisburg Dome. Gregory (1950) assigned 404 to 564 feet (123-172 m) of strata to the upper red member in the Zion National Park region. These widely varying thicknesses may be due in part to differences in placing the lower contact, and perhaps to structural complications. The upper red member was probably deposited in tidal-flat and coastal plain environments.

Moenkopi Formation, undifferentiated (Trm)

Numerous fault blocks along the Hurricane fault zone contain steeply west-dipping Moenkopi red beds. These blocks may contain lower, middle, or upper red bed member strata.

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 carapace along the axis of the Virgin anticline, whereas the Petrified Forest Member is both poorly and exceptionally well exposed in adjacent strike valleys. The Chinle Formation is Late Triassic in age, based principally on vertebrate and plant remains, and was deposited in a variety of fluvial and lacustrine environments (Stewart and others, 1972; Dubiel, 1994). Shinarump strata were deposited principally in braided-stream channels in which paleoflow was generally to the north and northwest; Petrified Forest fluvial systems mimicked this paleoflow, but with a much greater abundance of high-sinuosity stream deposits and floodplain mudstones (Dubiel, 1994). In southwestern Utah, the TR-3 regional unconformity (Pipiringos and O'Sullivan, 1978) separates Early Triassic (Moenkopi Formation) and Late Triassic (Chinle Formation) rocks and marks a change from mostly shallow-marine to continental sedimentation. In the Hurricane quadrangle, the TR-3 unconformity is a disconformity with minor channeling at the base of the Shinarump Conglomerate Member. Dubiel (1994) assigned Chinle strata to the early Carnian to late Norian (Late Triassic) with an unconformity of several million years separating the two members; no evidence of such an unconformity was found in the quadrangle.

Shinarump Conglomerate Member (Trcs): Because of its resistance to erosion, the Shinarump Conglomerate Member forms a prominent carapace along the axis of the Virgin anticline. It is nearly everywhere well exposed in cliffs along the interior of the anticline at Little Purgatory. Shinarump strata are also exposed northwest of LaVerkin Creek and at the entrance to Timpoweap Canyon.

The Shinarump Conglomerate consists of a laterally and vertically variable sequence of cliff-forming, fine- to very coarse-grained sandstone, pebbly sandstone, and minor 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-yellowish-brown hues are common. Small, subrounded pebbles 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 to low-sinuosity fluvial systems dominated by sand waves and point-bar deposits (Dubiel, 1994). In the Hurricane 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 Conglomerate Member and suggest minor movement along and between bedding planes, even where beds are not otherwise affected by faulting or subsidiary folding. Where Shinarump strata are faulted, the sandstones are non-calcareous and commonly have slickensided surfaces. 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 in length are common though not abundant. Plant trash, replaced by iron-manganese oxides, is also common.

The Shinarump Conglomerate varies widely in thickness. Stewart and others (1972) measured 162 feet (49 m) of Shinarump strata at East Reef. Southwest of Quail Creek reservoir Shinarump strata are 104 feet (32 m) thick, and at the southern end of Washington Black Ridge these beds are 165 feet (50 m) thick (Biek, 1997). Proctor (1953) measured 115 feet (35 m) of Shinarump strata along the Virgin anticline north of Highway 9. Proctor and Brimhall (1986) reported Shinarump strata are 95 feet (29 m) thick in the Silver Reef mining district. To the south in the Washington Dome quadrangle, Higgins (1998) reported that Shinarump strata vary from 5 to 200 feet (1.5-61 m) thick. 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 to difficulty in placing the locally gradational upper contact.

In the Hurricane quadrangle, the upper contact with the Petrified Forest Member is only exposed along the northeast flank of the Virgin anticline; it is best exposed in the southwest corner of section 17, T. 41 S., R. 13 W. In this area, the contact corresponds to a prominent lithologic and color change, from yellowish-brown sandstone and pebbly sandstone of the Shinarump Conglomerate below to the brightly colored, varicolored swelling claystones of the Petrified Forest Member above. Along the northwest flank of the Virgin anticline, in the adjacent Harrisburg Junction quadrangle, the contact appears to be gradational and intertonguing (Biek, 1997).

Petrified Forest Member (Trcp, cp): Some of the best and most complete exposures of

Petrified Forest strata in southwestern Utah are found at East Reef, along the northeast flank of the Virgin anticline. Incomplete, fault-bounded blocks of Petrified Forest strata are also found along the Hurricane cliffs north of Hurricane.

The Petrified Forest Member consists of variably colored mudstone, claystone, siltstone, lesser sandstone and pebbly sandstone, and minor chert and nodular limestone; it contains a wider lithologic variation than might be expected given the prominent varicolored swelling mudstones that typify the member. Mudstones and claystones of the Petrified Forest Member are typically various shades of purple, although grayish-red, dark-reddish-brown, light-greenish-gray, brownish-gray, olive-gray, and similar hues are common. Bentonitic clays that swell conspicuously when wet are common and give weathered surfaces a "popcorn" appearance. These swelling clays are also responsible for numerous building foundation problems in the area.

Sandstones of the Petrified Forest Member exhibit a wide variation in grain size and bedding characteristics and are generally restricted to the lower and middle parts of the member. Locally, as north of Harrisburg Flat just west of Interstate 15 in the adjacent Harrisburg Junction quadrangle, lower Petrified Forest strata include a 0 to 40-foot- (0-12 m-) thick, ledge-forming, very pale-orange to pinkish-gray, medium- to coarse-grained, locally pebbly sandstone. This thick channel sandstone can be traced to the northeast where it forms the northeast-plunging, tightly folded Leeds anticline at Leeds Reef. Along the western flank of Leeds anticline, at the border of the Harrisburg Junction and Hurricane quadrangles, this thick Shinarump-like sandstone is overlain by up to a few ten's of feet of reddish-brown, slope-forming, thin-bedded siltstone and very fine-grained sandstone which in turn are overlain by another smaller, Shinarump-like channel sandstone. Small pebble-size clasts in these sandstones are primarily chert and quartzite; light-greenish-gray mudstone rip-up clasts are locally common. This entire Shinarump-like sandstone sequence was mapped as the Shinarump Conglomerate by Proctor (1953), Cook (1960), and Proctor and Brimhall (1986). Faulting renders the true stratigraphic position of this sandstone uncertain, but it probably corresponds to the basal Petrified Forest sandstones described at the southern end of Washington Black Ridge (Biek, 1997).

The middle part of the Petrified Forest Member is characterized by a very pale-orange, massively bedded, coarse- to very coarse-grained, pebbly sandstone that varies from about 10 to 52 feet (3-16 m) thick (Stewart and others, 1972; Biek, 1997); green and yellow-ochre stains from copper and uranium mineralization are common. The pebbles consist of rounded chert and lesser quartzite clasts.

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. Petrified logs - commonly splintery, poorly preserved, and several tens of feet in length - are common in channel deposits of the middle sandstone.

Petrified Forest strata commonly form rotational slumps, especially where exposed along steep hillsides. In the Hurricane quadrangle, such slumps are common below cliffs of Moenave strata along the northeast-plunging nose of the Virgin anticline.

A silicified bed up to one foot (0.3 m) thick occurs a few tens of feet above the medial sandstone interval. The best exposures of this bed are found at Buckeye Reef, in the NE1/4NE1/4NE1/4 section 12, T. 40 S., R. 14 W., and at East Reef, in the SE1/4NW1/4SE1/4 section 19, T. 41 S., R. 13 W. This bed is moderate red to moderate reddish orange, with streaks of light greenish gray. It appears similar to a silicified peat or silicified A- horizon paleosol. 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 of the Petrified Forest Member is known as the J-0 unconformity and represents a gap of about 10 million years during the Late Triassic and Early Jurassic (Pipiringos and O'Sullivan, 1978). Even though the color change between Petrified Forest and overlying Dinosaur Canyon strata is well developed in the East Reef area, and in the vicinity of Buckeye Reef, the contact is poorly exposed due to small-scale slumping and slopewash. The contact corresponds to a change from slope-forming purplish swelling mudstones below to brown, very fine- to fine-grained sandstone, silty sandstone, and lesser siltstone and mudstone above. The upper Petrified Forest mudstone interval contains abundant light-gray to light-olive-gray limestone nodules, while the upper 30 feet (9 m) of the member contains scattered selenite crystals.

The excellent exposures at East Reef were measured by Stewart and others (1972), who found 408 feet (124 m) of Petrified Forest strata. Proctor and Brimhall (1986) reported Petrified Forest strata are 446 feet (136 m) thick in the structurally and stratigraphically complex Buckeye Reef area. The member is estimated to be about 700 feet (213 m) thick in the St. George quadrangle to the southwest (Higgins and Willis, 1995) and the Washington Dome quadrangle to the south (Higgins, 1998). The Petrified Forest Member was deposited in fluvial, floodplain, and lacustrine environments (Dubiel, 1994); mottled, variegated mudstones probably represent paleosols. Abundant bentonitic mudstones in the Petrified Forest Member were probably derived from volcanic ash sourced at a magmatic arc along the continental margin to the west (Dubiel, 1994).

Moenkopi and Chinle Formations, undifferentiated (Tru)

A small block of undifferentiated Shinarump and probable upper red member strata is mapped at the base of the Hurricane Cliffs south of Nephis Twist. These west-dipping beds are caught up in the Hurricane fault zone and partly concealed by old alluvial fan deposits.

Jurassic

Moenave Formation

The Moenave Formation forms a distinctive, three-part clastic sequence that wraps around the northeast-plunging end of the Virgin anticline. Moenave strata are repeated by thrusting on the northwest flank of the Virgin anticline, and are complexly folded and faulted along the nose of the anticline. Steeply southeast-dipping but otherwise undisturbed Moenave strata are well exposed at East Reef. Incomplete, fault-bounded exposures are also found at the base of the Hurricane Cliffs in the vicinity of Nephis Twist.

The Moenave Formation is divided into, in ascending order, the Dinosaur Canyon Member, which consists of 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, which consists of varicolored, fine- to medium-grained sandstone that is host to the ore minerals of the Silver Reef mining district.

The Moenave Formation is 356 feet (108 m) thick at East Reef (Stewart and others, 1972). The formation is 391 feet (119 m) thick at Harrisburg Flat (Biek, 1997). Proctor and

Brimhall (1986) reported the Moenave Formation is just 261 feet (80 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. To the south in the Washington Dome quadrangle, Higgins (1998) reported that Moenave strata are 310 feet (94 m) thick. Higgins and Willis (1995) measured a complete section of Moenave strata just east of Middleton Black Ridge in the St. George quadrangle that totaled 420 feet (127 m) thick. The Moenave Formation is Lower Jurassic in age (Imlay, 1980; Miller and others, 1989; Olsen and Galton, 1977), and was deposited in a variety of fluvial and lacustrine environments.

Dinosaur Canyon Member (Jmd, d): The Dinosaur Canyon Member is exposed at the base of White, Butte, Buckeye, and East Reefs; in faulted blocks at the northeast-plunging nose of the Virgin anticline; and in incomplete faulted exposures at the base of the Hurricane Cliffs south of LaVerkin Creek. The member consists of interbedded, mostly slope-forming, generally thin-bedded, very fine- to fine-grained sandstone, very fine-grained silty sandstone, and lesser siltstone and mudstone. Planar, 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- to 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. About 25 feet (7.5 m) of brown sandstone, typical of underlying Dinosaur Canyon strata, overlie the dolomitic limestone and are here included in the Whitmore Point Member; they point to the conformable, intertonguing nature of this member contact. Thus, the contact used here 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, included in the Dinosaur Canyon Member, and the purplish-gray-green claystone of the Whitmore Point Member.

The Dinosaur Canyon Member is 200 feet (61 m) thick at East Reef (Stewart and others, 1972). These strata are 163 feet (50 m) thick at Harrisburg Flat in the Harrisburg Junction quadrangle to the west (Biek, 1997). Wilson and Stewart (1967) reported Dinosaur Canyon strata are about 200 feet (61 m) thick in the Leeds area. Higgins (1998) reported 155 feet (47 m) of Dinosaur Canyon strata in the Washington Dome quadrangle to the south. Dinosaur Canyon strata are 250 feet (76 m) thick east of Middleton Black Ridge, in the St. George quadrangle (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 overlying 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 at East Reef, on the northeast flank of the Virgin anticline.

The Whitmore Point Member consists of interbedded, varicolored mudstone and claystone; lesser moderate-reddish-brown, very fine- to fine-grained sandstone and siltstone; and several thin dolomitic limestone beds. 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, to 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 limestones appear bioturbated and contain grayish-orange-pink to moderate-reddish-brown chert nodules, locally abundant 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 and siltstones similar to those of the Dinosaur Canyon Member.

The upper contact is generally conformable, although local channeling and mudstone rip-up clasts are present at the base of the Springdale Sandstone Member. The upper contact 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 cliffs and ledges above gentle Whitmore Point slopes. Where Grapevine Wash passes through East Reef, in the NE1/4NE1/4SE1/4 section 19, T. 41 S., R. 13 W., the Springdale Sandstone cuts down into Whitmore Point strata, forming a channel about 25 feet (7.5 m) thick. Stewart and others (1972) assigned 61 feet (18 m) of strata to the Whitmore Point Member at East Reef, on the northeast flank of the Virgin anticline. The Whitmore Point Member is 64 to 126 feet (19-38 m) thick in the Harrisburg Junction quadrangle to the west (Biek, 1997). Wilson and Stewart (1967) reported the member is about 60 feet (18 m) thick in the Leeds area. To the south, along the southeast flank of Washington Dome, Higgins (1998) reported about 30 feet (9 m) of Moenave strata. Higgins and Willis (1995) reported the member is 55 feet (17 m) thick east of Middleton Black Ridge, in the St. George quadrangle. The Whitmore Point Member was deposited in floodplain and lacustrine environments.

Springdale Sandstone Member (Jms): The Springdale Sandstone Member is well exposed at White, Butte, Buckeye, and East Reefs, and in faulted exposures at the nose of the Virgin anticline; a poorly exposed, incomplete section is also found at the base of the Hurricane Cliffs, south of LaVerkin Creek. The Springdale Sandstone Member is host to ore deposits of the Silver

Reef mining district. 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 characteristic small, resistant, 0.13-inch (2 mm) diameter concretions in Springdale sandstones 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 commonly corresponds to a pronounced color, topographic, and lithologic change. The upper contact is well exposed but more difficult to pick at East Reef (figure 4). There, variously colored, ledge- and cliff-forming, thick to massively bedded, fine-grained sandstone of the Springdale Sandstone is overlain by reddish-brown, slope-forming, 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. The Springdale Sandstone is about 95 feet (29 m) thick in the Hurricane quadrangle (Stewart and others, 1972). The Springdale Sandstone Member attains a local maximum thickness of 164 feet (50 m) near Harrisburg Flat, in the adjacent Harrisburg Junction quadrangle (Biek, 1997). 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; Wilson and Stewart (1967) reported Springdale strata are about 95 feet (29 m) thick in this same area. One mile (1.6 km) south of Harrisburg Flat, along Cottonwood Creek, Springdale strata are 120 feet (36 m) thick (Biek, 1997). The member is 125 feet (38 m) thick in the Washington Dome quadrangle to the south (Higgins, 1998). Higgins and Willis (1995) reported the member is 115 feet (35 m) thick east of Middleton Black Ridge, in the St. George quadrangle. The Springdale Sandstone was probably deposited in braided-stream and minor floodplain environments.

(Figure 4 near here)

Kayenta Formation (Jk)

The Kayenta Formation consists of a thick, monotonous sequence of interbedded, thin- to medium-bedded, moderate-reddish-brown siltstone, fine-grained sandstone, and mudstone; a few thin dolostone beds are found in the lower part of the formation. 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) in the Gunlock area. Willis and Higgins (1996) later mapped just two informal members and reassigned most of the upper member of Willis and Higgins (1995) to the transition zone of the Navajo Sandstone. Wilson and Stewart (1967) described the Kayenta in the Leeds-St. George area as consisting of two parts, but much of their upper part included beds herein assigned to the Navajo Sandstone. In the Hurricane 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 remarkably well exposed at East Reef (figure 4). Kayenta strata are commonly mottled with small circular and irregularly shaped reduction spots. Planar, low-angle, and ripple cross-stratification is common. Kayenta sandstones are less commonly moderate reddish orange or yellowish gray. 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 thick (Tuesink, 1989; Sansom, 1992).

Previous workers variously included these transition beds in the upper Kayenta or lower Navajo, as discussed below. In coordination with the mapping of Higgins and Willis (1995), Willis and Higgins (1995), and Higgins (1998), I placed the Kayenta/Navajo contact at the top of the highest mudstone interval, thereby including several prominent ledge-forming sandstone beds in the upper Kayenta. 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. Transitional strata are thus included principally in the Navajo Sandstone.

The Kayenta Formation is 935 feet (285 m) thick at East Reef (Stewart and others, 1972). To the west, at Harrisburg Flat, Kayenta strata are 925 feet (282 m) thick (modified from Biek, 1997). Willis and Higgins (1995) reported a 787-foot (238-m) composite thickness of the lower and middle members in the greater St. George area, which are roughly equivalent to the Kayenta of this report. The Kayenta Formation was deposited in fluvial, distal fluvial/playa, and minor lacustrine environments (Sansom, 1992). The Kayenta Formation is Lower Jurassic in age (Imlay, 1980).

Navajo Sandstone (Jn)

The Navajo Sandstone and correlative sandstones are renown 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 renown too for their great thickness, locally exceeding 2,000 feet (609 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. The Navajo Sandstone consists almost entirely of poorly to moderately well-cemented, well-rounded, frosted quartz grains.

In the Hurricane quadrangle, the Navajo Sandstone is widely exposed along and north of the Virgin River; south of the river, the Navajo is almost entirely concealed by Quaternary basaltic rocks. Lower and middle Navajo strata are generally moderate reddish orange to moderate orange pink, although irregularly shaped areas are locally very pale orange to yellowish gray. 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 accumulate in channels and on broad, flat surfaces.

Along the southern flank of the Pine Valley Mountains, the contact between upper Kayenta and lower Navajo is conformable and gradational and records the transition from distal fluvial, to sabkha, to erg-margin and finally erg-center depositional environments (Tuesink, 1989; Sansom, 1992). Cook (1957) was among the first to recognize this transitional interval in Washington County, and in particular near Leeds, where he included about 100 feet (30 m) of these transitional beds in his lower Navajo. Hintze and others (1994) included these transitional 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 specify to which formation it belonged. This transitional zone is similarly well developed at East Reef, on the northeast flank of the Virgin anticline.

As previously described, I placed the Kayenta-Navajo contact at the top of the highest mudstone interval. This contact lies about 80 feet above the base of the transition interval as described by previous workers (Cook, 1957, 1960; Sansom, 1992; Biek, 1997). 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 adjacent Harrisburg Junction quadrangle. 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 trough cross-stratification. Wavy bedding, dark flaser-like laminae, and soft-sediment deformation features, including flame 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 typical of the main Navajo. Most of these transition beds belong to the crinkly and wavily laminated fine-grained or silty sandstone facies, with fewer wind ripple sets (Sansom, 1992).

Sansom (1992) defined the top of the transition zone as the highest well-defined sabkha-eolian cycle. Such cycles are generally 6 to 66 feet (2-20 m) thick and are 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 sandy eolian deposits, but she noted wide facies variations and an 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 massively cross-bedded sandstone 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.

The upper contact with the Temple Cap Formation, termed the J-1 unconformity by Pipiringos and O'Sullivan (1978), is well exposed north of the Virgin River, in the SE1/4 section 22, T. 41 S., R. 13 W. (figure 5). The contact is marked by a prominent change in lithology, with moderate-reddish-brown, thin-bedded siltstone and grayish-orange-pink, very fine-grained silty sandstone of the Temple Cap Formation overlying the planated surface of the massively cross-bedded Navajo Sandstone. The Navajo Sandstone is estimated to be 2,000 feet (610 m) thick in the Hurricane quadrangle.

(Figure 5 near here)

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 Hurricane quadrangle.

The Temple Cap Formation is only exposed north of the "radio tower" cinder cones, west of the confluence of the Virgin River and Ash Creek (figure 5). There, it forms conspicuous, varicolored, ledgy slopes atop a broad bench of Navajo Sandstone and below ledge-forming

Carmel strata. Temple Cap beds typically weather to soft, gypsiferous soils, making the excellent exposures here all the more remarkable.

The Temple Cap Formation typically consists of interbedded, slope-forming, moderate-reddish-brown, yellowish-gray, and light-gray mudstone, siltstone, very fine-grained silty sandstone, and lesser gypsum. The upper middle part of the formation is marked by a ledge-forming, thick-bedded, light-brown to grayish-orange, calcareous, fine-grained sandstone with low-angle cross-stratification. Gypsum varies from white to gray to pink and is both bedded and nodular in beds up to about 4 feet (1.3 m) thick. There are two small prospect pits for gypsum along the north end of the Temple Cap outcrop belt. Thin, pale-greenish-gray mudstone beds with abundant biotite, which are altered volcanic-ash layers, are common.

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 are 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 the top of a two-foot (0.6-m) thick, ledge-forming, laminated gypsum bed, below which lies about 80 feet (24 m) of interbedded, slope-forming, reddish-brown and light-gray mudstone, siltstone, and fine-grained silty sandstone typical of the Temple Cap Formation. Overlying lower

Co-op Creek strata consist of yellowish-gray, light-greenish-gray, and grayish-yellow calcareous mudstone and siltstone. This lower Co-op Creek sequence is about 30 feet (9 m) thick, considerably thicker than equivalent strata on the southern flank of the Pine Valley Mountains, which are about 6 feet (2 m) thick (Biek, 1997).

The Temple Cap Formation is about 220 feet (67 m) thick on the southwest side of hill 3662, in the E1/2 of section 22, T. 41 S., R. 13 W. Temple Cap strata vary from 187 to 236 feet (57-72 m) thick along the southeastern flank of the Pine Valley Mountains (Wright and others, 1979; Willis and Higgins, 1995; Biek, 1997). 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). (Christiansen and others, 1994) reported a bentonitic ash bed in Temple Cap strata at 169.4 Ma, a Bajocian age.

Co-op Creek Member of the Carmel Formation (Jc)

The Carmel Formation forms an eastward-thickening wedge, preserved beneath a regional unconformity termed the K-1 unconformity by Pipiringos and O'Sullivan (1978), across the southern flank of the Pine Valley Mountains. In the adjacent 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 (Biek, 1997). In the Hurricane quadrangle, however, only the lower Co-op Creek Member is preserved beneath the unconformity.

When viewed from a distance, Co-op Creek strata are readily divisible into two units, a thicker lower unit and a thin upper unit, 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. Collectively, these two unmapped units consist of a laterally variable sequence of interbedded, generally thin-bedded mudstone, siltstone, limestone, and, in the lower part, lesser gypsum.

The lower unit of the Co-op Creek Member is characterized by 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 2 feet (0.6 m) thick are also present.

The upper portion of the Co-op Creek Member is characterized by generally thin-bedded, coarse-grained, 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.

In the Hurricane quadrangle, the Co-op Creek Member is unconformably overlain by the Iron Springs Formation. Their contact corresponds to a change from ledge- and cliff-forming, pale-yellowish-brown fossiliferous limestone to interbedded, slope-forming, light-gray bentonitic mudstone and variously colored gray, yellowish-brown, and white siltstone and fine-grained sandstone.

The Co-op Creek Member is 130 feet (40 m) thick on the southwest side of hill 3662, in the E1/2 of section 22, T. 41 S., R. 13 W. Co-op Creek strata generally thicken eastward across the southern flank of the Pine Valley Mountains, from 285 to 448.5 feet (87-137 m) thick (Wright and others, 1979; Willis and Higgins, 1995; Biek, 1997). 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).

Triassic and Jurassic, undifferentiated

Chinle and Moenave Formations, undifferentiated (TrJu)

South of both LaVerkin Creek and Nephis Twist, two small, fault-bounded blocks at the base of the Hurricane Cliffs are mapped as Chinle and Moenave Formations undifferentiated. These blocks contain west-dipping, incomplete and highly attenuated sections of Shinarump, Petrified Forest, and Dinosaur Canyon strata.

Cretaceous

A thin bentonitic interval overlies the K-1 unconformity along the southern flank of the Pine Valley Mountains. In their mapping of 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 Pine Valley 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 thins from west to east across the flank of the Pine Valley Mountains, from about 90 feet (27 m) thick near Diamond Valley to about 20 to 25 feet (6-7.5 m) thick throughout the Harrisburg Junction quadrangle (Willis and Higgins, 1995; Biek, 1997). In the Hurricane quadrangle, the base of the Iron Springs Formation is marked by a light-gray-weathering bentonitic interval that is less than 5 feet (1.5 m) thick and which is overlain by light-brown to reddish-brown, fine-grained sandstone typical of the Iron Springs Formation. Similar bentonitic intervals comprise about 10 to 20 percent of the lower Iron Springs Formation in the Hurricane quadrangle. One or more of these bentonitic intervals may correlate with Pine Valley Mountain exposures; they are not mapped here due to problems of scale. 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 is exposed west of LaVerkin in the vicinity of Ash and LaVerkin Creeks. Only about the lower 600 feet (183 m) of the formation is exposed 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 Hurricane quadrangle, the lower part of the formation is comprised of about 10 to 20 percent of light-gray-weathering bentonitic mudstone that weathers to a characteristic "popcorn" surface.

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.

Jurassic and Cretaceous, undifferentiated

Carmel, Temple Cap, and Iron Springs Formations, undifferentiated (Jku)

A small exposure of nearly vertical Carmel (Co-op Creek Member), Temple Cap, and Iron Springs strata is mapped near the abandoned powerhouse in the Virgin River canyon in the NE1/4 section 22, T. 41 S., R. 13 W. These strata are likely in fault contact with one another and are possibly overturned, although limited outcrops render true relationships uncertain.

Quaternary

Basaltic flows and related deposits

Basaltic rocks from nine cinder cone complexes, five of which are located in the Hurricane quadrangle, are mapped. Basaltic flows are differentiated principally on morphology and field relationships, although several isolated exposures along the Virgin River and in the lower reaches of Frog Hollow remain undifferentiated. In the Hurricane area, basaltic flows are commonly partly covered by a veneer of eolian sand, and are so mapped with an 'e'; for example, Qbie. Alluvial gravel deposits that underlie basaltic flows are indicated by a 'g'; for example, Qbig. The oldest flow in the quadrangle appears to be the "remnants" flow, which caps Mollies Nipple and lies about 1,300 feet (396 m) above the Hurricane Fields at the top of the Hurricane Cliffs. The Ivans Knoll complex, which erupted from a vent or vents immediately south of Volcano Mountain, is about 350,000 years old, and is the second oldest basaltic unit in the quadrangle. Other basaltic flows in the quadrangle are somewhat younger and probably broadly contemporaneous based on a similar degree of erosion. One of these flows, at Volcano Mountain, is dated at about 260,000 years old.

Basaltic rocks cover most of the area south of the Virgin River and west of the Hurricane Cliffs, and are also exposed at East Reef, in the Toquerville area, in the southeast corner of the quadrangle, and in faulted exposures along the Hurricane fault zone. The most distinctive flows in the quadrangle are those found in the Toquerville area. They are lighter gray and coarser grained, and contain sparse olivine and common plagioclase phenocysts, compared to other flows. Most flows in the quadrangle are dark-gray, fine-grained olivine basalts that have a blocky, aa surface; rarely, ropey pahoehoe surfaces are preserved. Most flows in the quadrangle maintain a relatively constant thickness of 20 to 30 feet (6-9 m), but are in excess of 170 feet (52 m) thick where they fill old channels.

The best cinder cone exposures, described below, are found where the Virgin River has breached the north side of the "radio tower" cone. Except for the Ivans Knoll cinder cone, which is almost entirely removed by erosion, cinder cones in the Hurricane quadrangle each have moderately developed vertical rills. The tops of many cones are partly covered with aggultinate and large bombs, which record a change from volatile-rich Strombolian- to volatile-poor Hawaiian-style eruptions (Fischer and Schminke, 1984; Sanchez, 1995). Most of the cones are breached by lava flows, and small lava lakes are found at the "cinder pits" and Ivans Knoll cones.

In the greater Hurricane area, the location of volcanic vents appears to be joint controlled but not fault controlled (Sanchez, 1995). Sanchez tried to show that cone allignments match local joint maxima data of LeFebvre (1961). Vent allignments at individual volcanic centers trend north in the Hurricane quadrangle, except at East Reef, where they trend northeast, parallel to the Virgin anticline axis. However, trying to allign vents at separate volcanic centers is a problematic and somewhat arbitrary exercise.

These basaltic 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. 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 remnants 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. While such stage designations are useful for flows at the interior of large, fault-bounded blocks, the complex down-cutting history near the Hurricane fault zone renders stage designations misleading. Hamblin (1970) shows, for example, the Ivans Knoll flow to be classified as both stage II and stage IV. These stage designations were misassigned based on differential erosion of demonstrably single basaltic flows. Hamblin's stage designations are thus not used in this report.

Sanchez (1995) studied the composition and evolutionary history of the alkali basalt volcanoes near Hurricane, as well as theoretical aspects of mantle properties beneath the Basin and Range and Colorado Plateau transition zone. He classified these volcanic rocks as low-silica basanites, basanites, and alkali basalts on the total alkali versus silica (TAS) diagram of LeBas and others (1986). Based principally on geochemical correlation, Sanchez (1995) mapped these rock types for the volcanic centers south of the Virgin River; his resulting map differs in two significant respects from this mapping as described below. Sanchez (1995) also discussed the trace element geochemistry for these basaltic rocks and suggested that they represent magmas that had an oceanic island basalt (OIB)-like garnet-free source, but that show variable amounts of mixing with lithospheric mantle. The primitive geochemistry of the the low-silica basanite and basanite suggests that they rose rapidly from a site of partial melting to the surface. Sanchez (1995) showed that the geochemical variation among the basalts of the greater Hurricane area cannot be due to simple fractional crystalization of a single magma, similar to the findings of Best and Brimhall (1974), who studied basaltic rocks of the western Grand Canyon region. Sanchez (1995) also showed that most cones in the Hurricane area are classified as monocyclic (single event) and monogenetic (single source), meaning that most erupted from a single source over a relatively short time span (probably less than 100 years); the Ivans Knoll/Volcano Mountain complex, however, is polycyclic and polygenetic.

"Remnants" flow (Qbm): In the Hurricane quadrangle, the "remnants" flow is only exposed at Mollies Nipple, although additional exposures are located to the south. The margins of this flow are eroded and the flow rests high above the Hurricane Cliffs, apparently offset along the Hurricane fault zone. Sanchez (1995) was unable to locate a cinder cone or vent for this flow. Based on exposures at Mollies Nipple, the "remnants" flow is a medium-gray, medium-grained olivine basalt with prominent columnal jointing. It is about 25 feet (7.5 m) thick and overlies the lower red member of the Moenkopi Formation. Geochemically, a single sample collected at Mollies Nipple is classified as a basalt on the TAS diagram of LeBas and others (1986) (figure 6, table 1). These results differ significantly from Sanchez (1995), who reported two correlative samples to the south are classified as geochemically primitive, low-silica basanites. Map relationships clearly show these flows to be correlative; resolution of conflicting chemistries awaits detailed mapping in The Divide quadrangle.

(Figure 6 near here)

Ivans Knoll flow, cinder cone, and associated deposits (Qbi, Qbic, Qbie, Qbig): The Ivans Knoll flow forms a highland that slopes radially away from the hills near the common border of sections 5 and 8, T. 42 S., R. 13 W., immediately south of Volcano Mountain. All that remains of the cinder cone or cones associated with the Ivans Knoll flow are small cinder deposits (Qbic) in the SE1/4 section 5, T. 42 S., R. 13 W. The margins of the Ivans Knoll flow are eroded and the flow itself is mostly concealed beneath thick stage V-VI caliche (Birkeland and others, 1991) and lesser eolian sand (Qe2 and Qbie), and thus forms a much smoother surface than adjacent basaltic flows. Deposits associated with the Volcano Mountain complex conceal the northern margin of the Ivans Knoll flow. The best exposures of the Ivans Knoll flow are found in cliffs in the southwestern corner of the quadrangle, about 200 feet (61 m) above local drainages to the west.

The Ivans Knoll flow is a medium-gray, fine- to medium-grained olivine basalt that generally consists of at least two flow units. Five samples from this study (figure 6, table 1), and eight reported in Sanchez (1995), show that it is classified as a basalt on the TAS diagram of LeBas and others (1986). Abundant olivine phenocrysts up to about 0.1 inch (3 mm) across are the only recognizable mineral in hand samples.

Based both on field mapping and geochemical correlation, the Ivans Knoll flow is believed to underlie the town of Hurricane, where it is concealed by younger mixed alluvial and eolian deposits (Sanchez, 1995; this report). The Ivans Knoll flow reappears to the north, in faulted exposures at the entrance to Timpoweap Canyon, and to the southeast along the Hurricane Cliffs, at least as far south as the NW1/4 section 11, T. 42 S., R. 13 W. Exposures on the south side of the Virgin River canyon, under the Highway 9 bridge, reveal a single flow unit that is about 170 feet (52 m) thick and reaches to current river level. The base is marked by a rubbly zone with pillow basalts that is 20 to 40 feet (6-12 m) thick. This rubbly zone is overlain by about 10 feet (3 m) of dense, fine-grained basalt with few columnal joints, which in turn is overlain by about 100 feet (30 m) of similar basalt but with prominent columnal joints. The upper about 20 feet (6 m) of this exposure consist of vesicular basalt with few columnal joints.

This same stratigraphic sequence is present in exposures on the footwall of the Hurricane fault zone, from Timpoweap Canyon, south to the center of section 35, T. 41 S., R. 13 W. (figure 7), where ancestral Virgin River gravels locally underlie the flow (Qbig). At the south side of the entrance to Timpoweap Canyon, this flow is offset about 240 feet (73 m) along the Hurricane fault zone. This flow yielded an $^{40}Ar/^{39}Ar$ isochron date of 353 +/- 45 ka (Sanchez, 1995), and was previously dated by the potassium-argon method by Damon (cited by Best and others, 1980) at 289 +/- 86 ka.

(Figure 7 near here)

The Ivans Knoll flow is also well exposed in the cliffs east and south of Hurricane, where it is preserved on the footwall of the Hurricane fault zone. Where it overlies Permian carbonates, only a thin scab remains. More extensive exposures are found in pre-Ivans Knoll erosional embayments developed on less resistant Moenkopi strata and at the entrance to Gould Wash. In the Hurricane Cliffs, the Ivans Knoll flow generally consists of two to four flow units. Immediately east of Hurricane, in a Highway 59 roadcut, the Ivans Knoll flow consists of two otherwise similar flows separated by about 20 feet (6 m) of ancestral Virgin River gravel.

An unusual circular depression in excess of 1,000 feet (305 m) in diameter, breached on the east by a small drainage, is found at the center of section 9, T. 42 S., R. 13 W. It may represent a collapse feature associated with a subsidiary vent. Basalt exposures at Ivans Knoll itself may represent a series of lava lakes that now stand above the moderately sloping flanks of the volcano.

Toquerville flow (Qbt): The Toquerville flow forms a broad, east-dipping slope southwest of Toquerville where it is about 20 to 30 feet (6-9 m) thick. It thickens dramatically to the east, where it fills the ancestral Ash Creek drainage; there it is exposed at current base level and so is in excess of 120 feet (37 m) thick. The Toquerville flow thins to the south where it is exposed in cliffs above the LaVerkin Creek drainage and appears to interfinger with older alluvial-fan deposits. The ridge immediately east of Toquerville is covered with extensive basalt colluvium and locally capped by the Toquerville flow that, in the Hurricane quadrangle, lies up to 800 feet (244 m) above adjacent base level of Ash and LaVerkin Creeks. The margins of the flow are eroded. At its southern end, the Toquerville flow lies about 200 feet (61 m) above the Virgin River. These map patterns suggest that the gradient of Ash Creek has increased since emplacement of the flow.

The Toquerville flow is the most distinctive basaltic flow in the Hurricane quadrangle. It is generally a medium-light-gray, medium- to coarse-grained basalt with sparse 1 mm-size olivine and abundant plagioclase phenocrysts to 8 mm in length. Some exposures are darker gray and finer grained, but all are characterized by sparse olivine phenocrysts compared to other Hurricane-area flows. The Toquerville flow is locally composed of at least four flow units. Nine geochemical analyses show the Toquerville flow show is a basalt or borderline trachy-basalt on the TAS diagram of LeBas and others (1986) (figure 6, table 1).

The Toquerville flow may be sourced at a cinder cone about 2 miles (3.2 km) north of Pintura, in section 19, T. 39 S., R. 12 W. This cone was not mentioned by Schramm (1994), whose work focused on structural geology, or Sanchez (1995), who worked south of the Virgin River. Nevertheless, Sanchez (1995) noted the geochemical similarity between the Toquerville and Ivans Knoll flows, and tentatively correlated them on this basis. That correlation required an awkward drainage reversal of Ash Creek since the flow's emplacement. Such a reversal is not needed if the northern cone is the source of the Toquerville flow. If this cone is indeed the vent for the Toquerville flow, the flow is about 12 miles (19 km) long.

__East Reef flow and cinder cone (Qber, Qberc):__ The East Reef flow flowed at least 1.5 miles (2.4 km) down the ancestral Grapevine Wash to the present confluence with the Virgin River. At the confluence, it lies about 160 feet (49 m) above the Virgin River. Farther up Grapevine Wash, the East Reef flow locally overlies thin, unmapped gravels that are likely correlative with older alluvial-fan deposits, and is overlain by level 5 stream-terrace deposits; both of these gravel deposits are characterized by abundant Pine Valley intrusive clasts. The margins of the flow are eroded and it maintains a relatively constant thickness of 25 to 30 feet (7.5-9 m) along its length.

The East Reef flow is a medium-dark-gray, fine-grained olivine basalt that is classified as a basanite on the TAS diagram of LeBas and others (1986) (figure 6, table 1). The source vent for the East Reef flow is a cinder cone complex (Qberc), located in the NW1/4 section 20, T. 41 S., R. 13 W., composed of two or possibly three vents, each breached by erosion or basaltic flows. Each cone has moderately well-developed rill weathering, and each is being quarried for cinders.

__The Divide flow (Qbd):__ The Divide flow is exposed south of Frog Hollow in the southeastern corner of the quadrangle. It appears to lie at a slightly higher elevation than the Gould Wash flow, but differentation of the two flows is difficult due to similar geomorphic expression and lithologies. Both The Divide and Gould Wash flows are dark-gray, very fine-grained olivine basalts with abundant 1 mm-size olivine phenocrysts as the only recognizable mineral in hand samples. Geochemically, The Divide flow is classified as a basanite on the TAS diagram of LeBas and others (1986) (figure 6, table 1). Sanchez (1995) also classified The Divide flow as a basanite and noted that it was sourced at a cinder cone to the south, west of Little Creek Mountain. The margins of The Divide flow are partly eroded and it appears to lie several tens of feet above current base level of Frog Hollow. The Divide flow is probably 20 to 30 feet (6-9 m) thick in the Hurricane quadrangle.

Gould Wash flow (Qbgw): The Gould Wash flow is well exposed along Gould Wash and Frog Hollow in the southeastern corner of the Hurricane quadrangle. Like The Divide flow, it is a dark-gray, very fine-grained olivine basalt with abundant 1 mm-size olivine phenocrysts as the only recognizable mineral in hand samples. Geochemically, the Gould Wash flow is classified as a basalt on the TAS diagram of LeBas and others (1986) (figure 6, table 1). The flow is probably sourced at a cinder cone in the upper reaches of Gould Wash, north of Little Creek Mountain.

In the Hurricane quadrangle, the Gould Wash flow is generally 20 to 30 feet (6-9 m) thick and its margins are partly eroded. The flow lies about 160 feet (49 m) above Gould Wash in the west-central part of section 13, T. 42 S., R. 13 W. In the upper reaches of Frog Hollow, the Gould Wash flow lies at current base level and is spectacularly exposed at the box canyon in the SW1/4SE1/4SW1/4 section 14, T. 42 S., R. 13 W. There, the flow plugs a slot canyon cut into

Fossil Mountain strata. A remnant of the Gould Wash flow is exposed in the lower reaches of Frog Hollow.

"Cinder pits" flow, cinder cone, and associated deposits (Qbp, Qbpc, Qbpe): The "cinder pits" flow is named for the cinder cone complex in section 28, T. 41 S., R. 13 W. This complex is made of two overlapping cones, each with moderately well-developed rill weathering, that are breached on the southeast side by basaltic flows. The larger of the two cones is quarried for cinders. Sanchez (1995) described a small lava lake at the "cinder pits" cone.

The "cinder pits" flow is a medium-gray to dark-gray, fine-grained olivine basalt that has 1-mm-size olivine phenocrysts as the only recognizable mineral in hand sample. In the SW1/4SE1/4NE1/4 section 29, T. 41 S., R. 13 W., the "cinder pits" flow consists of two flows separated by several feet of unmapped, poorly exposed gravel; these flows overlie about 7 feet (2 m) of planar bedded, coarse sand and cinders over Navajo Sandstone. Geochemical analyses show the "cinder pits" flow is classified as an alkaili basalt on the TAS diagram of LeBas and others (1986) (figure 6, table 1). Sanchez (1995) showed the "cinder pits" basalts to be chemically transitional between the Volcano Mountain basanites and Ivans Knoll alkali basalts. Where partially concealed by eolian sand and pedogenic carbonate deposits, the flow is mapped as Qbpe.

Map relationships suggest that the "cinder pits" flow is locally overlain by, and thus slightly older than, the adjacent Volcano Mountain (Qbv1) and "radio tower" (Qbr) flows, although cinder cone preservation is similar for each of the volcanic centers.

"Radio tower" flow, cinder cone, and associated deposits (Qbr, Qbrc, Qbre): The "radio tower" flow is named for a cinder cone complex just northwest of Hurricane, in section 27, T. 41 S., R. 13 W. This complex is composed of four overlapping cinder cones (Qbrc) that have moderately well-developed rill erosion and are partly breached by erosion or basaltic flows; a much smaller vent is present to the north, just across the Virgin River. The vents trend due north. Although the cinder cone complex is only locally disturbed by quarrying, cinder cone stratigraphy is well-exposed on the north side of the complex where it is breached by erosion along the Virgin River (figure 8). There, about 5 feet (1.5 m) of coarse ash and lapilli overlie the Navajo Sandstone, which is in turn overlain by an 80-foot- (24-m-) thick, cliff-forming basaltic flow and breccia unit with Navajo blocks and xenoliths; the remainder of the cone consists of scoria, bombs, and aggultinate. The cone is cut by a north-trending basanite dike.

(Figure 8 near here)

The "radio tower" flow is a medium-gray to dark-gray, fine-grained olivine basalt with 1 mm-size olivine phenocrysts as the only phenocryst phase. The "radio tower" flow is classified as a borderline basalt to basanite on the TAS diagram of LeBas and others (1986) (figure 6, table 1). Some of the best exposures of the "radio tower" flow are found at the NW1/4SW1/4NW1/4 section 26, T. 41 S., R. 13 W. where a series of four flow units are exposed. The "radio tower" flow clearly overlies the Ivans Knoll flow along the south and west sides of the Virgin River in the NW1/4SE1/4 section 26, T. 41 S., R. 13 W. Where partially concealed by eolian sand and pedogenic carbonate deposits, the flow is mapped as Qbre.

<u>Volcano Mountain flows, cinder cone, and associated deposits (Qbv_1, Qbv_2, Qbvc, Qbv_1e, Qbv_2e):</u> The Volcano Mountain flows were sourced at Volcano Mountain, a large cinder cone (Qbvc) in section 5, T. 42 S., R. 13 W. Like the "cinder pits" and "radio tower" cones, Volcano Mountain has moderately well-developed rill weathering and is locally quarried for cinders. The cone is spectacularly breached on its north side by the Qbv_1 flow; cinders associated with collapse of the cone were rafted northward on top of the Qbv_1 flow for a distance of at least one mile (1.6 km).

The Volcano Mountain flow is clearly divisible into two flows in the Hurricane quadrangle and probably a third, older flow in the adjacent Harrisburg Junction quadrangle; from youngest to oldest and shortest to longest, these flows are denoted Qbv_1, Qbv_2, and Qbv_3. These flows flowed north and then southwest toward and down the Virgin River drainage; the longest flow, Qbv_3, is about 8 miles (13 km) long and is only exposed in the Harrisburg Junction quadrangle (Biek, 1997). Both the Qbv_1 and Qbv_2 flows have a very rough, blocky surface thinly covered by eolian sand and pedogenic carbonate deposits (Qbv_1e, Qbv_2e). Although the contact between these flows is nowhere exposed, they are readily differentiated based on stratigraphic position and morphology. The Qbv_1 flow yielded an $^{40}Ar/^{39}Ar$ isochron date of 258,000 +/- 24 ka (Sanchez, 1995).

The Qbv_2 flow is generally a medium-gray, medium- to coarse-grained olivine basalt that is classified as a basalt on the TAS diagram of LeBas and others (1986) (figure 6, table 1). The Qbv_1 flow is a medium-gray to dark-gray, fine-grained olivine basalt that is classified as a basanite on the TAS diagram of LeBas and others (1986) (figure 6, table 1); both flows are about 35 to 45 feet (11-14 m) thick.

Based on geochemical correlation of flows in the Hurricane and Harrisburg Junction quadrangles, Sanchez (1995) assigned the Qbv_1 flow to the "cinder pits" complex and the Qbv_2 and Qbv_3 flows to the Ivans Knoll complex. These geochemical correlations are at odds with relationships observed in the field and visible on aerial photographs and point to the overlapping geochemistry of some of these volcanic centers. Unpublished maps of Hamblin depict the Volcano Mountain flows substantially as mapped here.

Basaltic flows and associated deposits, undivided (Qb, Qbc, Qbe): Basaltic flows along the Virgin River canyon, and in the lower reaches of Frog Hollow, are undivided due to the uncertainity in differentiating similar, isolated outcrops. Many of these flows plug the ancestral Virgin River channel and consist of a single flow unit in excess of 150 feet (46 m) thick. Where covered by eolian sand and pedogenic carbonate deposits, these flows are mapped as Qbe. Thin, planar-bedded cinder deposits exposed in the Virgin River canyon are locally mapped as Qbc.

Alluvial Deposits

Older alluvial-fan deposits (Qafo): Older alluvial-fan deposits are found along the nose of the Virgin anticline where they form an extensive, locally deeply dissected surface; these deposits originate from the Leeds Creek drainage northwest of Leeds. Older alluvial-fan deposits, sourced in the Wet Sandy Creek drainage northwest of Anderson Junction, are also found west and south of Toquerville. Additonal older alluvial-fan deposits, sourced in the LaVerkin Creek drainage, are mapped north of LaVerkin. The deposits sourced from the flanks of the Pine Valley Mountains consist of very poorly sorted sand to boulders with clasts in excess of ten feet (3 m) in diameter. Most clasts, and all of the larger clasts, are from the Pine Valley intrusive complex; Carmel and Iron Springs clasts are also common, and west and south of Toquerville, these deposits contain abundant Cambrian or Precambrian quartzite clasts. Qafo deposits sourced in the Pine Valley Mountains are generally 0 to 50 feet (0-15 m) above nearby drainages and range from 0 to about 40 feet (0-12 m) thick. They are correlative with level 6 stream-terrace deposits.

Deposits sourced in the LaVerkin Creek drainage contain mostly Permian clasts and lack Pine Valley intrusive clasts. These deposits are in excess of 160 feet (49 m) thick in the NE1/4 section 14, T. 41 S., R. 13 W., are locally faulted along the Hurricane fault zone, and are correlative with level 6 stream-terrace deposits. Exposures in Nephis Twist, in the SE1/4SW1/4SW1/4 section 12, T. 41 S., R. 13 W., reveal an angular unconformity in these deposits. Some of the best faulted exposures are found in the SE1/4SE1/4NW1/4 and NE1/4NE1/4NW1/4 section 13, T. 41 S., R. 13 W.

Stream-terrace deposits (Qal_{2-7}): Six levels of inactive stream-terrace deposits are mapped in the Hurricane quadrangle. These terrace deposits are restricted to modern drainages and locally truncate older alluvial-fan deposits described above. They consist of moderately to well-sorted, usually poorly cemented sand, silt, clay, and pebble to boulder gravel that form isolated, level to gently sloping surfaces above modern drainages. Level 7 deposits are found only east of the Hurricane fault zone above Timpoweap Canyon, where they are in excess of 300 feet (92 m) above modern base level. Level 6 deposits form broad terraces at Toquerville and LaVerkin and are 190 to 270 feet (58-82 m) above modern base level. Level 5 deposits form prominent terraces along Grapevine Wash, and locally along the Virgin River, and are 140 to 190 feet (43-58 m) above modern base level. Level 4 deposits are 90 to 140 feet (27-43 m) and level 3 deposits are 30 to 90 feet (9-27 m) above modern base level. Level 2 deposits are generally 10 to 30 feet (3-9 m) above modern base level. Each of these deposits varies from about 0 to 30 feet (0-9 m) thick. Level 7 deposits are likely middle to late Pleistocene, level 6 to level 3 deposits late Pleistocene, and level 2 deposits late Pleistocene to Holocene in age.

Alluvial-fan deposits (Qaf_1, Qaf_2): Alluvial-fan deposits consist of poorly to moderately sorted, boulder- to clay-size sediment deposited at the base of the Hurricane Cliffs and locally at the mouths of active drainages. Qaf_1 deposits form active depositional surfaces and are correlative with modern alluvial and colluvial deposits; well-preserved debris flow levies are found on Qaf_1 deposits along the Hurricane Cliffs south of Frog Hollow. Qaf_2 deposits form deeply incised surfaces correlative with level 2 alluvial deposits and correlative and gradational with older colluvial deposits. Alluvial-fan deposits vary from about 0 to 50 feet (0-15 m) thick.

Modern alluvial deposits (Qal_1): Modern alluvial deposits are 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 10 feet (3 m) above current stream levels. The deposits 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 may be somewhat thicker. Modern alluvial 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 sediment deposited by slopewash, soil creep, and debris flows on moderate slopes. Thin colluvial deposits are common on most slopes in the quadrangle but are only mapped where they conceal large areas of bedrock. These deposits locally include talus, mixed alluvial and colluvial, and eolian deposits that are too small to be mapped separately. Older colluvial deposits (Qco) form incised, largely inactive surfaces correlative and gradational with level 2 and level 3 stream-terrace deposits; modern colluvial deposits (Qc) form active depositional surfaces that are correlative and gradational with modern alluvial-fan deposits. Older colluvial deposits (Qco) are probably Pleistocene to Holocene in age. Both deposits vary from 0 to 30 feet (0-9 m) thick.

Eolian deposits

Older eolian-sand and caliche deposits (Qe_2): These deposits generally form smooth, gently sloping surfaces covered with abundant pedogenic calcium carbonate (caliche) (Stage V-VI of Birkeland and others, 1991) and sparse eolian sand. These deposits are generally equivalent to the lower part of the eolian-sand deposits described below; most of the overlying unconsolidated sand has been removed by erosion. Older eolian-sand and caliche deposits are mapped atop the western portion of the Ivans knoll flow. These deposits generally range from 0 to 10 feet (0-3 m) thick.

Eolian-sand deposits (Qe): Eolian sand (Qe) covers broad, irregular areas over the Kayenta-Navajo outcrop belt, and over basaltic flows south of the Virgin River. The sand is well rounded, well- to very well-sorted, fine- to medium-grained quartz derived from Navajo and upper Kayenta strata. It forms an irregular blanket, stabilized in part by sparse vegetation, that varies from 0 to about 20 feet (0-6 m) thick. In most areas, eolian-sand deposits sand likely overlie a thick pedogenic calcium carbonate (Stage IV to V of Birkeland and others, 1991), which is rarely exposed in washes and as isolated nodules at the surface. Some of the best exposures of this caliche are found in a wash in the NE1/4NW1/4NE1/4 section 17, T. 41 S., R. 13W. Large exposures of older eolian-sand and caliche deposits are mapped separately.

Human-made deposits (Qf, Qfl, Qfm)

Human-made deposits are divided into artificial fill (Qf), landfill deposits (Qfl), and mine-dump deposits (Qfm). Artificial fill is only mapped where it forms large deposits in cross-cutting drainages of Interstate 15 and Highways 9 and 59, and in two small deposits northeast of Leeds and southwest of LaVerkin. These deposits consist of engineered fill and general borrow material and vary greatly in thickness. Although only a few areas of artificial fill are mapped, fill should be anticipated in all developed areas, many of which are shown on the topographic base map. Landfill deposits are mapped east of Leeds, near the center of section 8, T. 41 S., R. 13 W., and north of Hurricane at the common border of sections 26 and 27, T. 41 S., R. 13 W. These inactive landfills contain municipal trash and general borrow. Waste rock from mining is mapped near Buckeye Reef and northeast of East Reef. Only the larger deposits, which consist principally of angular blocks of Springdale strata, and a reclaimed tailings pile, are mapped.

Mass-movement deposits

Older landslide deposits (Qmsm, Qmsc, Qmsb): Deeply dissected, chaotically oriented blocks of mostly Moenave strata on the northeast-plunging nose of the Virgin anticline are mapped as Qmsm. These deposits are preserved as erosional remnants south of a trio of fault-bounded, west-dipping Moenave blocks; the base of the deposits decreases in elevation to the south, suggesting that they were derived from the west-dipping Moenave blocks. The southern edge of these landslide deposits lies at an elevation comparable to level 5 stream-terrace deposits, suggesting they are probably late Pleistocene in age. The landslide deposits rest principally on Petrified Forest strata and consist primarily of large (up to tens of feet in length), intact blocks of Springdale strata; Whitmore Point and Dinosaur Canyon strata are locally involved in these landslide deposits.

A coherent landslide block of Co-op Creek strata (Qmsc), dipping east at about 30 degrees, is mapped near the center of section 22, T. 41 S., R. 13 W. This deposit overlies Temple Cap strata and, based on its deeply dissected nature and elevation above current base level, is probably also of late Pleistocene age. Large blocks of basalt (Qmsb), many composed of a single flow unit several tens of feet thick, are mapped on the floor of the Virgin River canyon. They overlie level 2 stream-terrace deposits and so are probably Holocene in age.

Landslide deposits (Qms): Landslide deposits are mapped throughout the quadrangle and are characterized by moderately subdued hummocky surfaces and internal scarps, indicative of middle to late Holocene movement (figure 9). Basal detachments occur most commonly in the Petrified Forest Member of the Chinle Formation, the upper red member of the Moenkopi Formation, and the Woods Ranch Member of the Toroweap Formation. The slides themselves incorporate these units and overlying formations. Landslides are discussed in more detail in the geologic-hazards section of this report.

(Figure 9 near here)

Talus deposits (Qmt): Talus is mapped only at the base of Sandstone Mountain, where it forms a large, cone-shaped deposit. The talus consists of angular Navajo blocks deposited by rock-fall processes. These deposits are gradational with colluvial deposits and are probably several tens of feet thick.

Mixed-environment deposits

Older alluvial and colluvial deposits (Qaco): Older mixed alluvial and colluvial deposits are mapped only east of Hurricane, where they overlie the Ivans Knoll flow. They are similar to modern alluvial and colluvial deposits, except that they form incised, inactive surfaces up to about 20 feet (6 m) above cross-cutting drainages. They consist principally of poorly to moderately sorted, locally derived or reworked sediments. These deposits are less than about 20 feet (6 m) thick.

Younger alluvial and colluvial deposits (Qac): Younger mixed alluvial and colluvial deposits are 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. Some deposits occur in narrow washes that receive significant slopewash sediment from adjacent slopes. Younger mixed alluvial and colluvial deposits are gradational and correlative with modern alluvial and colluvial deposits. Most younger mixed alluvial and colluvial deposits are less than about 20 feet (6 m) thick.

Older alluvial and eolian deposits (Qaeo): Older mixed alluvial and eolian deposits are mapped west of Hurricane, south of Toquerville, and in the southeastern corner of the quadrangle, where they form incised, inactive, gently sloping surfaces about 20 feet (6 m) above modern drainages. Older mixed alluvial and eolian deposits consist of poorly to moderately sorted, locally gypsiferous, clay- to boulder-size sediments with well-sorted eolian sand and reworked eolian sand, commonly with well-developed pedogenic calcium carbonate. The mixed deposits are less than about 30 feet (9 m) thick.

Younger alluvial and eolian deposits (Qae): Younger mixed alluvial and eolian deposits are mapped in modern channels and over broad, gently sloping depressions throughout the quadrangle. They consist of poorly to moderately sorted, locally gypsiferous, clay- to boulder-size sediments with well-sorted eolian sand and reworked eolian sand. Younger mixed alluvial and eolian deposits are gradational and in part correlative with modern alluvial and eolian deposits. Most younger mixed alluvial and eolian deposits are less than about 20 feet (6 m) thick; deposits in the Hurricane Fields may locally be several tens of feet thick.

Older gypsiferous alluvial and eolian deposits (Qaeg): Older gypsiferous alluvial and eolian deposits are mapped in the southeastern corner of the quadrangle. They are similar and correlative to older alluvial and eolian deposits except that they contain a significant component of gypsum derived from weathering of the Moenkopi Formation. They form deeply dissected deposits that weather to a soft, white, powdery soil. These deposits are generally less than about 30 feet (9 m) thick.

Alluvial, eolian, and colluvial deposits (Qaec): Mixed alluvial, eolian, and colluvial deposits are mapped in several areas south of the Virgin River. These deposits consist principally of poorly to moderately sorted, clay- to small boulder-size sediments with well-sorted eolian sand and reworked eolian sand, but with a significant component of colluvial or slopewash sediment. Mixed alluvial, eolian, and colluvial deposits are generally less than about 20 feet (6 m) thick.

Stacked-unit deposits (Qe/Qafo)

Eolian-sand deposits that overlie older alluvial-fan deposits in the north-central part of the quadrangle are mapped as Qe/Qafo.

STRUCTURE

Regional Setting

The Hurricane 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 lies on the intermediate structural block thus created, bounded on the east by the Hurricane fault zone and on the west by the Gunlock-Grand Wash faults (figure 1). The Hurricane quadrangle itself straddles the eastern margin of this block. Displacement on the Grand Wash-Gunlock fault decreases northward whereas displacement on the Hurricane fault zone increases to the north. As discussed by Schramm (1994), these faults probably form a displacement transfer zone, in which decreasing slip on one fault is compensated for by increasing slip on another. Such a transfer zone would account for the relatively wide width of the transition zone in southwestern Utah.

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 one of its two most prominent structural features - the Virgin anticline, which plunges northeast in the northwest part of the quadrangle. A number of comparatively shallow, west-dipping thrust faults repeat Triassic and Jurassic strata on the northwest flank of the anticline. The nose of the anticline is marked by at least two subsidiary folds and numerous normal faults. A basal detachment is postulated in underlying Cambrian and Precambrian strata (Davis, 1977). The Hurricane fault zone, the other prominent structural feature in the quadrangle, is a major, active, north-trending, high-angle, west-dipping normal fault that may have begun to form as early as Late Miocene to Early Pliocene.

Folds

Virgin Anticline

The Virgin anticline is a 30-mile (48-km) long, northeast-trending, generally symmetrical fold that is co-linear with the Kanarra anticline to the north. The anticline has three similar structural domes along its length. From south to north these are Bloomington dome, Washington Dome, and Harrisburg Dome, each of which is cored by the Permian Kaibab Formation. Only the northeast-plunging nose of the Virgin anticline is contained within the Hurricane quadrangle. There, it is neatly outlined by the resistant Shinarump Conglomerate Member of the Chinle Formation, which forms a carapace around a central core of Moenkopi strata that outcrops in Little Purgatory, along the axis of the fold.

In the Hurricane quadrangle, the Virgin anticline is an open, upright, symmetrical fold with flank dips of 25 to 35 degrees; it plunges to the northeast at about 10 to 15 degrees. The nose of the anticline is complicated by numerous normal faults and subsidiary folds, discussed separately.

Leeds Anticline, Leeds Syncline, and Subsidiary Folds

The northwestern flank of the Virgin anticline is marked by parallel, 2 to 3 mile (3-5 km) long, Sevier-age subsidiary folds of the Leeds anticline and Leeds syncline (Proctor, 1953). The Leeds anticline is best exposed at Buckeye Reef, northwest of Leeds. There the Springdale Sandstone forms the crest of this fold, which plunges about 10 degrees north. South of Buckeye Reef, the anticlinal axis bends abruptly to the southwest along Leeds Reef. The Leeds anticline is bounded on the east by a west-dipping thrust fault, which truncates the southern portion of the anticline. Leeds Reef, which forms 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) and that here, as previously discussed, are reassigned to the basal Petrified Forest Member.

The Leeds syncline, which lies between and roughly parallel to the Leeds and Virgin anticlines, plunges gently northeast beneath the town of Leeds. The syncline is poorly exposed and truncated by a west-dipping thrust fault at the base of Leeds Reef, thus the axial trace of the syncline has not been mapped. It is cored by Petrified Forest strata, while the west-dipping limb of the Virgin anticline forms its eastern limb. The Leeds syncline re-emerges and is mapped at Buckeye Reef (Big Hill), north of Leeds.

An unnamed syncline comparable in size to the Leeds syncline is found east of the Virgin anticline axis in the NW1/4 section 8, T. 41 S., R. 13 W. The syncline plunges to the northeast at about 15 degrees parallel to the trace of the Virgin anticline axis. Based on limited exposures of Moenave strata to the southeast, a north- to northeast-trending, and probably north-plunging, anticline is mapped in the E1/2 of sections 8 and 17, T. 41 S., R. 13 W. Both of these folds are Sevier-age structures. Based on gravity data, Cook and Hardman (1967) suggested that the Virgin and Kanarra anticlines are one and the same, only separated by the Hurricane fault zone. The presence of these subsidiary folds on the plunging nose of the Virgin anticline suggests that while the Virgin and Kanarra anticlines are colinear and likely genetically related, they are individual structural units. Stewart and others (1997) also showed that the Virgin and Kanarra anticlines are separated by a syncline.

Numerous small, open folds are found in the footwall of the Hurricane fault zone. Most trend parallel to the Hurricane fault zone, are clearly related to fault drag and differential movement on closely spaced faults, and are thus Late Tertiary to Quaternary in age. Most folds mapped in Harrisburg strata, which trend oblique to the Hurricane fault zone, likely formed as a result of pre-Triassic gypsum dissolution; similar folds in Timpoweap strata probably resulted from draping of beds over Permian-Triassic paleotopography. Timpoweap strata in particular form a gently undulating surface above the Permian-Triassic unconformity.

Faults

Thrust Faults

Several west-dipping thrust 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 in the extreme northwestern corner of the quadrangle, and can be traced at least 7 miles (11 km) to the southwest (Biek, 1997). The fault repeats the Moenave Formation in the reefs. Based on surface and subsurface data, the fault dips about 30 degrees west-northwest (Proctor and Brimhall, 1986). Proctor and Brimhall (1986) estimated that, in the Silver Reef mining district, the Springdale Sandstone Member was displaced eastward at least 2,000 feet (610 m) on this fault.

Proctor and Brimhall (1986) also described a smaller west-dipping thrust fault between Buckeye and Butte Reefs. The fault is only exposed immediately north of Interstate 15, due north of Leeds, where it places Petrified Forest and Dinosaur Canyon strata on the Springdale Sandstone. This fault can be traced southwest into the Harrisburg Junction quadrangle, where it truncates the Leeds anticline at Leeds Reef. A northeast-trending splay of this thrust fault is inferred in the center of section 13, T. 41 S., R. 14 W. based on outcrop patterns of Shinarump and Petrified Forest strata. This splay appears to die out in the west limb of the Virgin anticline.

A minor thrust fault, with stratigraphic separation of a few tens of feet, cuts up through

Shnabkaib, upper red, and Shinarump strata at the north end of Little Purgatory, on the west limb of the Virgin anticline. This fault is similar to faults in the Harrisburg Junction quadrangle (Biek, 1997).

Schramm (1994) and Stewart and Taylor (1996) mapped a small thrust fault in the footwall of the Hurricane fault zone that is herein reinterpreted simply as local dissolution structures in, and paleotopography on, the Harrisburg Member of the Kaibab Formation. They suggested that this "thrust" was related to compression at a fault bend and was therefore of Late Tertiary to Quaternary age. Map relationships and a slight right-lateral component of slip on the Hurricane fault zone in this area suggest, however, that the footwall of the Hurricane fault zone in this area should be a zone of tensile, not compressional, stress.

Reverse Fault

An east-dipping reverse fault is mapped west of Ash Creek and north of the Virgin River where is repeats Temple Cap, Carmel, and Iron Springs strata (figure 10). Fault plane exposures in the NW1/4NE1/4NE1/4 section 22, T. 41 S., R. 13 W. show that the fault trends N.20^{0}E. and dips about 65 degrees east; the rake of slickenlines is 80 degrees south, indicating a slight right-lateral component of displacement. The fault can be traced from the Virgin River northward for nearly two miles (3 km). Stratigraphic separation appears to increase to the north and may be as great as a few hundred feet. Displacement on the fault can only be constrained as post-Iron

Springs (Late Cretaceous); it is probably Sevier in age. Lovejoy (1964) misidentified this fault as the main Hurricane fault in his failed attempt to show that the Hurricane fault zone was primarily a Laramide reverse fault.

(Figure 10 near here)

High-angle Normal Faults

Hurricane fault zone: The Hurricane fault zone is a major, active, high-angle, west-dipping normal fault that stretches at least 155 miles (250 km) from south of the Grand Canyon northward to Cedar City. The total stratigraphic separation generally increases northward along the fault, from less than 200 feet (61 m) south of the Grand Canyon (Hamblin, 1970) to 8,265 feet (2,520 m) near Toquerville (Stewart and Taylor, 1996). The Hurricane fault zone has been called a normal dip-slip fault (Huntington and Goldthwait, 1904; Gardner, 1941; Cook, 1960; Averitt, 1962; Hamblin, 1965, 1970; Kurie, 1966; Stewart and Taylor, 1996), a reverse fault (Lovejoy, 1961), and Moody and Hill (1956) proposed that the Hurricane fault zone had a significant component of left-lateral slip along it. Based principally on studies in southern Nevada and the Beaver Dam Mountains, Anderson and Barnhard (1993) also suggested that the Hurricane fault zone has a substantial component of left-lateral slip. As described below, recent studies in the greater Hurricane area (Schramm, 1994; Stewart and Taylor, 1996; this report) unequivocally show that Pliocene to Quaternary displacement on the Hurricane fault zone is normal dip-slip, locally with a slight right-lateral component of displacement. No evidence was found to support the Hurricane fault zone being a re-activated Sevier-age structure.

Stewart and Taylor (1996) defined a fault-segment boundary just north of Toquerville, thus dividing the Hurricane fault zone to the north into the Ash Creek segment, which has purely dip-slip movement, and to the south into the Anderson Junction segment, which shows dominantly dip-slip movement with a small dextral-slip component. Such segment boundaries are important because they may be sites of significant strain, may impede fault-rupture propogation, and may influence the locations of earthquakes. Schramm (1994) and Stewart and Taylor (1996) documented 1,475 feet (450 m) of stratigraphic separation on basalt flows in the hanging wall and footwall at the segment boundary that yielded $^{40}Ar/^{39}Ar$ isochron dates of 840 +/- 30 ka and 880 +/- 20 ka, respectively (Ben Everitt, personal communication, June 10, 1998); the rate of stratigraphic displacement here is thus about 2 inches/100 years (5 cm/100 years). They further found a total stratigraphic separation at this boundary of 8,265 feet (2,520 m).

Published estimates of normal separation on the Hurricane fault zone vary almost by an order of magnitude, from 1,410 to 13,120 feet (430 to 4,000 m) (Anderson, 1980). This discrepency arises in part from measurements taken along different segments of the fault, but is principally due to a failure to subtract from the apparent, or stratigraphic, throw: 1) pre-Hurricane fault, Sevier-age folding, 2) reverse-drag flexure of the hanging wall, and 3) rise-to-the-fault flexure in the footwall (Anderson and Christenson, 1989). To avoid these complications, Anderson and Mehnert (1979) measured the top of the Navajo Sandstone on either side of the Hurricane fault zone, away from the effects of the fault zone and Virgin anticline, and found a normal displacement of just 2,000 to 2,800 feet (610-854 m) at about the latitude of Pintura. Anderson and Christenson (1989) revised these estimates and found tectonic displacements of about 3,600 feet (1,098 m) and 4,900 feet (1,494 m) at the latitudes of St. George and Toquerville, respectively. A simple calculation using the base of the Navajo Sandstone about 10 miles (16 km) on either side of the Hurricane fault zone, shows a tectonic displacement of about 3,600 feet (1,098 m) at the latitude of Hurricane.

The stratigraphic separation along the Hurricane fault zone in the Hurricane quadrangle can only be crudely estimated because bedrock in the hanging wall adjacent to the fault is everywhere concealed beneath younger Quaternary deposits. Based on interpretations of five cross-sections (Plate 2), it appears that the stratigraphic separation may approach 9,000 feet (2,744 m) immediately north of LaVerkin and decrease both to the north and south to about 6,000 to 7,000 feet (1,829-2,134 m), respectively. The apparent greater displacement near LaVerkin probably reflects proximity to the northeast-plunging nose of the Virgin anticline; more gently dipping beds on the flank of the anticline to the south, and subsidiary folds to the north, may account for apparent decreases in stratigraphic separation in those areas.

The age of first movement on the Hurricane fault zone is unknown, but based on a constant displacement rate determined from offset Quaternary basalts, Stewart and Taylor (1996) consider it to have begun as early as Late Miocene or Early Pliocene. This estimate, however, is based on total stratigraphic separation and not tectonic displacement as described above and may thus yield an inappropriately old age for initiation of faulting. Anderson and Mehnert (1979) and Anderson and Christenson (1989) consider the Hurricane fault zone to be a Late Pliocene to Quaternary feature.

The Hurricane fault zone is considered an active fault because of offset Quaternary basaltic flows, fault scarps in alluvial fans, and recent seismic activity, including the 1992 St. George earthquake, which is believed to have occurred on the Hurricane fault zone (Stewart and others, 1997). Anderson and Christenson (1989) summarized strong evidence for a substantial rate of Late Pleistocene surface offset on the Ash Creek segment, and new dates on basaltic flows there suggest a rate of stratigraphic throw of about 1,715 feet (523 m) per million years. Anderson and Christenson (1989) further considered that the most recent surface faulting ruptures on the Hurricane fault zone in southwestern Utah were late Pleistocene in age.

In the Hurricane quadrangle, the Anderson Junction segment of the Hurricane fault zone is itself composed of three discrete, straight-line segments. South of Mollies Nipple the fault trends due north; between Mollies Nipple and LaVerkin, the fault trends about N.20^{0}E.; and north of LaVerkin, the fault trends about N.15^{0}W. Each of these short segments is characterized by a series of down-to-the-west faults that bound blocks of west-dipping Permian, Triassic, and Jurassic strata; the fault cuts progressively younger strata northward through the quadrangle.

The footwall is marked by particularly complex faulting at the intersection of these segments. The fault zone itself varies from as little as 1,000 feet (305 m) wide at Frog Hollow to 6,000 feet (1,829 m) wide near Toquerville. Numerous slickenlines on west-dipping faults, some of which are shown on the geologic map, show a rake of 80 to 85 degrees to the north, indicating a slight component of right-lateral slip; antithetic faults typically show a slight right-lateral displacement as well. A west-dipping fault plane in the NW1/4NW1/4 section 11, T. 42 S., R. 13 W., which places undivided Moenkopi red beds against Timpoweap strata, shows a rake of 80 degrees south, indicating a slight left-lateral component of displacement for this small block.

North of LaVerkin, the Hurricane fault zone is marked by a west-dipping panel of Moenkopi strata that appears to have formed as a relay ramp (Peacock and Sanderson, 1994) between two en echelon segments of the fault zone. Although cut by numerous east- and west-dipping faults, the panel shows a complete section of Moenkopi strata.

Although it is well exposed along its entire length, particularly instructive exposures of the Hurricane fault zone are found: 1) near the entrance to Frog Hollow, where fault drag in Brady Canyon and Woods Ranch strata is well developed; 2) in a small wash in the NE1/4NW1/4SE1/4SE1/4 section 10, T. 42 S., R. 13 W., where basal Woods Ranch strata are faulted down against Brady Canyon strata; 3) in the NW1/4NW1/4 section 11, T. 42 S., R. 13 W., where fault-bounded, west-dipping blocks of Moenkopi and Fossil Mountain strata are well exposed; 4) in the SE1/4 section 35, T. 41 S., R. 13 W., where fault planes literally shine like mirrors in the sun; 5) at the entrance to Timpoweap Canyon, where steeply west-dipping Moenkopi and Chinle strata are faulted down against the Toroweap Formation; 6) immediately north of Highway 9, in the NW1/4SE1/3NE1/4 section 13, T. 41 S., R. 13 W., where the lower red member is faulted down against the Rock Canyon Conglomerate, and northward along this same fault to the center of the SE1/4 section 12, T. 41 S., R. 13 W., where the fault dies out into a number of smaller east-dipping faults; and 7) in the lower reaches of Nephis Twist, where Petrified Forest, Moenave, Kayenta, and Navajo strata are found (figure 11).

(Figure 11 near here)

Fault scarps in Quaternary deposits are uncommon in the Hurricane quadrangle. Older alluvial-fan deposits are locally in fault contact with Triassic strata north of LaVerkin and scarps in old colluvial deposits (Qco) are present west of Mollies Nipple. Two closely spaced strands of the Hurricane fault zone are exposed in a small wash in the SE1/4SE1/4NW1/4 section 13, T. 41 S., R. 13 W. (Schramm, 1994) in deposits mapped as Qafo. There, one fault dips about 60 degrees west and shows about 9 feet (3 m) of offset and the other strand dips 73 degrees west and has about 4 feet (1.2 m) of offset; no scarp is preserved on either fault. Elsewhere, the westernmost trace of the Hurricane fault zone is concealed by colluvial and alluvial-fan deposits, and possibly by regrading associated with construction.

At the entrance to Timpoweap Canyon, the Hurricane fault zone places steeply west-dipping upper Moenkopi and Chinle strata down against Toroweap and Fossil Mountain strata. A 170-foot- (52-m-) thick basalt flow from Ivans Knoll, which plugged the ancestral Virgin River channel, was dated at 353 +/- 45 ka (Sanchez, 1995) and shows about 240 feet (73 m) of stratigraphic offset at the entrance to the canyon, yielding a rate of stratigraphic displacement of about 0.75 inch/100 years (2 cm/100 years); a splay of the Hurricane fault zone offsets the basalt in the footwall about 20 feet (6 m) (figure 7). The basalt reaches to current base level under the Highway 9 bridge. Hamblin and others (1981) published a schemmatic cross-section across the Hurricane fault zone through this area, but miscorrelated basaltic flows across the fault zone, apparently mistaking the "radio tower" flow on the hanging wall for the Ivans Knoll flow on the footwall. Although their basic premise is sound - that is, the amount of down-cutting is largely a function of the amount and rate of uplift - they incorrectly concluded that the Virgin River has yet to re-establish its pre-Ivans Knoll flow profile. Since about 350,000 years ago, erosion on the footwall block has amounted to about 410 feet (125 m) - through the basalt flow, which is about 170 feet (52 m) thick, and an additional 240 feet (73 m) through Permian strata - while on the hanging wall, erosion has only cut down to near the base of the basalt. These numbers, and the fact that no falls and only minor rapids are present in Timpoweap Canyon, suggest that the Virgin River has indeed established its pre-Ivans Knoll flow profile.

Other normal faults: A series of mostly north- and northeast-trending normal faults, which likely formed during the Late Cretaceous Sevier Orogeny to accommodate tight folding on the nose of the Virgin anticline, are found in the northwestern corner of the quadrangle. The

Shinarump carapace itself, on the nose of the Virgin anticline, is cut by a number of down-to-the-west and down-to-the-east normal faults with displacements up to several tens of feet. Four larger down-to-the-east normal faults are found immediately to the northeast, where they create a series of west-dipping Moenave blocks. The westernmost of these faults in well exposed in Grapevine Wash, where the fault plane dips 70 degrees southeast with nearly vertical slickenlines, and places the middle sandstone of the Petrified Forest Member against Shinarump strata. Stratigraphic separation on this fault and the other three faults increases northward to several hundred feet along section line D-D'.

Several northwest-, north-, and northeast-trending normal faults are mapped along the Kayenta-Navajo outcrop belt north of the Virgin River. An excellent exposure of fault zone breccia and clay mineralization is found in the Navajo Sandstone in the NE1/4NE1/4SE1/4 section 20, T. 41 S., R. 13 W. There, the fault trends N.50°W., is nearly vertical, and creates a locally brecciated zone 10 to 15 feet (3-4.5 m) wide. A dark-reddish-brown clay zone up to 4 inches (10 cm) thick seals the Navajo Sandstone on both sides of this fault zone.

A north-trending, down-to-the-east normal fault, antithetic to the Hurricane fault zone, is mapped along the western edge of the Hurricane Fields where it cuts the 350,000-year-old Ivans Knoll flow. Offset on the fault is uncertain but probably on the order of a few tens of feet. Anderson and Christenson (1989) considered it to be Early to Middle Pleistocene in age. They also mapped three adjacent, subparallel faults based on the unpublished mapping of Hamblin; no evidence of these faults was found during this mapping. A similar down-to-the-east fault offsets the Toquerville flow southwest of Toquerville.

Joints

Joints are common in all bedrock units in the Hurricane 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."

Joint density in the Navajo Sandstone varies considerably across the Hurricane quadrangle. Some areas are intensely jointed, forming joint zones (Hurlow, 1998), while others are broken by only widely spaced joints. Because the Navajo Sandstone is commonly pervasively jointed, it is more easily eroded and forms fewer massive, high cliffs than is typical of less jointed exposures a few tens of miles to the east. The most prominent joints trend subparallel and perpendicular to the Navajo outcrop belt and 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 are mapped.

ECONOMIC GEOLOGY

Sand and Gravel

Sand and gravel are currently being mined from level 3 stream-terrace deposits along the Virgin River in the SW1/4 section 30, T. 41 S., R. 13 W., and from older alluvial-fan deposits north of LaVerkin. The Utah Department of Transportation Materials Inventory of Washington County contains basic analytical information on these and other aggregate deposits in the quadrangle (UDOT, 1964). Abandoned sand and gravel pits are common throughout the quadrangle, and are shown with a symbol. Most are found in deposits mapped as Qafo, Qaf_1, Qal_1, and Qal_6. Deposits mapped as Qafo north of the Virgin River, although not as well sorted as Virgin River gravels, may provide a significant source of coarse sand and gravel.

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

Gypsum

Two small gypsum prospects are located in Temple Cap strata northwest of LaVerkin, in the NE1/4 section 15, T. 41 S., R. 13 W. These prospects may intermittently provide small blocks of white, gray, or pink massive gypsum (alabaster) for use in sculpting.

The Woods Ranch Member of the Toroweap Formation, the Harrisburg Member of the Kaibab Formation, and the Shnabkaib Member of the Moenkopi Formation locally contain gypsum, but these deposits occur principally as impure beds and gypsiferous mudstone and are probably not now of economic importance; no prospects in these units are known in the quadrangle. Woods Ranch strata in particular, however, could provide small blocks of massive white gypsum for sculpting. Some of the best Woods Ranch gypsiferous exposures are found in the NE1/4SE1/4SE1/4 section 10, T. 42 S., R. 13 W. and in the lower reaches of Frog Hollow.

Building and Ornamental Stone

The Timpoweap Member, Springdale Sandstone-lower Kayenta, and basaltic flows have each been quarried for building or ornamental stone in the greater Hurricane area. Each of the quarries is small, having produced rough blocks for building and landscaping. The Hurricane Valley Pioneer Heritage Museum is made of Springdale or lower Kayenta sandstone quarried just west of the quadrangle boundary at Berry Springs; the central monument supporting the sculpture "Pioneer Gratitude" is made of what appears to be upper Timpoweap strata. Several historic buildings in and near the Town of Leeds are made of what appears to be Springdale

Sandstone. Basaltic blocks, columns, and cinders are widely used in the Hurricane-LaVerkin areas for use in retaining walls, landscaping, and building foundations. Cinders are intermittently quarried from the "cinder pits", "radio tower", East Reef cones.

The Shinarump Conglomerate is widely quarried in nearby areas 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. "Picture stone" is also common in the Iron Springs Formation. While "picture stone" is common in the area, no workings are known in the quadrangle.

Most bedrock units in the Hurricane quadrangle could be suitable as sources of decorative stone for landscaping. The upper part of the Timpoweap Member in particular contains uniformly colored, grayish-orange, thin- to thick-bedded, evenly bedded, very fine-grained, slightly calcareous sandstone that would serve as good flagstone. The best exposures of this stone are found between Gould Wash and Frog Hollow. Petrified wood from the Petrified Forest Member of the Chinle Formation is locally used as an ornamental stone; collection of petrified wood from public lands is now limited by law.

Clay

Although no clay pits are known in the Hurricane quadrangle, the Petrified Forest Member of the Chinle Formation contains brightly colored bentonitic clay that is locally used to line retaining ponds. Petrified Forest Member clays are well exposed in the northwest corner of the quadrangle, along the nose of the Virgin anticline.

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 northeast-plunging nose of the Virgin anticline: White, Buckeye, and Butte Reefs are located on the anticline's northwestern flank, while East Reef is located on the anticline's northeastern flank. 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." Many but not all of the adits and shafts of the Silver Reef mining district are shown on the topographic base map; more detailed maps are on file at the Utah Abandoned Mines Reclamation Program office.

The principal mining activity in the district lasted only through 1888, with lessee operations through 1909, after which operations essentially ceased. About 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. 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 to 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 occurrences 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. The white, middle sandstone of the Petrified Forest Member was extensively prospected in and especially north of East Reef, in section 17, T. 41 S., R. 13 W. Poehlmann and King (1953) noted that uranium mineralization was controlled by lithology and structure, with faults and joints serving as conduits for transporting mineralized solutions to the favorable beds. Several hundred tons of uranium ore were 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 (Chris Rohrer, Utah Abandoned Mine Land Reclamation Program, verbal communication, April 7, 1997). In 1998, a Canadian mining company began re-evaluating a portion of the Silver Reef mining district.

Other prospects

Several prospect pits are found along the Hurricane fault zone immediately south of Highway 9, in the SE1/4 section 11, T. 42 S., R. 13 W., and west of Mollies Nipple. Small pits at the first location are in Harrisburg, Rock Canyon, or Timpoweap strata; a short adit is found in the NE1/4SE1/4SE1/4 section 13, T. 41 S., R, 13 W. Minor fracture-controlled malachite staining is locally apparent; records of the Economic Geology Program at the Utah Geological Survey show this to be an area of disseminated lead-zinc mineralization. The prospect located west of Mollies Nipple is found in highly fractured Queantoweap strata with indications of uranium mineralization.

Oil and Natural Gas

Three unsuccessful wildcat wells, now abandoned, were drilled in the Hurricane quadrangle. According to records at the Utah Division of Oil, Gas and Mining (DOGM), the W. W. Toney #1 well (API #43-053-20498), located in the SE1/4SW1/4 section 11, T. 41 S., R. 13 W., was drilled to a depth of 80 feet (24 m) and abandoned in 1937. The Wilson Fee # 1 well (API #43-053-30002), located in the SW1/4SW1/4NW1/4 section 23, T. 41 S., R. 13 W., was drilled to a total depth of 2,000 feet (610 m) and converted to a water well in the late 1960s or early 1970s. No other DOGM information is available for these wells.

The Toledo Mining Company, Hiko Bell No. 1 Federal well (API #43-053-30005) was drilled and abandoned in 1971. The well, shown on the topographic base map by the symbol *DH*, is located in the SE1/4SE1/4SW1/4 section 11, T. 42 S., R. 13 W. The well was abandoned at a total depth of 7,060 feet (2,152 m) in the Cambrian Bright Angel Shale. A log of the well is available.

The Virgin oil field, the oldest oil field in Utah, was first developed in 1907 following the discovery of oil and asphalt seeps about 4 miles (6 km) east of the Hurricane quadrangle near the town of Virgin. Similar oil seeps in carbonate rocks of the upper Timpoweap Member are found on either side of Highway 59 in the Hurricane quadrangle, from the mapped oil seep at the common border of sections 1 and 12, T. 42 S., R. 13 W., upstream along the western tributary of Chinatown Wash for at least 2,000 feet (610 m) (Blakey, 1979). Another seep is located immediately south of Highway 9, just east of the quadrangle boundary. The primary productive interval at the Virgin oil field is the uppermost part of the Timpoweap Member of the Moenkopi Formation. Significant shows of oil at the Virgin oil field are also reported from the Kaibab and Pakoon Formations, and the Callville Limestone. The Virgin field produced 201,127 barrels of oil and was shut-in in 1967 (Stowe, 1972).

The Anderson Junction oil field is a small, now abandoned field that produced from Hurricane fault zone-associated structures at a depth of about 4,000 feet (1,220 m) in the Pennsylvanian Callville Formation (Peterson, 1974). The field was discovered in 1968 and re-entered and produced again for a short time in the mid 1980s. Cumulative production from the field is 1,380 barrels of oil (Peterson, 1974; Stowe, 1972).

The lower part of the upper red member of the Moenkopi Formation is marked by a 100-foot- (30 m-) thick, light-yellowish-brown, cliff-forming sandstone (the "Purgatory Sandstone") that stands in marked contrast to the enclosing red beds. No evidence of oil was found at this horizon, but the yellowish color of the 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°F (42°C) at Pah Tempe Hot Springs (also known as LaVerkin or Dixie hot springs), located at the entrance to Timpoweap Canyon between Hurricane and LaVerkin. These hot springs issue from a series of springs in and immediately above the bed of the Virgin River east of the fault zone upstream for a distance of about 1,200 feet (366 m). Springs on the south side of the river are developed.

The source of the recharge to Pah Tempe Hot Springs is not known (Everitt and Einert, 1994). Hot water appears to rise up through permeable Permian strata east of the Hurricane fault zone, which, at the entrance to Timpoweap Canyon, places impermeable Moenkopi red beds against highly permeable and cavernous Permian strata. The fault zone itself acts as a seal, preventing ground water from migrating further downstream. Low-temperature geothermal resources in the St. George basin 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).

Everitt and Einert (1994) discuss the results of a natural slug test that resulted when, in April 1985, a sinkhole appeared in the bed of the Virgin River just east of the quadrangle boundary, about 2 miles (3.2 km) (straightline distance) upstream of Pah Tempe Hot Springs. The sinkhole captured an estimated 7,200 acre-feet (9,408,960 m^3) of water over a period of several months. The discharge at the hot springs surged from 11 to about 20 cfs (0.3-0.6 m^3/second), the temperature dropped about 9^0F (5^0C), and the total dissolved solids (TDS) dropped by about 2,000 mg/L. These parameters returned to normal after about 2 ½ years. Between 1960 and 1982, the hot springs averaged about 104^0F (40^0C) and 9,600 to 9,900 TDS. Mundorff (1970) summarized physical and chemical parameters of the Pah Tempe Hot Springs. He noted that the average annual dissolved-solids discharge at the springs is about triple that of the Virgin River just upstream of the springs.

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 (Anonymous, 1993) summarized 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 Hurricane 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). Ash Creek, with an average annual flow of 3,540 acre-feet (4,626,072 m^3) near Pintura, and LaVerkin Creek, with an estimated average annual flow of about 3,100 acre-feet (4,051,080 m^3), are the only other perennial streams in the quadrangle (Cordova and others, 1972). Gould Wash, Frog Hollow, and Grapevine Wash commonly have small flows during wetter parts of the year.

Herbert (1995) conducted a seepage study of selected reaches of the Virgin River between Ash Creek and Harrisburg Dome, and found that the portion of the Virgin River in the Hurricane quadrangle had a net gain of about 10.7 cubic feet per second (0.32 m^3/second), meaning that in this stretch, the river gains water probably due to ground water seepage.

The main dam of the proposed Sand Hollow dam will be located in the extreme southwest corner of the Hurricane quadrangle (Greystone, 1997). The Sand Hollow reservoir will have a storage capacity of 28,000 acre-feet (36,590,400 m^3) and will cover 960 acres (384 hectares). It will be operated as an off-line reservoir for storage of excess Virgin River water, similar to Quail Creek reservoir in the adjacent Harrisburg Junction quadrangle. Anticipated seepage into the underlying Navajo Sandstone will replenish local ground water and effectively serve to increase the reservoir's capacity. A well-field will be designed to re-capture this ground water.

Ground Water

The principal aquifers in the St. George basin are found in Navajo and unconsolidated Quaternary strata; Moenkopi, Chinle, Moenave, and Kayenta strata are locally important aquifers. In the Hurricane quadrangle, most wells tap Navajo and Kayenta strata, and Quaternary alluvial deposits. The Hurricane city well is located on the western flanks of the Ivans Knoll volcanic complex. It has a hydraulic conductivity of 3.34 feet/day (1.02 m/day) and a specific capacity of 7.6 gallons per minute per foot of drawdown (Hurlow, 1998). Alluvial deposits in the Hurricane Fields area are thin, commonly less than a few tens of feet thick, and therefore serve only small domestic and irrigation needs. Bedrock outcrops along the Virgin River and a pronounced gravity high west of the Hurricane fault zone (Cook and Hardman, 1967) preclude the presence of a deep, fault-bounded, sediment-filled basin west of the Hurricane fault zone.

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, 1998). West of the Hurricane fault zone, ground water in the Navajo aquifer generally moves west toward the Virgin River. The Virgin River forms the major base level in the area.

Hurlow (1998) reported on the geology and ground-water conditions of the central Virgin River basin, which includes the Hurricane quadrangle west of the Hurricane fault zone. He noted that fracture permeability strongly influences ground-water conditions in the Navajo Sandstone and that north of the Virgin River, the Navajo Sandstone is characterized by a dense fracture network of variable orientation. He further 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. Fault gouge and clay mineralization, as noted earlier, is locally common along faults in the Navajo Sandstone and probably restricts transverse permeability.

Two large springs, the Pah Tempe Hot Springs and lower Ash Creek spring, as well as several smaller springs, are mapped in the quadrangle. Lower Ash Creek spring is located in the SE1/4NE1/4SW1/4 section 11, T. 41 S., R. 13 W. near the base of the Toquerville flow; it has a discharge of 5.9 cfs or 2,660 gpm (0.18 m^3/second or 10,081 liters per minute) and is relatively fresh with a total dissolved solids content of 544 (Mundorff, 1971). Freethey (1993) also provides the results of chemical analyses of this spring. Physical and chemical parameters of Pah Tempe Hot Springs are discussed under the geothermal resources section of this report.

Ground water quality in the St. George basin was reported in Cordova and others (1972), Cordova (1978), and 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. Several wells southwest of Hurricane contain relatively high sulfate concentrations.

GEOLOGIC HAZARDS

Earthquakes

The Hurricane quadrangle lies within the Intermountain seismic belt, a north-trending zone of pronounced, shallow seismicity that trends from northern Arizona to western Montana; in Utah, it includes the transition zone between the Basin and Range and Colorado Plateau physiographic provinces (Smith and Arabasz, 1991). Three major faults - the Gunlock, Washington, and Hurricane - are known to have Quaternary offset in southwestern Utah (Earth Science Associates, 1982; Anderson and Christenson, 1989; Christenson, 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 (Stewart and others, 1997). 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.

Christenson 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 Christenson (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. On July 16, 1998, a magnitude 3.7 earthquake with an epicenter about 3 miles northeast of St. George was felt locally.

The most recent large earthquake in the greater St. George area occurred on September 2, 1992 (Black and Christenson, 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. Everitt (1992) noted that following the earthquake, the flow at Pah Tempe Hot Springs decreased drammatically, water emerged from new sources at lower elevations and closer to the river, and flow ceased at springs more than 1 foot (0.3 m) above the river. Black and others (1995) discussed other geologic effects of the St. George earthquake. Residents near the Town of Leeds noted a landslide scarp about 500 feet (152 m) long, with a headwall scarp up to 6 feet (2 m) high, that formed during the St. George earthquake; the scarp is located at the common border of section 7 and 8, T. 41 S., R. 13 W.

As the 1992 St. George earthquake demonstrated, hazards associated with earthquake activity include ground shaking, liquefaction, flooding, rock falls, and other seismically induced slope failures (Christenson, 1992; Black and Christenson, 1993; Black and others, 1995; Stewart and others, 1997). 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 by certain foundation materials, further damaging structures, and may lead to liquefaction. Rock falls and landslides are of increasing concern as development encroaches on steep slopes. The Hurricane quadrangle is located in the Uniform Building Code seismic zone 2B, an area of moderate seismic risk with a moderate potential for earthquake ground shaking (International Conference of Building Officials, 1997; Christenson and Nava, 1992).

Mass Movements

Landslides

In the Hurricane 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 Woods Ranch Member of the Toroweap Formation. Several large landslide complexes that involve these and adjacent overlying strata were mapped. Most of these slides are characterized by hummocky topography and moderately subdued internal scarps and so should be considered capable of renewed movement, especially if disturbed by construction activities. Christenson and Deen (1983) and Christenson (1992) considered that most of the movement in landslides to the west in the greater St. George area apparently took place in the Pleistocene when conditions were wetter than at present.

Perhaps the most prominent landslides occur along the oversteepened walls of the Virgin River canyon. On the south side of the Virgin River, south of the confluence of Ash Creek and LaVerkin Creek, two large rotational slumps are characterized by a partly subdued hummocky topography developed in "radio tower" basaltic flows (figure 9). These landslides were probably initiated by lateral migration of the Virgin River and likely involve Carmel and Iron Springs strata at their bases. To the east, several large rotational slumps occur in Woods Ranch and overlying Fossil Mountain strata. The largest of these is located on the north side of the river in the NE 1/4NE1/4 section 25, T. 41 S., R. 13 W. and the NW1/4NW1/4 section 30, T. 41 S., R. 12 W. It is characterized by arcuate tensional fractures in Fossil Mountain strata that trend parallel to the cliff and are mostly filled with slopewash deposits.

Numerous rotational slumps, mapped as Qms and characterized by a moderately subdued hummocky topography, are found in Petrified Forest and overlying Moenave strata on the northeast-plunging nose of the Virgin anticline; deeply dissected, significantly older landslides mapped as Qmsm are also found in this area. In the NE1/4SW1/4 section 8, T. 41 S., R. 13 W., an incipient landslide is present due west of the old Leeds landfill. Fractures up to several feet wide and 20 feet (6 m) deep are found in Springdale strata at the top of the hill. These fractures trend parallel to the hillside and likely reflect incipient failure of underlying Whitmore Point strata. Some of these fractures appear new, with soil and roots adhering to the walls, and may have formed during the 1992 St. George earthquake.

The ridge immediately east of Toquerville is capped in part by Petrified Forest strata that is largely concealed beneath basalt colluvium. Faulting and poor exposures conspire to make mapping there difficult, but the western flank of the ridge may contain unrecognized landslide deposits.

Rock falls

Evidence of rock falls are found throughout the quadrangle as accumulations 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. Numerous isolated rock falls characterized by unweathered surfaces and fresh scars are found along the Hurricane Cliffs and cross-cutting drainages. Slopes that are oversteepened by construction activities may present additional rock-fall hazards.

Most map units within the quadrangle are capable of producing rock falls, especially where exposed in steep cliffs. Particularly large blocks of basalt, mapped as Qmsb, are found along the Virgin River canyon, attesting to the jointed basalt's proclivity for producing rock falls. Rock-fall hazards become ever more insidious as an expanding population encroaches upon steeper slopes. The extent of the hazard can be assessed by the relative abundance of rock-fall debris at the base of a slope. The relative hazard varies locally and depends upon the distance from the base of the slope, nature and stability of slope debris, and local topography (Christenson, 1992).

Problem Soil and Rock

Expansive soil and rock

Expansive soil and rock contain 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 (Christenson and Deen, 1983; Christenson, 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 (Christenson, 1992). Petrified Forest strata crop out along the nose of the Virgin anticline in the northwestern corner of the quadrangle, and also in fault-bounded blocks along the Hurricane fault zone north of Hurricane.

Expansive clays are also known to occur in the Shnabkaib Member, and, to a lesser extent, in the lower, middle, and upper red members of the Moenkopi Formation (Christenson, 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 (Christenson 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 may be 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 Shnabkaib Member of the Moenkopi Formation, the Harrisburg Member of the Kaibab Formation, and the Woods Ranch Member of the Toroweap 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. Older mixed alluvial and eolian deposits with a significant component of gypsum are mapped in the southeast corner of the quadrangle.

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 soil and rock

Collapse-prone soils are known to occur in the Hurricane area (Christenson 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. Some wind-blown deposits are also susceptible to hydrocompaction. 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.

Erosional pipes form when surface runoff erodes vertically downward through poorly lithified bedrock as well as overlying alluvial, colluvial, and landslide deposits. Piping produces a system of tunnels, small caves, and pseudo-karst topography that collectively serves to channel runoff underground. The principal danger associated with piping is roof collapse and entrapment. Although erosional pipes are not mapped, they are locally common on Petrified Forest strata.

Several sinkholes of uncertain origin have opened over time in the vicinity of Hurricane (Solomon, 1993). All have occurred in unconsolidated alluvium overlying basaltic flows, possibly due to the collapse of lava tubes. Lava tubes plugged with basalt are common in exposures along the Virgin River canyon, and open tubes are known on the southern flanks of the "radio tower" volcanic complex.

At least two karst-like collapse features occurred recently immediately outside the quadrangle. In April 1985, a large sinkhole appeared in the bed of the Virgin River and swallowed the entire flow of the river for several months (Everitt and Einert, 1994). A similar sinkhole appeared in the channel of LaVerkin Creek in July 1996 (Lund, 1996). A partly excavated hole about 20 feet (6 m) deep is present in alluvial deposits in the NE1/4NE1/4NW1/4 section 12, T. 41 S., R. 13 W., on a minor terrace of LaVerkin Creek. The initial origin of this hole is unknown, but it may be a collapse feature associated with dissolution of probable underlying Shnabkaib strata. Anomalous attitudes in the SE1/4SE1/4NE1/4 section 12, T. 41 S., R. 13 W. and the SE1/4NW1/4 section 13, T. 42 S., R. 13 W. may result from poorly expressed collapse features.

Flooding

In the Hurricane quadrangle, the Virgin River and its floodplain are contained within a relatively narrow, mostly undeveloped corridor bounded by resistant strata and basalt flows. Damage associated with a major Virgin River flood would likely be restricted to this narrow corridor within the quadrangle. The potential hazard associated with flash floods and debris flows in tributary drainages, however, is much more serious.

The lower reaches of Ash Creek and LaVerkin Creek are partly developed and both streams drain large upstream areas. New development is also occurring along the base of the Hurricane Cliffs near the commonly dry Gould Wash, Frog Hollow, and smaller drainages (figure 12). Flash floods from rapid snowmelt or thunderstorm cloudbursts can turn these normally tranquil streams and 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. Where undisturbed by development, well-developed debris-flow levies are still locally visible at the base of the Hurricane Cliffs, especially south of Frog Hollow. These levies attest to the powerful effects of heavy rainfall events over even very small catchment basins.

(Figure 12 near here)

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 of the AMLRP at Silver Reef, which began in 1988. A variety of methods were used to seal over 500 adits and shafts in this portion of the district. Detailed maps and information on mine openings are available from the AMLRP. Some adits and shafts are shown on the topographic base map. Inventory of mine workings at East Reef began in 1997 and reclamation work is scheduled to follow. Many, but not all, of the mine openings in the East Reef area are shown on the topographic base map.

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 (1992a, 1992b, 1995) evaluated the radon-hazard potential of the greater St. George area. Although the Hurricane quadrangle was not included in his study area, results of those studies may be useful in a general way because of similarities in the region's geology. In his radon-hazard-potential map of Utah, Black (1993) showed the Hurricane quadrangle to have a moderate to high radon-hazard potential, with high radon-hazard potentials in Triassic and Jurassic strata of the Virgin anticline. 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.

Solomon'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 was mined from the Springdale Sandstone Member of the Moenave Formation and the middle sandstone of the Petrified Forest Member of the Chinle Formation in the Silver Reef mining district. The indoor-radon hazard may be greater in structures built on these formations or on sediments or tailings derived from them.

Volcanism

Basaltic flows and 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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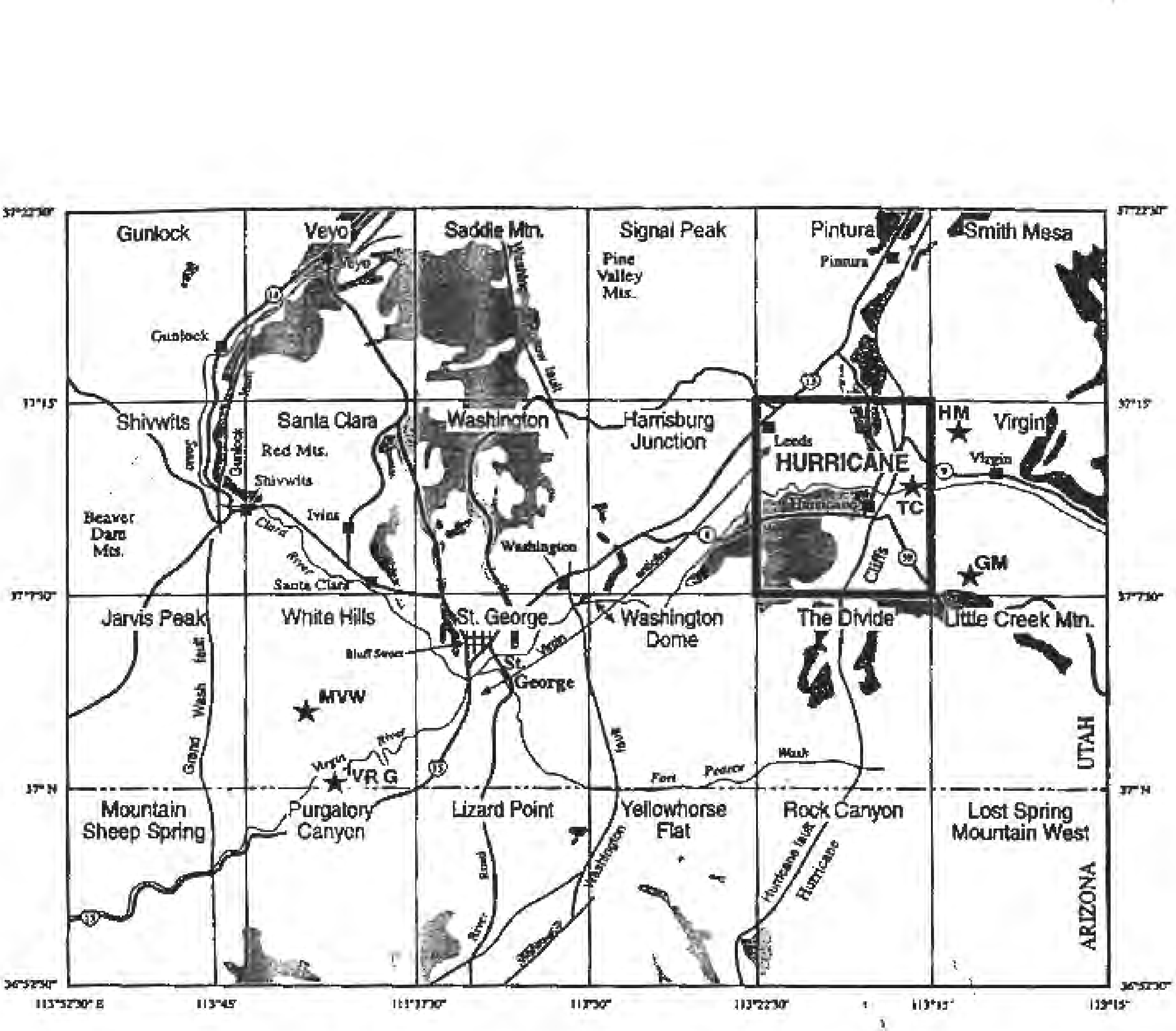

Figure 1 Location of the Hurricane and surrounding quadrangles, with major geographic and geologic features; basalt flows are shaded. This quadrangle is one of several 7.5' quadrangles recently mapped as part of the UGS effort to map the geology of the rapidly growing St. George basin. Additional geologic maps and reports are available for the Harrisburg Junction quadrangle (Biek, 1997), Santa Clara quadrangle (Willis and Higgins, 1996), St. George quadrangle (Higgins and Willis, 1995), Washington quadrangle (Willis and Higgins, 1995), Washington Dome quadrangle (Higgins, 1998), and the White Hills quadrangle (Higgins, 1997). Previously completed maps of the Jarvis Peak quadrangle (UGS OFR 212), Shivwits quadrangle (UGS Map 153), and several Arizona quadrangles are also available. MVW = Mountain Valley Wash; TC = "Timpoweap Canyon," HM = Hurricane Mesa, GM = Gooseberry Mesa, and VRG = Virgin River Gorge.

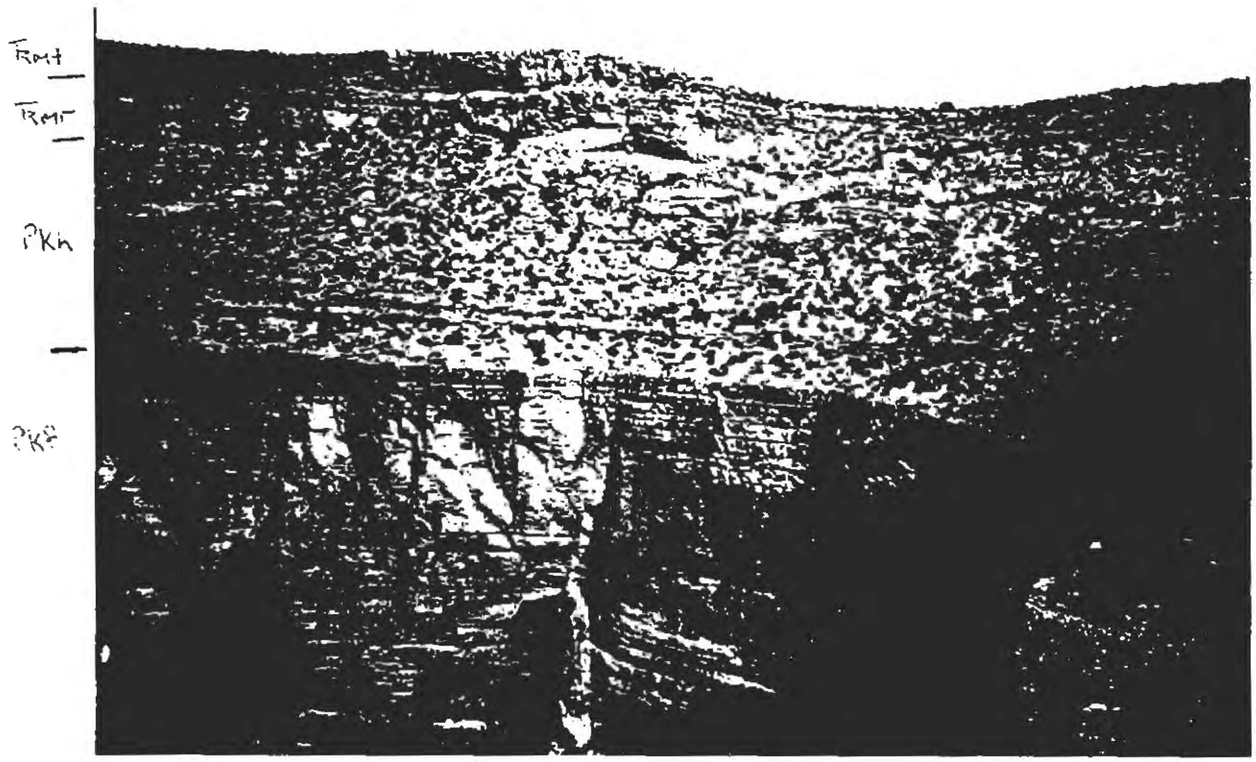

Figure 2 Looking north to the head of the Frog Hollow box canyon in the SW1/4SE1/4SW1/4 section 14, T. 42 S., R. 13 W. Cliff-forming Fossil Mountain strata is overlain by mostly slope-forming Harrisburg strata. Ledge-forming middle Harrisburg strata (unit 5 of Nielson, 1986) is overlain by channel-form conglomerates of the Rock Canyon Conglomerate; Timpoweap strata form the skyline in this photo. Note basaltic flow (Qbd) at right.

Figure 3 Looking northwest at the Rock Canyon Conglomerate, which here reaches up to 25 feet (7.5 m) thick, in the upper reaches of Frog Hollow, in the NW1/4SE1/4SE1/4 and NE1/4SW1/4SE1/4 section 14, T. 42 S., R. 13 W. Note prominent, large-scale, low-angle cross-stratification of the Rock Canyon Conglomerate, which overlies the resistant, middle Harrisburg Member (unit 5 of Nielson, 1986). Thin-bedded Timpoweap limestones overlie the Rock Canyon Conglomerate, except at the west end of the photo. The Pine Valley Mountains are in the distance.

Figure 4 Looking north at a portion of East Reef, imediately north of Grapevine Wash; the East Reef cinder cone forms the skyline on the right. Here moderately southeast-dipping Springdale and Kayenta strata are beveled flat and capped by level 6 stream-terrace deposits. These spectacular exposures point to the gradational nature of the Springdale-Kayenta contact, which is placed at the base of the first laterally continuous mudstone bed.

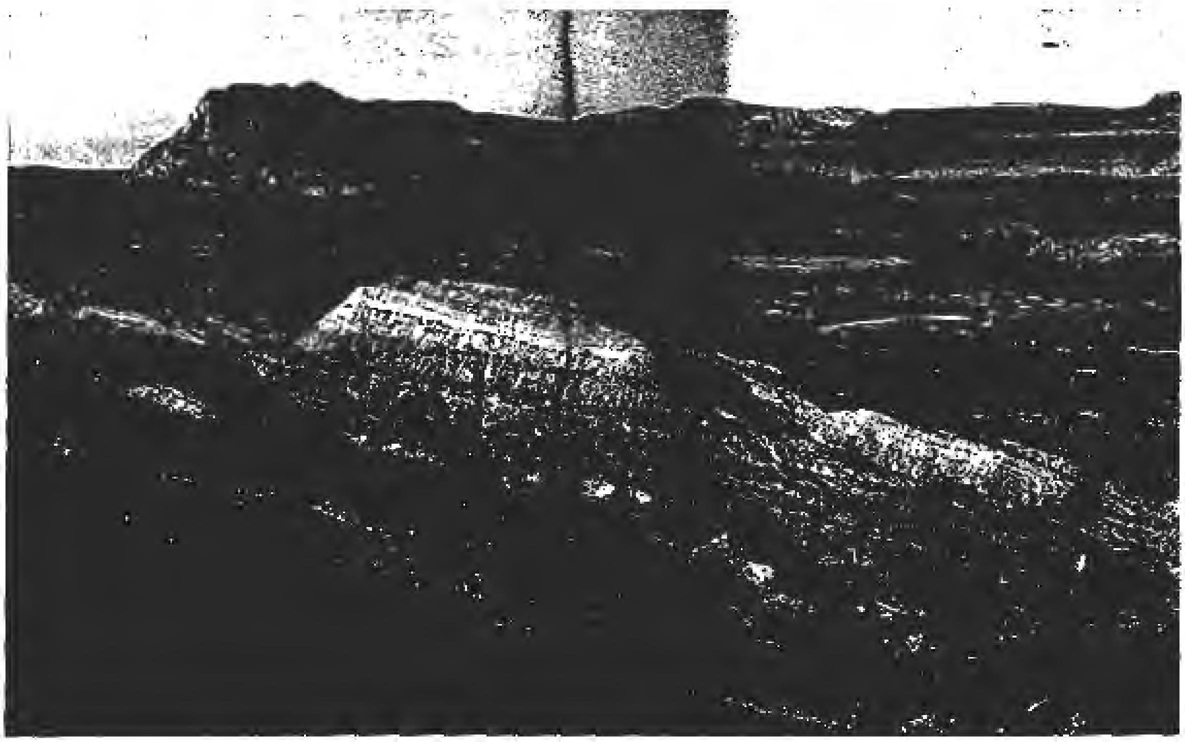

Figure 5 Looking north at hill 3662 in the E1/2 section 22, T. 41 S., R. 13 W.; Toquerville and Black Ridge in distance at left. Sage-covered, east-dipping planar surface of Navajo Sandstone at lower left is unconformably overlain by red- and white-banded Temple Cap strata. Hill 3662 itself is capped by Co-op Creek strata. Steeper dips in these strata at the right margin of the photo are a result of an east-dipping reverse fault (see figure 10).

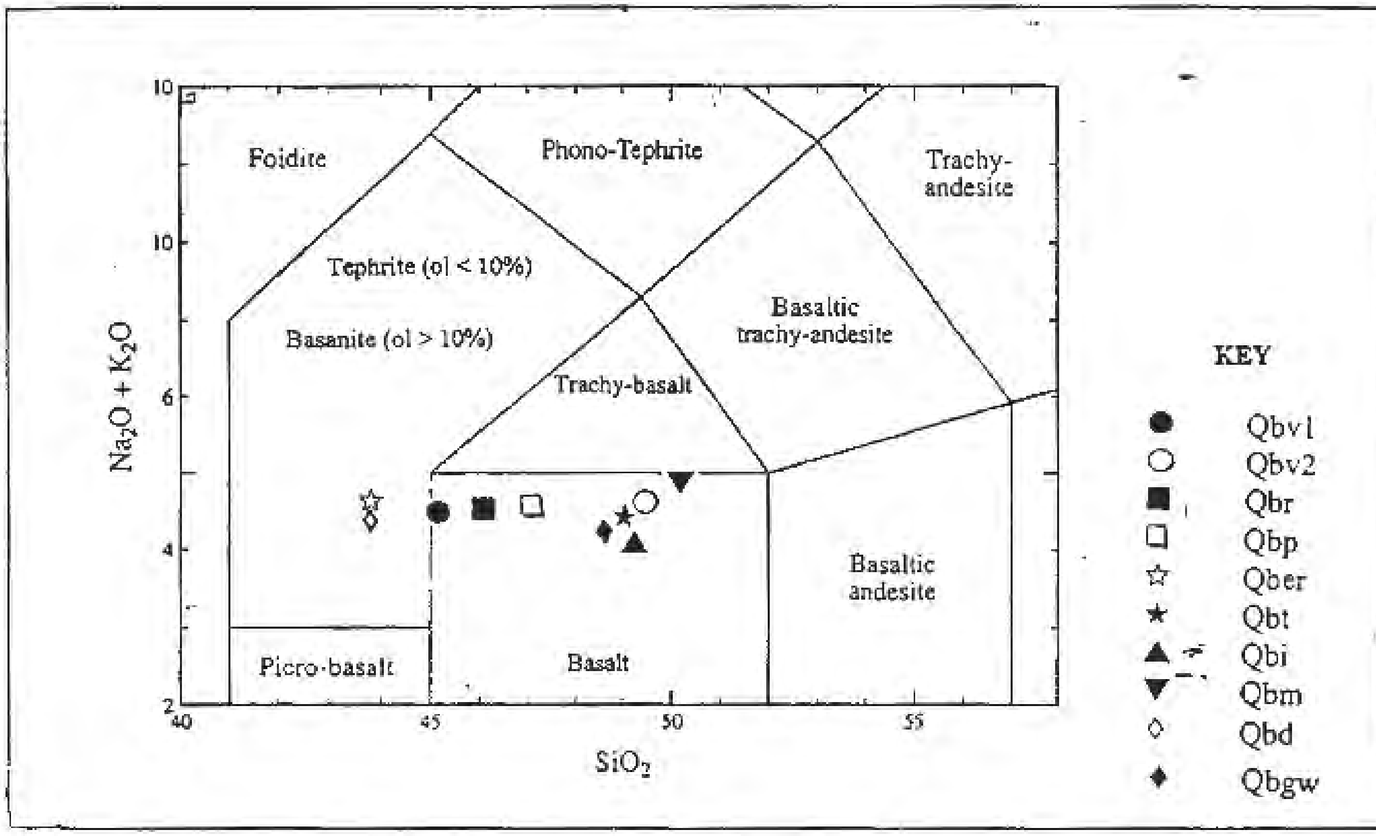

Figure 6 Geochemical classification of basaltic rocks in the Hurricane quadrangle using scheme of LeBas and others (1986). Averages are shown; see Table 1 for analytical results.

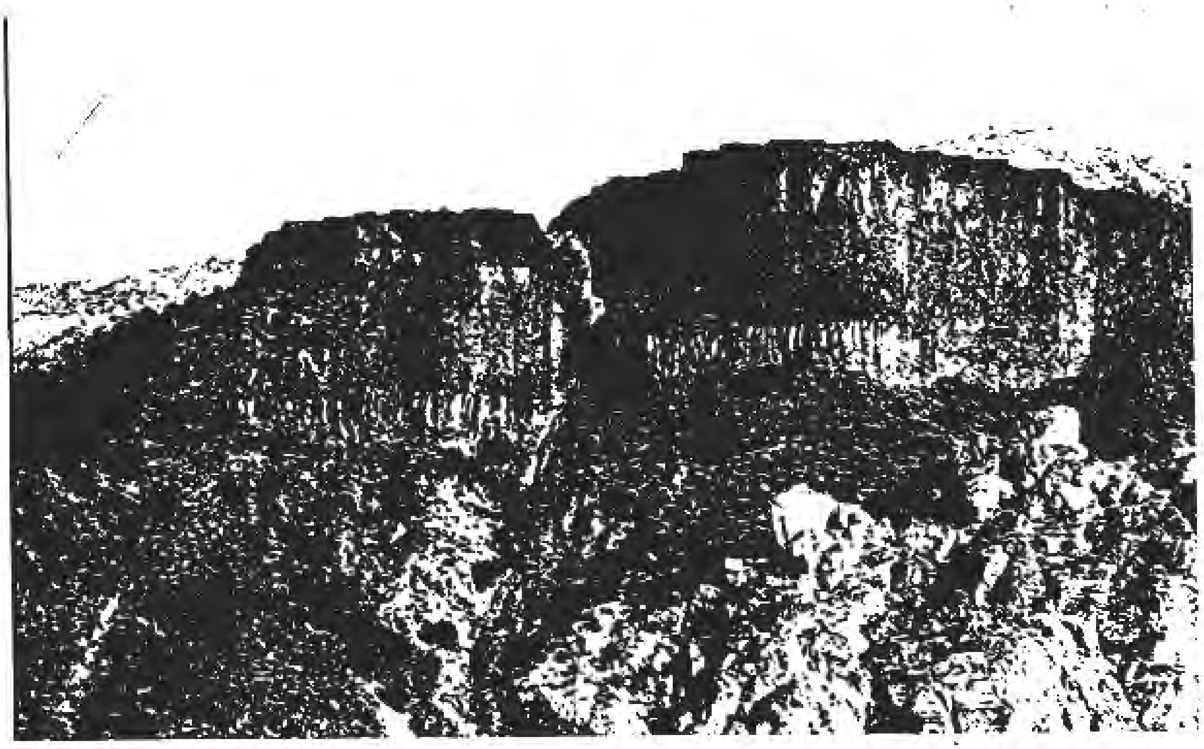

Figure 7 Looking northeast at the Ivans Knoll flow (Qbi) on the footwall of the Hurricane fault zone, at the north side of the entrance to Timpoweap Canyon. This flow yielded an $^{40}Ar/^{39}Ar$ isochron age of 353,000 +/- 45 ka (Sanchez, 1995) and is offset about 240 feet (m) along the Hurricane fault zone; the flow is also offset about 20 feet (6 m) along a splay of the fault zone. This flow reaches up to 170 feet (52 m) thick and appears to consist of a single flow unit that filled the ancestral Virgin River drainage. The base is marked by a rubbly zone with pillow basalts that is about 20 to 40 feet (6-12 m) thick and which is overlain by about 10 feet (3 m) of dense, fine-grained olivine basalt with few columnal joints; this is overlain by up to 100 feet (30 m) of similar basalt that is prominently jointed, and capped by about 20 feet (6 m) of vesicular basalt with few joints. The Fossil Mountain Member of the Kaibab Formation crops out at the lower right.

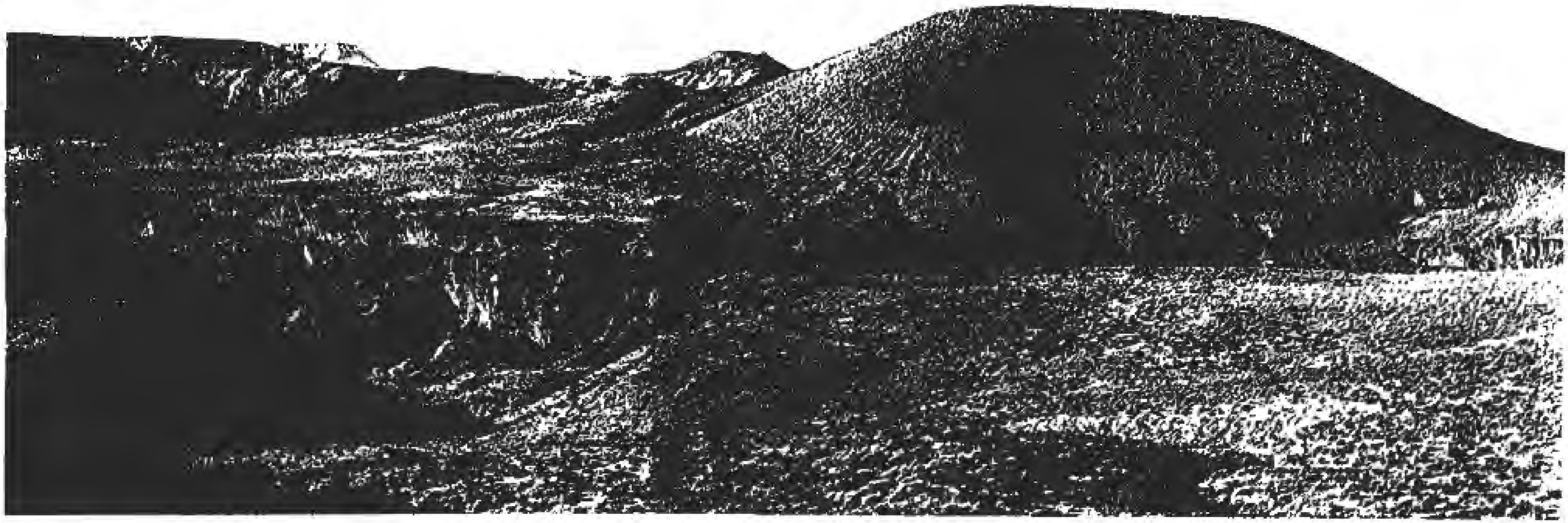

Figure 8 Looking south at the "radio tower" cone, which is partly eroded by the Virgin River. Note dike at base near center of cone. Two prominent flows are seen in the vertical south wall of the Virgin River canyon in the left half of the photo. The upper flow is the "radio tower" flow (Qbr). The source of the lower, thicker flow is uncertain; it may be the Ivans Knoll flow, which is well exposed further upstream near the entrance to Timpoweap Canyon. The Hurricane Cliffs are in shadow at left.

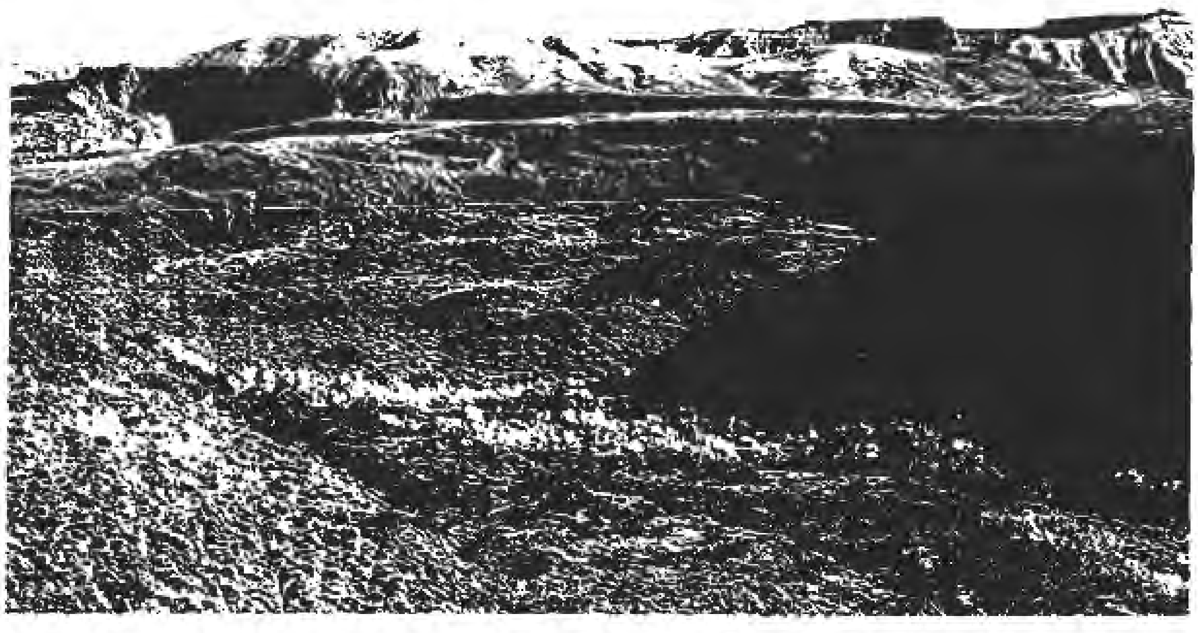

Figure 9 Looking southeast across the Virgin River to landslide deposits in the NW1/4NW1/4 section 26, T. 41 S., R. 13 W., due north of Hurricane. Only basaltic rocks of the "radio tower" flow are visible in the landslide, although Co-op Creek strata does crop out in the shadow at right. The landslide itself probably involves Iron Springs strata at depth. The entrance to Timpoweap Canyon is at the left margin of the photo.

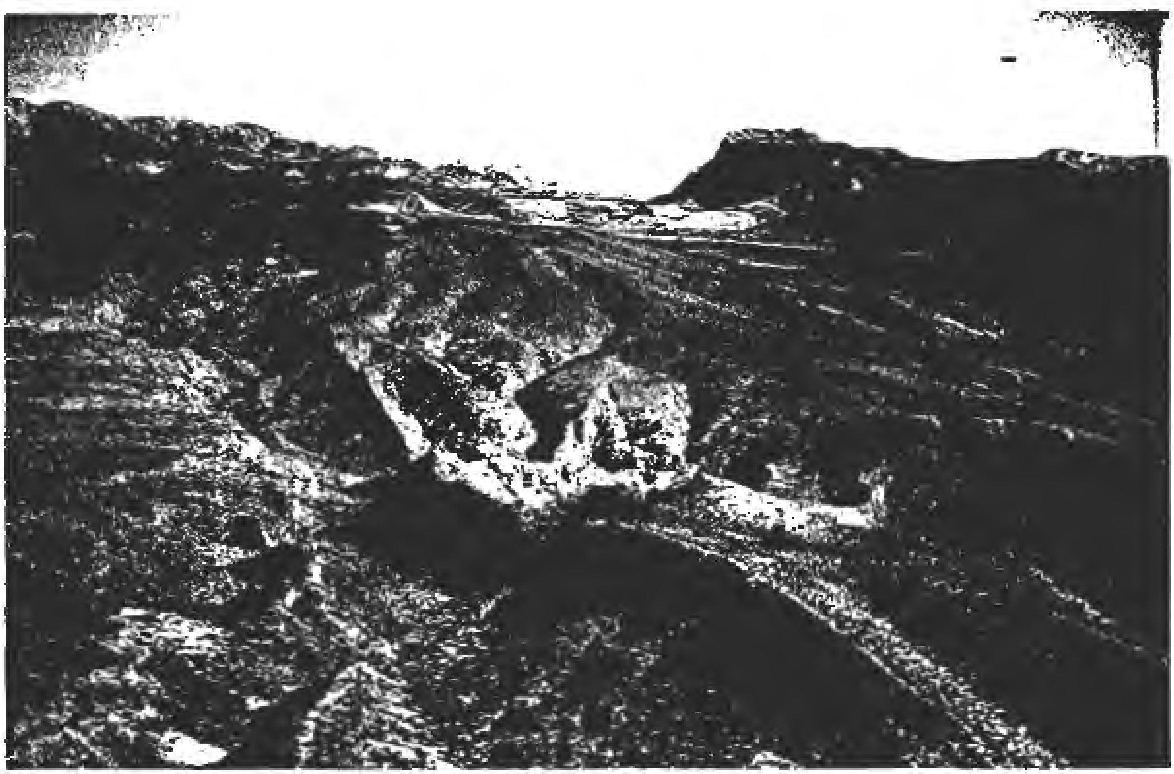

Figure 10 Looking north from hill 3662 in the E1/2 section 22, T. 41 S., R. 13 W. Black Ridge and the Hurricane Cliffs form the skyline at right-center of the photo, while the Pine Valley Mountains are seen at the left. Temple Cap strata form trough at left margin of photo and are faulted down against the Navajo Sandstone. The Co-op Creek Member forms prominent ridges in center of photo and is in part duplicated by an east-dipping reverse fault.

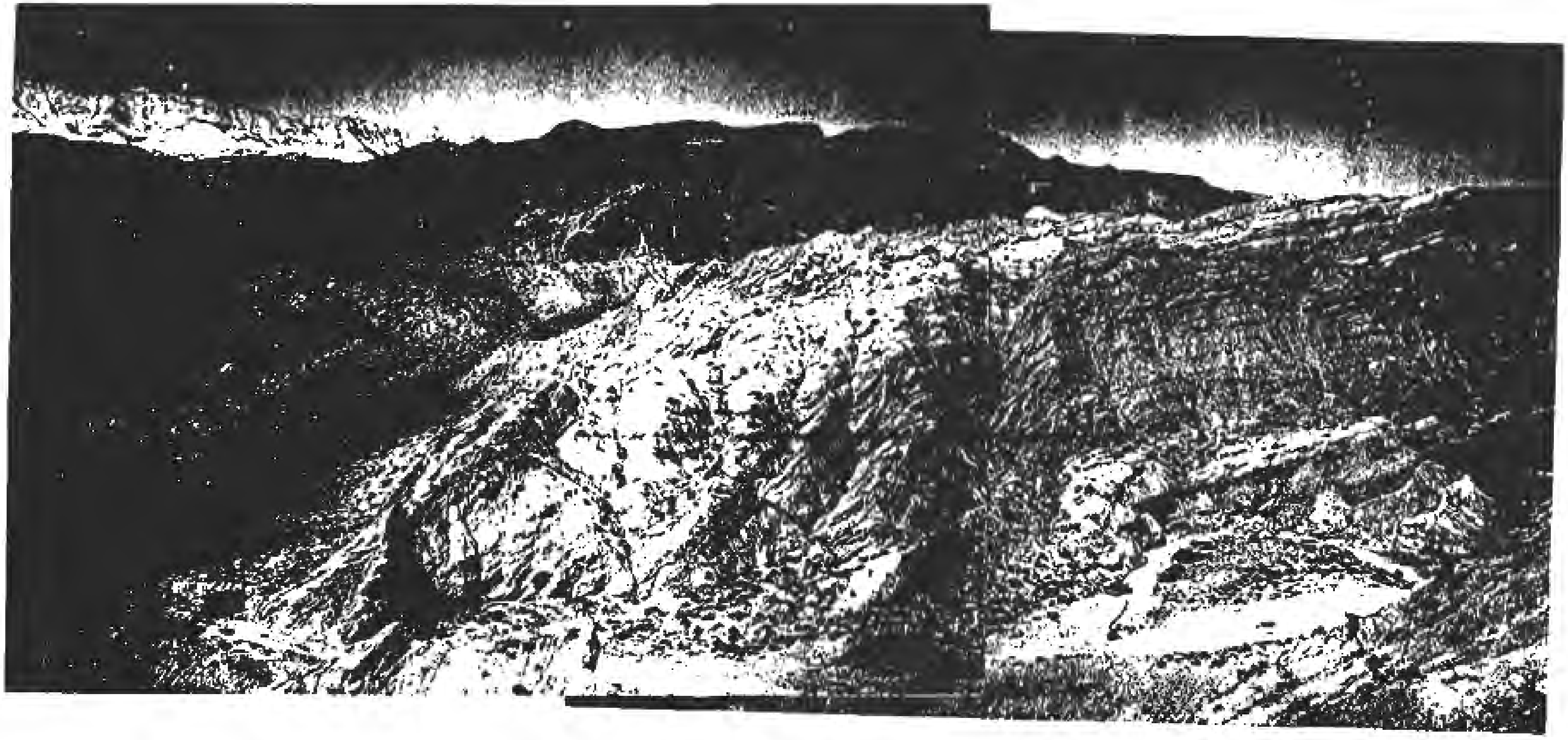

Figure 11 Looking north across Nephis Twist at a portion of the Hurricane fault zone. Note increased dips of middle red and Shnabkaib strata near center of photo due to fault drag. West-dipping Petrified Forest and Moenave strata form low, sage-covered area to left of fault.

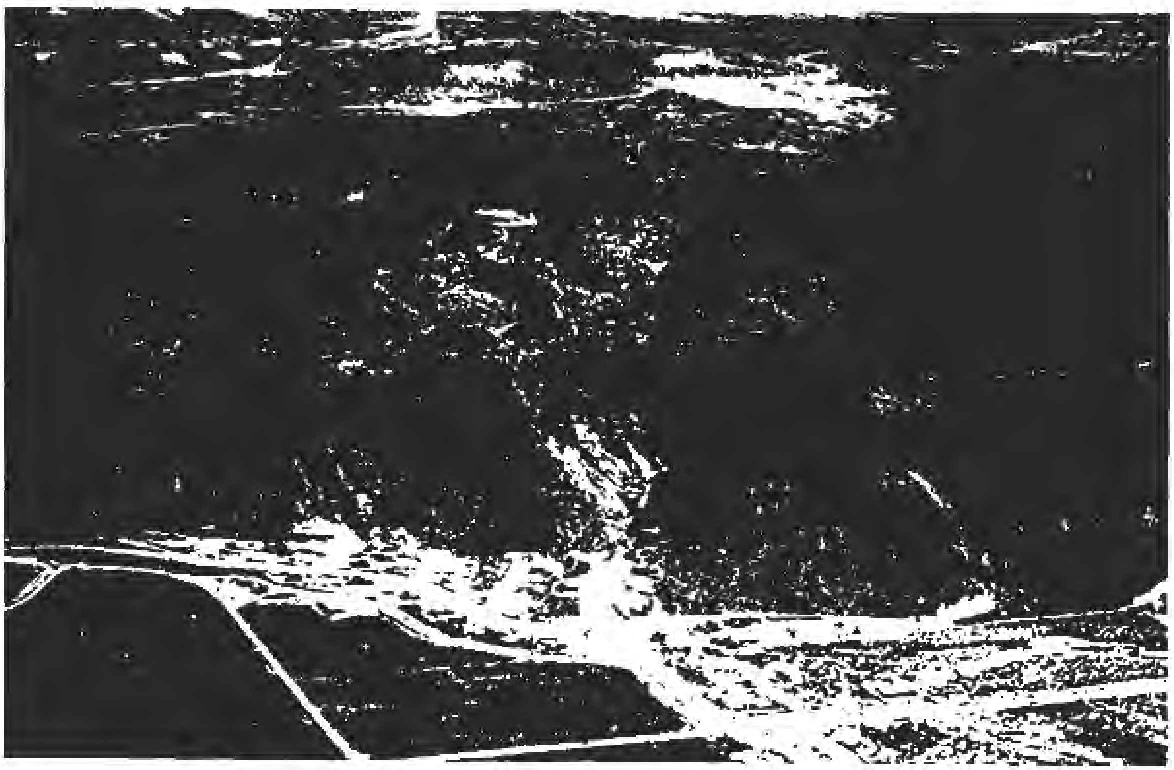

Figure 12 Oblique aerial view looking southeast at new development along the Hurricane fault zone in the SE1/4 section 10, T. 42 S., R. 13 W. Although the drainage basin above this development is comparatively small, well-developed debris flow levies nearby show that even such small basins produce debris flows. The vertical cliffs here are formed principally in Fossil Mountain strata, with Toroweap and west-dipping, fault-bounded Moenkopi strata below. Harrisburg strata form the rounded, lighter gray hills above, which are capped by a thin, darker brown sequence of Timpoweap strata. Photo by Janice Higgins.

Table 1
Whole Rock Chemical Analyses

Flow / Sample	Qbm	Qbi					
	VR-4106	VR-123-7	VR-123-8	VR-123-11	VR-123-11A	VR-124-2	VR-124-5
long.(°W)	113.296	11.352	113.362	113.364	113.364	113.335	113.333
lat. (°N)	37.128	37.172	37.164	37.126	37.126	37.160	37.147
X-Ray Fluorescence Analyses, wt.%							
SiO_2	50.03	49.49	49.73	50.36	50.32	48.66	47.83
TiO_2	1.40	1.43	1.41	1.42	1.41	1.42	1.40
Al_2O_3	16.24	16.54	16.24	16.17	16.29	16.42	16.08
Fe_2O_3	10.71	10.62	10.64	10.65	10.61	10.83	10.48
MnO	0.16	0.17	0.16	0.16	0.16	0.16	0.16
MgO	6.77	6.47	6.58	6.75	6.59	6.51	6.41
CaO	9.38	9.65	9.49	9.49	9.45	10.21	10.75
Na_2O	3.63	3.22	3.16	3.32	3.14	3.03	3.15
K_2O	1.19	0.93	1.08	1.10	1.01	0.81	0.84
P_2O_5	0.36	0.31	0.38	0.42	0.40	0.29	0.30
Cr_2O_3	<0.01	0.02	0.02	0.02	<0.01	<0.01	0.02
Total	99.88	98.41	98.85	99.48	98.99	98.79	98.64
ICP-MS, ppm							
Rb	12	11	12	15	15	10	9
Ba	644	513	712	706	669	456	537
Nb	12	10	11	12	12	8	9
Sr	608	564	692	734	722	498	524
Zr	152	161	179	176	177	143	152
Y	26	27	27	28	27	26	26
Cs	1	<1	<1	<1	<1	<1	<1
Hf	4	4	5	5	5	4	4
La	32	25	34	37	37	22	23
Ta	1	<1	<1	1	1	<1	<1

Flow Sample long.(°W) lat. (°N)	VR -113-2 113.295 37.253	VR-113-3 113.297 37.232	Qbt VR 4204 113.275 37.237	VR 4205 113.280 37.233	VR-113-4 113.297 37.243	VR-114-2 113.283 37.236	VR-116-7 113.283 37.202
X-Ray Fluorescence Analyses, wt.%							
SiO_2	48.72	49.64	49.30	48.15	49.27	49.29	49.02
TiO_2	1.49	1.50	1.49	1.91	1.48	1.47	1.91
Al_2O_3	16.42	16.37	16.26	15.88	16.62	16.56	16.08
Fe_2O_3	11.23	11.02	11.42	10.46	10.84	11.12	10.15
MnO	0.17	0.16	0.17	0.16	0.16	0.17	0.15
MgO	6.69	6.73	7.18	7.54	6.73	7.00	7.57
CaO	9.72	9.74	9.77	7.52	9.60	9.68	7.76
Na_2O	3.16	3.35	3.07	3.92	3.26	3.24	3.61
K_2O	0.78	0.74	0.82	1.90	0.80	0.71	1.50
P_2O_5	0.28	0.28	0.26	0.58	0.25	0.27	0.57
Cr_2O_3	<0.01	0.03	<0.01	<0.01	0.01	0.03	<0.01
Total	98.77	99.09	99.75	98.03	98.53	98.91	98.73
ICP-MS, ppm							
Rb	12	15	9	13	15	12	12
Ba	316	379	284	518	317	318	577
Nb	7	7	9	25	8	7	21
Sr	424	444	416	790	443	423	789
Zr	149	150	133	241	153	146	250
Y	28	27	26	26	28	27	27
Cs	<1	<1	1	1	<1	<1	<1
Hf	4	3	3	5	4	4	6
La	20	20	17	37	21	19	39
Ta	<1	<1	<1	2	<1	<1	2

Flow	Qbt		Qber		Qbgw			
Sample	VR-116-8	VR-116-9	VR-122-1	VR-122-2	VR-19-1	VR-124-8	VR-4108*	VR710-1*
long. (°W)	113.281	113.278	113.349	113.343	113.285	113.294	113.249	113.220
lat. (°N)	37.208	37.213	37.199	37.208	37.127	37.135	37.125	37.105
X-Ray Fluorescence Analyses, wt.%								
SiO_2	49.19	49.27	43.75	43.48	49.15	48.96	48.69	50.06
TiO_2	1.41	1.93	2.32	2.36	1.66	1.67	1.69	1.61
Al_2O_3	14.91	16.05	12.13	11.88	13.84	13.62	14.12	14.20
Fe_2O_3	11.79	10.24	12.49	12.50	11.73	11.63	11.22	11.24
MnO	0.16	0.14	0.18	0.18	0.17	0.16	0.16	0.16
MgO	8.54	7.29	11.40	11.48	8.95	8.94	7.31	7.95
CaO	8.79	8.02	10.61	10.75	9.48	9.89	9.56	9.76
Na_2O	3.03	3.53	2.89	2.90	3.12	3.02	3.13	3.10
K_2O	0.95	1.58	1.70	1.80	0.89	0.86	1.48	0.88
P_2O_5	0.29	0.57	0.74	0.72	0.45	0.46	0.47	0.48
Cr_2O_3	<0.01	<0.01	0.03	0.04	0.03	0.04	0.01	0.01
Total	98.76	99.68	98.11	98.27	99.34	99.24	97.84	99.63
ICP-MS, ppm								
Rb	15	11	23	25	14	11	13	8
Ba	573	1375	1055	907	627	578	692	661
Nb	13	22	55	54	28	28	38	31
Sr	515	1020	1005	933	617	623	619	617
Zr	140	254	225	214	138	142	145	147
Y	21	27	25	23	22	22	22	24
Cs	<1	<1	<1	<1	<1	<1	1	0.1
Hf	4	6	6	6	4	4	3	4
La	27	36	57	54	38	35	41	40
Ta	1	1	5	6	2	2	3	3

Flow Sample	Qbgw VR710-2*	 VR710-3*	Qbd VR710-4*	 VR41-07*	Qbp VR-123-5	Qbr VR-116-1	 VR-116-2
long.(°W) lat. (°N)	113.234 37.111	113.264 37.120	113.266 37.119	113.280 37.088	113.321 37.182	113.290 37.196	113.290 37.196
X-Ray Fluorescence Analyses, wt.%							
SiO_2	48.42	46.90	43.97	43.62	49.38	49.46	44.35
TiO_2	1.61	1.67	2.61	2.60	1.68	1.38	2.36
Al_2O_3	13.77	13.35	10.95	10.99	14.99	14.84	12.50
Fe_2O_3	11.73	11.93	13.30	13.35	11.53	11.71	12.73
MnO	0.17	0.17	0.19	0.19	0.16	0.17	0.18
MgO	9.67	10.13	12.35	12.27	8.57	8.00	11.26
CaO	9.56	10.61	10.76	10.77	8.57	8.89	10.74
Na_2O	3.26	2.99	2.93	2.70	3.09	2.99	3.07
K_2O	0.88	0.93	1.42	1.74	1.23	1.04	1.45
P_2O_5	0.45	0.50	0.74	0.78	0.43	0.34	0.78
Cr_2O_3	0.03	0.04	0.04	0.03	0.01	0.03	0.05
Total	99.92	99.82	99.26	99.04	99.21	98.46	99.05
ICP-MS, ppm							
Rb	10	11	20	20	16	17	28
Ba	611	696	665		534	709	1160
Nb	29	36	64	69	23	13	58
Sr	593	669	833	846	554	664	976
Zr	131	145	239	219	156	122	216
Y	22	23	28	27	23	22	25
Cs	0.1	0.1	0.3	1	<1	<1	<1
Hf	3	3	6	6	5	4	6
La	36	43	54	55	30	37	62
Ta	2	3	5	7	2	1	5

Flow Sample	Qbr VR-116-3	VR-116-4	VR-123-1	VR-123-2	VR-123-3	VR-123-4	Qbv₁ VR-123-6	VR-124-7	VR-1016-10	VR-1016-12
long. (°W) lat. (°N)	113.290 37.196	113.290 37.196	113.300 37.196	113.304 37.197	113.306 37.196	113.302 37.178	113.322 37.183	113.339 37.170	113.347 37.191	113.337 37.195
X-Ray Fluorescence Analyses, wt.%										
SiO_2	45.21	44.57	44.40	49.48	45.18	45.80	45.27	44.58	44.59	45.68
TiO_2	2.25	2.27	2.19	1.38	2.37	2.49	2.32	2.31	2.42	2.32
Al_2O_3	13.03	12.71	12.61	14.99	12.96	13.08	12.78	12.54	12.28	12.84
Fe_2O_3	12.71	12.68	12.51	11.86	12.58	12.44	12.37	12.57	12.62	12.59
MnO	0.18	0.18	0.18	0.17	0.18	0.17	0.17	0.17	0.18	0.17
MgO	10.50	10.65	11.02	8.03	10.12	9.46	10.48	10.97	10.67	10.70
CaO	10.30	10.36	10.62	9.12	10.15	10.45	10.17	10.38	9.95	10.24
Na_2O	3.19	3.06	3.22	2.94	3.32	3.09	3.18	2.59	3.12	2.96
K_2O	1.52	1.52	1.40	0.88	1.48	1.47	1.43	1.32	1.66	1.37
P_2O_5	0.74	0.72	0.69	0.32	0.71	0.73	0.66	0.66	0.70	0.64
Cr_2O_3	0.05	0.05	0.04	0.03	0.04	0.02	0.04	0.05	0.05	0.05
Total	99.65	98.68	98.60	99.02	98.77	99.07	98.48	99.05	98.37	98.28
ICP-MS, ppm										
Rb	22	23	24	13	19	17	19	15	19	18
Ba	1060	1070	894	619	908	890	804	791	844	851
Nb	50	51	51	12	53	51	42	42	51	43
Sr	968	972	935	673	942	971	875	1125	933	898
Zr	200	200	202	124	210	220	191	194	221	191
Y	23	23	23	21	23	24	23	24	24	24
Cs	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Hf	5	5	6	3	6	6	5	6	6	6
La	61	61	51	31	53	52	47	47	52	48
Ta	5	5	5	<1	5	5	4	4	5	4

Flow Sample long. (°W) lat. (°N)	Qbv HQ-01 113.366 37.181	HQ-02 113.359 37.184	VR-115-2 113.292 37.201	VR-115-3 113.304 37.200	VR-115-5 113.304 37.199	Qb VR-115-6 113.311 37.200	VR-115-7 113.301 37.200	VR-116-5 113.282 37.198	VR-116-6 113.284 37.199
X-Ray Fluorescence Analyses, wt.%									
SiO_2	49.42	49.66	44.40	48.81	44.43	44.63	44.06	44.63	44.93
TiO_2	1.49	1.37	2.27	1.43	2.20	2.15	2.24	2.17	2.28
Al_2O_3	14.59	15.13	12.46	15.18	12.71	13.04	12.49	13.06	12.92
Fe_2O_3	11.98	11.80	12.51	12.04	12.51	12.25	12.23	12.27	12.39
MnO	0.17	0.17	0.18	0.17	0.18	0.18	0.18	0.18	0.17
MgO	7.95	7.81	11.01	7.61	11.17	10.49	11.16	10.37	10.33
CaO	8.78	8.96	10.69	9.02	10.74	10.65	10.52	10.74	10.22
Na_2O	3.09	3.13	3.03	3.09	2.97	3.24	3.04	3.24	3.23
K_2O	1.09	0.97	1.67	1.04	1.55	1.39	1.70	1.58	1.66
P_2O_5	0.36	0.32	0.75	0.38	0.71	0.71	0.74	0.77	0.73
Cr_2O_3	0.03	0.03	0.05	0.03	0.04	0.04	0.05	0.04	0.01
Total	98.45	98.63	98.96	98.67	98.85	98.48	98.38	99.09	98.97
ICP-MS, ppm									
Rb	15	15	25	16	23	27	26	25	24
Ba	685	630	1030	835	1050	1075	1025	1100	1070
Nb	13	12	58	12	52	52	55	53	53
Sr	640	681	960	656	927	967	938	993	982
Zr	133	121	214	124	196	197	208	196	201
Y	24	22	25	23	23	24	24	24	23
Cs	<1	<1	<1	<1	<1	<1	<1	<1	<1
Hf	4	4	6	3	5	6	6	5	6
La	34	32	62	36	57	63	60	64	62
Ta	1	1	5	1	5	4	5	5	5

Flow Sample	VR-1016-1	VR-1016-2	Qb VR-1016-9	VR-1016-11	VR-1016-16
long. (°W) lat. (°N)	113.373 37.180	113.373 37.180	113.349 37.191	113.338 37.195	113.331 37.194
X-Ray Fluorescence Analyses, wt.%					
SiO_2	45.00	44.93	45.03	49.30	44.69
TiO_2	2.21	2.23	2.16	1.39	2.14
Al_2O_3	13.06	13.16	13.08	14.76	12.72
Fe_2O_3	12.52	12.47	12.27	11.89	12.22
MnO	0.18	0.18	0.18	0.17	0.18
MgO	10.51	10.85	10.53	8.15	10.66
CaO	10.72	10.64	10.90	8.91	10.46
Na_2O	3.17	3.00	3.54	3.05	3.34
K_2O	1.40	1.53	0.96	1.02	1.37
P_2O_5	0.72	0.76	0.75	0.32	0.74
Cr_2O_3	0.05	0.05	0.04	0.03	0.05
Total	99.51	99.81	99.50	98.62	98.45
ICP-MS, ppm					
Rb	20	21	13	15	22
Ba	1020	981	969	626	982
Nb	50	49	50	12	48
Sr	1135	997	982	632	959
Zr	202	199	198	127	203
Y	25	24	24	22	23
Cs	<1	<1	<1	<1	<1
Hf	6	6	6	4	6
La	59	58	57	30	55
Ta	5	5	5	1	5

Notes: Samples located outside Hurricane quadrangle are marked with an *.
Sample locations are based on North American Datum of 1983.

Map Unit Descriptions

(Note: an abbreviated one- or two-letter map symbol is used for some units in congested parts of the map.)

QUATERNARY

Alluvial deposits

Qal_1 **Modern alluvial deposits** - Moderately to well-sorted sand, silt, clay and local pebble to boulder gravel; includes river-channel, floodplain, and local small alluvial-fan and colluvial deposits; includes minor terraces up to 10 feet (3 m) above current base level; generally 0 to 10 feet (0-3 m) thick.

Qal_{2-7} **Stream-terrace deposits** - Moderately to well-sorted sand, silt, and pebble to boulder gravel that forms isolated, level to gently sloping surfaces above modern drainages; subscript denotes relative ages and heights above modern drainages; level 7 deposits are in excess of 300 feet (92 m); level 6 deposits are 190 to 270 feet (58-82 m); level 5 deposits are 140 to 190 feet (43-58 m); level 4 deposits are 90 to 140 feet (27-43 m); level 3 deposits are 30 to 90 feet (9-27 m); and level 2 deposits are about 10 to 30 feet (3-9 m) above modern drainages; deposited principally in river-channel and floodplain environments; truncates older alluvial-fan deposits (Qafo); 0 to 30 feet (0-9 m) thick.

Qaf_1, Qaf_2

Alluvial-fan deposits - Poorly to moderately sorted boulder- to clay-size sediment deposited at the base of the Hurricane Cliffs and locally at the mouths of active drainages; level 2 deposits form deeply incised surfaces up to 30 feet (9 m) above active drainages; 0 to 50 feet (0-15 m) thick.

Qafo **Older alluvial-fan deposits** - Poorly to moderately sorted sand to boulder deposits that form broad, deeply dissected surfaces north of the Virgin River; deposits west of LaVerkin Creek contain common Pine Valley intrusive clasts, some in excess of 10 feet (3m) in diameter, and are 0 to 40 feet (0-12 m) thick; deposits sourced in the LaVerkin Creek drainage contain common Permian clasts but lack PVI clasts and are in excess of 160 feet (49 m) thick.

Colluvial deposits

Qc, Qco **Colluvial deposits** - Poorly to moderately sorted, angular, clay- to boulder-size, locally derived material deposited by slopewash, soil creep, and debris flows; locally includes talus, alluvial, and eolian deposits; older colluvial deposits (Qco) form incised, largely inactive surfaces; 0 to 30 feet (0-9 m) thick.

Eolian Deposits

Qe **Eolian-sand deposits** - Well- to very well-sorted, very fine- to medium-grained, well-rounded, frosted quartz sand; derived principally from the Navajo and Kayenta Formations; underlain by thick pedogenic carbonate in most areas; deposited as an irregular blanket from 0 to 20 feet (0-6 m) thick.

Qe_2 **Older eolian-sand and caliche deposits** - Pedogenic carbonate with lesser eolian sand that forms planar surfaces atop the Ivans knoll flow; 0 to 10 feet (0-3 m) thick.

Human-made deposits

Qf **Artificial fill** - Fill used to create roadbeds and building foundations. Consists of engineered fill and general borrow material. Although only a few deposits are mapped, fill should be anticipated in all developed areas, many of which are shown on the topographic base map; thickness variable.

Qfl **Landfill deposits** - Common trash and general borrow material; thickness variable.

Qfm **Mine-dump deposits** - Waste rock from mining; thickness variable.

Mass-movement deposits

Qms **Landslide deposits** - Very poorly sorted, clay- to boulder-size, locally derived material deposited principally by rotational slump processes; commonly characterized by hummocky topography, numerous internal scarps, and chaotic bedding attitudes; failure planes occur most commonly in Petrified Forest, Shnabkaib, upper red, Woods Ranch, and Iron Springs strata; the slides themselves incorporate these and overlying map units; thickness highly variable.

Qmt **Talus deposits** - Very poorly sorted, angular boulders and lesser fine-grained interstitial sediments; locally derived material deposited by rock-fall processes at the base of Sandstone Mountain; several tens of feet thick.

Qmsm, Qmsc, Qmsb

Older landslide deposits - Deeply dissected, chaotically oriented blocks up to tens-of-feet in length; "m" represents deposits principally in Moenave strata, "c" in Co-op Creek strata, and "b" in basaltic strata; variable thickness.

Mixed-environment deposits

Qac, Qaco

Alluvial and colluvial deposits - Poorly to moderately sorted, clay- to boulder-size, locally derived sediments deposited in swales and small drainages; gradational with alluvial and colluvial deposits; older deposits (Qaco) form incised, inactive surface on footwall of Hurricane fault zone; generally less than 20 feet (6 m) thick.

Qae, Qaeo

Alluvial and eolian deposits - Poorly to moderately sorted, locally gypsiferous, clay- to boulder-size sediments, with well-sorted eolian sand and reworked eolian sand; younger (Qae) deposits are found in modern channels and broad depressions; older (Qaeo) deposits commonly have a well-developed pedogenic carbonate and form incised, inactive, gently sloping surfaces about 20 feet (6 m) above modern drainages; generally less than 30 feet (9 m) thick.

Qaeg **Older gypsiferous alluvial and eolian deposits (Qaeg)** - Poorly to moderately sorted, gypsiferous, clay- to boulder-size sediments, with well-sorted eolian sand and reworked eolian sand; forms deeply dissected deposits that weather to a soft, white, powdery, gypsiferous soil; generally less than 30 feet (9 m) thick.

Qaec **Alluvial, eolian, and colluvial deposits** - Poorly to moderately sorted, clay- to small boulder-size sediments, with well-sorted eolian sand and reworked eolian sand; deposited in modern channels and swales; generally less than 20 feet (6 m) thick.

Stacked-unit deposits

Qe/Qafo

Eolian sand over older alluvial-fan deposits - Well-sorted eolian sand deposits over older alluvial-fan deposits.

Basaltic flows and related deposits

Qbm **"Remnants" flow** - Medium-gray, medium-grained olivine basalt that caps Mollies Nipple; about 25 feet (7.5 m) thick.

Qbi, Qbic, Qbie, Qbig

Ivans Knoll flow, cinder cone, and associated deposits - Medium-gray, fine- to medium-grained olivine basalt (Qbi) that forms highland immediately south of Volcano Mountain; also exposed at entrance to Timpoweap Canyon and southward along Hurricane Cliffs where it is up to 170 feet (52 m) thick and offset along Hurricane fault zone; includes pillow basalts at base of flow near Timpoweap Canyon; dated at 353,000 +/- 45 ka (Sanchez, 1995). Qbic denotes small cinder deposits of remnant cone; Qbie denotes partial cover of eolian sand and pedogenic carbonate up to several feet thick; Qbig denotes ancestral Virgin River gravels, which underlie flow, up to about 20 feet (6 m) thick.

Qbt **Toquerville flow** - Medium-light-gray, medium- to coarse-grained basalt or borderline trachy-basalt with sparse olivine and abundant plagioclase phenocrysts; generally 20 to 30 feet (6-9 m) thick, but is in excess of 120 feet (37 m) thick where it fills ancestral Ash Creek drainage.

Qber, Qberc

East Reef flow and cinder cone - Medium-dark-gray, fine-grained basanite (Qber) about 25 to 30 feet (7.5-9 m) thick. Qberc denotes cinder cone with moderately well-developed rill erosion.

Qbd **The Divide flow** - Dark-gray, very fine-grained olivine basanite; probably 20 to 30 feet (6-9 m) thick.

Qbgw **Gould Wash flow** - Dark-gray, very fine-grained olivine basalt; generally 20 to 30 feet (6-9 m) thick.

Qbp, Qbpc, Qbpe

"Cinder pits" flow, cinder cone, and associated deposits - Medium- to dark-gray, fine-grained olivine basalt (Qbp). Qbpc denotes cinder cone complex with moderately well-developed rill erosion; Qbpe denotes partial cover of eolian sand and pedogenic carbonate up to several feet thick.

Qbr, Qbrc, Qbre

"Radio tower" flow, cinder cone, and associated deposits - Medium- to dark-gray, fine-grained olivine basalt to borderline basanite (Qbr). Qbrc denotes cinder cone complex with moderately well-developed rill erosion; Qbre denotes partial cover of eolian sand and pedogenic carbonate up to several feet thick.

Qbv_1, Qbv_2, Qbvc, Qbv_1e, Qbv_2e

Volcano Mountain flows, cinder cone, and associated deposits - Divisible into two flows in the Hurricane quadrangle, and a third in the adjacent Harrisburg Junction quadrangle. The youngest, Qbv_1, flow is a medium- to dark-gray, fine-grained olivine basanite dated at 258 +/- 24 ka (Sanchez, 1995) whereas the underlying Qbv_2 flow is medium-gray, medium- to coarse-grained basalt; both flows are about 35 to 45 feet (11-14 m) thick and form very rough, blocky surfaces partially covered with eolian sand and pedogenic carbonate (Qbv_1e, Qbv_2e) up to several feet thick. Qbvc denotes cinder cone with moderately well-developed rill erosion.

Qb, Qbc, Qbe

Basaltic flows and associated deposits, undifferentiated - Isolated basaltic flows (Qb) locally in excess of 150 feet (46 m) thick; thin, planar-bedded cinder deposits (Qbc); and basaltic flows partially covered with eolian sand and pedogenic carbonate (Qbe) up to several feet thick.

unconformity

JURASSIC and CRETACEOUS Undifferentiated

Jku **Carmel, Temple Cap, and Iron Springs Formations, undifferentiated** - Nearly vertical beds mapped in Virgin River gorge just west of Highway 9.

CRETACEOUS

Iron Springs Formation

Ki Interbedded, ledge-forming, mildly calcareous, cross-bedded, fine- to medium-grained sandstone and less resistant, poorly exposed sandstone, siltstone, and bentonitic mudstone; variously colored grayish orange, pale yellowish orange, dark yellowish orange, white, and pale reddish brown, and commonly heavily stained by iron-manganese oxides; deposited in braided-stream and floodplain environments; only about the lower 600 feet (183 m) of the formation is exposed in the quadrangle, but the formation is about 3,500 to 4,000 feet (1,067-1,220 m) thick in the area.

unconformity (K-1)

TRIASSIC and JURASSIC Undifferentiated

TrJu **Chinle and Moenave Formations, undifferentiated** - West-dipping, fault-bounded blocks of Shinarump, Petrified Forest, and Dinosaur Canyon strata at the base of the Hurricane Cliffs.

JURASSIC

Carmel Formation

Jc **Co-op Creek Member** - Laterally variable sequence of interbedded, generally thin-bedded, mudstone, siltstone, limestone, and, in the lower portion, lesser gypsum and very fine- to fine-grained sandstone; the lower portion of the member weathers to a pale yellowish gray, while the upper portion weathers to distinctly darker-yellowish-brown hues; both form steep ledgy slopes; upper portion abundantly fossiliferous with *Pentacrinus* sp. columnals, bivalves, and mollusks; deposited in a variety of shallow marine, shoreline, and sabhka environments; 130 feet (40 m) thick.

Temple Cap Formation

Jtc Interbedded, slope- and ledge-forming, moderate-reddish-brown, yellowish-gray, and light-gray mudstone, siltstone, very fine-grained silty sandstone, and lesser gypsum; a ledge-forming, light-brown to grayish-orange, calcareous, fine-grained sandstone with low-angle cross-stratification is found in the upper middle part of the formation; forms conspicuous bright-red and gray slopes that weather to soft, gypsiferous soils; gypsum is white to gray to pink and both bedded and nodular in beds up to about 4 feet (1.3 m) thick; contains several zones of thin, white to pinkish-gray chert nodules that may be silicified bentonite; 220 feet (67 m) thick.

unconformity (J-1)

Navajo Sandstone

Jn Moderate-reddish-orange to moderate-orange-pink, massively crossbedded, poorly to moderately well-cemented, well-rounded, fine- to medium-grained, frosted quartz sandstone; locally very pale orange to yellowish gray, especially in upper part; strongly jointed; lower 300 feet (90 m) forms transition zone characterized by planar-bedded, very fine- to fine-grained sandstone and silty fine-grained sandstone with thin mudstone interbeds, and less common but resistant cross-stratified sandstone; wavy bedding, dark flaser-like laminae, and soft-sediment-deformation features, including diapiric and load structures, are common in transition zone; deposited in a vast coastal and inland dune field, transition zone represents deposition in a sabhka environment; about 2,000 feet (610 m) thick.

Kayenta Formation

Jk Interbedded, thin- to medium-bedded, moderate-reddish-brown siltstone, fine-grained sandstone, and mudstone with planar, low-angle, and ripple cross-stratification; contains several thin, light-olive-gray weathering, light-gray dolostone beds; lower part generally weathers to poorly exposed, commonly gypsiferous slopes, upper part to ledges and small cliffs; deposited in fluvial, distal fluvial/playa, and minor lacustrine environments; 935 feet (285 m) thick.

Moenave Formation

Jm Moenave Formation, undivided - shown on cross section only.

Jms **Springdale Sandstone Member** - Medium to massively bedded, fine-grained or rarely medium-grained sandstone, with planar and low-angle cross-stratification, and minor, thin, discontinuous lenses of intraformational conglomerate and thin interbeds of moderate-reddish-brown or greenish-gray mudstone and siltstone; weathers to rounded cliffs and ledges; contains locally abundant petrified and carbonized fossil plant remains; host to ore deposits of the Silver Reef mining district; deposited in braided-stream and minor floodplain environments; 95 feet (25 m) thick.

Jmw **Whitmore Point Member** - Interbedded, pale-red-purple, greenish-gray, and blackish-red mudstone and claystone, and lesser moderate-reddish-brown very fine- to fine-grained sandstone and siltstone; contains several 3- to 18-inch- (8- to 120-mm-) thick, bioturbated, cherty, very light-gray to yellowish-gray dolomitic limestone beds with algal structures and fossil fish scales of *Semionotus kanabensis;* lower 25 feet (8 m) consists of brown sandstones similar to those of the Dinosaur Canyon Member; weathers to poorly exposed, brightly colored slopes; deposited in floodplain and lacustrine environments; 61 feet (18 m) thick.

Jmd, d **Dinosaur Canyon Member** - Interbedded, generally thin-bedded, moderate-reddish-brown to moderate-reddish-orange, very fine- to fine-grained sandstone, very fine grained silty sandstone, and lesser siltstone and mudstone with planar, low-angle, and ripple cross-stratification; slope forming; 200 feet (61 m) thick.

unconformity (J-0)

TRIASSIC

Tru **Moenkopi and Chinle Formations, undifferentiated**
West-dipping, fault-bounded block of Shinarump and probable upper red strata mapped at the base of the Hurricane Cliffs south of Nephis Twist.

Chinle Formation

Trcp,cp **Petrified Forest Member** - Varicolored colored bentonitic mudstone, claystone, siltstone, lesser sandstone and pebbly sandstone, and minor chert and nodular limestone; lower part contains Shinarump-like sandstone and pebbly sandstone lenses up to 40 feet (12 m) thick; mudstones weather to a "popcorn" surface and are responsible for numerous foundation problems in the area; commonly forms slumps, especially along steep hillsides; contains petrified wood, especially in the upper part of the member; deposited in a variety of fluvial, floodplain, and lacustrine environments; 400 feet (121 m) thick.

Trcs **Shinarump Conglomerate Member** - Laterally and vertically variable sequence of cliff-forming, fine- to very coarse-grained sandstone, pebbly sandstone, and minor pebbly conglomerate; clasts are subrounded quartz, quartzite, and chert; mostly thick to massively bedded with both planar and low-angle cross-stratification, although thin, platy beds with ripple cross-stratification occur locally; predominantly pale- to dark-yellowish orange; heavily stained by iron-manganese oxides, locally forming "picture stone"; contains poorly preserved petrified wood and plant trash, commonly replaced almost entirely by iron-manganese oxides; forms a prominent carapace along northeast-plunging nose of the Virgin anticline; variable thickness from about 115 to 162 feet (35-49 m) thick, probably due to paleotopography and deposition in braided-stream channels.

unconformity (Tr-3)

Moenkopi Formation

Trm **Moenkopi Formation, undifferentiated** - West-dipping, fault-bounded blocks of lower, middle, and upper red strata mapped along the Hurricane fault zone.

Trmu, mu

Upper red member - Interbedded, mostly thin- to medium-bedded, moderate-reddish-orange to moderate-reddish-brown siltstone, mudstone, and very fine- to fine-grained sandstone with planar, low-angle, and ripple cross-stratification; forms ledgy slopes and cliffs; includes a prominent, medium to massively bedded, cliff-forming, 108-foot- (33-m-) thick, pale-yellowish-orange to grayish-orange, fine-grained sandstone (the "Purgatory Sandstone") with both planar and low-angle cross-stratification; deposited in a tidal-flat environment; 400 feet (121 m) thick.

Trms, ms

Shnabkaib Member - Forms "bacon striped," ledgy slopes of laminated to thin-bedded, gypsiferous, pale-red to moderate-reddish-brown mudstone and siltstone, resistant, white to greenish-gray gypsum and lesser thin, laminated, light-gray dolostone beds; gypsum occurs as laterally continuous, massive beds, finely laminated, commonly silty or muddy beds, and nodular intervals that range from less than one inch to about 9 feet (0.01 to 3 m) thick; gypsum also occurs as secondary cavity fillings and cross-cutting veins; weathers to soft, punky, gypsiferous soils; deposited in a variety of supratidal, intertidal, and subtidal environments on a broad, coastal shelf of very low relief; estimated to be about 600 to 700 feet (182-212 m) thick.

Trmm, mm

Middle red member - Interbedded, laminated to thin-bedded, moderate-reddish-brown to moderate-reddish-orange siltstone, mudstone, and very fine-grained sandstone; white to greenish-gray gypsum beds and veins are common, especially in the lower part of the member; deposited in a tidal-flat environment; about 400 to 500 feet (121-151 m) thick.

Trmv, mv

Virgin Limestone Member - Very pale-orange to yellowish-gray, finely crystalline limestone and silty limestone, light-gray to light-olive-gray coarsely crystalline fossiliferous limestone with locally abundant circular and five-sided crinoid columnals, gastropods, and brachiopods, and siltstone and mudstone; contains three prominent limestone ledges, separated by poorly exposed mudstone slopes; deposited in a variety of shallow-marine environments; 100 feet (30 m) thick.

Trml, ml

Lower red member - Interbedded, laminated to thin-bedded, moderate-reddish-brown mudstone and siltstone with local, thin, laminated, light-olive-gray gypsum beds and veinlets; deposited in a tidal-flat environment; about 250 feet (76 m) thick.

Trmt, mt

Timpoweap Member - Lower part consists of light-brown weathering, light-gray to grayish-orange, thin- to thick-bedded, even-bedded limestone and cherty limestone; upper part consists of grayish orange, thin- to thick-bedded, even-bedded, very-fine grained sandstone, siltstone, and mudstone; both parts form low cliffs and ledges and form a gently undulating surface on top of the Permian-Triassic unconformity; deposited in a shallow-marine environment; 30 to 130 feet (9-40 m) thick.

Trmr, mr

Rock Canyon Conglomerate Member - Consists of two main rock types: a pebble to cobble, clast-supported conglomerate with rounded chert and minor limestone clasts derived from Harrisburg strata, which was deposited in paleovalleys and is 0 to at least 80 feet (0-24 m) thick; and a widepsread but thin angular breccia that varies from 0 to 10 feet (0-3 m) thick and probably formed as a regolith deposit on Harrisburg strata.

unconformity (Tr-1)

PERMIAN

Pu **Toroweap and Kaibab Formations, undifferentiated** - Fault-bounded, highly fractured and brecciated blocks of Toroweap and Kaibab strata mapped along the Hurricane fault zone.

Kaibab Formation

Pk Kaibab Formation, undivided - shown in cross section only.

Pkh **Harrisburg Member** - Laterally variable sequence of mostly slope-forming, interbedded, medium- to very thick-bedded, laminated and massive gypsum, gypsiferous mudstone, and thin- to thick-bedded limestone and cherty limestone; contains a resistant, cliff- and ledge-forming medial white chert and limestone interval; deposited in a complex sequence of shallow-marine and sabhka environments; 100 to 160 feet (30-49 m) thick.

Pkf **Fossil Mountain Member** - Lithologically uniform, light-gray, thick- to very thick-bedded, even-bedded, fossiliferous limestone and cherty limestone; "black-banded" due to abundant reddish-brown, brown, and black chert; forms prominent cliff; deposited in a shallow-marine environment; 208 to286 feet (63-87 m) thick.

Toroweap Formation

Ptw, w **Woods Ranch Member** - Interbedded, laterally variable, slope-forming, yellowish-gray to light-gray, laminated to thin-bedded dolostone and similarly bedded black chert, massive gypsum and gypsiferous mudstone, limestone, and collapse breccia; local intraformational conglomerate or breccia at base; deposited in a complex sequence of shallow-marine and sabhka environments; 130 to 200 feet (40-61 m) thick.

Ptb, b **Brady Canyon Member** - Lithologically uniform, light- to medium-gray, medium- to coarse-grained, thick- to very thick-bedded, even-bedded fossiliferous limestone and cherty limestone; forms prominent cliff; deposited in a shallow-marine environment; 160 to 230 feet (49-70 m) thick.

Pts, s **Seligman Member** - Yellowish-brown, planar-bedded, locally gypsiferous, very fine-grained sandstone and siltstone; slope-forming; deposited in sabhka and nearshore environments; 30 to 50 feet (9-15 m) thick.

Queantoweap Sandstone

Pq Yellowish-brown, massively bedded to cross-bedded, very fine- to fine-grained noncalcareous sandstone; forms steep slopes; deposited in a shallow-marine environment; only upper 200 feet (61 m) exposed.

Subsurface Units

Pzu Paleozoic, undivided - shown in cross section only.