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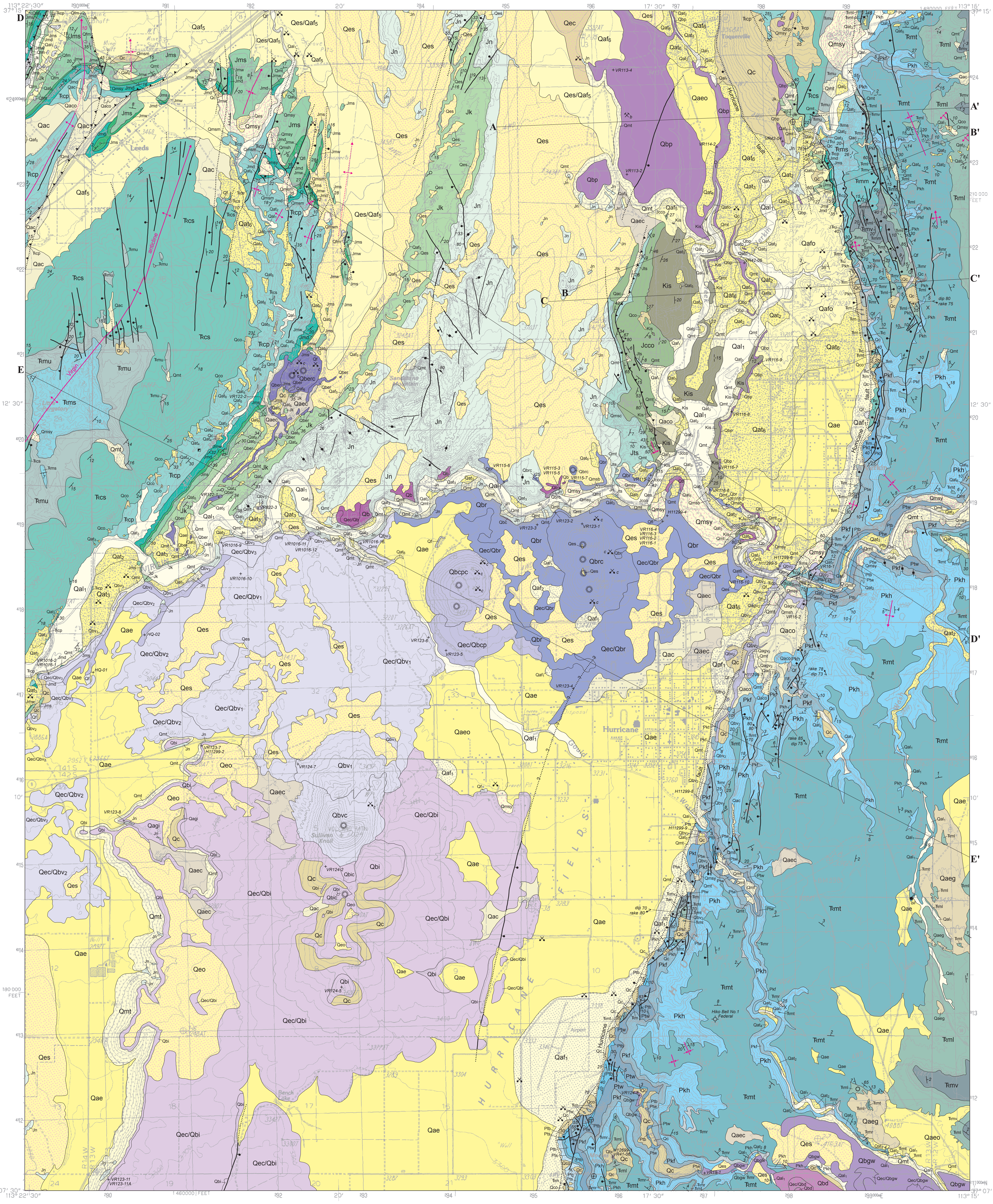
Plate 1
Utah Geological Survey Map 187
Geologic Map of the Hurricane 7.5' Quadrangle



Base from U.S. Geological Survey,
Hurricane 7.5' provisional quadrangle, 1986

SCALE 1:24,000

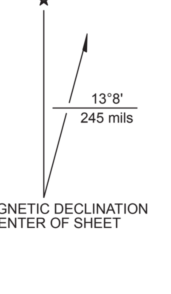
1 0.5 0 1 MILE

1000 0 1000 2000 3000 4000 5000 6000 7000 FEET

1 0.5 0 1 KILOMETER

CONTOUR INTERVAL 40 FEET
SUPPLEMENTAL CONTOUR INTERVAL 20 FEET
DATUM IS MEAN SEA LEVEL

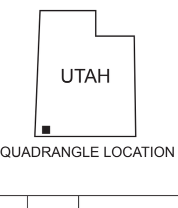
Field work by author in 1997-98
Grant C. Willis, Project Manager
Digital cartography by James Parker and Kent D. Brown,
Utah Geological Survey, and
Southern Utah University GIS/GPS Program,
David J. Maxwell, Director



2002 MAGNETIC DECLINATION
AT CENTER OF SHEET

GEOLOGIC MAP OF THE HURRICANE 7.5' QUADRANGLE
WASHINGTON COUNTY, UTAH

by
Robert F. Biek
2002



QUADRANGLE LOCATION

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

ADJOINING 7.5' QUADRANGLE NAMES

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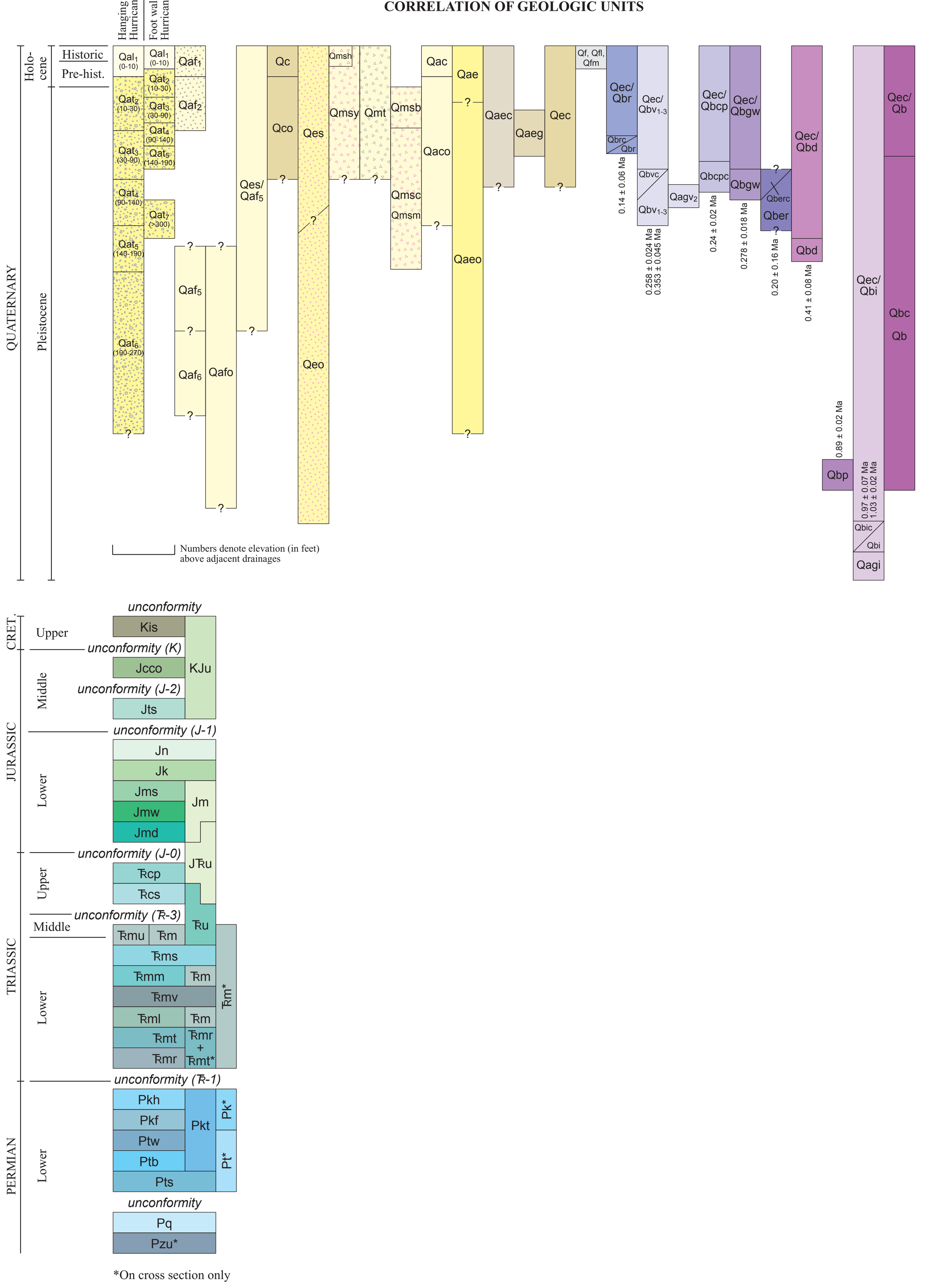
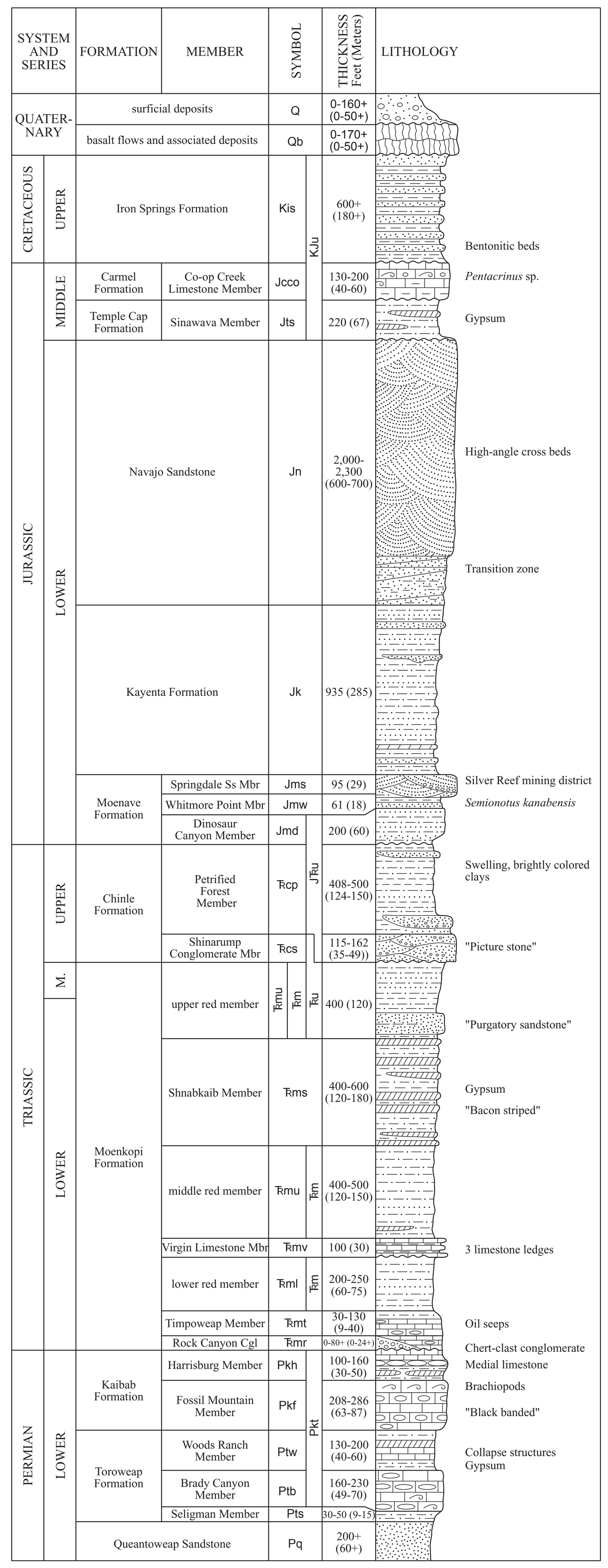
CORRELATION OF GEOLOGIC UNITS



*Cross section only

LITHOLOGIC COLUMN



DESCRIPTION OF GEOLOGIC UNITS

COL1PLACEHOLDER

Basaltic flows and related deposits

Qbr, Qbrc, Qec/Qbr — "Radio tower" flow, cinder cones, and associated deposits - Medium- to dark-gray, fine-grained olivine basalt to borderline basanite (Qbr); yielded an $^{40}Ar/^{39}Ar$ age of 0.14 ± 0.06 Ma; up to 180 feet (55 m) thick where it fills ancestral Virgin River channel. Qbrc denotes cinder cone complex with moderately well-developed rill erosion. Qec/Qbr denotes partial cover of eolian sand and pedogenic carbonate up to several feet thick.

Qbv_1, Qbv_2, Qbvc, Qec/Qbv_1, Qec/Qbv_2, Qec/Qbv_3, $Qagv_2$ — "Volcano Mountain" flows, cinder cone, and associated deposits - Divisible into three flows in the Hurricane quadrangle. The youngest flow, Qbv_1, is a medium- to dark-gray, fine-grained olivine basanite, whereas the underlying Qbv_2 flow is medium-gray, medium- to coarse-grained basalt; Qbv_1 and Qbv_2 flows yielded $^{40}Ar/^{39}Ar$ ages of 0.258 ± 0.024 Ma and 0.353 ± 0.045 Ma, respectively (Sanchez, 1995); both flows are generally 35 to 45 feet (11-14 m) thick and form very rough, blocky surfaces partially covered with eolian sand and pedogenic carbonate (Qec/Qbv_1, Qec/Qbv_2) up to several feet thick; the Qbv_2 flow is up to 170 feet (50 m) thick where it fills the ancestral Virgin River channel. $Qagv_2$ denotes ancestral Virgin River gravels up to about 20 feet (6 m) thick under the Qbv_2 flow. The Qbv_3 flow is a dark-gray, very fine-grained olivine basalt 0 to 100 feet (0-30 m) thick, whose upper surface is beveled flat by Virgin River erosion and locally concealed by eolian sand and pedogenic carbonate (Qec/Qbv_3). Qbvc denotes cinder cone, breached by the Qbv_1 flow, with moderately well-developed rill erosion.

Qbcpc, Qec/Qbcp — "Cinder pits" flow, cinder cones, and associated deposits - Medium- to dark-gray, fine-grained olivine basalt (mapped as Qec/Qbcp due to partial cover of eolian sand and pedogenic carbonate up to several feet thick); yielded an $^{40}Ar/^{39}Ar$ age of 0.24 ± 0.02 Ma. Qbcpc denotes cinder cone complex with moderately well-developed rill erosion.

Qbgw, Qec/Qbgw — Gould Wash flow and associated deposits - Dark-gray, very fine-grained olivine basalt; generally 20 to 30 feet (6-9 m) thick. Yielded an $^{40}Ar/^{39}Ar$ age of 0.278 ± 0.018 Ma (Downing, 2000). Qec/Qbgw denotes partial cover of eolian sand and pedogenic carbonate up to several feet thick.

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

Qbd, Qec/Qb — The Divide flow and associated deposits - Dark-gray, very fine-grained olivine-bearing basanite; about 20 to 30 feet (6-9 m) thick. Yielded an $^{40}Ar/^{39}Ar$ age of 0.41 ± 0.08 Ma (Higgins, 2000). Qec/Qbd denotes partial cover of eolian sand and pedogenic carbonate up to several feet thick.

Qbp — Pintura flow - Medium-light-gray, medium- to coarse-grained basalt or trachybasalt with sparse olivine and abundant plagioclase phenocrysts; yielded five $^{40}Ar/^{39}Ar$ ages of about 850,000 years; 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. Erupted from a vent near Pintura about 12 miles (19 km) north of the Virgin River.

Qbi, Qbic, Qec/Qbi, Qagi — 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 Mollies Nipple; yielded two $^{40}Ar/^{39}Ar$ ages of 0.97 ± 0.07 and 1.03 ± 0.02 Ma. Qbic denotes small cinder deposits of remnant cone. Qec/Qbi denotes partial cover of eolian sand and pedogenic carbonate up to several feet thick. Qagi denotes ancestral Virgin River gravels under flow that are up to about 20 feet (6 m) thick.

Qb, Qbc, Qec/Qb — Basalt flows and cinder deposits, undivided and associated deposits - Isolated basalt flows (Qb) and cinder deposits (Qbc) of uncertain correlation along the Virgin River; Qec/Qb denotes partial cover of eolian sand and pedogenic carbonate up to several feet thick.

unconformity

CRETACEOUS and JURASSIC Undifferentiated

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

CRETACEOUS

Kis — Iron Springs Formation - 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 locally heavily stained by iron-manganese oxides; deposited in braided-stream and flood-plain environments; only about the lower 600 feet (180 m) of the formation is exposed in the quadrangle, but the formation is about 3,500 to 4,000 feet (1,100-1,200 m) thick in the area.

unconformity (K)

JURASSIC and TRIASSIC Undifferentiated

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

JURASSIC

Carmel Formation

Jcco — Co-op Creek Limestone Member - Interbedded, generally thin-bedded mudstone, siltstone, limestone, and, in the lower portion, minor gypsum; the lower portion of the member weathers to a pale yellowish gray, whereas 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 sabkha environments; 130 to 200 feet (40-60 m) thick.

Temple Cap Formation

Jts — Sinawava Member - 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 present in the upper middle part of the formation; forms conspicuous bright-red and gray ledgy 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 white to pinkish-gray chert nodules in lower part; about 220 feet (67 m) thick.

unconformity (J-1)

Jn — Navajo Sandstone - Moderate-reddish-orange to moderate-orange-pink, massively cross-bedded, 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 siltstone interbeds, and less common but resistant cross-stratified sandstone; wavy bedding, dark flaser-like laminae, and soft-sediment-deformation features, including flame and load structures, are common in transition zone; deposited in a vast coastal and inland dune field; transition zone represents deposition in a sabkha environment; about 2,000 to 2,300 feet (600-700 m) thick.

Jk — Kayenta Formation - 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 dolomite 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 very thick-bedded, yellowish-gray to pale-pink, 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; hosts ore deposits of the Silver Reef mining district; deposited in braided-stream and minor flood-plain environments; about 95 feet (29 m) thick.

Jmw — Whitmore Point Member - Thin-bedded, 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-thick (7-48 cm), bioturbated, cherty, very light-gray to yellowish-gray dolomitic limestone beds with algal structures and fossil fish scales of *Semionotus kanabensis*; lower 25 feet (7.5 m) consists of brown sandstone similar to that of the Dinosaur Canyon Member; weathers to poorly exposed, brightly colored slopes; deposited in flood-plain and lacustrine environments; 61 feet (18 m) thick.

Jmd — 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; mostly slope forming; 200 feet (60 m) thick.

unconformity (J-0)

TRIASSIC

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

Chinle Formation

Ʀcp — Petrified Forest Member - Varicolored, typically gray to purple, 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; mudstone weathers to a "popcorn" surface and causes foundation problems; commonly forms slumps, especially along steep hillsides; contains petrified wood, especially in the upper part of the member; deposited in a variety of fluvial, flood-plain, and lacustrine environments; about 408 to 500 feet (124-150 m) thick.

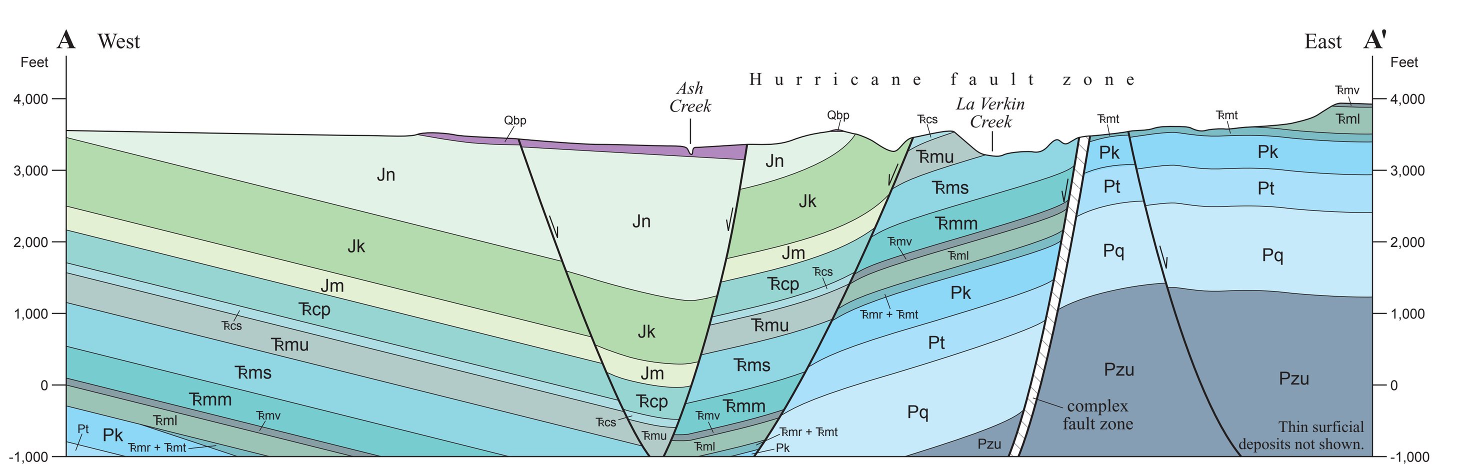
Ʀcs — Shinarump Conglomerate Member - Laterally and vertically variable, cliff-forming, pale to dark yellowish orange, fine- to very coarse-grained sandstone, pebbly sandstone, and minor pebbly conglomerate; clasts are subrounded quartz, quartzite, and chert; mostly thick to very thick-bedded with both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

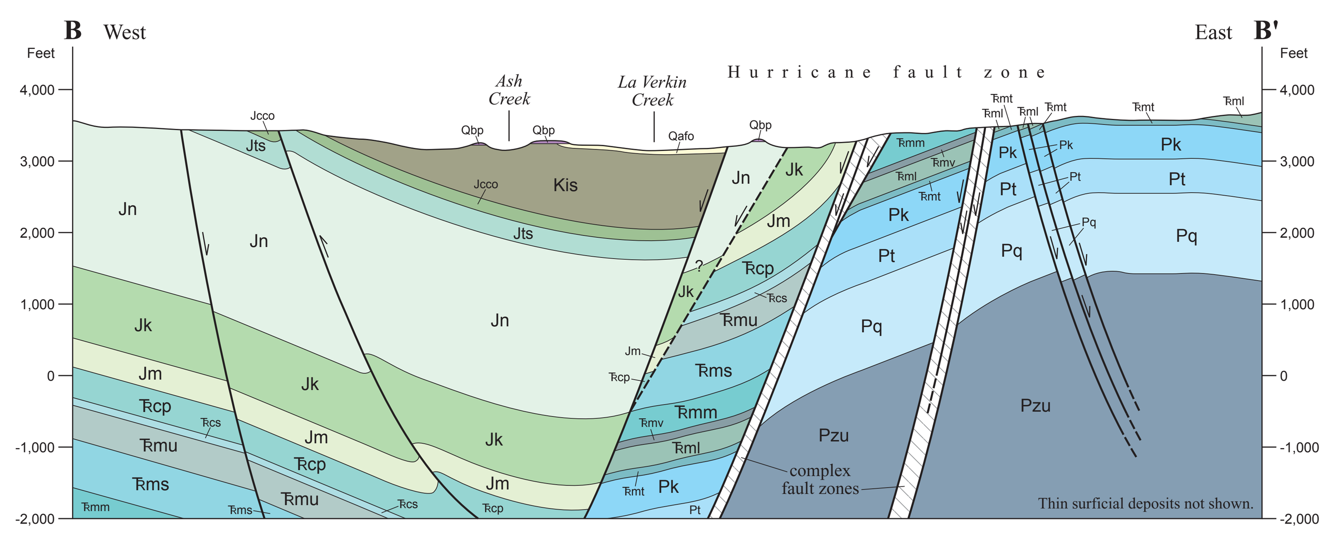
unconformity (Ʀ-3)

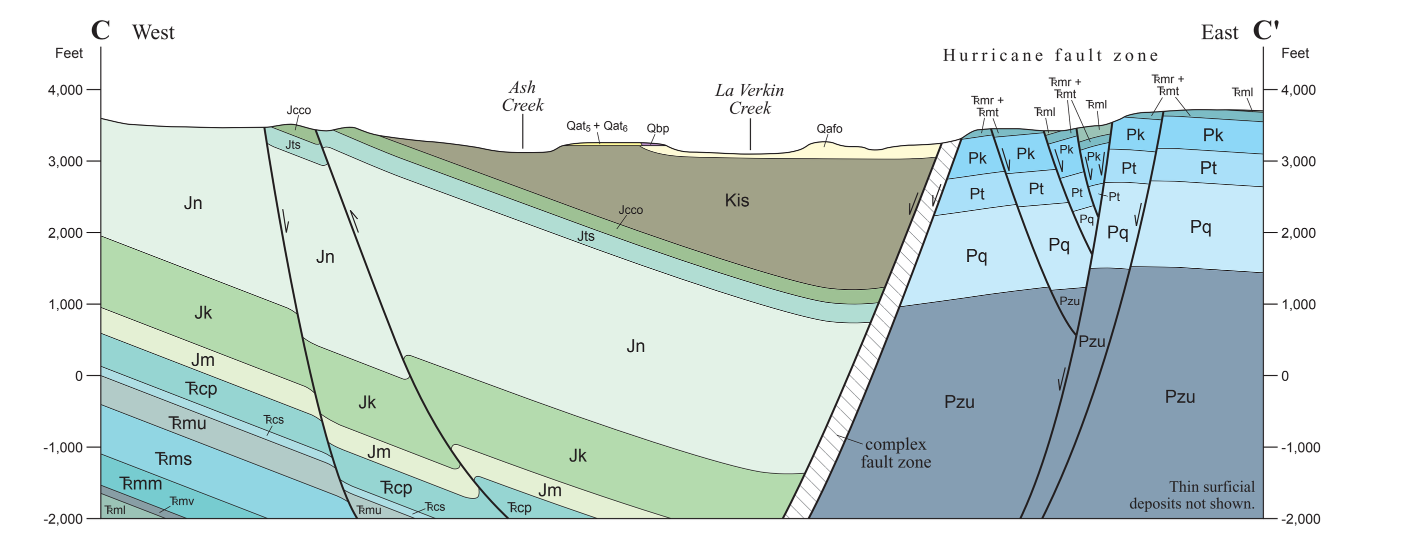
Moenkopi Formation

Ʀm — Moenkopi Formation, undifferentiated - West-dipping, fault-bounded blocks of lower, middle, and upper red strata along the Hurricane fault zone. Also used on cross section.

Ʀmu — Upper red member - Interbedded, mostly thin- to medium-bedded, moderate-reddish-orange to moderate-reddish-brown siltstone, mudstone, and very fine- to fine-grained COL4PLACEHOLDER

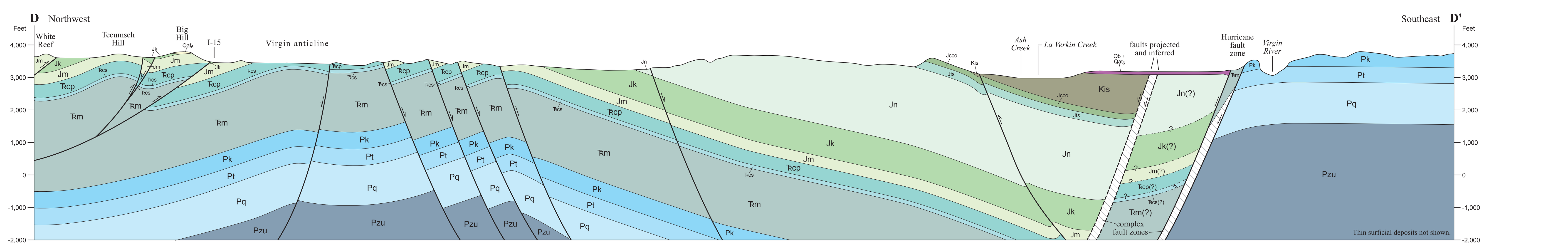


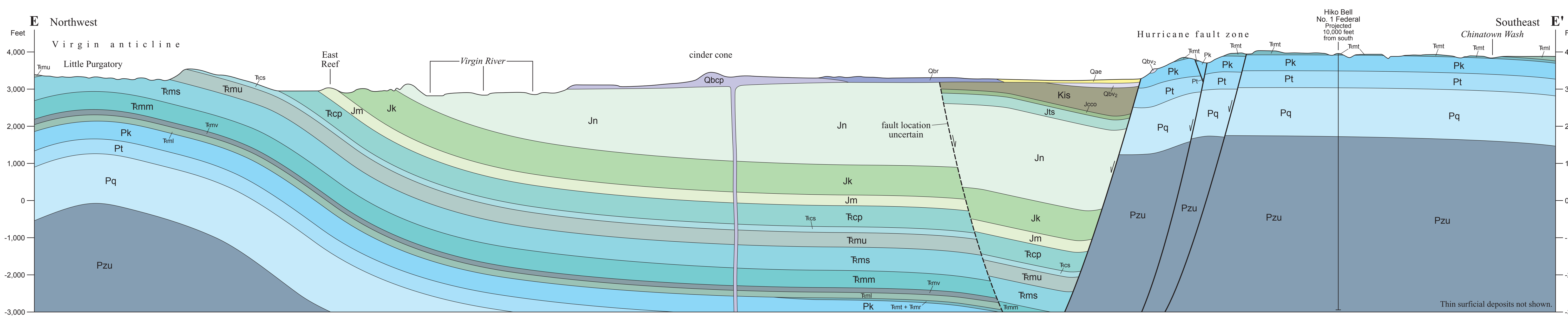




GEOLOGIC SYMBOLS

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





GEOLOGIC MAP OF THE HURRICANE QUADRANGLE, WASHINGTON COUNTY, UTAH

by

Robert F. Biek

View northeast to the Volcano Mountain flow on the footwall of the Hurricane fault, at the north side of the entrance to Timpoweap Canyon.

STATEMAP Agreement No. 1434-HQ-97-AG-01797

MAP 187
Utah Geological Survey
a division of
Utah Department of Natural Resources
in cooperation with
U.S. Geological Survey
2003

UTAH GEOLOGICAL SURVEY

UTAH GEOLOGICAL SURVEY

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The UGS Library is open to the public and contains many reference works on Utah geology and many unpublished documents on aspects of Utah geology by UGS staff and others. The UGS has several computer databases with information on mineral and energy resources, geologic hazards, stratigraphic sections, and bibliographic references. Most files may be viewed by using the UGS Library. The UGS also manages the Utah Core Research Center which contains core, cuttings, and soil samples from mineral and petroleum drill holes and engineering geology investigations. Samples may be viewed at the Utah Core Research Center or requested as a loan for outside study.

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11/02

GEOLOGIC MAP OF THE HURRICANE QUADRANGLE, WASHINGTON COUNTY, UTAH

by

Robert F. Biek

ABSTRACT

The Hurricane quadrangle lies in the transition zone between the Colorado Plateau and Basin and Range physiographic provinces. About 8,200 feet (2,500 m) of sedimentary rock ranging in age from the Early Permian Queantoweap Sandstone to the Late Cretaceous Iron Springs Formation is exposed in the quadrangle. Eight Quaternary basaltic flows or groups of flows, five cinder cone complexes, and a variety of Quaternary deposits are also present. The strata have been affected by both the Late Cretaceous Sevier orogeny and late Cenozoic extension.

The Virgin anticline, an open, upright, symmetrical, Sevier-age fold, plunges gently to the 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. A series of down-to-the-west and down-to-the-east normal faults is present on the nose of the anticline.

The Anderson Junction segment of the Hurricane fault consists of three straight sections in the quadrangle that trend due north, N. 20° E., and N. 15° W. Each of these sections 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. The intersections of these sections exhibit complex faulting in the footwall. At the entrance to Timpoweap Canyon, a 0.353 ± 0.045 Ma basalt flow is displaced about 240 feet (73 m) across the Hurricane fault, yielding a rate of stratigraphic displacement of about 8.16 inches/1,000 years (0.21 mm/yr) for this portion of the fault. Stratigraphic separation on the Hurricane fault may approach 10,000 feet (3,000 m) between Hurricane and LaVerkin, and decrease to the north to 5,000 to 6,000 feet (1,500-1,800 m) between LaVerkin and Toquerville. Tectonic displacement on the fault zone is probably about 3,600 feet (1,100 m) in the Hurricane quadrangle.

Primary geologic resources in the quadrangle include sand and gravel, cinders, building and ornamental stone, clay, and silver. The Silver Reef mining district, which includes the northwest portion of the quadrangle, produced approximately 8 million ounces (226,800 kg) of silver prior to 1910, and small amounts of gold, silver, copper, and uranium oxide between 1949 and 1968. The Navajo Sandstone and, locally, unconsolidated deposits are important groundwater sources in this arid region. Geologic hazards in the quadrangle include earthquakes, landslides, rock falls, problem soil and rock, floods, debris flows, radon, and other hazards.

INTRODUCTION

The Hurricane quadrangle covers about 60 square miles (156 km^2) 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. An important concern is that this new development is encroaching into geologically hazardous areas. Geologic hazards present in the Hurricane quadrangle and surrounding area include earthquakes, landslides and rock falls, expansive and collapsible soil and rock, flooding, and other hazards. Rapid development also puts pressure on the region's natural resources – especially scarce gravel and water, silver and other metals, and open space. This geologic map and report contain much of the basic geologic information needed to address these and other issues.

The report also contains a detailed discussion of the geologic structure and stratigraphy of the quadrangle. I hope that this map and report will prompt further field inspection and more detailed mapping of geologically hazardous areas and interesting geologic sites.

The Hurricane quadrangle lies in the transition zone between the Colorado Plateau and Basin and Range physiographic provinces. Strata in the Hurricane quadrangle are typical of the generally flat-lying rocks of the Colorado Plateau. However, locally they are cut by thrust faults and folded into the Virgin anticline and subsidiary folds by the Late Cretaceous Sevier orogeny, cut by the late Tertiary-Quaternary Hurricane fault, and partially covered by Quaternary basalt flows and cinder cones. In southwestern Utah, the transition zone encompasses the area between two major down-to-the-west normal fault zones – the Gunlock-Grand Wash faults to the west and the Hurricane fault to the east – that "step down" from the Colorado Plateau to the Basin and Range (figure 1). Displacement on the Gunlock-Grand Wash faults decreases northward whereas displacement on the Hurricane fault increases to the north. As discussed by Schramm (1994), these faults may form a displacement transfer zone, in which decreasing slip on one fault is compensated for by increasing slip on another. Such a transfer zone would account for the relatively wide width of the transition zone in southwestern Utah. The Hurricane quadrangle straddles the eastern edge of the structural block between the faults and includes the Hurricane fault. Stratigraphic separation on the Hurricane fault may approach 10,000 feet (3,000 m) in the quadrangle; tectonic displacement on the fault is probably about 3,600 feet (1,100 m).

The greater St. George area, including the Hurricane quadrangle, has been the focus of numerous topical geological investigations, many of which are cited elsewhere in this report. Dobbin (1939) prepared a small-scale geologic map for his study of the structural geology of the St. George basin. Gardner (1941) included a 1:320,000-scale geologic map with his report of the Hurricane fault 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 in his report on the geology

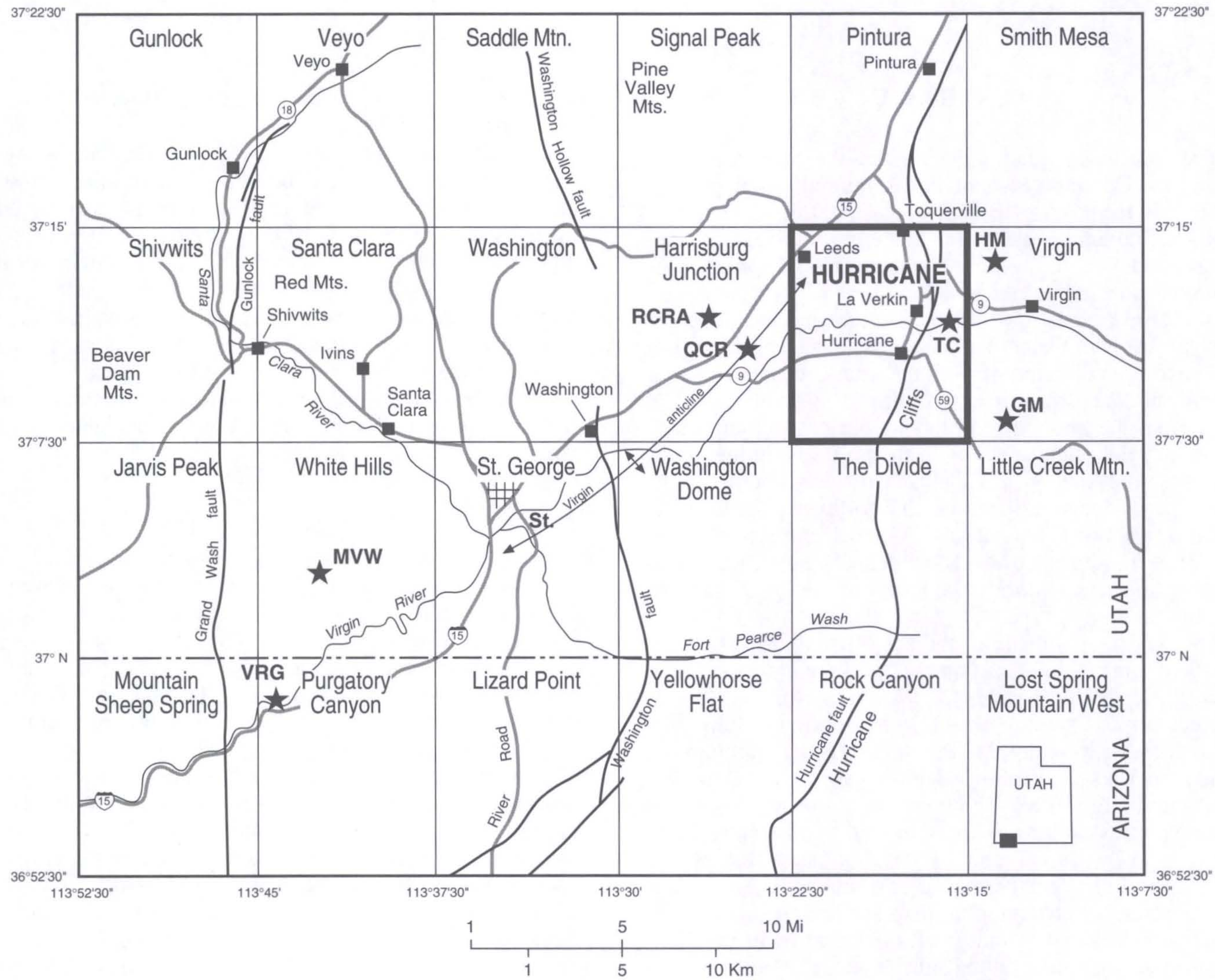

Figure 1. Location of the Hurricane and surrounding 7.5' quadrangles, and major geographic and geologic features. HM = Hurricane Mesa, GM = Gooseberry Mesa, MVW = Mountain Valley Wash, QCR = Quail Creek Reservoir, RCRA = Red Cliffs Recreation Area, TC = Timpoweap Canyon, and VRG = Virgin River Gorge.

of the Zion National Park region. Marshall (1956a, 1956b) made 1:24,000-scale photogeologic maps of the Little Creek Mountain and Virgin quadrangles, east of Hurricane. Cook (1957) mapped the Pine Valley Mountains, and later expanded that study to include the geology of all of Washington County at 1:125,000 (Cook, 1960). Nielson and Johnson (1979) mapped the lower part of the canyon east of Pah Tempe Hot Springs (locally known as Timpoweap Canyon) 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°x2° quadrangle, which includes the Hurricane quadrangle. Schramm (1994) mapped the Hurricane fault north of LaVerkin at a scale of 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 a scale of 1:52,000.

Geologic maps (1:24,000 scale) and reports are available for the following quadrangles: Gunlock (Hintze and others, 1994), Harrisburg Junction (Biek, in press), Jarvis Peak (Hammond, 1991), Pintura (Hurlow and Biek, 2000), Santa Clara (Willis and Higgins, 1996), St. George (Higgins and Willis, 1995), Shivwits (Hintze and Hammond, 1994), The Divide (Higgins, 2000), Washington (Willis and Higgins, 1995), Washington Dome (Higgins, 1998), and White Hills (Higgins, 1997) (figure 1). Billingsley (1990a, 1990b, 1992a, 1992b) published 1:24,000-scale geologic maps of the Lizard Point, Purgatory Canyon, Yellowhorse Flat, and Rock Canyon quadrangles, respectively. The 1:24,000-scale geologic maps that border the Hurricane quadrangle were completed 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

About 8,200 feet (2,500 m) of Lower Permian to Upper Cretaceous sedimentary strata is exposed in the Hurricane quadrangle, providing a record of changing environmental conditions through 275 million years of geologic time. These rocks were deposited in a variety of shallow marine, tidal-flat, sabkha, sand-desert, coastal-plain, river, and lake environments reminiscent of the modern Caribbean Sea, Gulf Coast coastal plain, Sahara Desert, and coastal Arabian Peninsula, among other places. Hintze (1993), Biek (1999, 2000), and Biek and others (2000a) provided popular narrative histories of these units.

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 represent a partly eroded fault scarp developed principally in overlying Permian Toroweap and Kaibab strata, with slivers of west-dipping Triassic Moenkopi beds caught up in the fault zone. North of LaVerkin and south of Stewart and Taylor's (1996) fault segment boundary, the fault zone is more complex, but exhibits a nearly complete section of the Moenkopi Formation and portions of the Triassic Chinle Formation, and the Jurassic Moenave, Kayenta, and Navajo Formations. Gently undulating beds of the Timpoweap Member of the Moenkopi Formation hold up the broad bench east of the Hurricane fault. 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 toward the Hurricane fault, where the youngest sedimentary strata in the quadrangle, the Upper Cretaceous Iron Springs Formation, are exposed in the Ash Creek and LaVerkin Creek drainages. Eight Pleistocene basaltic lava flows or groups of flows, erupted from five cinder cone complexes within the Hurricane quadrangle and from three additional cinder cone complexes outside the quadrangle, are also present, as are a variety of Quaternary deposits.

Permian

Queantoweap Sandstone (Pq)

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

In the Hurricane quadrangle, the Queantoweap Sandstone is exposed only along the Hurricane Cliffs west of Mollies Nipple. There, it consists of yellowish-brown, very thick-bedded to cross-bedded, very fine- to fine-grained, noncalcareous sandstone that forms steep, ledgy slopes. Queantoweap strata are highly fractured due to their proximity to the Hurricane fault, and commonly are stained by iron-manganese oxides. The upper contact is poorly exposed in the Hurricane quadrangle. I chose it 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 (60 m) of the formation is exposed in the Hurricane quadrangle. Hintze (1986) estimated Queantoweap strata to be 1,500 to 2,000 feet (450-600 m) thick to the west in the Beaver Dam Mountains, and Billingsley (1997) measured a section of 1,020 feet (311 m) in the Hurricane Cliffs, just south of the Utah-Arizona border, that is 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 Lower Permian Toroweap Formation consists of the Seligman, Brady Canyon, and Woods Ranch Members that record a major west-to-east marine trangresssion followed by a regression (McKee, 1938; Rawson and Turner-Peterson, 1979; Nielson, 1981, 1986; Sorauf and Billingsley, 1991). These units are exposed in the Hurricane Cliffs south of LaVerkin.

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

The Seligman Member changes from interbedded sandy siltstone, gypsum, sandstone, and dolomitic limestone in southern and western exposures (approximately near the Utah-Arizona border and in the Beaver Dam Mountains, respectively) to sandstone in northern exposures near Kanarraville (Nielson, 1986). Seligman strata also thin to the north and east in southwestern Utah, and in the Hurricane quadrangle they are about 30 to 50 feet (9-15 m) thick. The Seligman Member varies from 50 to 200 feet (15-60 m) thick in the Beaver Dam Mountains (Hintze, 1986). Higgins (1997) reported that the Seligman Member is 100 feet (30 m) thick to the southwest, in the Virgin River Gorge in the White Hills quadrangle. Nielson (1986) suggested that the Seligman Member in southern and western exposures was deposited in sabkha and tidal-flat environments that developed after regression of the Permian sea. Lithologies found in the Hurricane quadrangle also suggest deposition in sabkha 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): The Brady Canyon Member is the middle, cliff-forming, lithologically uniform 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, planar-bedded limestone and cherty limestone; it is dolomitic and locally sandy near the base. It contains disarticulated brachiopods, and crinoid, coral, and sponge fragments. Chert is present as large, light-grayish-brown, concentrically zoned nodules. These nodules weather dark brown, are typically about one foot (0.3 m) long parallel to bedding planes, and commonly form irregular masses. Brady Canyon strata are commonly riddled with small caves. Whereas 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, creating distinctive black-banded outcrops.

The unconformable contact between Brady Canyon and overlying Woods Ranch strata corresponds to 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 (300 m) east of the canyon entrance, about 80 feet (24 m) of relief exists 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 (Nielson, 1981; this report). Reeside and Bassler (1921) measured 200 feet (60 m) of what are now identified as Brady Canyon strata near Pah Tempe Hot Springs, at the entrance to Timpoweap Canyon. Brady Canyon strata are 250 feet (75 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): 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 in the lower reaches of Timpoweap Canyon, Gould Wash, and Frog Hollow.

The Woods Ranch Member is a laterally variable sequence of interbedded, yellowish-gray to light-gray, laminated to thin-bedded dolomite and similarly bedded black chert, gypsum and gypsiferous mudstone, limestone, and collapse breccia. Generally, the lower, thicker part consists 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 (McKee, 1938); and the thin upper part consists of gypsiferous mudstone, dolomite, and chert. The middle limestone interval thickens northward from the Utah-Arizona border to Kanarraville, where it may constitute more than half of the member; it is missing in areas of exceptional gypsum accumulation (Nielson, 1986).

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 dolomite, limy dolomite, and black nodular and ribbon chert. These beds are locally deformed along the edges of collapse structures and chaotically jumbled within the collapse structures.

A yellowish-brown intraformational conglomerate or breccia locally marks the base of the Woods Ranch Member. 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 NE1/4SE1/4SE1/4 section 10, T. 42 S., R. 13 W. Both areas are overlain by about 200 feet (60 m) of gypsum and gypsiferous mudstone and lack the limestone of the Hurricane Cliffs tongue.

The contact with the overlying Fossil Mountain Member of the Kaibab Formation appears to be conformable and gradational. I placed it at 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 dolomites are locally cliff-forming in 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 (40-60 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 (90 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. In their measured section near Pah Tempe Hot Springs, Reeside and Bassler (1921) reported only 100 feet (30 m) of strata now known as Woods Ranch, about half of the true thickness at this location. Woods Ranch strata are about 200 feet (60 m) thick in the Virgin River Gorge (Higgins, 1997). 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 sabkha 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 lower Fossil Mountain Member and the upper Harrisburg Member (Nielson, 1981; Sorauf and Billingsly, 1991). These members are exposed in the Hurricane Cliffs and in deep drainages that cut across the Hurricane bench. The Kaibab Formation is late Early Permian (Leonardian) in age (King, 1930; McKee, 1938; Rawson and Turner-Peterson, 1979; Sorauf and Billingsley, 1991).

Fossil Mountain Member (Pkf): The Fossil Mountain Member forms a prominent cliff and the sheer walls of many box canyons along the Hurricane Cliffs south of Utah Highway 9 (figure 2). It is also exposed in several drainages north of Utah Highway 9. Fossil Mountain strata consist of a lithologically uniform sequence of light-gray, thick- to very thick-bedded, planar-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, which may comprise 30 percent or more of the member. Fossil Mountain limestones are very rough weathering due to the presence of disseminated chert. Whole silicified brachiopods are characteristic of the member and are most abundant in the uppermost beds. Silicified

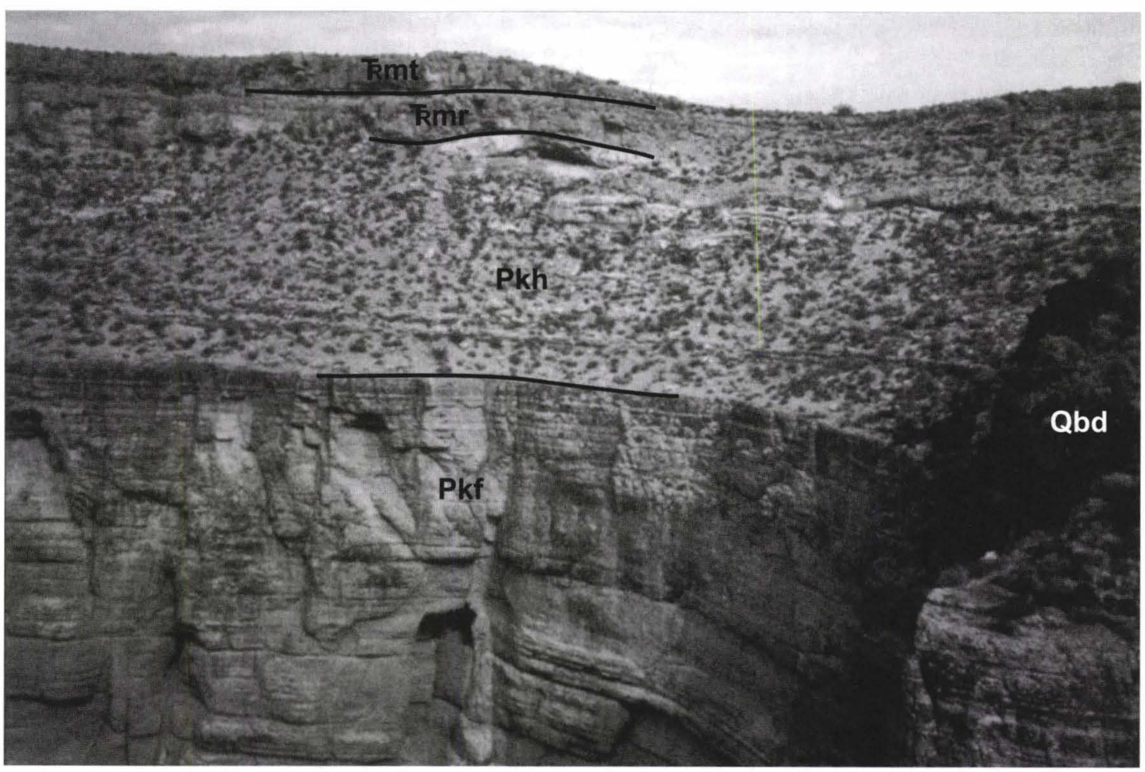

Figure 2. *View north to the head of the Frog Hollow box canyon in the SW1/4SE1/4SW1/4 section 14, T. 42 S., R. 13 W. Cliff-forming Fossil Mountain strata (Pkf) are overlain by mostly slope-forming Harrisburg strata (Pkh). Ledge-forming middle Harrisburg strata (unit 5 of Nielson, 1986) are unconformably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

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. I placed it 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).

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 total 280 feet (85 m) thick. Fossil Mountain strata are about 300 feet (90 m) thick in the Virgin River Gorge of southwestern Utah (Higgins, 1997) and 250 to 300 feet (75-90 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): Reeside and Bassler (1921) named the Harrisburg Gypsiferous Member for exposures along the southeast side of Harrisburg Dome; Sorauf (1962) later renamed it simply the Harrisburg Member. 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 in Timpoweap Canyon, immediately east of the Hurricane quadrangle (figure 1). A second section, typical of western exposures, is in Mountain Valley Wash, southwest of Bloomington (figure 1). These reference sections illustrate the rapid east-west lithologic changes characteristic of the Harrisburg Member.

The Harrisburg Member consists of slope- and ledge-forming, thin- to very thick-bedded gypsum, gypsiferous mudstone, limestone, and cherty limestone (figure 2). Nielson (1981, 1986) recognized 11 lithologic units in the Harrisburg Member, which can be grouped into a lower slope-forming interval; a middle limestone, cherty limestone, and chert interval that forms a low cliff; and an upper slope-forming interval. Interbedded, irregularly bedded, gray- to yellowish-brown, gypsiferous mudstone, gypsum, and thin limestone, cherty limestone, and dolomite characterize both the lower and upper slope-forming intervals. Intraformational breccias and minor intraformational pebbly conglomerates, probably formed as a result of gypsum dissolution, are locally present.

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. Angular, very coarse sand- to pebble-size chert clasts that form both clast- and matrix-supported limestone breccias characterize the cherty limestones. 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 consists of highly fractured nodules and lenticular beds. Nielson (1986) interpreted this distinctive white chert as a weathering horizon.

The upper contact of the Harrisburg Member is 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 incised down to, but rarely into, the middle limestone and chert unit of the Harrisburg Member (figure 2). Locally, erosion of upper, slope-forming Harrisburg strata exceeds 80 feet (24 m). As a result, the upper contact with the Rock Canyon Conglomerate Member - or where not present, the Timpoweap Member of the Moenkopi Formation - is commonly present in a ledgy or cliff-forming interval, and so is difficult to locate without careful examination. 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. During mapping, these contacts must be walked out in their entirety, even across drainages a few hundred feet wide. In a general sense, Harrisburg strata 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 (30-50 m) thick in the Hurricane quadrangle as a result of pre-Moenkopi erosion (Nielson, 1981). Reeside and Bassler (1921) assigned 150 feet (45 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 (0-90 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 sabkha environments (Nielson, 1981; 1986), and is considered to be late Early Permian (Leonardian) in age (Sorauf and Billingsly, 1991).

Toroweap and Kaibab Formations, undifferentiated (Pkt)

Due to structural complexity and alteration along the Hurricane fault, 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. I mapped two small areas east of Hurricane, which likely consist of Fossil Mountain and Woods Ranch strata, as undifferentiated Toroweap and Kaibab 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 in southwestern Utah consists of three transgressive members (the Timpoweap, Virgin Limestone, and Shnabkaib Members) each overlain by an informally named regressive 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 to early Middle 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 (Morales, 1987; Blakey, 1989; Dubiel, 1994). The transgressive members generally thicken, and the red bed members thin, from east to west across southwestern Utah. The entire Moenkopi section generally thickens westward.

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

The Hurricane Cliffs north of Utah Highway 9 contain a complete, though highly faulted, section of Moenkopi strata. At Hurricane Mesa immediately east of the Hurricane quadrangle, Moenkopi strata are about 1,500 feet (457 m) thick. The upper five members present in the Harrisburg Junction quadrangle are about 1,600 to 1,800 feet (500-550 m) thick (Biek, in press). 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. The five upper members of the Moenkopi Formation present in the Washington Dome quadrangle to the southwest are about 1,900 feet (580 m) thick (Higgins, 1998).

Rock Canyon Conglomerate Member (Ꞓmr): The Rock Canyon Conglomerate Member consists of two main rock types: a rounded pebble and cobble conglomerate that occupies paleovalleys, and a widespread, but thin, 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 in the Hurricane quadrangle are 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, in section 11, T. 42 S., R. 13 W.; and northeast of LaVerkin, in the NE1/4NE1/4SE1/4 and NW1/4SE1/4NE1/4 section 13, T. 41 S., R. 13 W. as well as in exposures to the west along the base of the Hurricane Cliffs. The best exposures of thin breccias are 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-grained sandstone matrix; small boulder-size clasts are locally common at the base of the deposits. Clasts are chert and minor limestone derived from Harrisburg Member strata. 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. Rock Canyon conglomeratic strata 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). 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.

Rock Canyon Conglomerate breccia deposits are present over paleohigh 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. Due to the scale of plate 1, I mapped only the thicker deposits. Elsewhere, unmapped Rock Canyon breccia deposits that vary from less than 1 foot to about 2 feet (<0.3-0.6 m) thick typically form the contact between Harrisburg and Timpoweap strata.

The upper contact with the Timpoweap Member is gradational, and Nielson (1991) noted that Rock Canyon strata locally interfinger with Timpoweap strata in southwestern Utah. In the Hurricane quadrangle, I placed the contact at the base of the first yellowish-brown-weathering, thin-bedded, planar-bedded, laterally extensive limestone of the Timpoweap Member (figures 2 and 3).

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 of 0 to 200 feet (0-60 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 regolith (Nielson, 1991).

Timpoweap Member (Ꞓmt): The Timpoweap Member was named by Gregory (1950) for exposures in the lower reaches of Timpoweap Canyon, although he did not 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 at the top of the Hurricane Cliffs.

The lower part of the Timpoweap Member consists of light-brown-weathering, light-gray to grayish-orange, thin- to thick-bedded, planar-bedded limestone and cherty limestone. Chert is present principally as disseminated 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 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, pla-

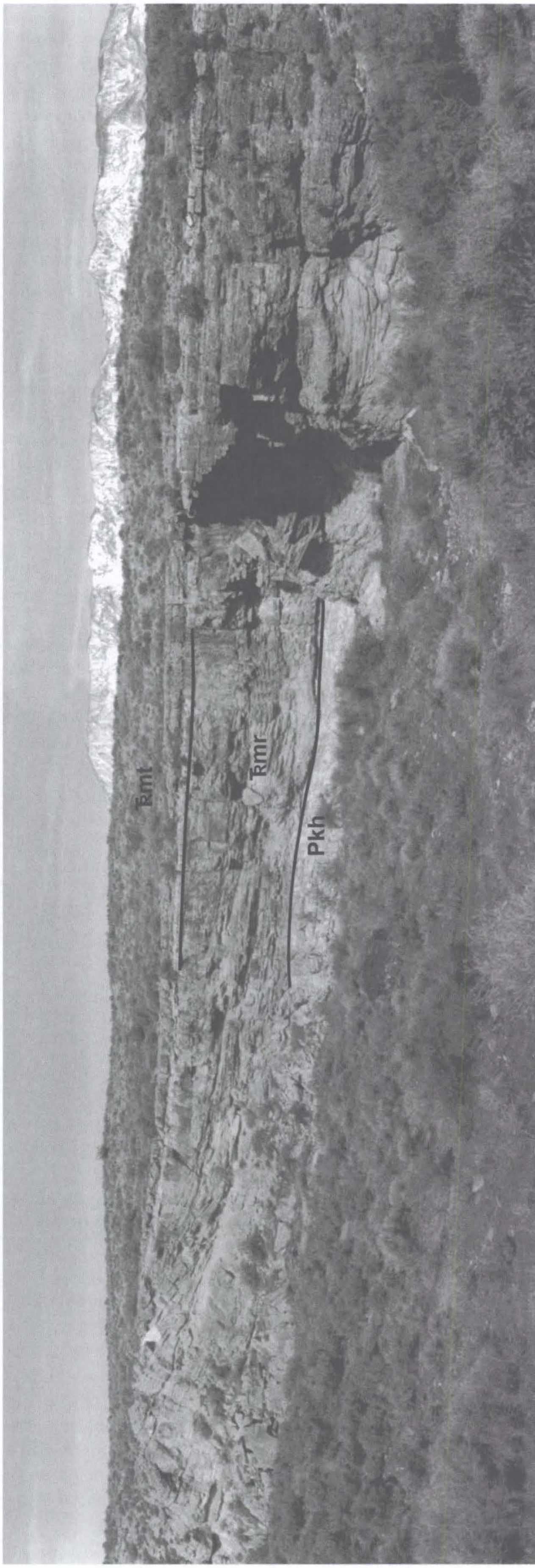

Figure 3. *View northwest in the upper reaches of Frog Hollow, in the NW¼SE¼SE¼ and NE¼SW¼SE¼ section 14, T. 42 S., R. 13 W. Note prominent, large-scale, low-angle cross-stratification of the Rock Canyon Conglomerate, which here is up to 25 feet (7.5 m) thick. Here, the Rock Canyon Conglomerate (TRmr) overlies the resistant, middle Harrisburg Member (Pkh) (unit 5 of Nielson, 1986), and is overlain by thin-bedded Timpoweap limestones (TRmt), except at the west (left) end of the photo. The Pine Valley Mountains are in the distance.*

nar-bedded, slightly calcareous, very fine-grained sandstone with both planar and ripple cross-stratification, and similarly colored, thin-bedded siltstone and mudstone. The area between Gould Wash and Frog Hollow provides the best exposures of these upper sandstone beds. I mapped an oil seep in upper Timpoweap strata in Chinatown Wash, immediately east of Utah Highway 69, and additional seeps are upstream. Other oil seeps in Timpoweap strata are known in the Virgin quadrangle to the east (Biek and others, 2000b).

The entire Timpoweap-lower red member succession is gradational and conformable in the Hurricane quadrangle. I placed the upper contact of Timpoweap strata with the lower red member at 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. Although yellowish-brown clastic strata locally intertongue with red beds of the lower red member, it is impractical to differentiate yellowish-brown, similarly colored and similarly weathering clastic and carbonate strata of the upper Timpoweap Member as suggested by Nielson and Johnson.

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. I estimate Timpoweap strata are probably about 30 to 130 feet (9-40 m) thick in the Hurricane quadrangle. The Timpoweap Member is missing along the central portion of the Virgin anticline (Nielson, 1981; Biek, in press; Higgins, 1998), but is 75 to 110 feet (23-34 m) thick farther southwest 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, filling paleotopography at the top of the Kaibab Formation (Nielson and Johnson, 1979; Nielson, 1981).

Lower red member (TRml): The lower red member is present along the base of Hurricane and Gooseberry Mesas, in the northeast and southeast corners of the quadrangle, respectively. Erosional outliers are present at Mollies Nipple and on the south side of Timpoweap Canyon; lower red strata are also present in fault-bounded blocks along the Hurricane fault.

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. I placed the upper contact of the lower red member at the base of the lowest Virgin Member limestone bed.

Based on map patterns, the lower red member is about 200 to 250 feet (60-75 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, and Biek (2002) reported lower red strata of about 280 feet (85 m) thick in the Kolob Arch quadrangle. Higgins (1998) measured thickness variations from 25 to 200 feet (8-60 m) at Washington Dome to the southwest, probably due to fault attenuation. Along the flanks of the Bloomington Dome to the southwest, lower red strata are 25 to 300 feet (8-90 m) thick, again probably due to fault attenuation (Higgins and Willis, 1995). In the White Hills quadrangle, the lower red member varies from 0 to 200 feet (0-60 m) thick due to paleotopography (Higgins, 1997). The lower red member was probably deposited in a tidal-flat environment and is disconformably overlain by the Virgin Limestone Member throughout southwestern Utah (Stewart and others, 1972; Nielson and Johnson, 1979).

Virgin Limestone Member (TRmv): 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. The member weathers to three 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.

The Hurricane quadrangle does not contain a complete, unfaulted section of the Virgin Limestone Member, but I estimate it is about 100 feet (30 m) thick in this quadrangle. Gregory (1950) reported that the member varies from 8 to 116 feet (2.5-35 m) thick in the Zion National Park region, but it is about 200 feet (60 m) thick in the Kolob Canyons part of the park (Biek, 2002). Along the southwestern flank of Harrisburg Dome, the Virgin Limestone Member is about 85 feet (26 m) thick (Biek, in press). 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, the Virgin Limestone Member is 134 feet (41 m) thick (Higgins and Willis, 1995). 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). I placed the upper contact 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): In the Hurricane quadrangle, the middle red member is exposed only in a complexly faulted section along the Hurricane Cliffs north of Utah 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.

I placed the upper contact 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 (30-90 m) thick, although the contact appears relatively straightforward in the Hurricane quadrangle.

The Hurricane quadrangle does not contain a complete, unfaulted section of the middle red member, but I estimate it is about 400 to 500 feet (120-150 m) thick in the area. Gregory (1950) reported the member is 436 to 520 feet (133-159 m) thick in the Zion National Park region. The middle red member is about 400 to 500 feet (120-150 m) thick along the southeastern flank of Harrisburg Dome (Biek, in press). 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 (120 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 (Stewart and others, 1972; Dubiel, 1994).

Shnabkaib Member (TRms): 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 ("bacon-striped") 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 in laminated to thin beds; strata with ripple cross-stratification are rarely exposed. Gypsum is present in: laterally continuous, very thick 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 1 inch to about 9 feet (0.01-3 m) thick. The Shnabkaib Member also contains thin, laminated, light-gray dolomite beds that, being more resistant than enclosing rocks, weather out, causing dolomite debris to accumulate at the surface. Shnabkaib strata weather to soft, punky, gypsiferous soils commonly covered by a delicate microbiotic crust.

The upper contact of the Shnabkaib Member is gradational. I placed it at the top of the highest thick gypsum bed, above which are 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 thickness of the Shnabkaib Member in the Hurricane quadrangle is uncertain, but it is probably 400 to 600 feet (120-180 m). Biek (in press) estimated the Shnabkaib

Member to be 600 to 700 feet (180-210 m) thick in the Harrisburg Junction quadrangle. Reeside and Bassler (1921) assigned 630 feet (192 m) to the member at Harrisburg Dome. Higgins (1998) reported that Shnabkaib strata total about 750 feet (230 m) thick in the Washington Dome quadrangle. The Shnabkaib Member is 996 feet (304 m) thick in the St. George quadrangle to the southwest (Higgins and Willis, 1995). The Shnabkaib Member thins eastward, and it is only about 300 feet (90 m) thick at Hurricane Mesa and Little Creek Mountain. 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): 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 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 very thick-bedded, 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 is present 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 very thick 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 is 108 feet (33 m) thick southeast of Quail Creek Reservoir, in the NE1/4 section 35, T. 41 S., R. 14 W. (Biek, in press), and is comparably thick in the Hurricane quadrangle.

The upper red member is about 400 feet (120 m) thick in the Hurricane quadrangle, and it is 397 feet (120 m) thick southwest of Quail Creek Reservoir (Biek, in press). To the south in the Washington Dome quadrangle, Higgins (1998) reported that upper red strata are 475 feet (145 m) thick. The upper red member is 363 feet (111 m) thick south of St. George, on the northwest flank of the Virgin anticline (Higgins and Willis, 1995). Proctor (1953) measured 376 feet (115 m) of what are now called upper red strata north of Utah 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, about twice the thickness reported by subsequent workers (Willis and Hylland, 2002; Biek, 2002). 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 (Stewart and others, 1972; Dubiel, 1994).

Moenkopi Formation, undifferentiated (TRm)

Numerous fault blocks along the Hurricane fault contain steeply west-dipping Moenkopi red beds. These blocks may contain lower, middle, or upper red member strata that cannot be readily differentiated without intervening transgressive strata.

Chinle Formation

The Chinle Formation in southwestern Utah consists of the Shinarump Conglomerate and Petrified Forest Members. The Shinarump Conglomerate forms a prominent carapace along the axial surface 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 flood-plain 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) strata 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 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 very thick bedded with both planar and low-angle cross-stratification, although thin, platy beds with ripple cross-stratification are locally present. 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 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, and major joints trend subparallel to the strike and dip of bedding. Well-developed slickensides, having 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 folding. Shinarump strata are locally 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 are 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 in part by iron-manganese oxides. Small petrified logs several feet in length are common though not abundant. Plant fragments, replaced in part by iron-manganese oxides, are also common.

The Shinarump Conglomerate varies widely in thickness. 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 this unit is 165 feet (50 m) thick (Biek, in press). Proctor (1953) measured 115 feet (35 m) of Shinarump strata along the Virgin anticline north of Utah 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, Shinarump strata vary from 5 to 200 feet (1.5-60 m) thick (Higgins, 1998); Higgins and Willis (1995) reported similar thickness variations in the St. George quadrangle. 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 exposed only along the east side 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 bright, 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, in press).

Petrified Forest Member (Ꞧcp): Some of the best and most complete exposures of Petrified Forest strata in southwestern Utah are at East Reef, along the east side of the Virgin anticline. Incomplete, fault-bounded blocks of Petrified Forest strata are also present at the base of 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 foundation problems and mass movements in the area. Petrified Forest strata commonly form rotational slides, especially where exposed along steep hillsides. In the Hurricane quadrangle, such slides are common below cliffs of Moenave strata on the northeast-plunging nose of the Virgin anticline.

As its name implies, petrified wood, locally well silicified and brightly colored, is common in the Petrified Forest Member. Petrified wood is more abundant in uppermost Petrified Forest strata and is commonly found as reworked clasts in modern stream channels. Petrified logs - typically splintery, poorly preserved, and several tens of feet long - are common in channel deposits of the middle sandstone.

Sandstones of the Petrified Forest Member exhibit a wide variation in grain size and bedding characteristics and are generally restricted to the lower and middle parts of the member. Locally, such as north of Harrisburg Flat just west of Interstate 15 in the adjacent Harrisburg Junction quadrangle, lower Petrified Forest strata include a 0- to 40-foot-thick (0-12 m), 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 (Biek, in press). Along the west 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 tens of feet of reddish-brown, slope-forming, thin-bedded siltstone and very fine-grained sandstone, which in turn are overlain by another smaller, Shinarump-like channel sandstone. Small pebble-size clasts in these sandstones are primarily chert and quartzite, and light-greenish-gray mudstone rip-up clasts are locally common. Proctor (1953), Cook (1960), and Proctor and Brimhall (1986) mapped this entire Shinarump-like sandstone sequence as the Shinarump Conglomerate. Faulting renders the true stratigraphic position of this sandstone uncertain, but it probably corresponds to the basal Petrified Forest sandstones described at the southern end of Washington Black Ridge (Biek, in press).

Very pale-orange, very thick-bedded, coarse- to very coarse-grained, pebbly sandstone that varies from about 10 to 52 feet (3-16 m) thick characterizes the middle part of the Petrified Forest Member (Stewart and others, 1972; Biek, in press). Green and yellow-ochre stains from iron, copper, and uranium mineralization are common in this sandstone. The pebbles consist of rounded chert and lesser quartzite clasts.

A silicified bed up to 1 foot (0.3 m) thick is present a few tens of feet above the medial sandstone interval. The best exposures of this bed are at Buckeye Reef, in the NE1/4NE1/4NE1/4 section 12, T. 40 S., R. 14 W., and at East Reef, in the SE1/4NW1/4SE1/4 section 19, T. 41 S., R. 13 W. This bed is moderate red to moderate reddish orange, with streaks of light greenish gray. It appears similar to a silicified peat or paleosol. This is the "agate bed" noted by Proctor (1953) and included in the informally named "Fire Clay Hill bentonitic shales" unit.

The upper contact of the Petrified Forest Member is the J-0 unconformity, which represents a gap of about 10 million years during the Late Triassic and Early Jurassic (Pipiringos and O'Sullivan, 1978). Even though the color change between Petrified Forest and overlying Dinosaur Canyon strata is prominent in the East Reef and Buckeye Reef areas, the contact is poorly exposed due to small-scale slumping and slopewash. The contact corresponds to a change from slope-forming purplish swelling mudstones with abundant light-gray to light-olive-gray limestone nodules and scattered selenite crystals below, to moderate-reddish-brown, very fine- to fine grained sandstone, silty sandstone, and lesser siltstone and mudstone above.

Stewart and others (1972) measured 408 feet (124 m) of Petrified Forest strata at East Reef. Proctor and Brimhall (1986) reported Petrified Forest strata are 446 feet (136 m) thick in the structurally and stratigraphically complex Buckeye Reef area. I estimate the Petrified Forest Member is up to 500 feet (150 m) thick in the Hurricane quadrangle. The member is estimated to be about 700 feet (210 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, flood-plain, and lacustrine environments (Dubiel, 1994). Mottled, variegated mudstones probably represent paleosols. Abundant bentonitic mudstones in the Petrified Forest Member are probably derived from alteration of volcanic ash erupted from a magmatic arc along the continental margin to the west (Dubiel, 1994).

Moenkopi and Chinle Formations, undifferentiated (T̵Ru)

A small block of undifferentiated Shinarump and probable upper red member strata is present at the base of the Hurricane Cliffs south of Nephis Twist. These west-dipping beds are caught up in the Hurricane fault 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 complexly folded and faulted on the nose of the Virgin anticline, and thrust faults duplicate the formation on the northwest flank of the anticline. Steeply southeast-dipping, but otherwise undisturbed, Moenave strata are well exposed at East Reef. Incomplete, fault-bounded exposures are also present 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 moderate-reddish-brown, uniformly colored, slope-forming, very fine grained sandstone and lesser interbedded siltstone and mudstone; the Whitmore Point Member, which consists of varicolored, thin-bedded, slope-forming claystone, mudstone, siltstone, very fine- to fine-grained sandstone, and several dolomite beds; and the Springdale Sandstone Member, which consists of ledge-forming, rounded-weathering, varicolored, fine- to medium-grained sandstone that hosts 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) and 391 feet (119 m) thick at Harrisburg Flat (Biek, in press). 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 Early Jurassic in age (Olsen and Galton, 1977; Peterson and others, 1977; Imlay, 1980; Clark and Fastovsky, 1986) and was deposited in a variety of fluvial and lacustrine environments (Clemmensen and others, 1989; Blakey, 1994; Peterson, 1994; DeCourten, 1998).

Dinosaur Canyon Member (Jmd): The Dinosaur Canyon Member is exposed at the base of White, Butte, Buckeye, and East Reefs; in faulted blocks on the northeast-plunging nose of the Virgin anticline; and in incomplete, faulted sections 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 commonly form ledges. 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. I placed it at the base of a laterally persistent, thin-bedded, 6- to 18-inch-thick (15-46 cm), light-gray dolomitic limestone with algal structures, as I did in the adjacent Harrisburg Junction quadrangle. This bed appears bioturbated; weathers to mottled colors of yellowish gray, white, and grayish orange-pink; and contains light-brown to dark-reddish-brown, irregularly shaped chert nodules, some of which appear to fill burrows or root casts. About 25 feet (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. These strata point to the conformable, intertonguing nature of this member contact. Thus, the contact used here differs slightly from that used by Willis and Higgins (1995) and Higgins (1998) in the interim geologic maps of the Washington and Washington Dome quadrangles. 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; Willis and Higgins intend to adjust their contact to the same horizon mapped here.

The Dinosaur Canyon Member is 200 feet (60 m) thick at East Reef (Stewart and others, 1972), and 163 feet (50 m) thick at Harrisburg Flat in the Harrisburg Junction quadrangle to the west (Biek, in press). Wilson and Stewart (1967) re-ported Dinosaur Canyon strata are about 200 feet (60 m) thick in the Leeds area. The Dinosaur Canyon Member is 155 feet (47 m) thick in the Washington Dome quadrangle to the south (Higgins, 1998). Dinosaur Canyon strata are 250 feet (75 m) thick east of Middleton Black Ridge, in the St. George quadrangle (Higgins and Willis, 1995). The Dinosaur Canyon Member was deposited in river and flood-plain environments (Clemmensen and others, 1989; Blakey, 1994; Peterson, 1994; DeCourten, 1998).

Whitmore Point Member (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 on Whitmore Point strata are typically brightly colored and littered with a lag of resistant Whitmore Point lithologies, making the member an important marker horizon. Some of the best exposures are at East Reef, on the east side 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 Moenave members. 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 (7-48 cm) 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* (Hesse, 1935; Schaeffer and Dunkle, 1950), 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. I placed the upper contact at the base of thick- to very thick-bedded sandstones with planar and low-angle cross-stratification. The contact generally corresponds to a pronounced break in slope, with the resistant Springdale Sandstone forming prominent cliffs and ledges above gentle Whitmore Point slopes. Where Grapevine Wash passes through East Reef, in the NE1/4NE1/4SE1/4 section 19, T. 41 S., R. 13 W., the Springdale Sandstone fills a channel in Whitmore Point strata that is about 25 feet (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 east side 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, in press). 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 Whitmore Point strata, although her member contact is different from that used in this report. Higgins and Willis (1995) reported the member is 55 feet (17 m) thick east of Middleton Black Ridge, in the St. George quadrangle, although their member contact is different from that used in this report. Utah Geological Survey geologists have since decided that for mapping purposes the Whitmore Point Member should include a thin dolomitic limestone bed and overlying Dinosaur Canyon-like strata. The Whitmore Point Member was deposited in flood-plain and lacustrine environments (Clemmensen and others, 1989; Blakey, 1994; Peterson, 1994; DeCourten, 1998). Peterson and others (1977) and Imlay (1980) indicated that palynomorphs from the Whitmore Point Member date the unit as latest Sinemurian to earliest Pliensbachian (Early Jurassic). Olsen and Padian (1986) noted the fossil fish *Semionotus kanabensis* is not age diagnostic, and discussed the resolution of the long-standing debate on the age of the Moenave, Kayenta, and Navajo Formations.

Springdale Sandstone Member (Jms): The Springdale Sandstone Member is well exposed at White, Butte, Buckeye, and East Reefs, and in faulted outcrops on the nose of the Virgin anticline. A poorly exposed, incomplete section is also present at the base of the Hurricane Cliffs, south of LaVerkin Creek. The Springdale Sandstone Member hosts ore deposits of the Silver Reef mining district. In the district, the member was known as the Silver Reef sandstone, which was informally divided into the lower white to brown Leeds sandstone and the upper lavender Tecumseh sandstone (Proctor, 1953).

The Springdale Sandstone Member consists predominantly of medium- to very thick 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 reddish purple, pale yellowish orange, and dark yellowish orange, as opposed to moderate-reddish-brown hues that dominate Kayenta beds. Springdale strata also have common Liesegang banding; generally very thick bedding rather than thin to medium bedding typical of Kayenta strata; and characteristic small, resistant, 0.13-inch (2 mm) diameter concretions that give weathered surfaces a pimply appearance. Poorly cemented concretions up to 1 inch (25 mm) in diameter, which impart a pitted appearance to weathered surfaces, are also common in Springdale sandstones. Poorly preserved, petrified and carbonized fossil plant remains are locally abundant. Springdale sandstones also commonly concontain 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, 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 very thick-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 Member is about 95 feet (29 m) thick in the Hurricane quadrangle (Stewart and others, 1972). It is 120 to 164 feet (36-50 m) thick in the adjacent Harrisburg Junction quadrangle (Wilson and Stewart, 1967; Proctor and Brimhall, 1986; Biek, in press). 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

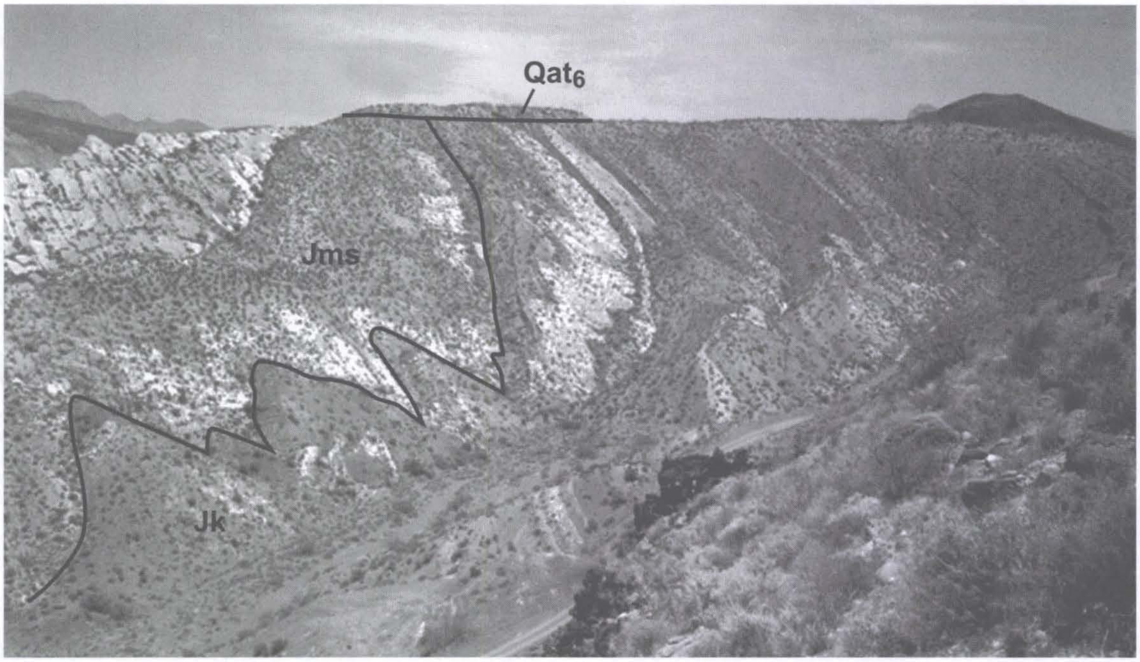

Figure 4. View north to East Reef immediately north of Grapevine Wash, with the East Reef cinder cone on the skyline at right. These spectacular exposures demonstrate the gradational nature of the Springdale-Kayenta contact, which I placed at the base of the first laterally continuous mudstone bed. Level 6 stream-terrace deposits (Qat_6) cap these southeast-dipping Springdale (Jms) and Kayenta (Jk) strata.

Springdale Sandstone was probably deposited in braided-stream and minor flood-plain environments (Clemmensen and others, 1989; Blakey, 1994; Peterson, 1994; DeCourten, 1998).

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, light-olive-gray-weathering, light-gray dolomite beds are present in the lower part of the formation. Kayenta strata generally weather to poorly exposed slopes, except in the upper part of the formation, which contains ledges and small cliffs. 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 also common. Rarely, Kayenta sandstones are 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.

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 containing two parts, but much of their upper part included beds I assign to the Navajo Sandstone. In the Hurricane quadrangle, I did not find suitable horizons for subdividing the Kayenta.

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 conjunction 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 (Biek, in press). The Kayenta Formation is Early Jurassic in age (Imlay, 1980) and was deposited in fluvial, distal fluvial/playa, and minor lacustrine environments (Sansom, 1992; Blakey, 1994; Peterson, 1994).

Navajo Sandstone (Jn)

The Navajo Sandstone and correlative sandstones are renowned 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 (Blakey and others, 1988). Navajo strata are renowned too for their great thickness, locally exceeding 2,000 feet (600 m), and for their 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. Sandstone grains are almost entirely poorly to moderately well-cemented, well-rounded and frosted quartz.

In the Hurricane quadrangle, the Navajo Sandstone is widely exposed along and north of the Virgin River. South of the river, the Navajo is mostly concealed by Quaternary basalt and younger sediments. 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 in broad, open swales.

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 to 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 their 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 east side 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 (24 m) above the base of the transition interval as described by previous workers (Cook, 1957, 1960; Sansom, 1992; Biek, in press). 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. She also noted that 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.

As I define them, the transition-zone beds are characterized by very fine- to fine-grained sandstone and silty fine-grained sandstone with thin siltstone 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. Although 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 that 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 of the Navajo Sandstone with the Temple Cap Formation, the J-1 unconformity of 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 corresponds to 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. I estimate the Navajo Sandstone to be about 2,000 to 2,300 feet (600-700 m) thick in the Hurricane quadrangle.

Temple Cap Formation

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 east of the Hurricane fault; only the Sinawava Member, which thickens westward, is in the Hurricane quadrangle.

Sinawava Member (Jts): The Sinawava Member 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, bright-red and gray, ledgy slopes atop a broad bench of Navajo Sandstone and below ledge-forming Carmel strata. Sinawava strata typically weather to soft, gypsiferous soils, making the excellent exposures here all the more remarkable.

The Sinawava Member typically consists of interbedded, slope-forming, moderate-reddish brown, yellowish-gray, and light-gray mudstone, siltstone, very fine-grained silty sandstone, and lesser gypsum. A ledge-forming, thick-bedded, light-brown to grayish-orange, calcareous, fine-grained sandstone with low-angle cross-stratification is in the upper middle part of the formation. 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. Two small prospect pits for gypsum are near the north end of the Sinawava outcrop belt. Thin, pale-greenish-gray mudstone beds with abundant biotite, which are altered volcanic-ash layers, are common.

The lower Sinawava Member also contains several zones of white to pinkish-gray chert nodules that weather out

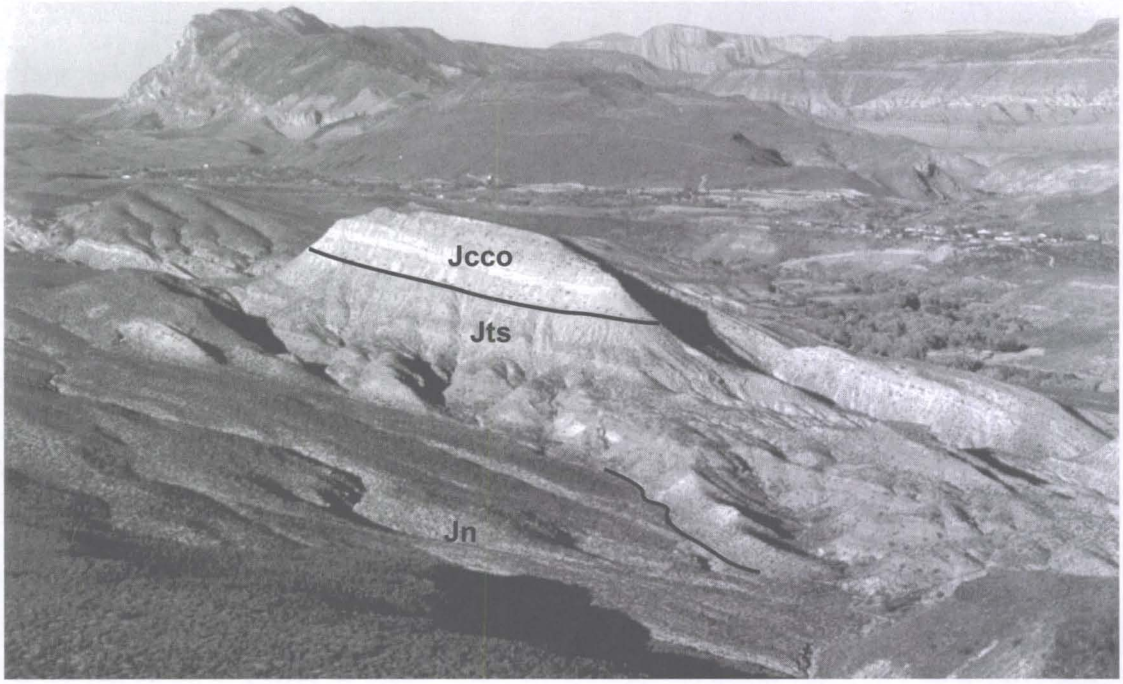

Figure 5. View north to hill 3662 in the E$^{1}/_{2}$ section 22, T. 41 S., R. 13 W., with Toquerville and Black Ridge in distance at left. Sage-covered, east-dipping planar surface of Navajo Sandstone (Jn) at lower left is unconformably overlain by red- and white-banded Temple Cap (Jts) strata. Hill 3662 is capped by Co-op Creek Limestone strata (Jcco). Steeper dips in these strata at the right margin of the photo are due to an east-dipping reverse fault (see figure 11).

and accumulate at the surface. The nodules are disc shaped, 0.25 to 1 inch (6-25 mm) thick and 1 to 3 inches (25-75 mm) in diameter. They are composed of an aggregate of much smaller blebs and flakes. These nodules may be silicified bentonite.

I placed the upper contact of the Sinawava Member with the Co-op Creek Limestone Member of the Carmel Formation at the top of a 2-foot-thick (0.6-m), 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 Sinawava Member. Overlying Co-op Creek Limestone strata are yellowish-gray, light-greenish-gray, and grayish-yellow calcareous mudstone and siltstone. This lower Co-op Creek Limestone 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, in press).

The Sinawava Member is about 220 feet (67 m) thick on the southwest side of hill 3662, in the E$^{1}/_{2}$ of section 22, T. 41 S., R. 13 W. Sinawava 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, in press). 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). Kowallis and others (reported in Christiansen and others, 1994) reported an $^{40}Ar/^{39}Ar$ age of 169.4 million years (Bajocian) obtained from a bentonitic ash bed in Temple Cap strata.

Carmel Formation

The Carmel Formation forms an eastward-thickening wedge, preserved beneath a regional unconformity, termed the K 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 Limestone Member and the upper Paria River Member – separated by mostly red mudstones of the Crystal Creek Member (Biek, in press). In the Hurricane quadrangle, however, only the lower Co-op Creek Limestone Member is preserved beneath the unconformity.

Co-op Creek Limestone Member (Jcco): When viewed from a distance, Co-op Creek Limestone strata are readily divisible into two units, a thicker lower unit and a thin upper unit, although I did not map them separately. The lower unit weathers to pale yellowish gray, whereas the upper unit weathers to distinctly darker yellowish-brown hues; both form steep, ledgy slopes. Collectively, these two unmapped units consist of interbedded, generally thin-bedded mudstone, siltstone, limestone, and, in the lower part, minor gypsum and very fine- to fine-grained sandstone.

Thin-bedded, yellowish-gray to very pale-orange limy mudstone, and interbedded, similarly colored siltstone and limestone characterize the lower unit of the Co-op Creek Limestone Member. 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.

Thin-bedded, coarse-grained, pale-yellowish-brown fossiliferous limestone, with abundant *Pentacrinus* sp. *columnals*, bivalves, and mollusks characterize the upper portion of the Co-op Creek Limestone Member. Many of the upper 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 Iron Springs Formation unconformably overlies the Co-op Creek Limestone Member. 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, reddish-brown, and white siltstone and fine-grained sandstone.

The Co-op Creek Limestone 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.; it probably is up to 200 feet (60 m) thick in the Hurricane quadrangle. Co-op Creek Limestone strata generally thicken eastward across the southern flank of the Pine Valley Mountains, from 285 to 449 feet (87-137 m) thick (Wright and others, 1979; Willis and Higgins, 1995; Biek, in press). The Carmel Formation is Bajocian to Bathonian (Middle Jurassic) in age (Imlay, 1980). It was deposited in a variety of shallow-marine, shoreline, and sabkha environments (Blakey and others, 1983).

Jurassic and Triassic, undifferentiated

Moenave and Chinle Formations, undifferentiated (JTRu)

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

Cretaceous

A thin bentonitic interval overlies the K 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 position and is of similar thickness as the Gunlock bentonitic bed, although it weathers to light brownish gray rather than moderate red, and lacks the 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 southern flank of the Pine Valley Mountains, from about 90 feet (27 m) thick near Diamond Valley (Willis and Higgins, 1995) to about 20 to 25 feet (6-7.5 m) thick throughout the Harrisburg Junction quadrangle (Biek, in press). 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 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, but they are not mapped here due to the scale of plate 1. Hintze and others (1994) reported a fission-track age of 80.0 ± 5 Ma (Campanian) using zircon from the bentonitic beds in the Gunlock area. Dyman and others (2002) obtained an $^{40}Ar/^{39}Ar$ age of 101.7 ± 0.42 Ma on sanadine from this bed. I have since revisited these exposures and now believe that the Gunlock-area section represents strata correlative with the Cedar Mountain Formation, which is newly recognized on the Kolob Plateau (Hylland, 2000; Biek and Hylland, 2002). The bentonitic bed mapped by Willis and Higgins (1995) and Biek (in press) is probably just the lowermost Iron Springs Formation and thus of early Late Cretaceous age.

Iron Springs Formation (Kis)

Only about the lower 600 feet (180 m) of the Iron Springs Formation is exposed in the quadrangle west of LaVerkin in the vicinity of Ash and LaVerkin Creeks, but the formation is about 3,500 to 4,000 feet (1,100-1,200 m) thick in the surrounding area (Cook, 1960; Hintze and others, 1994). The Iron Springs Formation 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 contains about 10 to 20 percent 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 age, and Goldstrand (1994) reported a Cenomanian to Santonian or early Campanian age for the formation. The basal Iron Springs Formation is thus early Late Cretaceous in age. 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 flood-plain environments; Fillmore (1991) also suggested that the formation was deposited in a sandy braidplain environment.

Cretaceous and Jurassic, undifferentiated

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

A small exposure of nearly vertical Carmel (Co-op Creek Limestone Member), Temple Cap (Sinawava Member), and Iron Springs strata is present 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 outcrop renders their relationships uncertain.

Quaternary

Basaltic Flows and Related Deposits

Basaltic rocks in the Hurricane quadrangle erupted from eight distinct vents, five of which are in the Hurricane quadrangle. These 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. They are part of the western Grand Canyon basaltic field, a large area of late Tertiary to Holocene basaltic volcanism in northwestern Arizona and adjacent Utah (Hamblin, 1970; Best and Brimhall, 1974). Although relatively small in volume compared to other volcanic fields in the western United States, these flows provide important constraints on local tectonic and geomorphic development. The region is known for its inverted valleys and isolated, basalt-capped buttes and mesas. Based on the degree of erosion and weathering of individual flows, Hamblin (1963, 1970, 1987) identified four major periods, or stages, of mafic volcanism in the western Grand Canyon region. Stage I flows are high, isolated 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 these stage designations are useful for comparison of flows within large, fault-bounded blocks, the complex downcutting history near the Hurricane fault can render stage designations misleading (Willis and Biek, in press). Because we also have many new $^{40}Ar/^{39}Ar$ and K-Ar ages on these flows, I do not use Hamblin's stage designations.

I differentiated basaltic flows in the Hurricane quadrangle and adjacent area using a combination of field relationships, hand sample identification, isotopic age determinations, and geochemistry; preliminary paleomagnetic data made available by Michael J. Hozik (The Richard Stockton College of New Jersey) have also been useful in correlating flows. Basalt flows in the Hurricane quadrangle range in age from about one million to 140,000 years old (table 1). Geochemical data for these flows are summarized in appendices A and B, and $^{40}Ar/^{39}Ar$ data is in appendix C. Most volcanic rocks in the Hurricane quadrangle are chemically classified as basalts using the total alkali versus silica (TAS) diagram of Le Bas and others (1986) (figure 6). The Divide flow (Qbd) and East Reef (Qber) flows plot as basanite or borderline basinite/basalt, whereas one of the Pintura flows plots as trachybasalt. Figure 7 shows the location of basalt samples, and those in the Hurricane quadrangle are also shown on plate 1.

Most basalt flows in the quadrangle are dark-gray, fine-grained olivine basalts that have a blocky, aa surface. Rarely, ropey pahoehoe surfaces are preserved. Olivine phenocrysts are typically the only mineral recognizable in hand samples, except for the Pintura flow (Qbp), which is the most distinctive flow in the quadrangle. The Pintura flow is lighter gray and coarser grained, and contains sparse olivine and common plagioclase phenocysts, compared to other flows. 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 stream channels along Ash Creek and the Virgin River. I use the term "flow units" to refer to pulses of lava from a single eruptive episode separated by relatively short time intervals, whereas flows are from different eruptions typically separated by enough time for weathering to occur. A single flow can contain one or more flow units.

Cinder cones in the Hurricane quadrangle have moderately developed radial rills, except for the Ivans Knoll cinder cone, which is almost entirely removed by erosion. The tops of many cones are partly covered with agglutinate and large bombs, which record a change from volatile-rich Strombolian to volatile-poor Hawaiian-style eruptions (Sanchez, 1995; Smith and others, 1999). Most of the cones are breached by lava flows. The "cinder pits" and Ivans Knoll cones contain small, solidified lava "lakes."

In the Hurricane area, the location of volcanic vents appears to be joint controlled but not fault controlled (San-

Table 1. *$^{40}Ar/^{39}Ar$ ages of basalt flows in the Hurricane quadrangle.*

Flow name	Symbol	Age Ma	Sample Number	Reference
Radio Tower	Qbr	0.14 ± 0.06	H11299-4	This report
Volcano Mountain	Qbv_1 Qbv_2 Qbv_3	0.258 ± 0.024 0.353 ± 0.045		Sanchez (1995) Sanchez (1995)
Cinder Pits	Qbcpc	0.24 ± 0.02	VR123-5	This report
Gould Wash	Qbgw	0.278 ± 0.018		Downing (2000)
East Reef	Qber	0.20 ± 0.16	VR122-2	This report
The Divide	Qbd	0.41 ± 0.08	TD12999-1	Higgins (2000)
Pintura	Qbp	0.89 ± 0.02 0.84 ± 0.03 0.88 ± 0.05 0.81 ± 0.10 0.87 ± 0.04	VR113-4 BR-1 AC-1 ACG-1 MH-1	This report Lund and Everitt (1998) Lund and Everitt (1998) Lund and others (2001) UGS unpublished data
Ivans Knoll	Qbi	0.97 ± 0.07 1.03 ± 0.02	H11299-2 VR123-11	This report This report

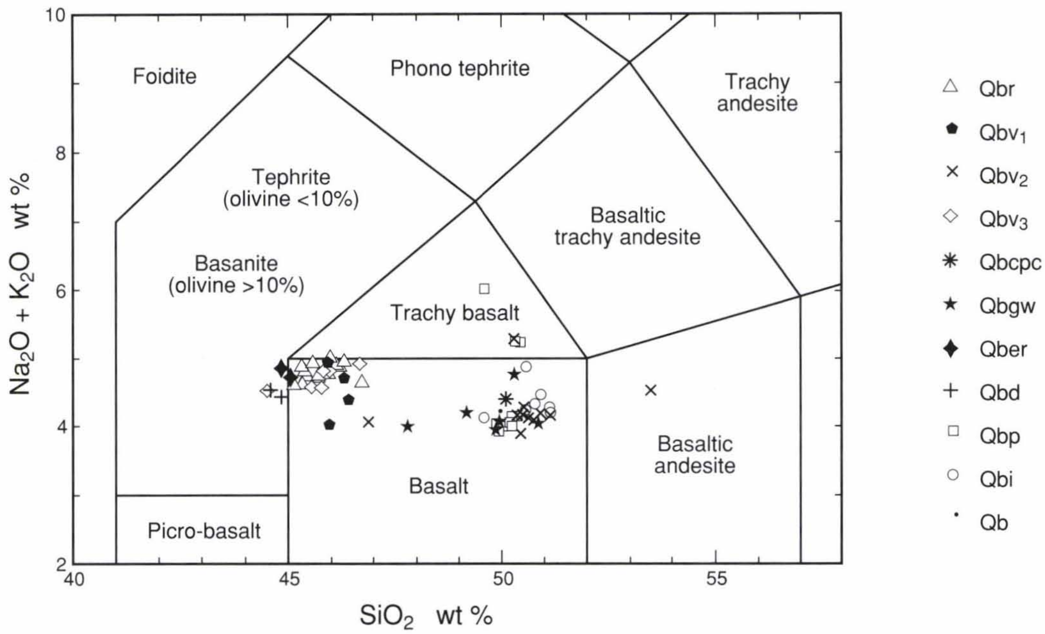

Figure 6. *Geochemical classification of basalts in the Hurricane quadrangle using scheme of Le Bas and others (1986). See appendices A and B for analytical results, and figure 7 and plate 1 for sample locations. Major oxides are normalized to 100 percent. See text for explanation of map unit symbols.*

chez, 1995). Sanchez suggested that cone alignments match joint orientation data of LeFebvre (1961). Vent alignments at individual volcanic centers trend north in the Hurricane quadrangle, except at East Reef, where they trend northeast, parallel to the Virgin anticline axial surface.

Sanchez (1995) studied the composition and evolutionary history of the basaltic 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 basanite, basanite, and alkali basalt on the total alkali versus silica (TAS) diagram of Le Bas and others (1986). Smith and others (1999) also discussed the trace-element geochemistry for these basaltic rocks and suggested that the variation in chemistry reflects melting of a heterogeneous lithospheric mantle, similar to the findings of Best and Brimhall (1974). The "primitive" geochemistry of the low-silica basanite and basanite suggests that they rose rapidly to the surface from a site of partial melting. Sanchez (1995) also classified most volcanoes in the Hurricane area 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.

In the Hurricane area, a veneer of eolian sand and pedogenic carbonate commonly partly covers the flows; I mapped such areas as Qec over the basalt flow (for example, Qec/Qbi). I use the symbol for alluvial gravel followed by a letter designating the flow name (for example, Qagi) to identify alluvial gravel deposits that underlie the flows. Cinder cones are designated by the letter "c" after the basalt flow symbol (for example, Qbic).

Ivans Knoll flow, cinder cone, and associated deposits (Qbi, Qbic, Qec/Qbi, Qagi): The Ivans Knoll flow forms a highland (locally known as Ivans Knoll) that slopes radially away from the hills immediately south of Volcano Mountain (Sullivan Knoll), near the common border of sections 5 and 8, T. 42 S., R. 13 W. An outlier of the Ivans Knoll flow, offset by the Hurricane fault, caps Mollies Nipple, high atop the Hurricane Cliffs. All that remains of the cinder cone or cones associated with the Ivans Knoll flow are two small areas of cinder deposits (Qbic) in the SE$^1/_4$ 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 caliche (stage V-VI of Birkeland and others, 1991) and lesser eolian sand (Qeo and Qec/Qbi), thus forming a much smoother surface than adjacent basalt flows. Deposits of the Volcano Mountain complex conceal the northern part of the Ivans Knoll flow. The best exposures of the Ivans Knoll flow are in cliffs in the southwestern corner of the Hurricane quadrangle, about 200 feet (60 m) above local drainages to the west; Utah Highway 9 road cuts provide good exposures as well.

The Ivans Knoll flow is a medium-gray, fine- to medium-grained olivine basalt that in most exposures consists of at least two flow units. Eight samples from this study (figure 6, appendices A and B), and eight reported in Sanchez (1995), show that it is classified as a basalt using the TAS diagram of Le Bas and others (1986). Abundant olivine phenocrysts are the only recognizable mineral in hand samples. Sample VR123-11 yielded an $^{40}Ar/^{39}Ar$ plateau age 1.03 ± 0.02 Ma for this flow.

Because Sanchez (1995) interpreted the Ivans Knoll flow to be about 350,000 years old, this one-million-year-old age created some uncertainity as to the flow's age and correlation. Michael J. Hozik (The Richard Stockton College of New Jersey, verbal communication, 1998) reported that the Ivans Knoll flow, as mapped here, has a normal magnetic signature, suggesting that it erupted during the Bruhnes normal polarity epoch and is younger than about 750,000 years old; lightening strikes at the Mollies Nipple erosional remnant rendered those paleomagnetic samples unusable. I obtained a subsequent Ivans Knoll sample that yielded an

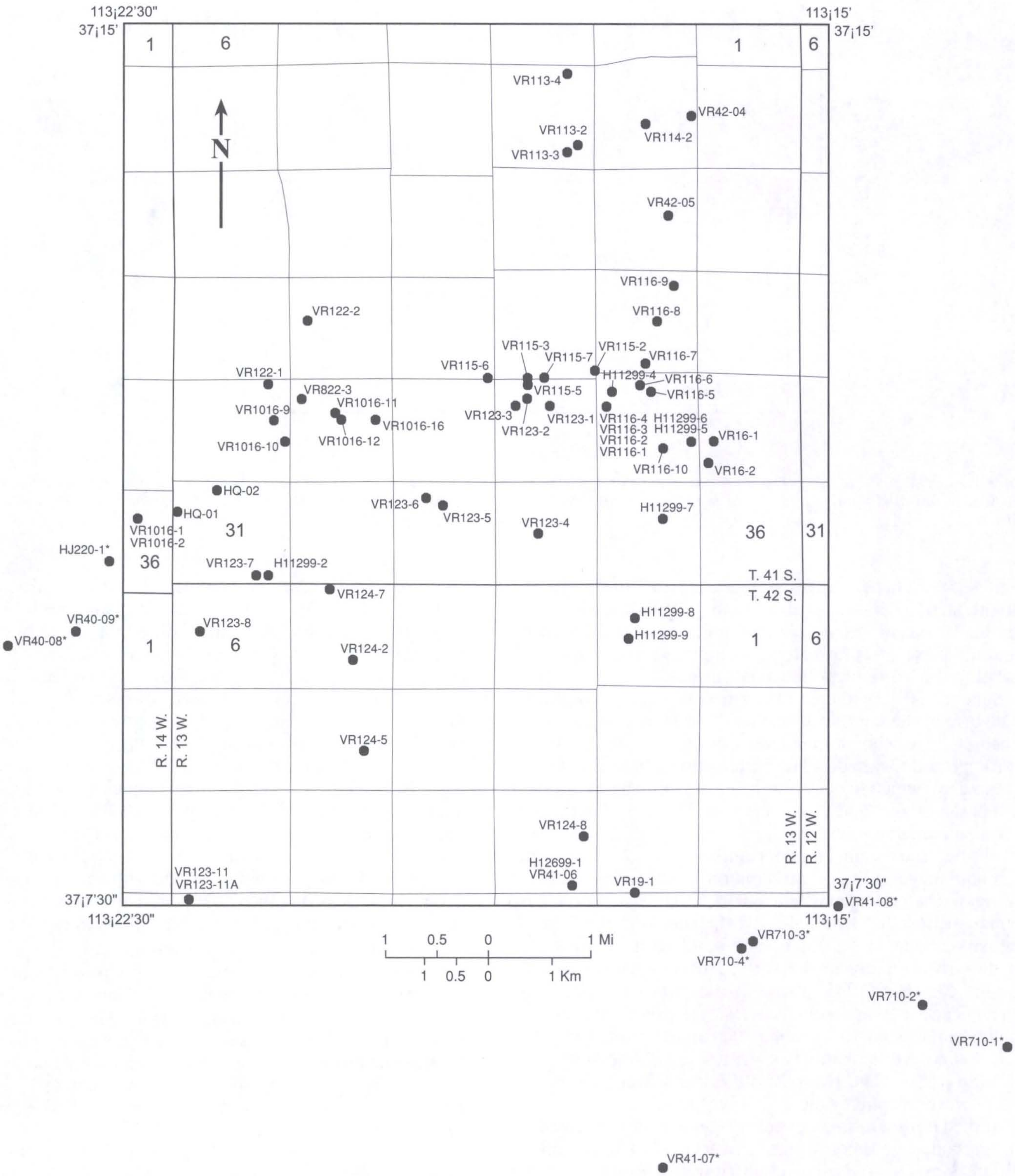

Figure 7. *Basalt sample locations. For more detail, see plate 1. Asterisk indicates sample is outside the Hurricane quadrangle.*

$^{40}Ar/^{39}Ar$ plateau age of 0.97 ± 0.07 Ma. I now believe that the Ivans Knoll flow erupted during the Jamarillo normal event (see, for example, Glen, 1982), a short-duration flip in the earth's magnetic field that occurred about 0.99 to 1.07 million years ago during the Matuyama reversed polarity epoch. Calculation of long-term regional downcutting rates along the Virgin River also support an age of about one million years for the Ivans Knoll flow (Willis and Biek, in press). The Ivans Knoll flow is thus considerably older than the flow exposed east of Hurricane in the Hurricane Cliffs. I correlate this latter flow with the Volcano Mountain complex of flows as discussed below.

An unusual circular depression over 1,000 feet (300 m) in diameter, breached on the east by a small drainage and partly filled with mixed alluvial and eolian deposits (Qae), is at the center of section 9, T. 42 S., R. 13 W. It may be the remains of a collapse feature associated with a subsidiary Ivans Knoll vent. To the west, basalt exposures at Ivans Knoll may be a series of solidified lava lakes that now stand above the moderately sloping flanks of the volcano.

Pintura flow (Qbp): The Pintura flow erupted principally from the Pintura volcanic field, which is about 2 miles (3.2 km) north of Pintura, in section 19, T. 39 S., R. 12 W.; a small vent is located at "Mystery Hill" at the north end of Black Ridge (Lund and Everitt, 1998; Hurlow and Biek, 2000). The flow is about 12 miles (19 km) long, reaching southward toward the Virgin River. In the Hurricane quadrangle, the Pintura flow forms a broad, east-dipping slope southwest of Toquerville where it is about 20 to 30 feet (6-9 m) thick. It thickens significantly to the east, where it fills the ancestral Ash Creek drainage to a depth greater than 120 feet (37 m). The Pintura flow thins to the south and interfingers with older alluvial-fan deposits above LaVerkin Creek. At its southern end, the Pintura flow lies about 200 feet (60 m) above the Virgin River. These map patterns suggest that the gradient of Ash Creek has steepened since emplacement of the flow. The Pintura flow also locally caps the ridge immediately east of Toquerville, on the footwall of the Hurricane fault, where it is up to 600 feet (180 m) above LaVerkin Creek.

The Pintura 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 small olivine phenocrysts and abundant larger plagioclase phenocrysts up to 0.25 inch (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. In the Hurricane quadrangle, the Pintura flow is locally composed of at least four flow units. Nine geochemical analyses show the Pintura flow is a basalt or trachybasalt on the TAS diagram of Le Bas and others (1986) (figure 6, appendix A).

The Pintura flow is widely exposed in the Pintura quadrangle to the north (Hurlow and Biek, 2000), and geochemical analyses show that it can be subdivided into three distinct chemical groups (Stan Hatfield, Southwestern Illinois College, written communication, July 14, 2000). In the Hurricane quadrangle, the Pintura flow plots in two separate fields on a variety of major, minor, and trace element variation diagrams. Sample VR113-4, southwest of Toquerville, yielded an $^{40}Ar/^{39}Ar$ plateau age of 0.89 ± 0.02 Ma. Three samples of the Pintura flow from the Pintura quadrangle yielded $^{40}Ar/^{39}Ar$ plateau ages of 0.84 ± 0.03, 0.88 ± 0.05, and 0.81 ± 0.10 Ma, and a fourth from the Smith Mesa quadrangle yielded an age of 0.87 ± 0.04 Ma (Lund and Everitt, 1998; W.R. Lund, written communication, July 14, 2000).

The Divide flow and associated deposits (Qbd, Qec/Qbd): The Divide flow is exposed south of Frog Hollow in the southeastern corner of the quadrangle. It appears to be at a slightly higher elevation than the Gould Wash flow, but differentiation of the two flows in the field is difficult due to similar geomorphic expression and lithology. The Divide and Gould Wash flows are dark gray and very fine grained, with abundant olivine phenocrysts the only recognizable mineral in hand samples. Geochemically, The Divide flow is a basanite using the TAS diagram of Le Bas and others (1986) (figure 6, appendices A and B). Sanchez (1995) and Higgins (2000) also classified The Divide flow as a basanite and noted that it erupted at a cinder cone and dike west of Little Creek Mountain in The Divide quadrangle. The margins of The Divide flow are partly eroded and it lies 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. The Divide flow yielded an $^{40}Ar/^{39}Ar$ plateau age of 0.41 ± 0.08 Ma (Higgins, 2000). Where it is partly concealed by eolian sand and pedogenic carbonate deposits, I mapped the flow as Qec/Qbd.

East Reef flow and cinder cones (Qber, Qberc): The East Reef flow erupted from two overlapping cinder cones (Qberc) at East Reef. Each cone was breached by basaltic flows, each has moderately well-developed rill weathering, and each is being excavated for cinders. The East Reef flow traveled at least 1.5 miles (2.4 km) down the ancestral Grapevine Wash to the present confluence with the Virgin River. At the confluence, the East Reef flow lies about 160 feet (50 m) above the Virgin River. Farther up Grapevine Wash, the 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 Le Bas and others (1986) (figure 6, appendix A). The flow yielded a poorly constrained $^{40}Ar/^{39}Ar$ plateau age of 0.20 ± 0.16 Ma, probably due to abundant groundmass glass and low radiogenic yield.

Gould Wash flow and associated deposits (Qbgw, Qec/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 dark gray and very fine grained, with abundant olivine phenocrysts as the only recognizable mineral in hand samples. It is locally concealed by eolian sand and pedogenic carbonate deposits (Qec/Qbgw). Geochemically, the Gould Wash flow is a basalt using the TAS diagram of Le Bas and others (1986) (figure 6, appendices A and B). The source of the flow is a cinder cone in the upper reaches of Gould Wash, north of Little Creek Mountain. Downing (2000) reported an $^{40}Ar/^{39}Ar$ age of 0.278 ± 0.018 Ma for the Gould Wash flow.

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 is about 160 feet (50 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. (figure 2). There, the flow plugs a slot canyon cut into Fossil Mountain strata. A remnant of the Gould Wash flow is present in the lower reaches of Frog Hollow.

"Cinder pits" flow, cinder cones, and associated deposits (Qbcpc, Qec/Qbcp): The "cinder pits" flow is named for the cinder pits in the cinder cone complex northwest of Hurricane, in section 28, T. 41 S., R. 13 W. This complex consists of two overlapping cones, each with moderately well-developed rill weathering, that are breached on the southeast side by basalt flows. The larger of the two cones is partially excavated for cinders. Sanchez (1995) described a small, solidified lava lake at the "cinder pits" cone.

Exposures of the "cinder pits" flow are limited to the area immediately south of the "cinder pits" cones. It is a medium-gray to dark-gray, fine-grained basalt with olivine phenocrysts as the only recognizable mineral in hand sample. The "cinder pits" flow is classified as a basalt using the TAS diagram of Le Bas and others (1986) (figure 6, appendix A). Sanchez (1995) reported that the "cinder pits" basalts are chemically transitional between the Volcano Mountain basanites and Ivans Knoll alkali basalts. Sample VR123-5 yielded an $^{40}Ar/^{39}Ar$ age of 0.24 ± 0.02 Ma. Map relationships show that the "cinder pits" flow is locally overlain by, and thus slightly older than, the adjacent Volcano Mountain (Qbv_1) and older "radio tower" (Qbr) flows. The thickness of the "cinder pits" flow is uncertain, but it is likely several tens of feet thick. I mapped the "cinder pits" flow as Qec/Qbcp because it is partially concealed by eolian sand and pedogenic carbonate deposits.

Volcano Mountain flows, cinder cone, and associated deposits (Qbv_1, Qbv_2, Qbv_3, Qbvc, Qec/Qbv_1, Qec/Qbv_2, Qec/Qbv_3, $Qagv_2$): The Volcano Mountain flows erupted from Volcano Mountain (also known as Sullivan Knoll), 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 erosion and is locally excavated for cinders. I divided the Volcano Mountain basalts into three flows in the Hurricane quadrangle. From youngest to oldest and shortest to longest, these flows are denoted Qbv_1, Qbv_2, and Qbv_3. These lavas flowed north and then southwest toward and down the Virgin River drainage. The Qbv_2 flow also flowed east and northeast, where it blocked the Virgin River and crossed the Hurricane fault; remnants of the Qbv_2 flow are preserved along the Hurricane Cliffs, on the footwall of the Hurricane fault, as described below. The longest flow, Qbv_3, is about 8 miles (13 km) long and is exposed only along the Virgin River in the Hurricane and adjacent Harrisburg Junction quadrangles (Biek, in press). The upper surface of the Qbv_3 flow is flat, planed off by Virgin River erosion, and locally covered by eolian sand and pedogenic carbonate deposits (Qec/Qbv_3) up to several feet thick. Both the Qbv_1 and Qbv_2 flows have a very rough, blocky surface locally covered by eolian sand and pedogenic carbonate deposits (Qec/Qbv_1, Qec/Qbv_2). Although the contacts between these flows are not exposed, the flows are readily differentiated based on stratigraphic position, morphology, and geochemistry.

The Qbv_3 flow is generally a dark-gray, very fine-grained olivine basalt as classified using the TAS diagram of Le Bas and others (1986) (figure 6, appendices A and B). The flow consists of one or two flow units and is typically about 40 feet (12 m) thick. It is up to about 100 feet (30 m) thick where it fills the ancestral Virgin River channel (NE1/4 section 30, T. 41 S., R. 13 W.), and thins to a few feet thick at its downstream end in the adjacent Harrisburg Junction quadrangle. Two flows are exposed just northwest of the "cinder pits" cone, in the SW1/4SE1/4NE1/4 section 29, T. 41 S., R. 13 W. The upper (Qbv_3) flow (sample VR1016-16) overlies several feet of ancestral Virgin River gravel, which in turn overlies an older flow of uncertain correlation. This older flow is exposed only in a vertical cliff and so is not differentiated from the Qbv_3 flow on plate 1; it overlies about 7 feet (2 m) of planar bedded, coarse sand and cinders deposited on the Navajo Sandstone.

The Qbv_2 flow is generally a medium-gray, medium- to coarse-grained olivine basalt as classified using the TAS diagram of Le Bas and others (1986) (figure 6, appendices A and B). It is typically about 35 to 45 feet (11-14 m) thick, but thickens greatly, as described below, where it fills paleotopography along the ancestral Virgin River and Gould Wash drainages. Based both on field mapping and geochemical correlation, the Qbv_2 flow probably underlies at least the eastern half of the town of Hurricane, where it is concealed by younger mixed alluvial and eolian deposits. The flow reappears to the north, in faulted exposures at the entrance to Timpoweap Canyon, and from there south along the Hurricane Cliffs to the NW1/4 section 11, T. 42 S., R. 13 W., just south of Gould Wash. Exposures on the south side of the Virgin River canyon, under the Utah Highway 9 bridge, reveal a single flow about 170 feet (50 m) thick that 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 prominent, widely spaced columnar joints (the lower colonnade), which in turn is overlain by about 100 feet (30 m) of similar basalt that is prominently and chaotically jointed (the entablature). The upper roughly 20 feet (6 m) of this exposure consists of vesicular basalt with few columnar joints (the upper colonnade).

This same sequence is present in exposures on the footwall of the Hurricane fault, from Timpoweap Canyon south to the center of section 35, T. 41 S., R. 13 W. (figure 8), where ancestral Virgin River gravels ($Qagv_2$) locally underlie the flow. Immediately east of Hurricane, in a Utah Highway 59 road cut, the Qbv_2 flow consists of two otherwise similar flows separated by about 20 feet (6 m) of ancestral Virgin River gravel. At the south side of the entrance to Timpoweap Canyon, this flow is displaced about 240 feet (73 m) across the Hurricane fault. This flow yielded an $^{40}Ar/^{39}Ar$ isochron age of 0.353 ± 0.045 Ma (Sanchez, 1995), and was previously dated by the potassium-argon method by Damon (cited by Best and others, 1980) at 0.289 ± 0.086 Ma. Paleomagnetic studies show that this flow has a normal polarity, which is consistent with the isotopic age determinations, and that there is less than 10° of reverse drag on the hanging-wall flow (Hozik, 1999). Both the declination and inclination of the magnetic vector from this flow are different than those from the Ivans Knoll flow, confirming that these are separate flows (Michael J. Hozik, The Richard Stockton College of New Jersey, written communication, December 6, 2000).

The Qbv_1 flow is a medium- to dark-gray, fine-grained olivine basalt as classified using the TAS diagram of Le Bas and others (1986) (figure 6, table 1). It is about 35 to 45 feet (11-14 m) thick. The Qbv_1 flow yielded an $^{40}Ar/^{39}Ar$ isochron age of 0.258 ± 0.024 Ma (Sanchez, 1995). The Qbv_1 flow breached the Volcano Mountain cinder cone on its north side, and cinders associated with collapse of the cone were rafted northward on top of the Qbv_1 flow for a distance of at least 1 mile (1.6 km).

Based on geochemistry, Sanchez (1995; see also Smith and others, 1999) correlated most of the Qbv_1 flow with the

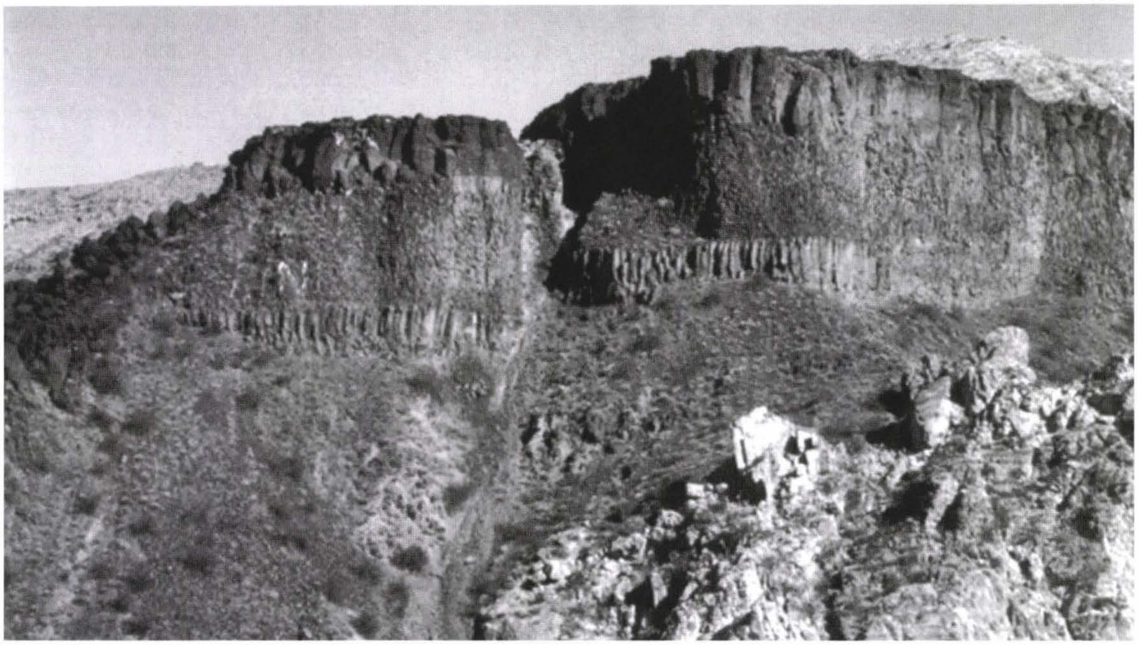

Figure 8. *View northeast to the Volcano Mountain Qbv_2 flow on the footwall of the Hurricane fault, at the north side of the entrance to Timpoweap Canyon. This flow yielded an $^{40}Ar/^{39}Ar$ isochron age of 0.353 ± 0.045 Ma (Sanchez, 1995) and is displaced about 240 feet (73 m) along the Hurricane fault. A small fault with about 20 feet (6 m) of displacement, at the center of the photograph, cuts this portion of the flow. This flow consists of a single flow unit up to 170 feet (50 m) thick where it filled the ancestral Virgin River channel. 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 prominent, vertical, columnar joints. This is overlain by up to 100 feet (30 m) of similar basalt that is prominently and chaotically jointed, and capped by about 20 feet (6 m) of vesicular basalt with few joints. The Fossil Mountain Member of the Kaibab Formation is exposed at the lower right.*

"cinder pits" complex and the Qbv_2 and Qbv_3 flows with the Ivans Knoll vent. Additional geochemical, paleomagnetic, and isotopic age data, as well as detailed field mapping, have led me to interpret these flows differently. Unpublished maps of W.K. Hamblin depict the Volcano Mountain flows substantially as mapped here. If my new correlations are correct, the Volcano Mountain vent produced flows of two distinct compositions. The Qbv_1 and Qbv_3 flows are of near basanite composition (similar to the "radio tower" flow), whereas the Qbv_2 flow is a basalt (similar to the Ivans Knoll flow). It appears that the magma chamber and plumbing system of the Volcano Mountain flows are more complex than for other volcanoes in the Hurricane volcanic field. Preliminary geochemical interpretations of the Pintura flows also show that the chemistry of those flows is more complex than for typical volcanoes in the region (Stan Hatfield, Southwestern Illinois College, written communication, July 14, 2000).

"Radio tower" flow, cinder cone, and associated deposits (Qbr, Qbrc, Qec/Qbr): The "radio tower" flow originated at a cinder cone complex just northwest of Hurricane, in section 27, T. 41 S., R. 13 W., that has a large radio tower on it. This complex includes four overlapping cinder cones (Qbrc) that have moderately well-developed rill erosion and are partly breached by basalt flows. A much smaller vent lies just across the Virgin River to the north. The vents are aligned almost due north, subparallel to major structures in the area. Although the cinder cone complex is only locally disturbed by excavations for cinders, cinder cone stratigraphy is well exposed on the north side of the complex where it is eroded along the Virgin River (figure 9). There, about 5 feet (1.5 m) of coarse ash and lapilli overlies the Navajo Sandstone. These pyroclastic deposits are overlain by an 80-foot-thick (24 m), cliff-forming basalt flow and flow breccia unit with Navajo xenoliths. The remainder of the cone consists of scoria, bombs, and agglutinate. The cone is cut by a north-trending dike (sample VR123-1) that is chemically classified as a basalt to borderline basanite on the TAS diagram of Le Bas and others (1986).

The "radio tower" flow is medium to dark gray and fine grained with olivine phenocrysts. The "radio tower" flow is a basalt to borderline basanite using the TAS diagram of Le Bas and others (1986) (figure 6, appendices A and B). Some of the best exposures of this flow are in the NW1/4 SW1/4NW1/4 section 26, T. 41 S., R. 13 W., where three flow units overlie the Volcano Mountain Qbv_2 flow. The "radio tower" flow also overlies the Volcano Mountain Qbv_2 flow along the south and west sides of the Virgin River in the NW1/4SE1/4 section 26, T. 41 S., R. 13 W. The "radio tower" flow is up to 180 feet (55 m) thick where it fills the ancestral Virgin River channel. The "radio tower" flow yielded an $^{40}Ar/^{39}Ar$ plateau age of 0.14 ± 0.06 Ma. Where partially concealed by eolian sand and pedogenic carbonate deposits, I mapped the flow as Qec/Qbr.

Basalt flows and cinder deposits, undivided and associated deposits (Qb, Qec/Qb): Lacking geochemistry, I could not confidently correlate several basalt outcrops along the Virgin River. These isolated exposures are labeled Qb to reflect that uncertainty. Where partly concealed by eolian sand, the symbol Qec/Qb is used. Basaltic cinders of uncertain correlation (Qbc) are present between the Cinder Pits and Radio Tower cones in a single exposure on the south side of the Virgin River canyon.

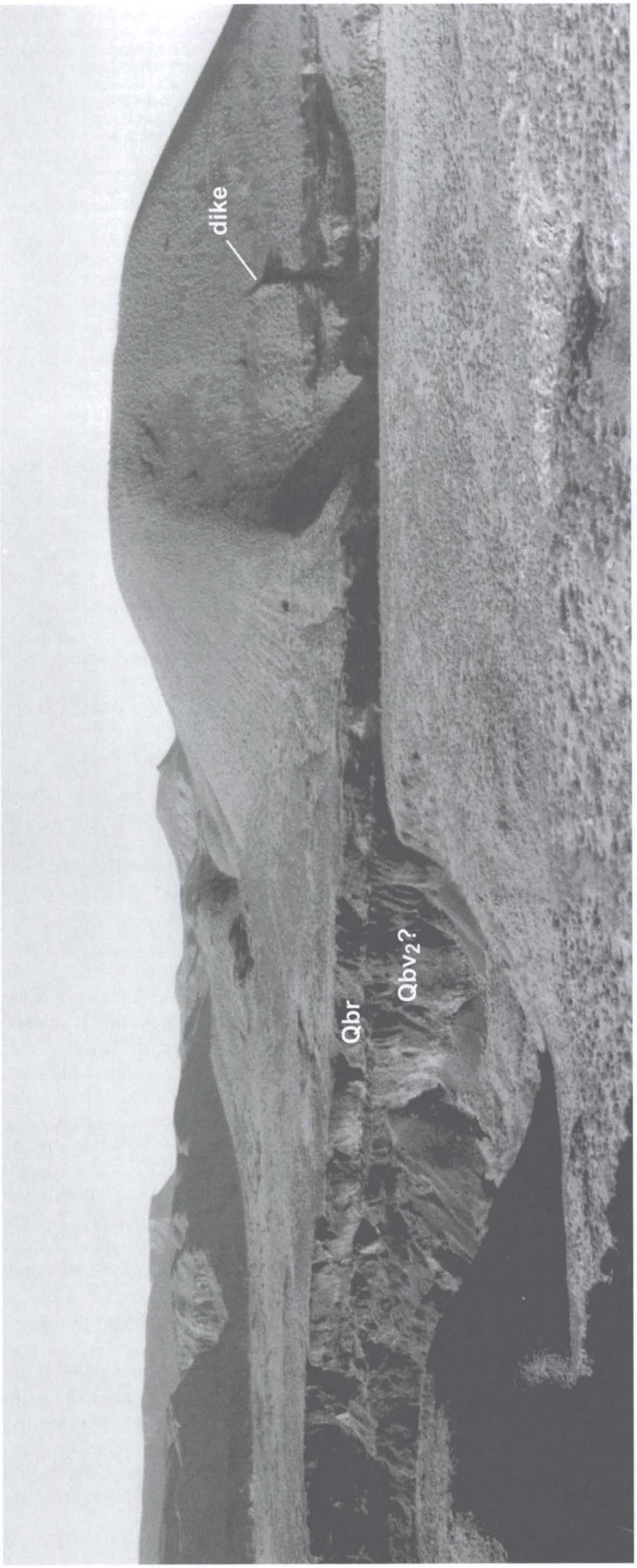

***Figure 9.** View south across the Virgin River canyon to the "radio tower" cone. Note dike at base near center of cone, and two prominent flows in the vertical south wall of the Virgin River canyon at left half of the photo. The upper flow is the "radio tower" flow (Qbr). The lower, thicker flow may be the Qbv_2 flow, which is well exposed farther upstream near the entrance to Timpoweap Canyon. The Hurricane Cliffs are in shadow at left.*

Additionally, in several areas along the Virgin River two or more flows or flow units are exposed in vertical cliff faces of the canyon walls. For example, two flows are present in the vicinity of sample VR1016-16, and two flows are present at and near samples VR116-1 through VR116-4, as described above in the Volcano Mountain and "radio towers" sections of this report. Additional geochemical sampling and mapping of the vertical and near-vertical canyon walls could reveal additional insight into the repeated plugging and subsequent exhumation of the ancestral Virgin River channel.

Alluvial Deposits

Older alluvial-fan deposits (Qaf_5, Qaf_6, Qafo): In the Hurricane quadrangle, older alluvial fan deposits are derived from three main drainages. Deposits derived from the Leeds Creek drainage northwest of Leeds form an extensive, locally deeply dissected surface (Qaf_5, Qaf_6) along the nose of the Virgin anticline. Older alluvial-fan deposits (Qaf_5, Qaf_6) derived from the Wet Sandy Creek drainage northwest of Anderson Junction are present west and south of Toquerville. Both these creeks drain the flanks of the Pine Valley Mountains and have very poorly sorted sand to boulders with clasts in excess of 10 feet (3 m) in diameter. Most clasts, and all of the larger clasts, are from the Pine Valley intrusive complex; Carmel and Iron Springs clasts are also common. West and south of Toquerville, these deposits contain abundant recycled Cambrian or Precambrian quartzite clasts. Level 5 alluvial-fan deposits derived from 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, in part, with level 5 and 6 stream-terrace deposits. I mapped two areas of level 6 alluvial-fan deposits atop Big Hill northwest of Leeds and west of Toquerville. These deposits occupy a similar topographic position as level 6 alluvial-fan deposits in the Harrisburg Junction quadrangle (Biek, in preparation); they are in excess of 200 feet (60 m) above adjacent drainages.

I also mapped additional older alluvial-fan deposits (Qafo) in the LaVerkin Creek drainage, north of LaVerkin. These deposits contain mostly Permian clasts and, except for their downstream end, lack Pine Valley intrusive clasts. They exceed 160 feet (50 m) in thickness in the NE1/4 section 14, T. 41 S., R. 13 W.; are locally faulted along the Hurricane fault; are correlative, in part, with level 6 stream-terrace deposits; and locally underlie the Pintura flow. Exposures in Nephis Twist, in the SE1/4SW1/4 SW1/4 section 12, T. 41 S., R. 13 W., reveal an angular unconformity in these deposits. Some of the best faulted exposures are in the SE1/4SE1/4NW1/4 and NE1/4 NE1/4NW1/4 section 13, T. 41 S., R. 13 W.

Stream-terrace deposits (Qat_{2-7}): I mapped six levels of stream-terrace deposits in the Hurricane quadrangle. The subscripts 2 to 7 denote the height of the deposits above adjacent drainages. Stream-terrace deposits are restricted to modern drainages and locally truncate older alluvial-fan deposits described above. The terrace deposits are moderately to well-sorted, typically poorly cemented sand, silt, clay, and pebble to boulder gravel that form level to gently sloping surfaces above modern drainages. Level 7 deposits are present only east of the Hurricane fault above Timpoweap Canyon, where they are more than 300 feet (90 m) above the Virgin River. Level 6 deposits form broad terraces at Toquerville and LaVerkin, and isolated remnants downstream above the Virgin River and in the Grapevine Wash drainage; they are 190 to 270 feet (58-82 m) above adjacent drainages. Level 5 deposits form prominent terraces along Grapevine Wash, and locally along the Virgin River and Ash Creek, and are 140 to 190 feet (43-58 m) above adjacent drainages. Level 4 deposits are 90 to 140 feet (27-43 m) and level 3 deposits are 30 to 90 feet (9-27 m) above adjacent drainages, and both are widespread along major drainages. Dalley and McFadden (1988) reported on 1,000 year-old Virgin Anasazi sites (Virgin Pueblo I and Early Pueblo II periods) that are preserved on level 3 terrace deposits northwest of Hurricane. Level 2 deposits are also widespread and are generally 10 to 30 feet (3-9 m) above adjacent drainages. Each of these terrace deposits varies from about 0 to 30 feet (0-9 m) thick.

The ages of stream-terrace deposits can be estimated based on long-term incision rates determined from dated basalt flows that entered the channel of the ancestral Virgin River. Willis and Biek (in press) found that long-term incision rates decrease from east to west across southwestern Utah, so that terrace deposits of a similar level are likely of different ages on the footwall and hanging wall of the Hurricane fault. Thus, whereas the subscripts 2 to 7 also denote the relative age of terrace deposits (youngest to oldest) west of or east of the Hurricane fault, correlation across the fault is not intended. Indeed, based on our long-term incision rates of 1.25 feet/1,000 years (0.38 m/ka) east of the fault and 0.43 feet/1,000 years (0.13 m/ka) west of the fault, level 7 deposits east of the fault may be correlative with level 4 deposits west of the fault. Still, all level 7 to level 4 deposits are likely middle Pleistocene, level 3 deposits middle to late Pleistocene, and level 2 deposits late Pleistocene to Holocene in age. Thus the subscripts 2 through 7 denote only the elevation above modern drainages and cannot be used to compare relative ages across the Hurricane fault. Conversely, the subscripts do indicate relative age when comparing deposits restricted to the hanging wall or footwall.

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. Level 1 deposits form active depositional surfaces and are correlative with younger alluvial and colluvial (Qac) deposits. Well-preserved debris-flow levees are present on Qaf_1 deposits along the Hurricane Cliffs south of Frog Hollow. I mapped a single level 2 alluvial-fan deposit near the confluence of Ash Creek and the Virgin River. This level 2 deposit has a deeply incised surface up to 30 feet (9 m) above the current drainage and is correlative with level 2 stream-terrace deposits; it is, in part, correlative and gradational with older colluvial (Qco) deposits. Alluvial-fan deposits vary from about 0 to 50 feet (0-15 m) thick.

Stream deposits (Qal_1): I mapped stream alluvium along the Virgin River and other principal drainages in the quadrangle. These alluvial deposits include river-channel and flood-plain sediments and minor terraces up to about 10 feet (3 m) above current stream levels. The deposits are 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. Stream alluvium is gradational with mixed alluvial and colluvial deposits, and locally includes small alluvial-fan and colluvial deposits. Where not constrained by topography, deposits along the Virgin River are marked by numerous meander scars.

Artificial Deposits (Qf, Qfl, Qfm)

I divided artificial deposits into artificial fill (Qf), landfills (Qfl), and mine dumps (Qfm). I mapped artificial fill only in large drainages crossed by Interstate 15 and Utah Highways 9 and 59, and in two small areas northeast of Leeds and southwest of LaVerkin. These deposits consist of engineered fill and general borrow material and vary greatly in thickness. Although I mapped only a few areas of artificial fill, fill should be anticipated in all developed areas, many of which are shown on the topographic base map. I mapped landfill deposits 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. I mapped waste rock from mining 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 shown.

Colluvial Deposits (Qc, Qco)

Colluvial deposits consist of poorly to moderately sorted, angular, clay- to boulder-size, locally derived sediment deposited principally by slopewash and soil creep on moderately steep slopes. Thin colluvial deposits are common on most slopes in the quadrangle, but I mapped them only where they conceal large areas of bedrock. These deposits locally include talus, mixed alluvium and colluvium, and eolian deposits that are too small to be mapped separately on plate 1. Older colluvial deposits (Qco) form incised, mostly inactive surfaces correlative with level 2 and level 3 stream-terrace deposits. Younger colluvial deposits (Qc) form active depositional surfaces that are correlative and gradational with younger alluvial-fan deposits (Qaf_1) and talus (Qmt). Older colluvial deposits (Qco) are probably late 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 (Qeo): These deposits generally form smooth, gently sloping surfaces with abundant pedogenic calcium carbonate (caliche) (Stage V-VI of Birkeland and others, 1991) and sparse eolian sand. I mapped the deposits atop the western portion of the Ivans Knoll flow. Unlike sand deposits draped over the Ivans Knoll flow (Qec/Qbi), basalt rarely pokes through to the surface of these older, thicker eolian deposits. Older eolian deposits (Qeo) are generally equivalent to the lower part of the eolian sand deposits (Qes) described below; most of the overlying unconsolidated sand has been removed by erosion. These deposits are generally 0 to 10 feet (0-3 m) thick.

Eolian sand deposits (Qes): Eolian sand (Qes) 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, very fine- to medium-grained, frosted quartz derived from Navajo and upper Kayenta strata. It forms an irregular blanket, stabilized in part by sparse vegetation, and varies from 0 to about 20 feet (0-6 m) thick. In most areas, eolian sand deposits 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 in a wash in the NE1/4NW1/4NE1/4 section 17, T. 41 S., R. 13W. I mapped large exposures of older eolian sand and caliche deposits separately as Qeo.

Mass-Movement Deposits

Older landslide deposits (Qmsm, Qmsc, Qmsb): I mapped large, displaced blocks of Moenave, Co-op Creek Limestone, and basalt as older landslides. Deeply dissected, chaotically oriented blocks of mostly Moenave strata (Qmsm) are present on the northeast-plunging nose of the Virgin anticline. The base of the deposits decreases in elevation to the south, suggesting that they are erosional remnants of a once larger deposit derived from a trio of fault-bounded, west dipping Moenave blocks to the north. The southern edge of these landslide deposits lies at an elevation comparable to level 5 stream-terrace deposits, suggesting they are probably middle 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 present in these landslide deposits.

I mapped a coherent landslide block of Co-op Creek strata (Qmsc), which dips east at about 30°, 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 middle to late Pleistocene in age. Large blocks of basalt (Qmsb), many from a single flow several tens of feet thick, are present on the floor of the Virgin River canyon between Hurricane and LaVerkin. They overlie level 2 stream-terrace deposits and so are probably late Pleistocene to Holocene in age.

Younger landslide deposits (Qmsy, Qmsh): Younger landslide deposits are present throughout the quadrangle and are characterized by moderately subdued hummocky surfaces and internal scarps, indicative of middle to late Holocene movement; some may be as old as late Pleistocene (figure 10). I mapped all but two as younger landslide deposits (Qmsy) in accord with mapping in the adjacent Harrisburg Junction quadrangle, where both older (Qmso) and younger (Qmsy) landslide deposits are present. Basal slip surfaces are most commonly in the Petrified Forest Member of the Chinle Formation, the upper red member of the Moenkopi Formation, the Woods Ranch Member of the Toroweap Formation, and the Iron Springs Formation. The slides incorpo-

Figure 10. View 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 basalt blocks of the "radio tower" flow are visible in the landslide, although Co-op Creek Limestone strata are exposed in the shadow at right. The landslide's basal slip surface is probably in Iron Springs strata. The entrance to Timpoweap Canyon is in the upper left corner of the photo.

rate these units and overlying formations. I mapped two slides with historical movement (Qmsh). One is in the Hurricane Cliffs east of Hurricane. This slide destroyed a portion of the Hurricane canal. The other historical slide is east of Leeds and is described under the geologic hazards section of this report. A small landslide scarp east of Leeds (see plate 1) formed during the 1992 St. George earthquake. Refer to the geologic-hazards section of this report for additional information about landslides in the quadrangle.

Talus deposits (Qmt): I mapped talus on and at the base of steep slopes. Talus consists of locally derived, very poorly sorted, angular boulders and minor fine-grained interstitial sediments and is deposited principally by rock fall. These deposits grade into 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 overlie the 353,000-year-old Volcano Mountain Qbv_2 flow in the footwall of the Hurricane fault, east of Hurricane; additional deposits are present northwest of Leeds. They are similar to younger alluvial and colluvial deposits, except that they form incised, inactive surfaces up to about 20 feet (6 m) above active drainages. Older mixed alluvial and colluvial deposits consist principally of poorly to moderately sorted, clay- to boulder-size, 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 present throughout the quadrangle. They consist principally of poorly to moderately sorted, locally derived or reworked sediments. These deposits typically are in small, nearly closed depressions that receive sediment from surrounding slopes, and in narrow washes that receive significant slopewash sediment. Younger mixed alluvial and colluvial deposits grade into and are correlative with stream (Qal_1), alluvial-fan (Qaf_1), and younger colluvial (Qc) 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 form incised, inactive, gently sloping surfaces about 20 feet (6 m) above modern drainages west of Hurricane, south of Toquerville, and in the southeastern corner of the quadrangle. 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. These mixed deposits are less than about 30 feet (9 m) thick.

Younger alluvial and eolian deposits (Qae): Younger mixed alluvial and eolian deposits occupy modern channels and broad, gently sloping depressions throughout the quadrangle. They consist of poorly to moderately sorted, locally gypsiferous, clay- to boulder-size sediment with well-sorted eolian sand and reworked eolian sand. Younger mixed alluvial and eolian deposits grade into and are in part correlative with younger alluvial (Qal_1) and eolian (Qes) 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.

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

Alluvial, eolian, and colluvial deposits (Qaec): Mixed alluvial, eolian, and colluvial deposits are present in active drainages and swales south of the Virgin River and at East Reef. These deposits consist chiefly of poorly to moderately sorted, clay- to small boulder-size sediment with well-sorted eolian sand and reworked eolian sand, as well as significant colluvium or slopewash. Mixed alluvial, eolian, and colluvial deposits are generally less than about 20 feet (6 m) thick.

Eolian and colluvial deposits (Qec): Mixed eolian and colluvial deposits are present west of Toquerville. These deposits consist of colluvial sediment derived from reworking of older alluvial fan deposits overlain by and intermixed with fine- to medium-grained eolian sand. These deposits are likely less than 20 feet (6 m) thick.

Stacked-Unit Deposits (Qes/Qaf_5)

I mapped eolian sand that overlies and partly conceals older alluvial-fan deposits in the north-central part of the quadrangle as Qes/Qaf_5. The sand is generally less than a few feet thick. Refer to the section of this report on basalt flows and related deposits for descriptions of similar eolian sand deposits that partly conceal basalt flows.

STRUCTURE

Regional Setting

The Hurricane quadrangle contains structural elements of both the Basin and Range and Colorado Plateau physiographic provinces. The quadrangle straddles the Hurricane fault, a major, active, north-trending, high-angle, west-dipping normal fault with significant Quaternary displacement. The quadrangle also contains the northeast-plunging nose of the Virgin anticline, which formed in the Late Cretaceous during the latter part of the Sevier orogeny. Two principal, west-dipping thrust faults repeat Triassic and Jurassic strata on the northwest flank of the anticline. Several smaller folds and numerous normal faults complicate the structure of the anticline's nose.

Folds

Virgin Anticline

The Virgin anticline is a 30-mile-long (48 km), northeast-trending, generally symmetrical fold that is co-linear with the Kanarra and Pintura anticlines to the north. The Virgin anticline has three similar structural domes along its length, each eroded to the level of the Permian Kaibab Formation. From southwest to northeast these are Bloomington dome, Washington Dome, and Harrisburg Dome. Only the northeast-plunging nose of the Virgin anticline is in the Hurricane quadrangle. The fold is made all the more visible by the resistant Shinarump Conglomerate Member of the Chinle Formation, which forms a carapace on Moenkopi strata exposed in Little Purgatory, along the axial surface of the fold.

In the Hurricane quadrangle, the Virgin anticline is an open, upright, symmetrical fold with flank dips generally of 25 to 35°; it plunges to the northeast at about 10 to 15°. Numerous normal faults and subsidiary folds, discussed separately, complicate the anticline's structure in the Hurricane and adjacent Harrisburg Junction quadrangles.

The age of formation of the Virgin anticline and subsidiary folds is difficult to determine because of inadequate cross-cutting relationships. The early Late Cretaceous Iron Springs Formation is the youngest bedrock unit involved in folding of the Virgin anticline. I believe the formation of the Virgin anticline is related to the Pintura anticline, a co-linear fold just to the north in the Pintura quadrangle. The Pintura anticline is unconformably overlain by the Canaan Peak Formation, the oldest beds of which are late Campanian (Late Cretaceous) in age (see, for example, Hurlow and Biek, 2000). The Virgin anticline thus likely formed between early and late Campanian time (about 84 to 72 million years ago), the youngest known age of the Iron Springs Formation and the oldest known age of the Canaan Peak Formation, respectively (Goldstrand, 1992, 1994), but both ages are poorly constrained. Davis (1999) suggested that the Virgin anticline formed above a blind, basal detachment in underlying Cambrian and Precambrian strata.

Leeds Anticline, Leeds Syncline, and other Subsidiary Folds

The Leeds anticline and Leeds syncline are 2- to 3-mile-long (3-5 km) subsidiary folds on the northwestern flank of the Virgin anticline (Proctor, 1953). I interpret both of these folds to be Sevier-age structures related to the Virgin anticline. The best exposures of the Leeds anticline are at Buckeye Reef, northwest of Leeds. There, the Springdale Sandstone forms the crest of the fold, which plunges about 10° north. South of Buckeye Reef, the axial surface bends abruptly to the southwest along Leeds Reef. The Leeds anticline is bounded on the east by what I interpret to be a west-dipping thrust fault, which truncates the southeast limb of the anticline. Leeds Reef, which forms the exposed core of the Leeds anticline, is upheld by folded beds previously mapped as the Shinarump Conglomerate Member of the Chinle Formation (Proctor, 1953; Proctor and Brimhall, 1986) and that I, as previously discussed, reassign to the basal Petrified Forest Member.

The Leeds syncline, which lies between and roughly parallel to the Leeds and Virgin anticlines, plunges gently northeast beneath the town of Leeds. A west-dipping thrust fault at the base of Big Hill truncates the syncline. Petrified Forest strata, mostly concealed by younger Quaternary deposits, forms the core of the syncline, whereas the west-dipping limb of the Virgin anticline forms its eastern limb. To the north at Big Hill, the Leeds syncline is present as a north trending fold subparallel to the Leeds anticline.

Other subsidiary, Sevier-age folds are present on the nose of the Virgin anticline. A syncline comparable in size to the Leeds syncline, which I call the Grapevine Wash syncline, lies east of the Virgin anticline axial surface in the NW1/4 section 8, T. 41 S., R. 13 W. The syncline plunges to the north-northeast at about 15°, parallel to the trace of the Virgin anticline axial surface. Based on limited exposures of Moenave strata to the southeast, in the E1/2 of sections 8 and 17, T. 41 S., R. 13 W., I mapped a north- to northeast-trending, and probably north-plunging, anticline, which I call the Grapevine Wash anticline. Based on gravity data, Cook and Hardman (1967) suggested that the Virgin and Kanarra anticlines are the same structure separated by the Hurricane fault. The presence of these subsidiary folds on the plunging nose of the Virgin anticline suggests that although the Virgin and Kanarra anticlines are co-linear and doubtless genetically related, they are individual structural units. Stewart and others (1997) also showed that the Virgin and Kanarra anticlines are separated by a syncline.

The footwall of the Hurricane fault contains numerous small, open folds, most of which trend parallel to the fault zone itself. Field relationships show that they are related to fault drag and differential movement on closely spaced faults, and thus are late Tertiary to Quaternary in age. Most folds mapped in Harrisburg strata 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 duplicate strata on the west flank of the Virgin anticline. Proctor (1948, 1953) first recognized the largest and westernmost fault amid considerable controversy over structural interpretations of the Silver Reef mining district. This fault separates Buckeye Reef and White Reef in the extreme northwest corner of the quadrangle, and extends at least 7 miles (11 km) to the southwest (Biek, in press). The fault repeats the Moenave Formation in the reefs. Based on surface and subsurface data, the fault dips about 30° west-northwest (Proctor and Brimhall, 1986). Proctor and Brimhall (1986) estimated that, in the Silver Reef mining district, the Springdale Sandstone Member of the Moenave Formation was displaced eastward at least 2,000 feet (600 m) on this fault.

Proctor and Brimhall (1986) also described a smaller west-dipping thrust fault between Buckeye and Butte Reefs. The only exposure of this fault is immediately north of Interstate 15, north of Leeds, where it places Petrified Forest and Dinosaur Canyon strata on the Springdale Sandstone. I interpret about 1,500 feet (450 m) of displacement on this fault (see plate 2, cross section D-D′). This is the same fault discussed previously that cuts the Leeds anticline and syncline. I mapped this fault to the southwest in the Harrisburg Junction quadrangle, where I interpret it to truncate the Leeds anticline at Leeds Reef. I infer a northeast-striking splay of this thrust fault in the center of section 13, T. 41 S., R. 14 W. based on outcrop patterns of Shinarump and Petrified Forest strata. This splay dies out in the west limb of the Virgin anticline.

A minor thrust fault, with stratigraphic separation of a few tens of feet, cuts Shnabkaib, upper red, and Shinarump strata at the north end of Little Purgatory, on the west limb of the Virgin anticline. Similar small faults are present in the Harrisburg Junction quadrangle (Biek, in press).

Schramm (1994) and Stewart and Taylor (1996) showed a small thrust fault in the footwall of the Hurricane fault that I reinterpret as local dissolution structures in, and paleotopography on, the Harrisburg Member of the Kaibab Formation. Based on subsequent fieldwork, W.J. Taylor (written communication, February 16, 1999) agreed that such a thrust is not present in the Hurricane quadrangle.

Reverse Fault

An east-dipping reverse fault repeats Temple Cap, Carmel, and Iron Springs strata west of Ash Creek and north of the Virgin River (figure 11). I traced the fault from the Virgin River northward for nearly 2 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 is post-Iron Springs (Late Cretaceous). It is probably a small back-thrust associated with formation of the Virgin anticline. Fault plane exposures in the NW1/4NE1/4NE1/4 section 22, T. 41 S., R. 13 W. show that the fault strikes N. 20° E. and dips about 65° east; the rake of slickenlines is 80° south, indicating a slight right-lateral component of displacement. Lovejoy (1964) misidentified this fault as the main Hurricane fault in his attempt to show that the Hurricane fault was primarily a Laramide reverse fault.

High-Angle Normal Faults

Hurricane fault: The Hurricane fault 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. Total stratigraphic separation generally increases northward along the fault, from less than 200 feet (60 m) south of the Grand Canyon (Hamblin, 1970) to 8,265 feet (2,520 m) near Toquerville (Stewart and Taylor, 1996). Interpretation of cross sections prepared for this mapping project suggests that stratigraphic separation may approach 10,000 feet (3,000 m) near Hurricane (plate 2). The Hurricane fault 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, 1964), and a fault with a significant component of left-lateral slip (Moody and Hill, 1956). Based principally on studies in southern Nevada and the Beaver Dam Mountains, Anderson and Barnhard (1993) also suggested that the Hurricane fault has a substantial component of left-lateral slip. As described below, studies in the greater Hurricane area (Schramm, 1994; Stewart and Taylor, 1996; Lund and Everitt, 1998; Lund and others, 2001; Hurlow and Biek, 2000; this report) unequivocally show that Pliocene to Quaternary displacement on the Hurricane fault is normal dip-slip, with a slight right-lateral component of displacement locally. I found no evidence to support the Hurricane fault being a reactivated Sevier-age structure, although it may sole into a Sevier detachment at depth.

Stewart and Taylor (1996) identified a structural fault-segment boundary at the south end of Black Ridge, just north of Toquerville, thus dividing the Hurricane fault into the Ash Creek segment to the north, which has purely dip-slip movement, and the Anderson Junction segment to the south, which shows dominantly dip-slip movement with a small right-lateral component of displacement. Segment boundaries are important because they may be sites of significant strain, may impede fault-rupture propagation, and may influence the locations of earthquakes. Paleoseismic investigations of Lund and others (2001) suggest that this structural boundary is a true seismogenic boundary as well.

Figure 11. *View north from hill 3662 in the E1/2 section 22, T. 41 S., R. 13 W. The Sinawava Member of the Temple Cap Formation (Jts) forms trough at left margin of photo and is locally faulted down against the Navajo Sandstone (Jn). The Co-op Creek Limestone Member of the Carmel Formation (Jcco) forms prominent ridges in the center of photo and is in part duplicated by an east-dipping reverse fault. Black Ridge and the Hurricane Cliffs form the skyline at right-center of the photo, and the Pine Valley Mountains are at the left.*

Published estimates of normal separation on the Hurricane fault in Utah vary by an order of magnitude, from 1,410 to 13,120 feet (430 to 4,000 m) (Anderson, 1980). This discrepancy arises in part from measurements taken along different segments of the fault, but is principally due to 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 at a sufficient distance from the fault to be representative of block interiors, and found a tectonic displacement (throw) of just 2,000 to 2,800 feet (600-850 m) at about the latitude of Pintura (see, for example, Swan and others [1980] for a discussion of apparent displacement versus tectonic displacement). Anderson and Christenson (1989) revised these estimates and found tectonic displacements of about 3,600 feet (1,100 m) and 4,900 feet (1,500 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, away from the effects of Sevier-age folding, shows a tectonic displacement of about 3,600 feet (1,100 m) at the latitude of Hurricane.

It is difficult to determine the stratigraphic separation along the Hurricane fault in the Hurricane quadrangle 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), I estimate the stratigraphic separation is 8,000 to 10,000 feet (2,400-3,000 m) between Hurricane and LaVerkin. Between LaVerkin and Toquerville, folding associated with a relay ramp between en echelon sections of the fault zone accommodates some of this displacement; there, stratigraphic separation is about 5,000 to 6,000 feet (1,500-1,800 m). These estimates are poorly constrained and depend greatly on interpretations of hanging-wall structure.

The age of first movement on the Hurricane fault is unknown, but based on a constant displacement rate determined from displaced Quaternary basalts, Stewart and Taylor (1996) considered 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) considered the Hurricane fault to be a Pliocene to Quaternary feature. Lund and others (2001) showed that the slip rate on the Hurricane fault appears to be decreasing during late Quaternary time, further complicating estimates of initial faulting.

Latest movement on the Hurricane fault is considered Holocene based on fault scarps in alluvium, displacment of Quaternary basaltic flows, and recent seismic activity, including the 1992 St. George earthquake, which probably occurred on the Hurricane fault (Arabasz and others, 1992; Lund and others, 2001). Lund and others (2001) considered the most recent surface faulting on the Hurricane fault in Utah to be Holocene based on limiting radiocarbon ages of faulted and unfaulted alluvial-fan deposits. Anderson and Christenson (1989) summarized strong evidence for a substantial rate of late Pleistocene displacement on the Ash Creek segment, and new dates on basaltic flows there suggest long-term slip rates of 18 to 23 inches/1,000 years (0.45-0.55 mm/yr) for about the past 850,000 years (Lund and others, 2001).

In the Hurricane quadrangle, the Anderson Junction segment comprises three discrete, straight-line sections. South of Mollies Nipple the fault strikes nearly north; between Mollies Nipple and LaVerkin, the fault strikes about N. 20° E.; and north of LaVerkin, the fault strikes about N. 15° W. Each of these short sections is characterized by a series of down-to-the-west faults that bound blocks of west-dipping Permian, Triassic, and (for the northern section) Jurassic strata. The fault cuts progressively younger strata at the surface northward through the quadrangle. Particularly complex faulting characterizes the footwall at the intersection of these sections. The fault zone varies from as little as 1,000 feet (300 m) wide at Frog Hollow to 6,000 feet (1,800 m) wide at Toquerville, near the Ash Creek-Anderson Junction segment boundary. Between LaVerkin and Toquerville, a west-dipping block of Moenkopi strata forms a relay ramp (see, for example, Peacock and Sanderson, 1994) between two en echelon faults. Although cut by numerous east- and west-dipping faults, the block shows a complete section of Moenkopi strata. Numerous slickenlines on west-dipping faults, some of which are shown on the geologic map, show a rake of 80 to 85° to the north, indicating a slight component of right-lateral slip. Antithetic faults typically show a slight right-lateral displacement as well. One 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° south, indicating a slight left-lateral component of displacement for this small block.

Although the footwall of the Hurricane fault is well exposed along its entire length, particularly instructive exposures are present: (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 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 Utah 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, which exposes blocks of Petrified Forest, Moenave, Kayenta, and Navajo strata (figure 12).

Fault scarps in Quaternary deposits are uncommon in the Hurricane quadrangle. Along the Hurricane fault, older alluvial-fan deposits (Qafo) are locally in fault contact with Triassic strata north of LaVerkin and older colluvial deposits (Qco) are faulted west of Mollies Nipple. Two closely spaced strands of the Hurricane fault, noted by Schramm (1994), are exposed in a small wash in the SE1/4SE1/4NW1/4 section 13, T. 41 S., R. 13 W. in deposits mapped as Qafo.

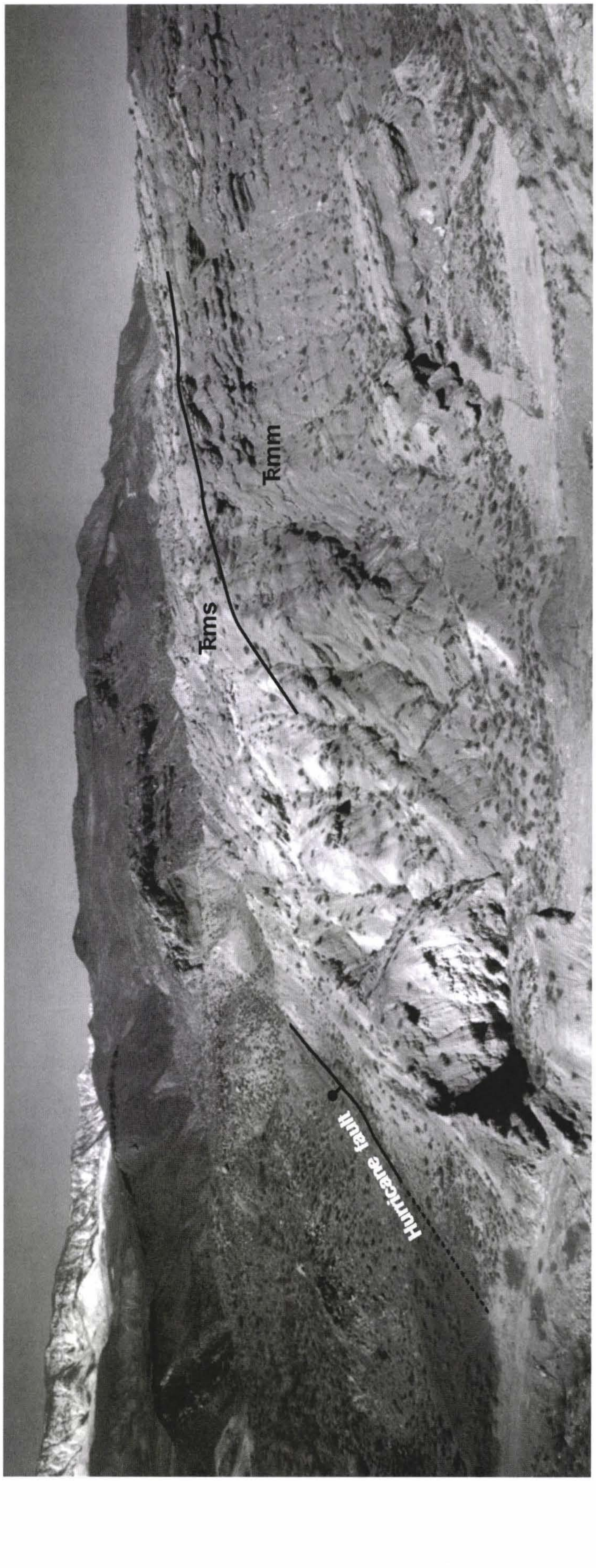

Figure 12. *View north across Nephis Twist where it crosses the Hurricane fault (T. 41 S., R. 13 W., SW1/4 section 12). Note increased dips of middle red (Ŧmm) and Shnabkaib (Ŧms) strata near center of photo due to fault drag. West-dipping Petrified Forest and Moenave strata form low, sage-covered area to left of fault.*

There, one fault dips about 60° west and shows about 9 feet (3 m) of displacement and the other strand dips 73° west and has about 4 feet (1.2 m) of displacement; both faults lack scarps. Elsewhere, the westernmost trace of the Hurricane fault is concealed by colluvial and alluvial-fan deposits, and possibly by grading associated with construction.

At the entrance to Timpoweap Canyon, the Hurricane fault places steeply west-dipping upper Moenkopi and Chinle strata down against Toroweap and Fossil Mountain strata, and also displaces a 0.353 ± 0.045 Ma (Sanchez, 1995) basalt flow that once plugged the ancestral Virgin River channel. This flow shows about 240 feet (73 m) of stratigraphic displacement at the entrance to the canyon, yielding a rate of stratigraphic displacement of about 8.16 inches/1,000 years (0.21 mm/yr). On the hanging wall, a splay of the Hurricane fault cuts the basalt in the footwall about 20 feet (6 m) (figure 8). The basalt extends to the river bed under the Utah Highway 9 bridge. Hamblin and others (1981) published a schematic cross section across the Hurricane fault through this area, but miscorrelated basaltic flows across the fault zone. Apparently, they mistook the "radio tower" flow on the hanging wall for the Volcano Mountain Qbv_2 flow on the footwall. Although their basic premise is sound – that is, the amount of downcutting is largely a function of the amount and rate of relative uplift – they incorrectly concluded that the Virgin River has yet to re-establish its pre-Volcano Mountain flow profile. In the past 350,000 years, 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, plus an additional 240 feet (73 m) through Permian strata – whereas 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-Volcano Mountain flow profile.

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

North of the Virgin River, the Kayenta-Navajo outcrop belt reveals several northwest-, north-, and northeast-striking normal faults of uncertain age. 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 strikes N. 50° W., is nearly vertical, and has a 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-northeast-striking, down-to-the-east normal fault, antithetic to the Hurricane fault, cuts the one-million-year-old Ivans Knoll flow along the western edge of the Hurricane Fields. Displacement 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 W.K. Hamblin, but I found no evidence of these faults. A similar down-to-the-east fault displaces the 850,000-year-old Pintura flow southwest of Toquerville.

Joints

Joints are common in all bedrock units in the Hurricane quadrangle, but are best developed in the Navajo Sandstone and the Shinarump Conglomerate Member of the Chinle Formation. Joints in the latter unit are generally widely spaced (a few tens of feet) and form a conjugate set subparallel to the strike and dip of bedding; the adjacent rock is 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), whereas others are broken by only widely spaced joints. Because the Navajo Sandstone is commonly pervasively jointed in the quadrangle, it is more easily eroded and forms fewer high cliffs than is typical of less jointed Navajo exposures a few tens of miles to the east. The most prominent joints strike 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. Plate 1 shows some of the larger, more prominent joints.

ECONOMIC GEOLOGY

Sand and Gravel

During the course of this mapping project, sand and gravel production was 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 Highways Materials Inventory of Washington County contains analytical information on these and other aggregate deposits in the quadrangle (Utah Department of Highways, 1964). Blackett and Tripp (1998) discussed issues affecting development of natural aggregate resources in the greater St. George area. Abandoned sand and gravel pits are common throughout the quadrangle, and are shown on the map with a symbol. Most pits are in deposits mapped as Qafo, Qaf_1, Qal_1, and Qat_6. Deposits mapped as Qafo, Qaf_5, and Qaf_6 north of the Virgin River, although not as well sorted as Virgin River gravels, may be a significant source of coarse sand and gravel.

Well-sorted eolian sand is present 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 in Temple Cap strata northwest of LaVerkin, in the NE1/4 section 15, T. 41 S., R. 13 W. These prospects probably 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 typically as impure beds and gypsiferous mudstone that are not currently of economic importance. No prospects in these units are known in the quadrangle. Woods Ranch strata, however, could provide small blocks of white gypsum for sculpting. Some of the best Woods Ranch gypsiferous exposures are in the NE1/4SE1/4SE1/4 section 10, T. 42 S., R. 13 W., and farther south in the lower reaches of Frog Hollow.

Building and Ornamental Stone

The Timpoweap Member, Springdale Sandstone, lower Kayenta, and basalt flows and cinders have all been used for building or ornamental stone in the greater Hurricane area. The quarries and pits are small, having produced rough material 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 (NW1/4 section 1, T. 42 S., R. 14 W.). The museum's 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. Basalt blocks, columns, and cinders are widely used in the Hurricane-LaVerkin areas for retaining walls, landscaping, and building foundations. Cinders are intermittently excavated from the "cinder pits," "radio tower," and East Reef cones.

The Shinarump Conglomerate is widely quarried in nearby areas for decorative stone and, when thinly cut, for "picture stone" that is made into tiles and coasters. The Shinarump Conglomerate contains prominent but widely spaced joints. Joints control staining by iron-manganese oxides, such that large blocks become concentrically zoned in a variety of interesting patterns. "Picture stone" is also common in the Iron Springs Formation. Although "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, planar-bedded, very fine-grained, slightly calcareous sandstone that would serve as good flagstone. The area between Gould Wash and Frog Hollow contains the best exposures of this stone. Petrified wood from the Petrified Forest Member of the Chinle Formation is used locally as an ornamental stone. The collection of petrified wood from public lands is now controlled 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 used locally 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 (chlorargyrite 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 was not until 1876 that the silver rush was underway in earnest (Proctor, 1953; Proctor and Brimhall, 1986). Proctor and Shirts (1991) provided a fascinating account of the discovery, disbelief, re-discovery, and development of this unusual mineral occurrence.

The Silver Reef mining district consists of four "reefs" along the northeast-plunging nose of the Virgin anticline. White, Buckeye, and Butte Reefs are on the anticline's northwest flank, whereas East Reef is on the anticline's east flank. The ore horizons are in 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 of the district are on file at the Utah Department of Natural Resources, Division of Oil, Gas and Mining, Abandoned Mines Reclamation Program.

The principal mining activity in the district lasted only through 1888, with lessee operations through 1909, after which operations essentially ceased. Prior to 1910, the district produced about 8 million ounces (226,800 kg) of silver, nearly 70 percent of which came from the prolific Buckeye Reef. Sporadic production between 1949 and 1968 amounted to about 30 ounces (0.85 kg) of gold, 166,000 ounces (4,706 kg) 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 (110 m) deep, and most ore bodies were lens shaped, averaging 200 to 300 feet (60-90 m) long by about half as wide. The ore averaged 20 to 50 ounces (0.6-1.4 kg) silver per ton, but varied from only a few ounces to about 500 ounces (14 kg) per ton (Proctor and Brimhall, 1986; Eppinger and others, 1990).

In the early 1950s, the U.S. Atomic Energy Commission initiated a drilling program to evaluate uranium mineralization 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 at and to the north of East Reef, in section 17, T. 41 S., R. 13 W. Poehlmann and King (1953) noted that uranium mineralization was controlled by lithology and structure, with faults and joints serving as conduits for transporting mineralized solutions to favorable beds. The Silver Reef mining district produced several hundred tons of uranium ore beginning with an initial shipment in 1950. Carnotite, the predominant uranium and vanadium mineral, appears as a cementing agent, and, more commonly, as a fracture filling and in association with carbonized wood fragments.

A leach-pad operation established between White and Buckeye Reefs to process tailings opened in 1979, but this venture closed with the collapse of silver prices (Chris Rohrer, Utah Abandoned Mine Land Reclamation Program, Division of Oil, Gas and Mining, verbal communication, April 7, 1997). In 1998, a Canadian mining company reevaluated a portion of the Silver Reef mining district (Van Splawn, 1998).

The genesis of the Silver Reef deposits has been the subject of considerable debate 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) discussed mineral occurrences and proposed models for the Silver Reef mining district. Several of these models were summarized by Houser and others (1988).

Other Prospects

I mapped several prospect pits along the Hurricane Cliffs immediately south of Utah 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 in the NE1/4SE1/4SE1/4 section 13, T. 41 S., R., 13 W. Minor fracture-controlled malachite staining is locally apparent in this area. Records of the Energy and Mineral Resources Program at the Utah Geological Survey show this is near an area of disseminated lead-zinc mineralization in the Kaibab Formation. The prospect west of Mollies Nipple is in highly fractured Queantoweap strata with indications of uranium mineralization.

In the early 1980s, URANEUZ USA Inc., a Reno, Nevada-based company, explored collapse features in the southeast corner of the Hurricane quadrangle, in section 13, T. 42 S., R. 13 W. (Larry Gore, Bureau of Land Management, verbal communication, 1999). Results of that drilling effort are not available.

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), 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), 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 in the SE1/4SE1/4SW1/4 section 11, T. 42 S., R. 13 W. The well was abandoned at a depth of 7,060 feet (2,152 m) in the Cambrian Bright Angel Shale. A log of the well is available at DOGM.

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 (Stowe, 1972). Similar oil seeps in carbonate rocks of the upper Timpoweap Member are present on both sides of Utah 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 (600 m) (Blakey, 1979). Another seep is immediately south of Utah Highway 9, just east of the quadrangle boundary (Biek and others, 2000b). The primary productive interval at the Virgin oil field is the uppermost part of the Timpoweap Member of the Moenkopi Formation. Stowe (1972) also reported significant shows of oil at the Virgin oil field 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, several miles to the north in the Pintura quadrangle, is a small, now abandoned field that produced from Hurricane fault-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 was 1,380 barrels of oil (Stowe, 1972; Peterson, 1974).

The lower part of the upper red member of the Moenkopi Formation contains a 100-foot thick (30 m), light-yellowish-brown, cliff-forming sandstone (the Purgatory sandstone), which stands in marked contrast to enclosing red beds. I found no evidence of oil at this horizon, but the yellowish color of the bed may have been caused by reducing hydrocarbon-bearing brines trapped in the core of the Virgin anticline prior to erosion.

Geothermal Resources

Budding and Sommer (1986) conducted an assessment of low-temperature geothermal resources in the St. George basin, which appear to be related to structure, rather than to recent volcanic activity. Basalts in the region originated at considerable depth, rising to the surface though narrow conduits, thus precluding the basaltic magmas from being a significant heat source (Budding and Sommer, 1986).

Budding and Sommer (1986) 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), the focal point of a private resort. These hot springs are just east of the Hurricane fault at the entrance to Timpoweap Canyon, between Hurricane and LaVerkin. They issue from and immediately above the bed of the Virgin River upstream for a distance of about 1,200 feet (370 m) beyond the developed pools.

The source of the recharge to Pah Tempe Hot Springs is not known (Everitt and Einert, 1994). Hot water probably rises through permeable Permian strata east of the Hurricane fault, which, at the entrance to Timpoweap Canyon, places impermeable Moenkopi red beds against highly permeable and cavernous Permian strata. The fault zone and red beds probably act as a flow barrier, preventing ground water from migrating farther downstream.

Everitt and Einert (1994) discussed 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 from 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. Discharge at the hot springs surged from 11 to about 20 cubic feet per second (0.3-0.6 m^3/s), the temperature dropped about 9°F (5°C), and the total dissolved solids (TDS) dropped by about 2,000 mg/L. The exact date of the surge is not known, but within a year all parameters began to recover and returned to normal after about 2.5 years. Between 1960 and 1982, the hot springs averaged about 104°F (40°C) and 9,600 to 9,900 mg/L TDS. Mundorff (1970) and Yelken (1996) summarized physical and chemical parameters of the Pah Tempe Hot Springs. They noted that the average annual dissolved-solids discharge at the springs is about triple that of the Virgin River just upstream of the springs. Because of this high salinity, water for Quail Creek Reservoir is collected upstream of the springs and piped to the reservoir.

WATER RESOURCES

With an average annual precipitation of 10 to 12 inches (25.4-30.5 cm) (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 development of the area. The 1993 State Water Plan for the Kanab Creek/Virgin River Basin (Utah Division of Water Resources, 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 in the St. George basin are cited below.

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/s), meaning that in this stretch the river gains water, probably due to ground-water inflow.

The main dam of the proposed Sand Hollow Reservoir will be in the extreme southwest corner of the Hurricane quadrangle. 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) (Graystone Environmental, 1997). It will be operated as an off-line reservoir to store 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 is planned to re-capture this ground water.

Ground Water

The principal aquifers in the St. George basin are in the Navajo Sandstone and unconsolidated Quaternary deposits. 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 on the western flank of the Ivans Knoll volcanic complex. It has a hydraulic conductivity of 3.34 feet per day (1.02 m/d) and a specific capacity of 7.6 gallons per minute per foot of drawdown (Utah Division of Water Rights data, reported in 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 (Cook and Hardman, 1967) preclude the presence of a deep, fault-bounded, sediment-filled basin west of the Hurricane fault.

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, ground water in the Navajo aquifer generally moves toward the Virgin River. The Virgin River forms the main 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. He noted that fracture permeability strongly influences the magnitude and anisotropy of hydraulic conductivity 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, as noted earlier, are locally common along faults in the Navajo Sandstone and probably restrict transverse permeability.

Plate 1 shows two large springs, the Pah Tempe Hot Springs and lower Ash Creek spring, as well as several smaller springs. Lower Ash Creek spring is in the SE1/4NE1/4SW1/4 section 11, T. 41 S., R. 13 W. near the base of the Pintura flow; it has a discharge of 5.9 cubic feet per second or 2,660 gallons per minute (0.18 m^3/s or 10,081 L/min) and is relatively fresh with a total dissolved solids content of 544 mg/L (Mundorff, 1971). Freethey (1993) also provided chemical analyses for this spring water. Refer to the geothermal resources section of this report for a discussion of physical and chemical parameters of Pah Tempe Hot Springs.

Cordova and others (1972), Cordova (1978), Clyde (1987), Freethey (1993), and Yelken (1996) reported on ground-water quality in the St. George basin. Water in the Navajo aquifer generally contains less than 1,500 mg/L, and commonly less than 500 mg/L, total 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

Geologic hazards are of increasing concern as the population of the greater St. George area, including the Hurricane quadrangle, expands into geologically hazardous areas. Geologic hazards in the quadrangle and surrounding area include hazards associated with earthquakes; mass movements, including landslides and rock falls; expansive, gypsiferous, and collapsible soil and rock; flooding; abandoned mines; radon; and other hazards. Christenson and Deen (1983), Christenson (1992), and Lund (1997a) provide non-technical summaries of such hazards in the greater St. George area. The Utah Geological Survey is creating a digital folio of GIS-based, 1:24,000-scale geologic hazard maps of the greater St. George area, including the Hurricane quadrangle.

Earthquakes

The Hurricane quadrangle lies within the Intermountain seismic belt, a north-trending zone of pronounced seismicity that extends 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 displacement in southwestern Utah (Earth Sciences Associates, 1982; Anderson and Christenson, 1989; Christenson, 1992; Hecker, 1993). The Hurricane fault in particular has a relatively high long-term slip rate, yet a general lack of evidence of recurrent Holocene movement makes it difficult to determine average recurrence intervals of surface-rupturing events (Stewart and others, 1997; Lund and Everitt, 1998; Lund and others, 2001). The region is generally considered capable of producing earthquakes of magnitude 7-7.5 (Arabasz and others, 1992), comparable to those that occurred prehistorically on the Wasatch fault 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 1850 to 1981; Anderson and Christenson (1989) updated that record through 1988. The largest earthquake, 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 (4.5 km) 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 magnitude of M_L 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 minor 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 dramatically, water emerged from new sources at lower elevations 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, including the Springdale landslide. Residents near the town of Leeds noted a landslide scarp about 500 feet (152 m) long, with a main scarp up to 6 feet (2 m) high, that formed during the St. George earthquake. The scarp is 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 hazard 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 in an area of moderate seismic risk (Christenson and Nava, 1992) and buildings should be constructed in accordance with the International Building Code (2000).

Mass Movements

Landslides

In the Hurricane quadrangle, strata especially susceptible to landslides include the Iron Springs Formation, 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. I mapped several large landslide complexes that involve these and adjacent overlying strata. Most of these slides are characterized by hummocky topography and moderately subdued internal scarps and should be considered capable of renewed movement, especially if altered by construction or other activities. Christenson and Deen (1983) and Christenson (1992) reasoned that most landslide movement to the west in the greater St. George area took place in the Pleistocene when conditions were wetter than at present, though historical movement is common in several areas.

The most prominent landslides in the Hurricane quadrangle are along the steep walls of the Virgin River canyon. On the south side of the Virgin River, south of the confluence of Ash and LaVerkin Creeks, two large rotational slumps are characterized by partly subdued hummocky topography developed in "radio tower" basaltic flows (figure 10). These landslides were probably initiated by lateral migration of the Virgin River and likely involve Carmel and Iron Springs strata. Up canyon to the east, Woods Ranch and overlying Fossil Mountain strata form several large rotational slumps. The largest of these is on the north side of the river in the NE1/4NE1/4 section 25, T. 41 S., R. 13 W. and the NW1/4NW1/4 section 30, T. 41 S., R. 12 W. Arcuate tensional fractures in Fossil Mountain strata, which strike parallel to the cliff and are mostly filled with slopewash deposits, characterize this landslide.

I mapped numerous rotational slumps characterized by moderately subdued hummocky topography (Qmsy) in Petrified Forest and overlying Moenave strata on the northeast-plunging nose of the Virgin anticline. I also mapped deeply dissected, significantly older landslides (Qmsm) in this area. In the NE1/4SW1/4 section 8, T. 41 S., R. 13 W., an incipient landslide (Qmsh) is present due west of the old Leeds landfill; fractures up to several feet wide and 20 feet (6 m) deep are present in Springdale strata at the top of the hill. These fractures strike 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, which 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 older landslide deposits.

Rock Falls

Rock-fall deposits 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 happen where resistant, fractured, or jointed strata break apart and tumble downslope. They are commonly associated with heavy rainfall events or earthquakes, but many are probably isolated random events after prolonged weathering. Numerous isolated rock falls, characterized by unweathered surfaces and fresh scars, are present along the Hurricane Cliffs and in drainages that cut across the cliffs. 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 present along the Virgin River canyon, attesting to the jointed basalt's proclivity for producing rock falls. Rock-fall hazards become of increasing concern 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 significantly when wet and shrink as they dry. This swelling and shrinking can cause 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 locally show through thin soils; 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). In the Hurricane quadrangle, Petrified Forest strata are exposed along the nose of the Virgin anticline in the northwestern corner of the quadrangle, and also in fault-bounded blocks along the Hurricane fault north of Hurricane.

Expansive clays are also present 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, and the Temple Cap, Carmel, and Iron Springs Formations. 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 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.

Dissolution of gypsum may lead to 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. Sulphate from gypsum dissolution can react with certain types of cement, weakening concrete structures.

Collapsible Soil

Christenson and Deen (1983) and Mulvey (1992) reported on collapse-prone soils in the Hurricane area. 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 form in geologically young, loose, dry, low-density deposits such as are common in Holocene alluvial fans and colluvium. Some wind-blown deposits are also susceptible to hydrocompaction. Hydrocompaction, or collapse, can happen 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.

Piping and Subsidence

Erosional pipes form when surface runoff erodes vertically downward through poorly lithified bedrock, or through alluvial, colluvial, or 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. I did not map erosional pipes, although they are locally common in Petrified Forest strata.

Several sinkholes of uncertain origin have opened in the vicinity of Hurricane (Solomon, 1993). All have involved unconsolidated alluvium overlying basaltic flows, and may represent 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.

Recently, at least two karst-like collapse features developed immediately outside the quadrangle. In April 1985, a large sinkhole formed 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 developed in the channel of LaVerkin Creek in July 1996 (Lund, 1997b). 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 gypsiferous 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. probably result from poorly expressed collapse features.

Flooding

In the Hurricane quadrangle, the Virgin River and its flood plain are in a relatively narrow, mostly undeveloped corridor bounded by resistant sedimentary 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 hazards of flash floods and debris flows in tributary drainages, however, are 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 present along the base of the Hurricane Cliffs near the normally dry Gould Wash, Frog Hollow, and smaller drainages (figure 13). 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 levees are still locally visible at the base of the Hurricane Cliffs, especially south of Frog Hollow. These levees attest to the powerful effects of heavy rainfall events over even very small catchment basins.

Abandoned Mines

The Abandoned Mine Land Reclamation Program (AMLRP), part of the Utah Division of Oil, Gas and Mining, recently completed reclamation 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 the western portion of the district and 184 adits and shafts in the East Reef area. Some adits and shafts are shown on the topographic base map. Detailed maps and information on mine openings are available from the AMLRP. Rohrer (1997) discussed reclamation of the western portion of the district.

Radon

Radon is an odorless, tasteless, colorless, radioactive gas present 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 the natural uranium content of soils or rocks, 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 be present.

Solomon (1992a, 1992b, 1995) evaluated the radon-hazard potential of the greater St. George area. Although the Hurricane quadrangle was not included in his studies, his results are useful in a general way because of similarities in the region's geology. Solomon's work suggested that the Petrified Forest Member of the Chinle Formation, and clasts from the Pine Valley intrusive complex, are a local source of uranium. Uranium was mined from the Springdale Sand-

__Figure 13.__ Oblique aerial view looking southeast at new development along the Hurricane fault 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 levees nearby show that even such small basins produce debris flows. The vertical cliffs here are principally 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 thin, darker brown Timpoweap strata. Photo by Janice Higgins, Utah Geological Survey.

stone 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.

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 be present in any given area. Testing of individual buildings is the only way to determine if unsafe levels of radon gas are present.

Volcanism

Basaltic flows and cinder cones show that the St. George basin was 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 suggest that additional eruptions may occur. Future eruptions can be expected to follow a similar pattern, producing relatively small cinder cones and lava flows that follow topographic lows. Such eruptions are likely to be preceeded by anomalous earthquake activity that may provide warning of an impending eruption. Bugden (1992) discussed possible volcanic hazards in southwestern Utah, including those associated with distant volcanoes.

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APPENDICES

Appendix A. Whole Rock Chemical Analyses

Flow	Qbi								Qbp				
Sample	H12699-1	VR41-06	VR123-7	VR123-8	VR123-11	VR123-11A	VR124-2	VR124-5	VR113-2	VR113-3	VR42-04	VR42-05	VR113-4
lat. (°N)	37.128	37.128	37.172	37.164	37.126	37.126	37.160	37.147	37.233	37.232	37.237	37.233	37.243
long.(°W)	113.296	113.296	113.352	113.362	113.364	113.364	113.335	113.333	113.295	113.297	113.275	113.279	113.297
X-Ray Fluorescence Analyses, wt.%													
SiO_2	50.06	50.03	49.49	49.73	50.36	50.32	48.66	47.83	48.72	49.64	49.30	48.15	49.27
TiO_2	1.37	1.40	1.43	1.41	1.42	1.41	1.42	1.40	1.49	1.50	1.49	1.91	1.48
Al_2O_3	16.03	16.24	16.54	16.24	16.17	16.29	16.42	16.08	16.42	16.37	16.26	15.88	16.62
Fe_2O_3	10.59	10.71	10.62	10.64	10.65	10.61	10.83	10.48	11.23	11.02	11.42	10.46	10.84
MnO	0.16	0.16	0.17	0.16	0.16	0.16	0.16	0.16	0.17	0.16	0.17	0.16	0.16
MgO	6.57	6.77	6.47	6.58	6.75	6.59	6.51	6.41	6.69	6.73	7.18	7.54	6.73
CaO	9.53	9.38	9.65	9.49	9.49	9.45	10.21	10.75	9.72	9.74	9.77	7.52	9.60
Na_2O	3.19	3.63	3.22	3.16	3.32	3.14	3.03	3.15	3.16	3.35	3.07	3.92	3.26
K_2O	1.01	1.19	0.93	1.08	1.10	1.01	0.81	0.84	0.78	0.74	0.82	1.90	0.80
P_2O_5	0.35	0.36	0.31	0.38	0.42	0.40	0.29	0.30	0.28	0.28	0.26	0.58	0.25
Cr_2O_3	0.03	<0.01	0.02	0.02	0.02	<0.01	<0.01	0.02	<0.01	0.03	<0.01	<0.01	0.01
LOI	-0.15	0.01	-0.44	-0.04	-0.38	-0.39	0.45	1.22	0.11	-0.47	0.01	0.01	-0.49
Total	98.89	99.88	98.41	98.85	99.48	98.99	98.79	98.64	98.77	99.09	99.75	98.03	98.53
Inductively Coupled Plasma-Mass Spectrometry, ppm													
Rb	11.6	12	11	12	15	15	10	9	12	15	9	13	15
Ba	630	644	513	712	706	669	456	537	316	379	284	518	317
Nb	11	12	10	11	12	12	8	9	7	7	9	25	8
Sr	582	608	564	692	734	722	498	524	424	444	416	790	443
Zr	172.5	152	161	179	176	177	143	152	149	150	133	241	153
Y	25.5	26	27	27	28	27	26	26	28	27	26	26	28
Cs	0.1	1	<1	<1	<1	<1	<1	<1	<1	<1	1	1	<1
Hf	4	4	4	5	5	5	4	4	4	3	3	5	4
La	33.0	32	25	34	37	37	22	23	20	20	17	37	21
Ta	0.5	1	<1	<1	1	1	<1	<1	<1	<1	<1	2	<1

Appendix A (continued)

Flow	Qbp				Qbd		Qber		Qbgw				
Sample	**VR114-2**	**VR116-7**	**VR116-8**	**VR116-9**	**VR710-4***	**VR41-07***	**VR122-1**	**VR122-2**	**VR19-1**	**VR124-8**	**VR41-08***	**VR710-1***	**VR710-2***
lat. (°N)	**37.236**	**37.202**	**37.208**	**37.213**	**37.119**	**37.088**	**37.199**	**37.208**	**37.127**	**37.135**	**37.125**	**37.105**	**37.111**
long.(°W)	**113.283**	**113.283**	**113.281**	**113.278**	**113.266**	**113.280**	**113.350**	**113.343**	**113.285**	**113.294**	**113.249**	**113.219**	**113.234**
X-Ray Fluorescence Analyses, wt.%													
SiO_2	49.29	49.02	49.19	49.27	43.97	43.62	43.75	43.48	49.15	48.96	48.69	50.06	48.42
TiO_2	1.47	1.91	1.41	1.93	2.61	2.60	2.32	2.36	1.66	1.67	1.69	1.61	1.61
Al_2O_3	16.56	16.08	14.91	16.05	10.95	10.99	12.13	11.88	13.84	13.62	14.12	14.20	13.77
Fe_2O_3	11.12	10.15	11.79	10.24	13.30	13.35	12.49	12.50	11.73	11.63	11.22	11.24	11.73
MnO	0.17	0.15	0.16	0.14	0.19	0.19	0.18	0.18	0.17	0.16	0.16	0.16	0.17
MgO	7.00	7.57	8.54	7.29	12.35	12.27	11.40	11.48	8.95	8.94	7.31	7.95	9.67
CaO	9.68	7.76	8.79	8.02	10.76	10.77	10.61	10.75	9.48	9.89	9.56	9.76	9.56
Na_2O	3.24	3.61	3.03	3.53	2.93	2.70	2.89	2.90	3.12	3.02	3.13	3.10	3.26
K_2O	0.71	1.50	0.95	1.58	1.42	1.74	1.70	1.80	0.89	0.86	1.48	0.88	0.88
P_2O_5	0.27	0.57	0.29	0.57	0.74	0.78	0.74	0.72	0.45	0.46	0.47	0.48	0.45
Cr_2O_3	0.03	<0.01	<0.01	<0.01	0.04	0.03	0.03	0.04	0.03	0.04	0.01	0.01	0.03
LOI	-0.63	0.41	-0.30	1.06	0.01	0.01	-0.13	0.18	-0.13	-0.01	0.01	0.18	0.37
Total	98.91	98.73	98.76	99.68	99.26	99.05	98.11	98.27	99.34	99.24	97.84	99.63	99.92
Inductively Coupled Plasma-Mass Spectrometry, ppm													
Rb	12	12	15	11	20	20	23	25	14	11	13	8	10
Ba	318	577	573	1375	665	715	1055	907	627	578	692	661	611
Nb	7	21	13	22	64	69	55	54	28	28	38	31	29
Sr	423	789	515	1020	833	846	1005	933	617	623	619	617	593
Zr	146	250	140	254	239	219	225	214	138	142	145	147	131
Y	27	27	21	27	28	27	25	23	22	22	22	24	22
Cs	<1	<1	<1	<1	0.3	1	<1	<1	<1	<1	1	0.1	0.1
Hf	4	6	4	6	6	6	6	6	4	4	3	4	3
La	19	39	27	36	54	55	57	54	38	35	41	40	36
Ta	<1	2	1	1	5	7	5	6	2	2	3	3	2

Appendix A (continued)

Flow	Qbgw	Qbcpc	Qbv_1				Qbv_2					
Sample	**VR710-3***	**VR123-5**	**VR123-6**	**VR124-7**	**VR1016-10**	**VR1016-12**	**H11299-5**	**H11299-6**	**H11299-7**	**H11299-8**	**H11299-9**	**HJ220-1**
lat. (°N)	**37.120**	**37.182**	**37.183**	**37.170**	**37.191**	**37.194**	**37.191**	**37.191**	**37.180**	**37.166**	**37.163**	**37.174**
long.(°W)	**113.264**	**113.319**	**113.322**	**113.339**	**113.347**	**113.337**	**113.275**	**113.275**	**113.280**	**113.285**	**113.286**	**113.378**
X-Ray Fluorescence Analyses, wt.%												
SiO_2	46.90	49.38	45.27	44.58	44.59	45.68	47.56	51.97	49.58	49.40	49.17	45.69
TiO_2	1.67	1.68	2.32	2.31	2.42	2.32	1.42	1.59	1.40	1.43	1.50	2.16
Al_2O_3	13.35	14.99	12.78	12.54	12.28	12.84	14.19	16.82	14.52	14.74	14.78	12.95
Fe_2O_3	11.93	11.53	12.37	12.57	12.62	12.59	10.47	8.53	11.98	11.74	11.94	12.26
MnO	0.17	0.16	0.17	0.17	0.18	0.17	0.17	0.11	0.17	0.17	0.17	0.17
MgO	10.13	8.57	10.48	10.97	10.67	10.70	5.86	4.11	8.16	7.91	7.60	9.92
CaO	10.61	8.57	10.17	10.38	9.95	10.24	11.05	10.04	8.83	8.73	8.87	10.78
Na_2O	2.99	3.09	3.18	2.59	3.12	2.96	2.86	3.39	3.06	2.98	3.07	2.70
K_2O	0.93	1.23	1.43	1.32	1.66	1.37	1.08	1.00	1.08	1.01	1.00	1.26
P_2O_5	0.50	0.43	0.66	0.66	0.70	0.64	0.33	0.33	0.32	0.30	0.31	0.68
Cr_2O_3	0.04	0.01	0.04	0.05	0.05	0.05	0.03	0.03	0.02	0.03	0.03	0.04
LOI	0.60	-0.42	0.39	0.91	0.13	-0.28	3.27	1.45	-0.41	-0.10	0.05	0.28
Total	99.82	99.21	98.48	99.05	98.37	98.28	98.29	99.37	99.12	98.44	98.49	98.89
Inductively Coupled Plasma-Mass Spectrometry, ppm												
Rb	11	16	19	15	19	18	13.8	11.2	12.6	12.8	9.0	12.6
Ba	696	534	804	791	844	851	513	625	619	522	517	1080
Nb	36	23	42	42	51	43	16	16	13	14	14	42
Sr	669	554	875	1125	933	898	490	543	554	462	481	890
Zr	145	156	191	194	221	191	142.0	137.0	123.0	124.5	129.5	185.5
Y	23	23	23	24	24	24	20.0	23.0	20.0	20.5	21.5	22.5
Cs	0.1	<1	<1	<1	<1	<1	1.7	0.2	0.2	0.3	0.1	0.4
Hf	3	5	5	6	6	6	4	4	3	3	4	5
La	43	30	47	47	52	48	28.0	30.5	31.5	26.5	27.5	54.0
Ta	3	2	4	4	5	4	0.5	0.5	0.5	0.5	0.5	2.5

Appendix A *(continued)*

Flow	Qbv$_2$								Qbv$_3$					
Sample	**HQ-01**	**HQ-02**	**VR16-1**	**VR16-2**	**VR40-09***	**VR116-1**	**VR123-2**	**VR1016-11**	**VR1016-1**	**VR1016-2**	**VR1016-9**	**VR1016-16**	**VR40-08***	**VR822-3**
lat. (°N)	**37.181**	**37.184**	**37.191**	**37.188**	**37.164**	**37.196**	**37.197**	**37.195**	**37.180**	**37.180**	**37.194**	**37.194**	**37.162**	**37.197**
long.(°W)	**113.366**	**113.359**	**113.271**	**113.272**	**113.384**	**113.290**	**113.304**	**113.338**	**113.373**	**113.373**	**113.349**	**113.331**	**113.396**	**113.344**
X-Ray Fluorescence Analyses, wt.%														
SiO_2	49.42	49.66	49.08	49.44	48.78	49.46	49.48	49.30	45.00	44.93	45.03	44.69	45.30	44.86
TiO_2	1.49	1.37	1.44	1.50	1.67	1.38	1.38	1.39	2.21	2.23	2.16	2.14	2.09	2.17
Al_2O_3	14.59	15.13	14.58	14.67	14.61	14.84	14.99	14.76	13.06	13.16	13.08	12.72	12.76	12.54
Fe_2O_3	11.98	11.80	11.55	11.35	11.11	11.71	11.86	11.89	12.52	12.47	12.27	12.22	12.11	12.25
MnO	0.17	0.17	0.17	0.16	0.16	0.17	0.17	0.17	0.18	0.18	0.18	0.18	0.17	0.18
MgO	7.95	7.81	6.61	7.71	7.74	8.00	8.03	8.15	10.51	10.85	10.53	10.66	9.90	10.55
CaO	8.78	8.96	9.28	8.91	8.35	8.89	9.12	8.91	10.72	10.64	10.90	10.46	10.38	10.68
Na_2O	3.09	3.13	2.96	2.96	3.07	2.99	2.94	3.05	3.17	3.00	3.54	3.34	2.91	3.15
K_2O	1.09	0.97	1.03	1.11	2.05	1.04	0.88	1.02	1.40	1.53	0.96	1.37	1.87	1.56
P_2O_5	0.36	0.32	0.34	0.34	0.51	0.34	0.32	0.32	0.72	0.76	0.75	0.74	0.66	0.68
Cr_2O_3	0.03	0.03	0.04	0.03	0.02	0.03	0.03	0.03	0.05	0.05	0.04	0.05	0.03	0.05
LOI	-0.50	-0.72	1.45	0.76	0.01	-0.39	-0.18	-0.37	-0.03	0.01	0.06	-0.12	0.01	0.12
Total	98.45	98.63	98.53	98.94	98.08	98.46	99.02	98.62	99.51	99.81	99.50	98.45	98.19	98.79
Inductively Coupled Plasma-Mass Spectrometry, ppm														
Rb	15	15	14.0	16.4	17	17	13	15	20	21	13	22	15	19.0
Ba	685	630	547	540	810	709	619	626	1020	981	969	982	1070	1095
Nb	13	12	14	15	32	13	12	12	50	49	50	48	47	52
Sr	640	681	478	482	666	664	673	632	1135	997	982	959	928	882
Zr	133	121	138.0	136.5	164	122	124	127	202	199	198	203	164	218
Y	24	22	21.5	21.5	23	22	21	22	25	24	24	23	23	23.0
Cs	<1	<1	2.2	1.5	1	<1	<1	<1	<1	<1	<1	<1	1	0.4
Hf	4	4	4	4	5	4	3	4	6	6	6	6	4	6
La	34	32	28.0	28.0	40	37	31	30	59	58	57	55	52	58.5
Ta	1	1	0.5	0.5	3	1	<1	1	5	5	5	5	4	3.0

Appendix A (continued)

Flow	Qbr														Qb
Sample	**H11299-4**	**VR115-2**	**VR115-5**	**VR115-6**	**VR116-2**	**VR116-3**	**VR116-4**	**VR116-10**	**VR123-1**	**VR123-3**	**VR123-4**	**VR115-7**	**VR116-5**	**VR116-6**	**VR115-3**
lat. (°N)	**37.198**	**37.201**	**37.199**	**37.200**	**37.196**	**37.196**	**37.196**	**113.280**	**37.196**	**37.196**	**37.178**	**37.200**	**37.198**	**37.199**	**37.200**
long.(°W)	**113.289**	**113.292**	**113.304**	**113.311**	**113.290**	**113.290**	**113.290**	**37.190**	**113.300**	**113.306**	**113.302**	**113.301**	**113.282**	**113.284**	**113.304**
X-Ray Fluorescence Analyses, wt.%															
SiO_2	45.10	44.40	44.43	44.63	44.35	45.21	44.57	44.82	44.40	45.18	45.80	44.06	44.63	44.93	48.81
TiO_2	2.23	2.27	2.20	2.15	2.36	2.25	2.27	2.26	2.19	2.37	2.49	2.24	2.17	2.28	1.43
Al_2O_3	12.76	12.46	12.71	13.04	12.50	13.03	12.71	12.60	12.61	12.96	13.08	12.49	13.06	12.92	15.18
Fe_2O_3	12.49	12.51	12.51	12.25	12.73	12.71	12.68	12.41	12.51	12.58	12.44	12.23	12.27	12.39	12.04
MnO	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.17	0.18	0.18	0.17	0.17
MgO	10.01	11.01	11.17	10.49	11.26	10.50	10.65	10.19	11.02	10.12	9.46	11.16	10.37	10.33	7.61
CaO	10.19	10.69	10.74	10.65	10.74	10.30	10.36	10.32	10.62	10.15	10.45	10.52	10.74	10.22	9.02
Na_2O	3.12	3.03	2.97	3.24	3.07	3.19	3.06	3.08	3.22	3.32	3.09	3.04	3.24	3.23	3.09
K_2O	1.69	1.67	1.55	1.39	1.45	1.52	1.52	1.65	1.40	1.48	1.47	1.70	1.58	1.66	1.04
P_2O_5	0.73	0.75	0.71	0.71	0.78	0.74	0.72	0.71	0.69	0.71	0.73	0.74	0.77	0.73	0.38
Cr_2O_3	0.05	0.05	0.04	0.04	0.05	0.05	0.05	0.04	0.04	0.04	0.02	0.05	0.04	0.01	0.03
LOI	0.02	-0.06	-0.36	-0.29	-0.42	-0.03	-0.09	0.33	-0.28	-0.32	-0.13	-0.03	0.04	0.10	-0.13
Total	98.57	98.96	98.85	98.48	99.05	99.65	98.68	98.59	98.60	99.77	99.07	98.38	99.09	98.97	98.67
Inductively Coupled Plasma-Mass Spectrometry, ppm															
Rb	20.2	25	23	27	28	22	23	19.8	24	19	17	26	25	24	16
Ba	991	1030	1050	1075	1160	1060	1070	986	894	908	890	1025	1100	1070	835
Nb	52	58	52	52	58	50	51	53	51	53	51	55	53	53	12
Sr	900	960	927	967	976	968	972	872	935	942	971	938	993	982	656
Zr	214	214	196	197	216	200	200	219	202	210	220	208	196	201	124
Y	22.5	25	23	24	25	23	23	22.5	23	23	24	24	24	23	23
Cs	0.6	<1	<1	<1	<1	<1	<1	0.4	<1	<1	<1	<1	<1	<1	<1
Hf	6	6	5	6	6	5	5	6	6	6	6	6	5	6	3
La	59.5	62	57	63	62	61	61	59.5	51	53	52	60	64	62	36
Ta	3.0	5	5	4	5	5	5	3.5	5	5	5	5	5	5	1

Notes: Samples located outside Hurricane quadrangle are marked with an *.
Sample locations are based on North American Datum of 1983.
LOI = loss on ignition.
All analyses performed by ALS Chemex, Inc., Sparks, NV.

Appendix B. Whole Rock Chemical Analyses Addendum.

Flow	Qbi	Qbd	Qbgw			Qbv_3	Qbv_2			Qbr
Sample	H12699-1	VR710-4*	VR710-1*	VR710-2*	VR710-3*	VR822-3	VR16-1	VR16-2	HJ220-1*	VR116-10
lat °N	37.128	37.119	37.105	37.111	37.120	37.197	37.191	37.188	37.174	37.190
long °W	113.296	113.266	113.219	113.234	113.264	113.344	113.271	113.272	113.378	113.280
Inductively Coupled Plasma-Mass Spectrometry, ppm										
Ce	66.5	106	77.5	70	80	111	55	56.5	105	110.5
Co	35.5	65.5	45	52	0.1	50	43	45.5	50.5	49.5
Cu	50	90	85	55	54	65	60	65	70	65
Dy	5.2	5.7	4	4	4.1	5	4.1	4.3	5	5.2
Er	3.2	2.4	2.3	1.8	2.2	2.4	2.4	2.3	2.5	2.3
Eu	1.8	2.6	1.9	1.8	1.8	2.7	1.5	1.6	2.6	2.5
Gd	5.9	8.6	5.8	5.6	6	8.2	5.3	5.1	8	7.9
Ga	18	19	19	19	19	20	19	19	21	21
Ho	1.1	0.9	0.8	3	0.8	1	.9	.8	.9	0.9
Pb	20	65	15	40	40	20	20	15	35	20
Lu	.4	0.3	0.2	0.2	0.3	.3	.3	.3	.3	0.3
Nd	30.5	48.5	34.5	31	35.5	50.5	26	26.5	49	49
Ni	55	345	150	215	235	175	130	175	185	185
Pr	7.9	12.5	9	7.7	9.1	12.5	6.4	6.6	12.2	12.5
Sm	5.9	9.6	5.9	5.3	6.2	8.8	5	5.2	8.9	8.4
Ag	<1	1	1	<1	<1	1	<1	<1	<1	1
Tb	.9	1.1	0.8	0.8	0.8	1.2	.9	.8	1	1.2
Ti	.5	<0.5	<0.5	<0.5	<0.5	<0.5	<.5	.5	<0.5	<0.5
Th	2	5	4	3	4	6	3	3	6	7
Tm	.4	0.3	0.3	0.3	0.3	0.3	.3	.3	.3	0.3
Sn	1	2	1	1	1	1	1	1	1	1
W	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
U	.5	1.5	1	1	1.5	2	.5	.5	1.5	2
V	200	235	185	180	190	265	200	200	270	260
Yb	2.6	1.7	1.9	1.7	1.6	1.8	2.2	2.1	1.9	1.9
Zn	80	140	120	115	120	115	105	105	115	125

Notes: Samples collected by the author outside Hurricane quadrangle are marked with an *.
Sample locations are based on North American Datum of 1927.
All analyses performed by ALS Chemex Labs, Inc., Sparks, NV.

Appendix C. Analytical data for $^{40}Ar/^{39}Ar$ ages. Samples run by the New Mexico Geochronological Research Laboratory.

Samples reported November 9, 1998.

ID	Temp (°C)	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$ (x 10-3)	$^{39}Ar_K$ (x 10-15 mol)	K/Ca	Cl/K (x 10-3)	$^{40}Ar^*$ (%)	^{39}Ar (%)	Age (Ma)	±2s (Ma)
VR123-11, G4:90, 160.20mg groundmass concentrate, J=0.000077877±0.12%, D=1.00513±0.00109, NM-90, Lab#=9241-01											
A	450	951.8	1.607	3185.5	0.111	0.32	87.0	1.1	0.7	1.5	8.4
B	625	83.52	4.565	261.9	0.411	0.11	15.2	7.7	3.3	0.91	0.23
C	700	25.33	4.249	62.14	0.805	0.12	5.1	28.7	8.3	1.02	0.09
D	800	14.61	2.982	25.08	2.77	0.17	6.0	50.7	25.7	1.04	0.03
E	875	11.8	1.738	15.34	2.80	0.29	7.5	62.5	43.2	1.04	0.03
F	975	12.96	1.037	18.88	3.25	0.49	12.8	57.4	63.5	1.04	0.02
G	1075	18.91	0.6597	39.48	2.16	0.77	18.6	38.4	77.0	1.02	0.04
H	1250	28.33	3.858	73.89	1.68	0.13	13.2	23.9	87.6	0.95	0.05
I	1650	33.66	12.68	92.85	1.99	0.040	11.8	21.3	100.0	1.02	0.05
total gas age			n=9		16.0	0.32				1.02	0.10
plateau			n=8	steps B-I	15.9	0.32			99.3	1.03	0.02
VR113-4, G6:90, 177.20mg groundmass concentrate, J=0.000078164±0.12%, D=1.00513±0.00109, NM-90, Lab#=9242-01											
A	450	396.4	2.046	1350.6	0.101	0.25	85.8	-0.7	0.7	-0.4	2.8
B	625	53.86	5.691	165.2	0.355	0.090	13.5	10.1	3.3	0.77	0.22
C	700	20.02	5.124	48.26	0.972	0.100	3.8	30.6	10.2	0.87	0.07
D	800	13.28	3.079	24.03	3.09	0.17	2.3	48.1	32.3	0.9	0.02
E	875	11.24	2.061	17.14	3.03	0.25	2.0	56.2	53.9	0.89	0.02
F	975	13.08	2.174	23.97	3.34	0.23	2.9	47.0	77.8	0.87	0.02
G	1075	24.10	2.512	60.40	1.46	0.20	6.1	26.6	88.2	0.91	0.06
H	1250	80.67	6.681	254.1	0.908	0.076	8.4	7.5	94.7	0.86	0.13
I	1650	132.3	27.86	435.8	0.74	0.018	7.9	4.3	100.0	0.82	0.34
total gas age			n=9		14.0	0.18				0.87	0.08
plateau			n=8	steps B-I	13.9	0.18			99.3	0.89	0.02

Notes:
Isotopic ratios corrected for blank, radioactive decay, and mass discrimination, not corrected for interferring reactions.
Individual analyses show analytical error only; mean age errors also include error in J and irradiation parameters.
Analyses in italics are excluded excluded from mean age calculations.
Correction factors:

$(^{39}Ar/^{37}Ar)_{Ca}$ = 0.00070±0.00005

$(^{36}Ar/^{37}Ar)_{Ca}$ = 0.00026±0.00002

$(^{38}Ar/^{39}Ar)_K$ = 0.0119

$(^{40}Ar/^{39}Ar)_K$ = 0.0250±0.0050

Samples reported January 24, 2000

ID	Temp (°C)	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$ (x 10-3)	$^{39}Ar_K$ (x 10-16 mol)	K/Ca	$^{40}Ar^*$ (%)	^{39}Ar (%)	Age (Ma)	±1s (Ma)
H11299-2, 175.14 mg Groundmass, J=0.000759297±0.10%, NM-103, Lab#=50109-01										
A	625	69.36	1.011	233.2	52.1	0.50	0.8	6.3	0.74	0.52
B	725	3.006	2.353	8.792	174.6	0.22	20.0	27.4	0.83	0.03
C	775	1.865	4.009	5.188	96.9	0.13	35.6	39.2	0.91	0.03
D	825	1.487	3.85	3.634	142.9	0.13	49.2	56.4	1.00	0.02
E	900	1.219	3.045	2.401	137.8	0.17	62.4	73.1	1.05	0.02
F	1000	1.333	2.722	2.845	113.9	0.19	53.8	86.9	0.99	0.02
G	1100	2.011	3.085	5.309	37.5	0.17	34.7	91.4	0.96	0.05
H	1275	3.377	22.64	15.92	47.9	0.023	16.2	97.2	0.76	0.06
I	1700	28.35	62.79	108.1	22.8	0.008	5.6	100	2.32	0.34
total gas age			n=9		826.4	0.18			0.96	0.15*
plateau		MSWD=10.6**	n=6	steps B-G	703.5	0.17		85.1	0.97	0.07*
isochron		MSWD=22.5*	n=8		$^{40}Ar/^{36}Ar$=283±10*				1.04	0.06*
H11299-4, 178.93 mg Groundmass, J=0.000759211±0.10%, NM-103, Lab#=50111-01										
B	725	8.151	0.7181	27.50	507.9	0.71	1.0	41.6	0.11	0.05
C	775	7.287	0.6470	24.51	46.9	0.79	1.4	45.4	0.14	0.06
D	825	8.304	0.8371	27.87	129.6	0.61	1.7	56.0	0.19	0.06
E	900	9.028	1.043	30.44	184.1	0.49	1.3	71.1	0.16	0.06
F	1000	9.541	1.794	32.59	106.1	0.28	0.6	79.8	0.08	0.06
G	1100	45.44	2.150	152.9	48.6	0.24	1.0	83.8	0.59	0.29
H	1275	37.41	11.64	130.5	185.0	0.044	-0.5	98.9	-0.25	0.26
I	1700	26.94	44.95	93.13	13.5	0.011	11.6	100.0	4.47	0.23
total gas age			n=8		1221.7	0.5			0.14	0.20*
plateau		MSWD=0.9	n=6	steps B-G	1023.2	0.59		83.8	0.14	0.06*
isochron		MSWD=1.4	n=7		$^{40}Ar/^{36}Ar$=296±2*				0.13	0.07*

VR122-2, 164.49 mg Groundmass, J=0.000758483±0.10%, NM-103, Lab#=50106-01										
A	625	13067.8	2.470	43595.3	2.83	0.21	1.4	0.2	238	442
B	725	68.35	0.2878	229.2	170.2	1.8	0.9	13.8	0.88	0.47
C	775	35.55	0.3241	119.8	68.3	1.6	0.5	19.2	0.25	0.26
D	825	14.99	0.4682	50.36	219.7	1.1	1.0	36.6	0.20	0.10
E	900	17.09	0.5741	57.37	148.3	0.89	1.1	48.4	0.26	0.12
F	1000	21.26	0.6662	71.37	127.0	0.77	1.0	58.5	0.31	0.15
G	1100	14.43	0.8645	49.02	108.7	0.59	0.1	67.2	0.02	0.12
H	1275	57.03	5.743	191.9	397.5	0.089	1.4	98.8	1.09	0.49
I	1700	191.5	33.54	622.8	15.6	0.015	5.4	100.0	14.4	1.6
total gas age			n=9		1258.0	0.78			1.3	2.6*
plateau		MSWD=0.1	n=6	steps B-G	842.1	1.12		66.9	0.20	0.16*
isochron		MSWD=0.5	n=8		$^{40}Ar/^{36}Ar$=299±3*				-0.07	0.08*

VR123-5, 165.44 mg Groundmass, J=0.000758162±0.10%, NM-103, Lab#=50107-01										
A	625	1148.8	1.119	3842.3	3.67	0.46	1.2	0.3	18	15
B	725	2.731	1.647	9.023	160.4	0.31	7.4	12.2	0.28	0.03
C	775	1.473	2.327	5.113	109.1	0.22	10.5	20.3	0.21	0.02
D	825	1.016	2.096	3.394	241.9	0.24	18.3	38.3	0.26	0.02
E	900	0.8724	1.285	2.72	298.1	0.40	20.0	60.5	0.24	0.01
F	1000	1.181	1.277	3.739	283.2	0.40	15.4	81.6	0.25	0.02
G	1100	2.876	1.670	9.884	108.3	0.31	3.3	89.7	0.13	0.04
H	1275	5.794	17.36	24.50	108.9	0.029	-0.2	97.8	-0.01	0.07
I	1700	12.88	18.28	41.66	30.2	0.028	16.2	100.0	2.89	0.16
total gas age			n=9		1343.6	0.30			0.33	0.15*
plateau		MSWD=0.9	n=5	steps B-F	1092.6	0.33		81.3	0.24	0.02*
isochron		MSWD=5.5**	n=8		$^{40}Ar/^{36}Ar$=290±6*				0.27	0.04*

Notes:
Isotopic ratios corrected for blank, radioactive decay, and mass discrimination, not corrected for interferring reactions.
Individual analyses show analytical error only; plateau and total gas age errors include error in J and irradiation parameters.
Analyses in italics are excluded from final age calculations.
n= number of heating steps
K/Ca = molar ratio calculated from reactor produced $^{39}Ar_K$ and $^{37}Ar_{Ca}$.
Discrimination (D) = 1.00676±0.00134 a.m.u.
* 2s error
** MSWD outside of 95% confidence interval

Appendic C. Analytical methods used for furnace analyses.

Sample preparation and irradiation:
Basalt samples provided by Robert Biek.
Groundmass concentrated by crushing, sieving, and hand-picking of any contaminant phases.
For samples reported November 9, 1998 (VR123-11, VR113-4):
Samples packaged and irradiated in machined Al discs for 0.5 hours in L67 position, Ford Research Reactor, University of Michigan.
For samples reported January 24, 2000 (VR122-2, VR123-5, H11299-2, H11299-4):
Groundmass concentrates were loaded into a machined Al disc and irradiated for:
NM-103 7 hours in D-3 position, Nuclear science Center, College Stations, TX.
NM-109 1 hour in the L67 position, Ford Research Reactor, University of Michigan
Neutron flux monitor Fish Canyon Tuff sanidine (FC-1). Assigned age = 27.84 Ma (Deino and Potts, 1990) relative to Mmhb-1 at 520.4 Ma (Samson and Alexander, 1987).

Instrumentation:
Mass Analyzer Products 215-50 mass spectrometer on line with automated all-metal extraction system.
Samples step-heated in Mo double-vacuum resistance furnace. Heating duration 10 minutes for 1998 samples, 7 minutes for 2000 samples.
Reactive gases removed by reaction with 3 SAES GP-50 getters, 2 operated at approximately 450°C and 1 at 20°C. Gas also exposed to a W filiment operated at approximately 2000°C.

Analytical parameters:
Electron multiplier sensitivity averaged $1x10^{-16}$ moles/pA.
For samples reported November 9, 1998 (VR123-11, VR113-4):
Total system blank and background for the furnace averaged 4200, 10, 9, 5, 15 x 10^{-18} moles at masses 40, 39, 38, 37, and 36, respectively for temperatures <1300°C.
For samples reported January 24, 2000 (VR122-2, VR123-5, H11299-2, H11299-4):
Total system blank and background averaged 200, 1, 0.1, 0.1, 1 x 10-17 moles.
J-factors determined to a precision of ± 0.1% by CO_2 laser-fusion of 4 single crystals from each of 6 or 3 radial positions around the irradiation tray.
Correction factors for interfering nuclear reactions were determined using K-glass and CaF2 and are as follows:
For samples reported November 9, 1998 (VR123-11, VR113-4):
$(^{40}Ar/^{39}Ar)K = 0.025\pm0.005$; $(^{36}Ar/^{37}Ar)Ca = 0.00026\pm0.00002$; and $(^{39}Ar/^{37}Ar)_{Ca} = 0.00070\pm0.00005$.
For samples reported January 24, 2000 (VR122-2, VR123-5, H11299-2, H11299-4):
NM-103 $(^{40}Ar/^{39}Ar)K = 0.0002 + 0.0003$; $(^{36}Ar/^{37}Ar)_{Ca} = 0.00028 + 0.000005$; and $(^{39}Ar/^{37}Ar)_{Ca} = 0.00089 + 0.00003$.
NM-109 $(^{40}Ar/^{39}Ar)K = 0.025 + 0.0003$; $(^{36}Ar/^{37}Ar)_{Ca} = 0.00026 + 0.00002$; and $(^{39}Ar/^{37}Ar)_{Ca} = 0.0007 + 0.00005$.

Age calculations:
Total gas ages and errors calculated by weighting individual steps by the fraction of ^{39}Ar released.
Plateau definition: 3 or more analytically indistinguishable contiguous steps comprising at least 50% of the total ^{39}Ar (Fleck et al., 1977).
Preferred age calculated for indicated steps when the sample does not meet plateau criteria.
Plateau or preferred ages calculated by weighting each step by the inverse of the variance.
Plateau and preferred age errors calculated using the method of (Taylor, 1982).
MSWD values are calculated for n-1 degrees of freedom for plateau and preferred ages.
Isochron ages, $^{40}Ar/^{36}$ Ari and MSWD values calculated from regression results obtained by the methods of York (1969).
Decay constants and isotopic abundances after Steiger and Jäger (1977).
All final errors reported at $\pm2\sigma$, unless otherwise noted.

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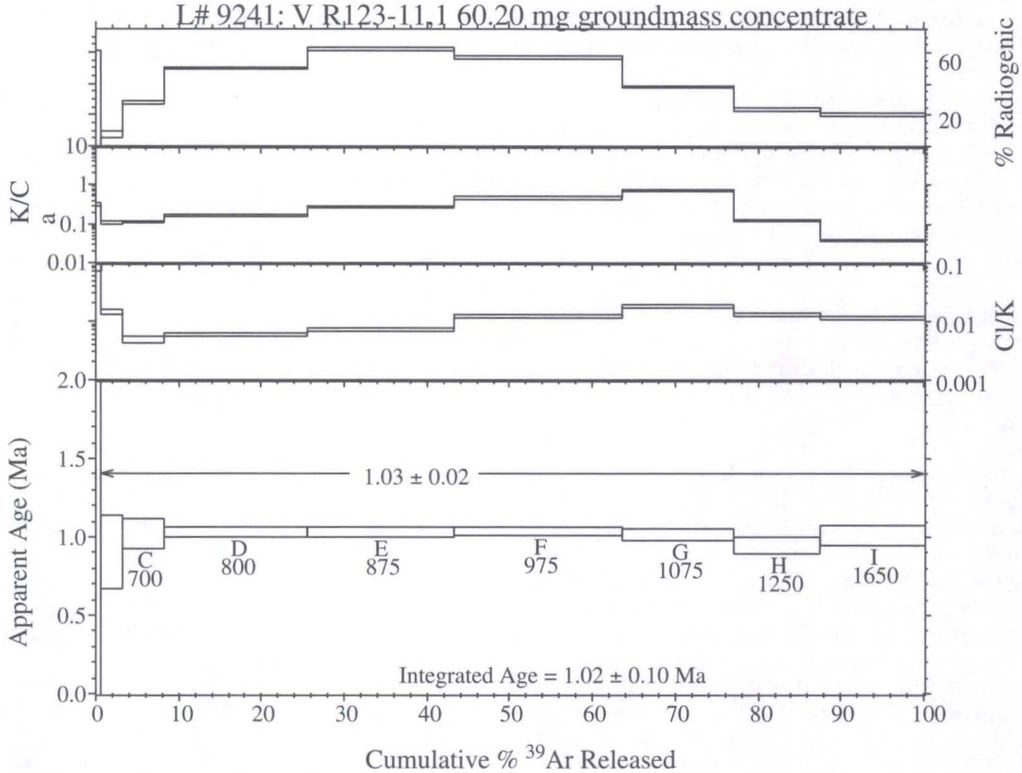
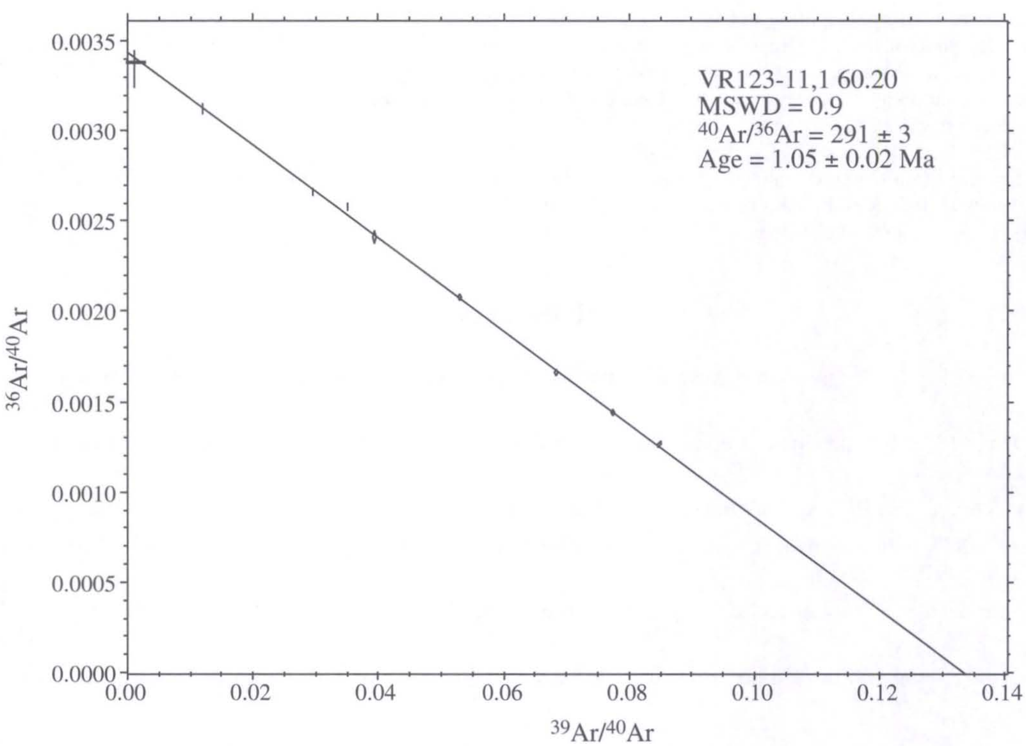
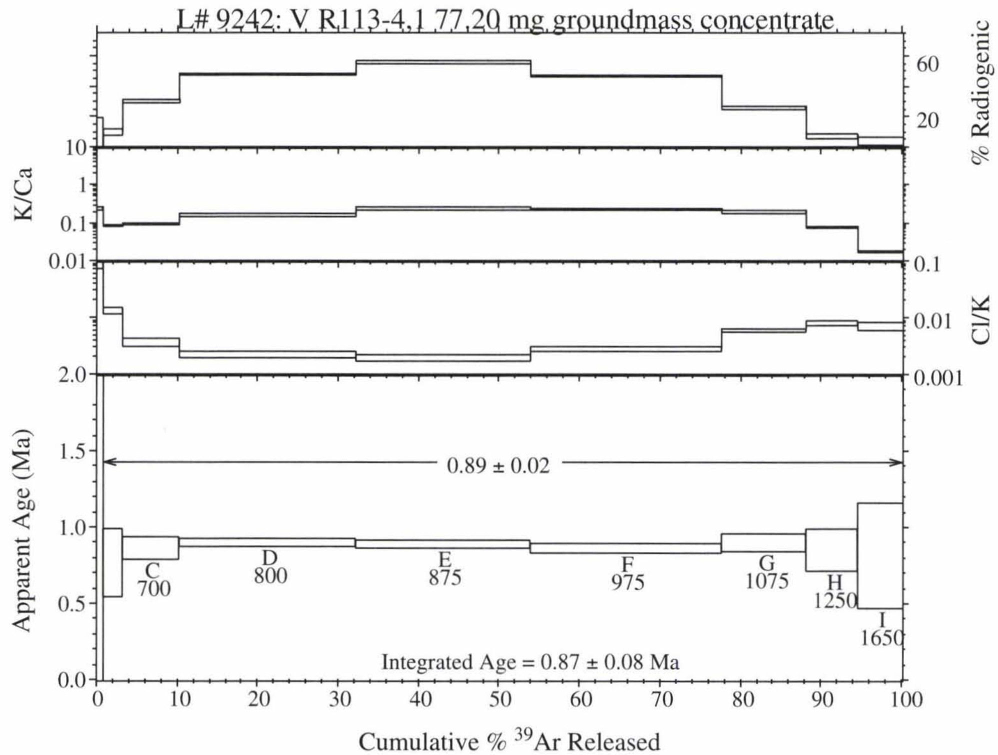
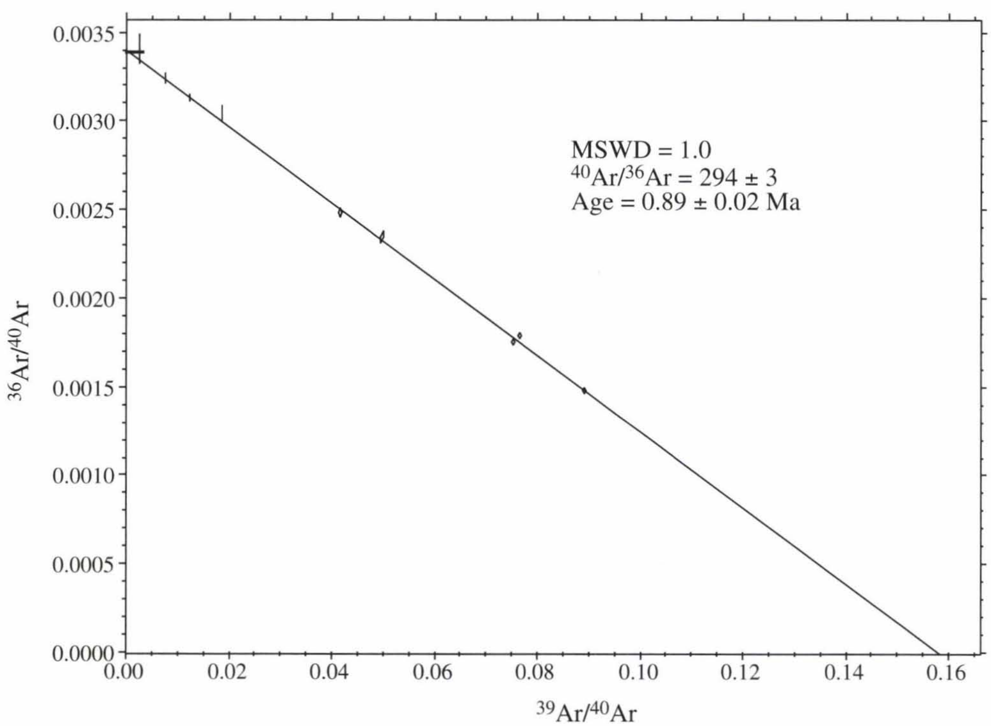




Age spectum and isochron for VR123-11.





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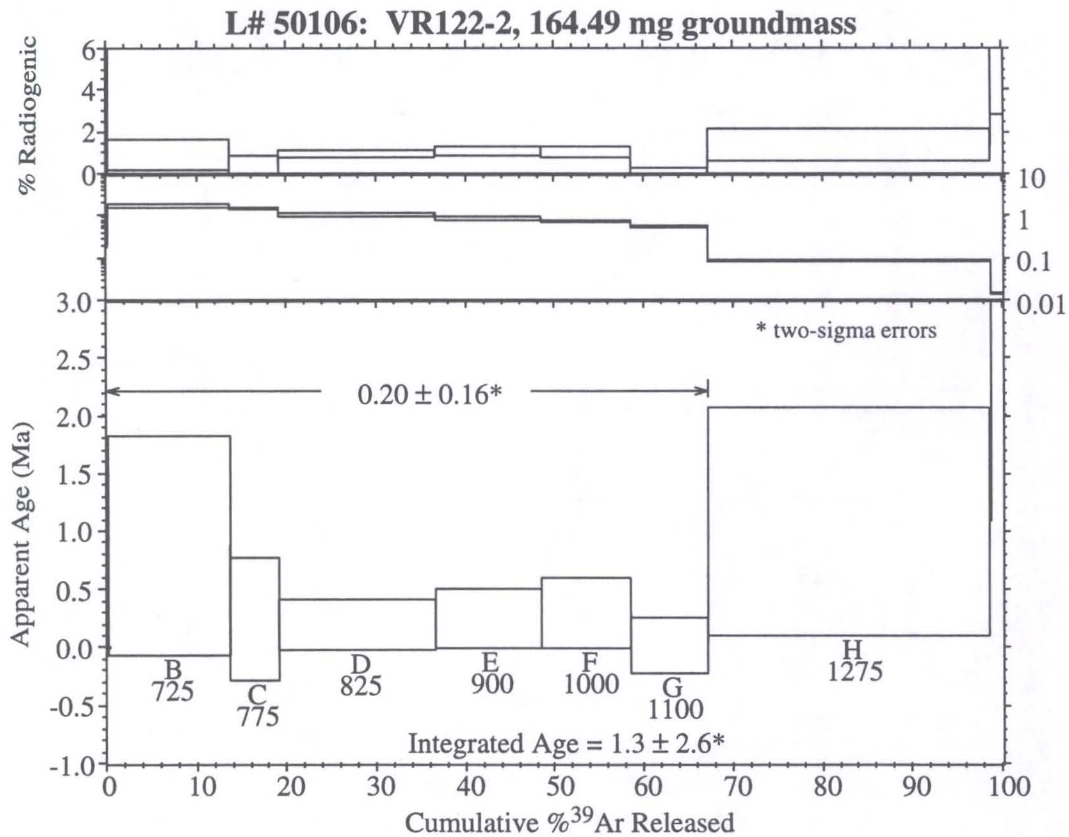

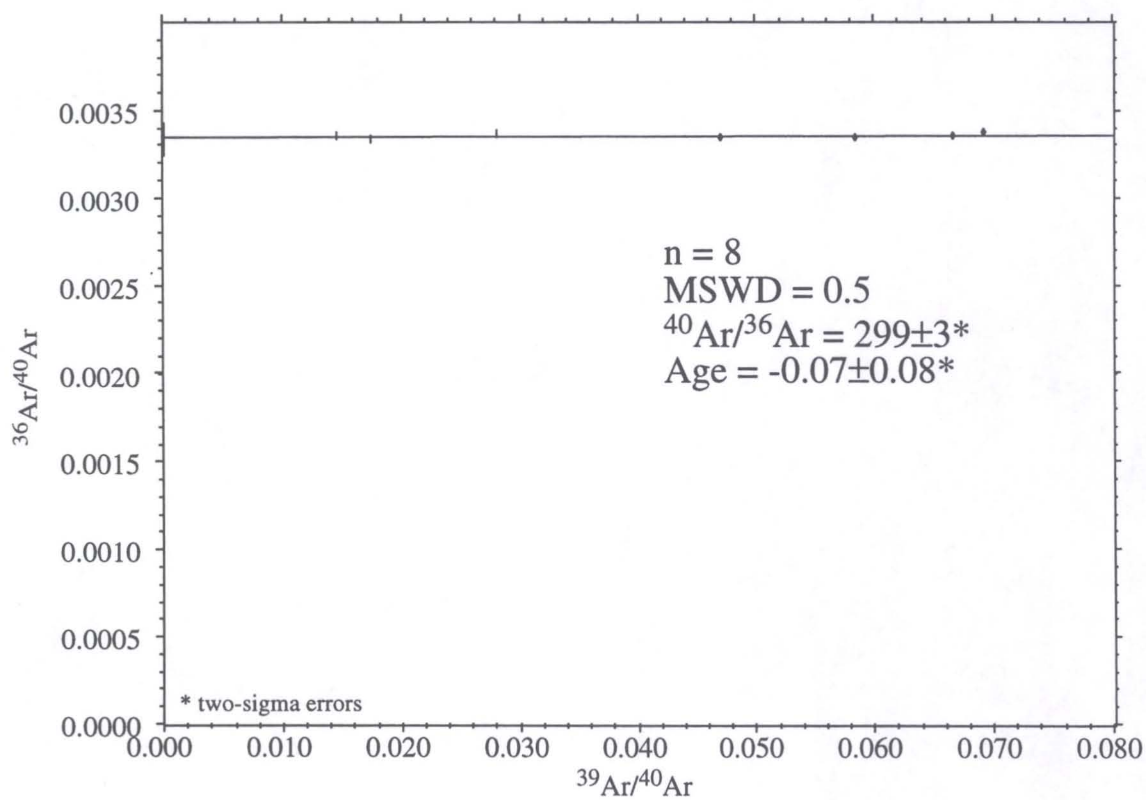

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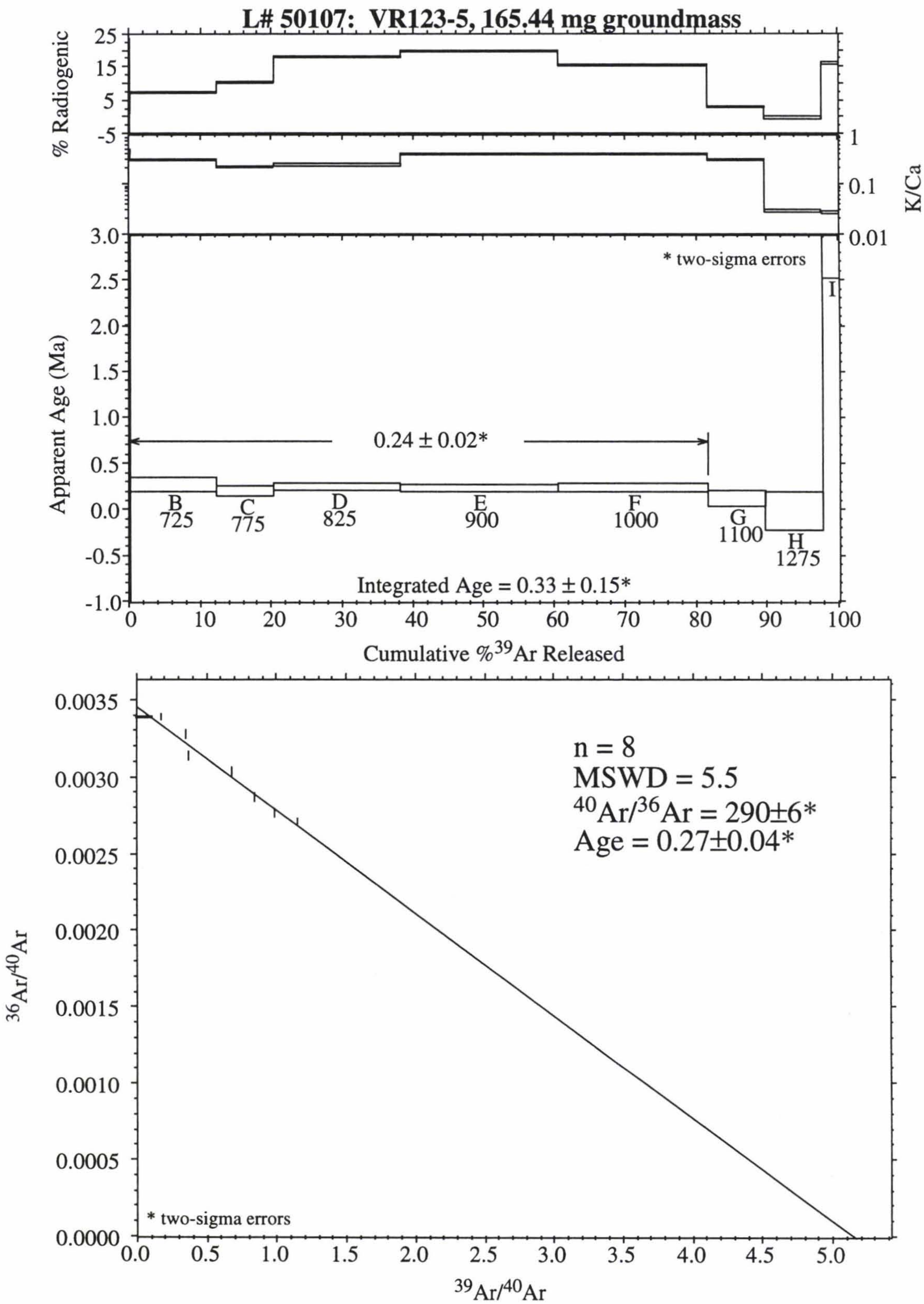

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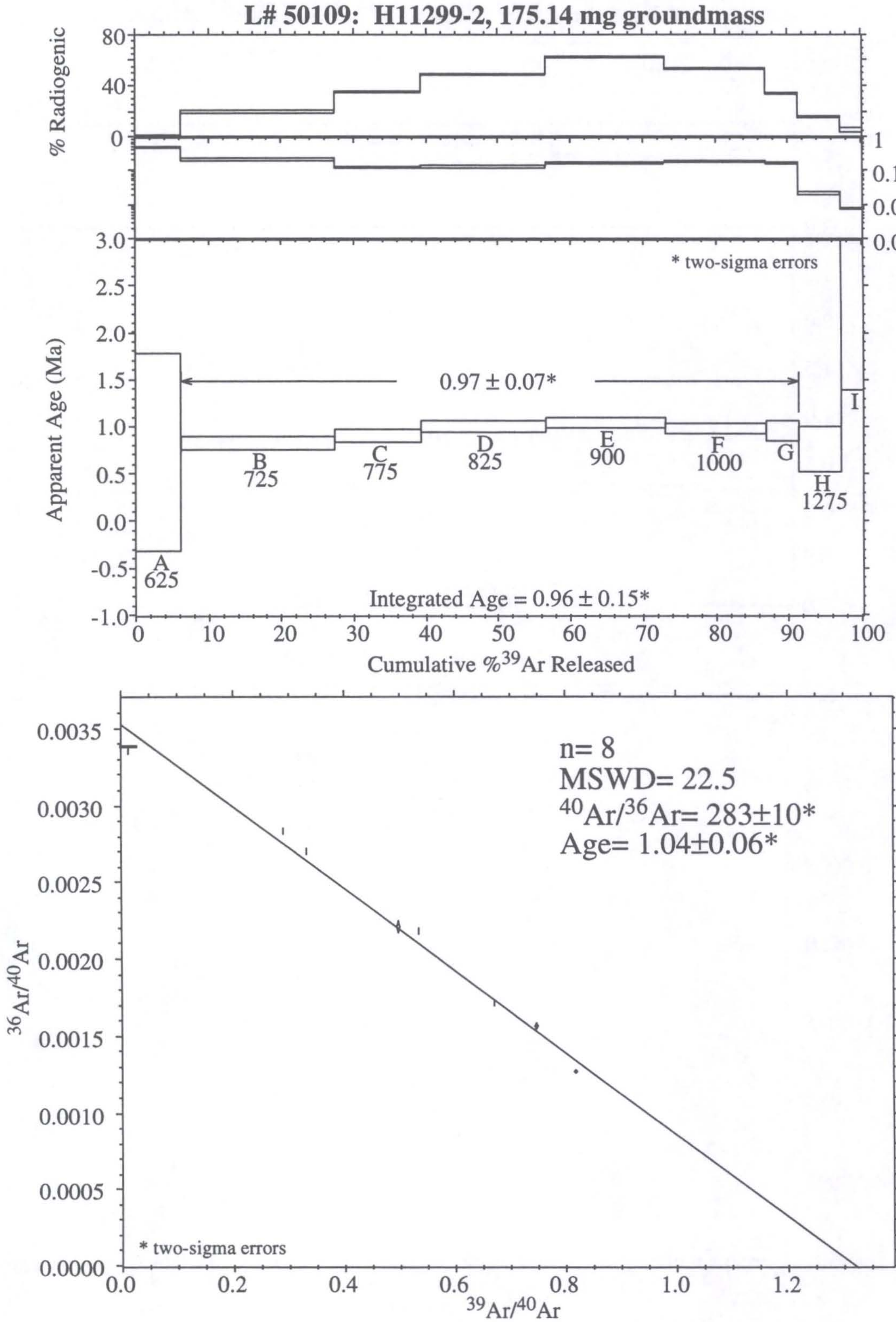

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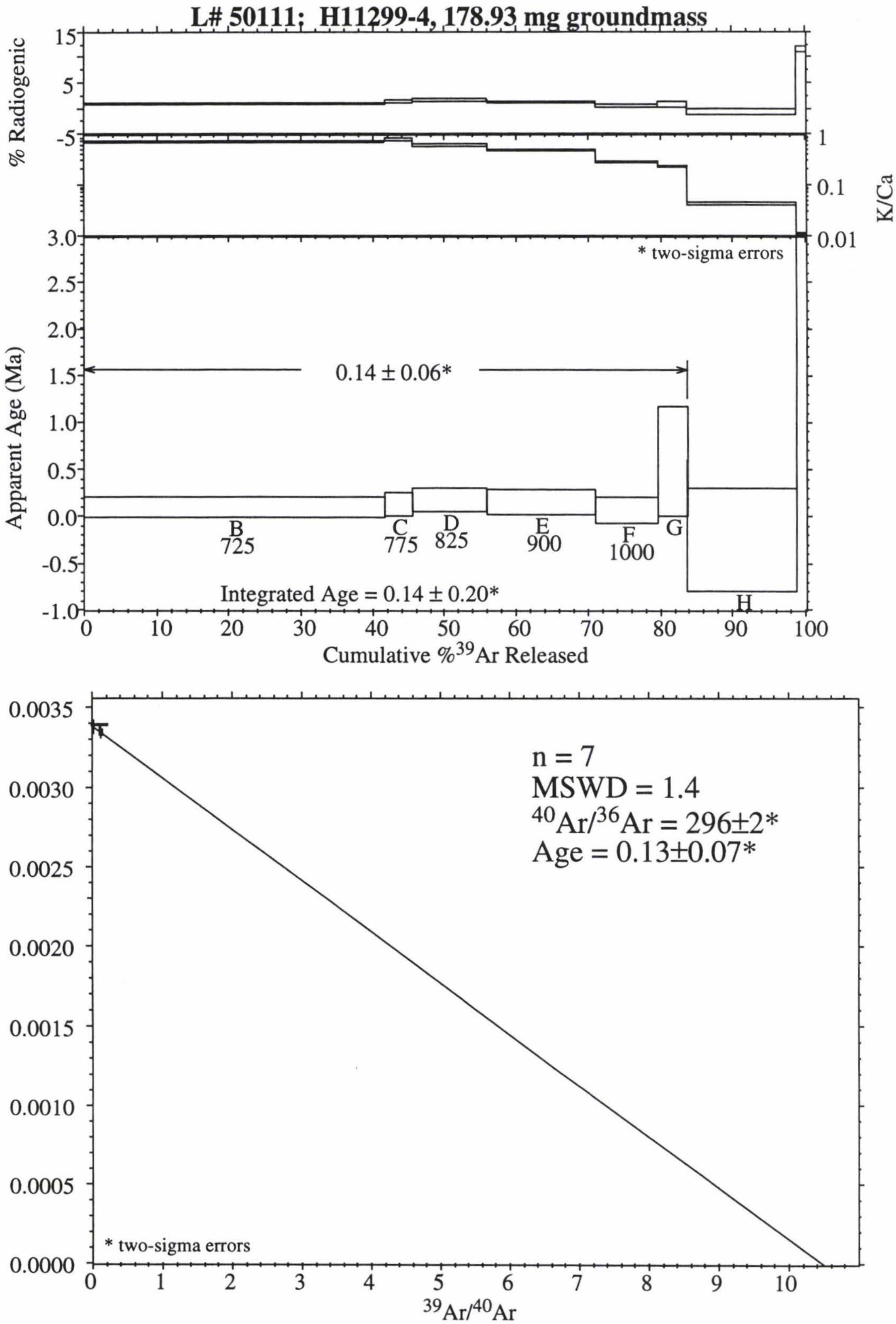

Age spectrum and isochron for H11299-4.