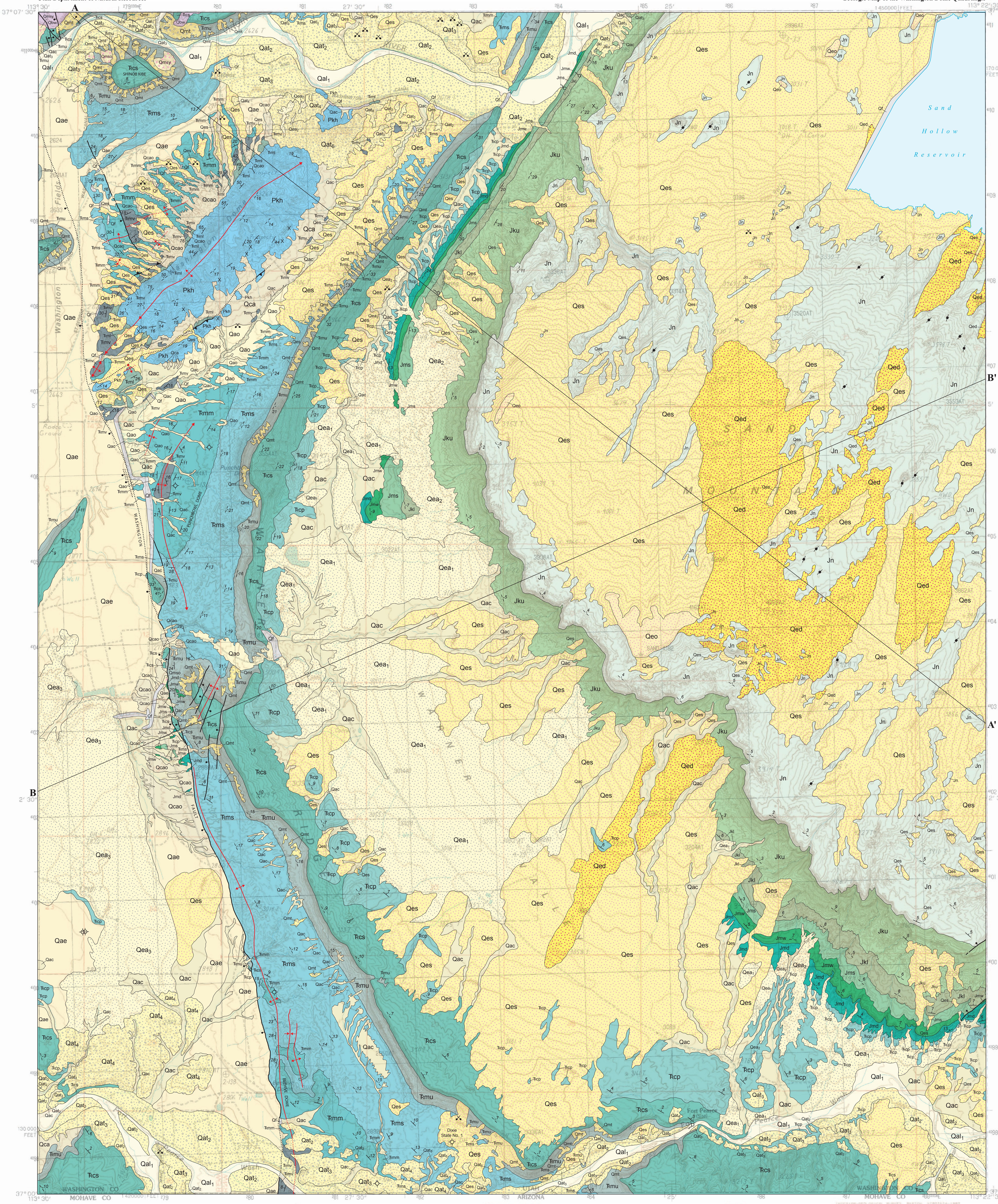



Base from U.S. Geological Survey,
Washington Dome 7.5 provisional quadrangle, 1986

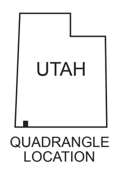
*Research supported by the Utah Geological Survey and U.S. Geological Survey, National Cooperative Geologic Mapping Program, under USGS STATEMAP award number 97AG01797. The views and conclusions contained in this document are those of the author and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S Government.*



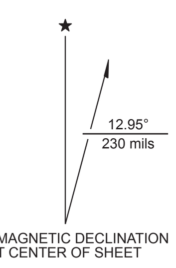
SCALE 1:24,000

KILOMETERS: 1 .5 0 1 2
METERS: 1000 0 1000 2000
MILES: 1 .5 0 1
FEET: 1000 0 1000 2000 3000 4000 5000 6000 7000 8000 9000 10000

(TOPOGRAPHIC) CONTOUR INTERVAL 20 FEET




QUADRANGLE LOCATION




2005 MAGNETIC DECLINATION AT CENTER OF SHEET

# GEOLOGIC MAP OF THE WASHINGTON DOME QUADRANGLE, WASHINGTON COUNTY, UTAH

by

**Janice M. Hayden**

**2005**

Field work by author in 1998
Robert F. Biek, Project Manager
GIS cartography by
Garrett Vice, DeRay Jensen, David Maxwell,
Southern Utah University
Cartography by James Parker,
Utah Geological Survey

| | | | |
|---|---|---|---|
| 1 | 2 | 3 | 1 Washington<br>2 Harrisburg Junction<br>3 Hurricane<br>4 St. George<br>5 The Divide<br>6 Lizard Point<br>7 Yellowstone Flat<br>8 Rock Canyon |
| 4 | | 5 | |
| 6 | 7 | 8 | |

ADJOINING 7.5 QUADRANGLE NAMES

ISBN 1-55791-719-1

QUATERNARY

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

Alluvial Deposits

**$Qal_1$** Stream deposits -- Moderately to well-sorted clay to fine gravel deposits in large active drainages; includes terraces up to 10 feet (3 m) above current channels; 0 to 20 feet (0-6 m) thick.

**$Qat_{2\text{-}6}$** Stream-terrace deposits -- Gravel to cobble-size clasts in a muddy to coarse-sand matrix; form a poorly sorted, indurated pedogenic carbonate-cemented conglomerate at several levels above the present flood plain; clasts are well rounded and many are exotic to the quadrangle, indicating a source several miles upstream; pedogenic carbonate (caliche) thicker in older deposits; subscripts denote relative height above the current drainage; level 2 deposits are 10 to 30 feet (3-10 m); level 3 deposits are 30 to 90 feet (10-27 m); level 4 are 90 to 140 feet (27-42 m); level 5 are 140 to 190 feet (42-57 m); and level 6 are 190 to 270 feet (57-82 m) above present channels; typically 0 to 40 feet (0-12 m) thick except for $Qat_6$, which may exceed 70 feet (20 m) thick.

**Qao** Older alluvial deposits -- Remnants of older, locally derived and moderately sorted clay- to boulder-size alluvial deposits; 10 to 20 feet (3-6 m) higher than and dissected by minor drainages; 0 to 20 feet (0-6 m) thick.

Eolian Deposits

**Qes** Eolian sand deposits -- Well- to very well sorted, very fine to medium-grained, well-rounded, usually frosted, mostly quartz sand; derived principally from the Navajo and Kayenta Formations; commonly deposited in irregular hummocky mounds on the lee side of ridges, as well as on Sand Mountain and in Warner Valley; locally forms poorly developed dunes; 0 to 50 feet (0-15 m) thick.

**Qed** Eolian dune sand deposits -- Same as eolian sand deposits, but forms dunes on Sand Mountain and in Warner Valley; 0 to 40 feet (0-12 m) thick.

**Qeo** Older eolian sand and caliche deposits -- Well-developed (stage IV) pedogenic carbonate (caliche) with lesser eolian sand; generally forms planar surfaces, higher than the surrounding Navajo Sandstone, that are covered with nodular caliche and sparse eolian sand; 0 to 10 feet (0-3 m) thick.

Mass-Movement Deposits

**Qmsy, Qmso** Landslide deposits -- Very poorly sorted clay- to boulder-size, locally derived debris in chaotic, hummocky mounds; mapped on steep slopes beneath the Washington basaltic flow and Shinarump Conglomerate; basal slip surfaces are in Petrified Forest or upper red strata; divided into younger (Qmsy) and older (Qmso) landslides based on degree of preservation of landslide features; thickness highly variable.

**Qmt** Talus deposits -- Very poorly sorted, angular boulders with minor fine-grained interstitial materials; deposited on and at the base of steep slopes; 0 to 20 feet (0-6 m) thick.

Mixed-Environment Deposits

**Qac** Mixed alluvial and colluvial deposits -- Poorly to moderately sorted clay- to boulder- sized material in minor drainages; gradational with colluvial deposits; includes stream deposits too small to map separately; 0 to 10 feet (0-3 m) thick.

**Qae** Mixed alluvial and eolian deposits -- Moderately to well-sorted, clay- to sand-sized material; locally includes abundant eolian sand and minor gravel; deposited in large, open, nearly flat areas such as Washington Fields; 0 to 30 feet (0-9 m) thick.

**Qca, Qcao** Mixed colluvial and alluvial deposits -- Poorly sorted, angular to rounded, fine-grained to boulder-sized material deposited on broad, low to moderate slopes; locally includes talus, eolian, or alluvial deposits; deposited by sheet-wash, debris-flow, and slope-creep processes and lack well-defined drainage pattern; younger (Qca) deposits form active depositional surfaces whereas older deposits (Qcao) are deeply incised and locally offset by the Washington fault; 0 to 30 feet (0-10 m) thick.

**$Qea_{1\text{-}3}$** Mixed eolian and alluvial deposits -- $Qea_1$ is well-sorted eolian sand with minor alluvial clay to gravel; locally reworked by alluvial processes; covers much of Warner Valley; $Qea_2$ is similar but lies 10 to 30 feet (3-10 m) above modern drainages, forming a higher bench with stage I pedogenic carbonate; $Qea_3$ is similar but lies 20 to 40 feet (6-12 m) above modern drainages and has very well developed (stage V-VI) pedogenic carbonate, which is resistant to erosion and forms the elevated surface of the "racetrack" (old landing strip) area in the southeast part of the quadrangle; 0 to 20 feet (0-6 m) thick.

Basaltic Lava Flow

**Qbw** Washington lava flow -- Dark-greenish-gray alkali olivine basalt lava flow with abundant small clinopyroxene and olivine phenocrysts (petrographically classified as an ankaramite and chemically as a basinite to picrobasalt); strongly jointed; caps ridge 360 feet (110 m) above the adjacent Virgin River; yielded two $^{40}Ar/^{39}Ar$ ages 0.98 ± 0.02 and 0.87 ±0.04 Ma (Biek, 2003a); 20 to 30 feet (6-10 m) thick.

*unconformity*

JURASSIC

**Jn** Navajo Sandstone -- Moderate-reddish-orange to moderate-reddish-brown, massively cross-bedded, moderately well-cemented, well-rounded, fine- to medium-grained, frosted quartz sandstone; eolian; strongly jointed; forms cliff. Lower several hundred feet forms transition zone characterized by planar bedded, very fine to fine-grained sandstone, silty fine-grained sandstone, and minor thin mudstone interbeds, and resistant cross-stratified sandstone; transition-zone strata locally exhibit wavy bedding and soft-sediment deformation features, including diapiric and load structures. Lower contact corresponds to a slight color change, with darker reddish-brown Kayenta strata below and lighter moderate-reddish-orange Navajo strata above. About 2000 feet (600 m) thick, but only lower 1000 feet (300 m) is in the quadrangle.

Kayenta Formation

**Jku** Upper member -- Interbedded moderate-reddish-brown siltstone, light-purplish-red to pale-reddish-brown mudstone, and moderate- to dark-reddish-brown, very fine grained, thin-bedded, calcareous, slightly mottled sandstone; punky gypsum in some intervals near the base; cross-cutting gypsum stringers are common; generally coarsens upward; forms slopes and small ledges near base and prominent ledges and cliffs near the top; 700 feet (210 m) thick.

**Jkl** Lower member -- Pale-reddish-brown to moderate-reddish-brown, thin-bedded siltstone and very fine grained, planar- to lenticular-bedded sandstone, interbedded with moderate-purple-red mudstone; three interbeds of light-pinkish-gray to light-olive-gray micritic dolomite, each about 6 inches (15 cm) thick, are present in the upper half; 145 feet (44 m) thick.

**Jm** Moenave Formation, undivided -- shown in cross section only

**Jms** Springdale Sandstone Member -- Pale-reddish-brown to grayish-yellow, fine- to medium-grained, medium- to very thick bedded, cross-bedded sandstone with minor, thin, discontinuous lenses of intraformational conglomerate and light-purple-gray siltstone near the middle; petrified wood is locally abundant; weathers to pale-pink, pinkish-gray, and pale-reddish-purple rounded ledges; 125 feet (38 m) thick.

**Jmw** Whitmore Point Member -- Pale-red-purple to greenish-gray claystone and mudstone interbedded with pale-brown to pale-red, thin-bedded siltstone with several 2- to 6-inch-thick (5-15 cm) beds of light-greenish-gray, bioturbated, dolomitic limestone that contain cherty algal structures and fossil fish scales of *Semionotus kanabensis*; forms slope; 30 feet (9 m) thick.

**Jmd** Dinosaur Canyon Member -- Interbedded, generally thin-bedded, moderate-red-brown siltstone, mudstone, and very fine grained, thin-bedded, pale-reddish-brown to grayish-red sandstone with cross-beds; planar, low-angle and ripple cross-stratification are common; very similar to the step-slope appearance of the Kayenta Formation; 155 feet (47 m) thick.

*unconformity*

TRIASSIC

Chinle Formation

**Ƭcp** Petrified Forest Member -- Light-brownish-gray to grayish-red-purple bentonitic shale and siltstone with several interbeds of pale-yellowish-brown, cross-bedded sandstone up to 10 feet (3 m) thick; petrified wood is common, and is locally well silicified and brightly colored; bentonitic shales weather to a "popcorn" surface with abundant mudcracks; forms well-developed strike valleys adjacent to more resistant cliffs of the Shinarump Conglomerate Member; 700 feet (210 m) thick.

**Ƭcs** Shinarump Conglomerate Member -- Varies from a dark-brown to moderate-yellowish-brown, medium- to coarse-grained sandstone with locally well-developed limonite bands ("picture rock" or "landscape stone") to a moderate-brown, pebbly conglomerate; mostly thick to very thick bedded with both planar and low-angle cross-stratification, although thin, platy beds with ripple cross-stratification occur locally; strongly jointed with common slickensides; contains poorly preserved petrified wood, commonly replaced in part by iron-manganese oxides; forms a cap rock above the Moenkopi Formation; deposited principally in braided stream channels; ranges from 5 to 200 feet (1.5-60 m) thick.

*unconformity*

Moenkopi Formation

**Ƭmu** Upper red member -- Interbedded moderate-reddish-brown, thin-bedded siltstone and moderate-reddish-orange, thin- to medium-bedded sandstone with planar, low-angle, and ripple cross-stratification; some thin gypsum beds and abundant discordant gypsum stringers; well-preserved ripple marks common in the siltstone; forms ledgy slopes and cliffs; a prominent, commonly cliff-forming, pale-yellowish-orange, fine-grained sandstone with Liesegang banding is present about 50 feet (15 m) above the base of the member; 475 feet (145 m) thick.

**Ƭms** Shnabkaib Member -- Interbedded light-gray to pale-red, "bacon-striped," laminated to thin-bedded, gypsiferous siltstone and laminated to very thick bedded gypsum that forms a ledgy slope; contains several thin interbeds of resistant dolomitic, unfossiliferous limestone near the base; gypsum also present as discordant veins; ripple marks are common; upper part is very gypsiferous and weathers to a powdery soil; forms a valley except where held up by more resistant overlying units; 730 feet (220 m) thick.

**Ƭmm** Middle red member -- Interbedded moderate-red to moderate-reddish-brown, laminated to thin-bedded siltstone, mudstone, and very fine grained sandstone; thin, white to greenish-gray gypsum beds and veins are common, especially in the upper part of the member, forms a slope; 400 feet (120 m) thick.

**Ƭmv** Virgin Limestone Member -- Three distinct, resistant, medium-gray to yellowish-brown limestone ledges interbedded with nonresistant, muddy siltstone and pale-reddish-brown, very thin bedded sandstone; limestone beds are 5 to 10 feet (1.5-3 m) thick and contain five-sided crinoid columnals; poorly preserved *Composita* brachiopods (Billingsley, 1992a) are found in the upper part of the lowest limestone bed, which is also the thickest; forms ledgy slope; total thickness varies from 25 to 115 feet (8-35 m) because of attenuation.

**Ƭml** Lower red member -- Moderate-reddish-brown siltstone, mudstone, and fine-grained, slope-forming sandstone; generally calcareous and has laminated interbeds and stringers of gypsum; ripple marks and small-scale cross-beds are common in the siltstone; thickness varies considerably from 25 to 200 feet (8-60 m) due to attenuation and paleotopography.

*unconformity*

PERMIAN

Kaibab Formation

**Pkh** Harrisburg Member -- Light-gray, fossiliferous, sandy, fine- to medium-grained limestone interbedded with red and gray gypsiferous siltstone, sandstone, and gray gypsum beds several feet thick; beds of cherty limestone and sandy limestone form a 30-foot-thick (9 m) resistant ledge near upper middle; solution of interbedded gypsum causes local distorted bedding; forms slope with limestone ledges; base is not exposed; incomplete exposed thickness is 200 feet (60 m).

Subsurface Units

**Pkf** Fossil Mountain Member of the Kaibab Formation -- shown in cross section only

**Pt** Toroweap Formation -- shown in cross section only

**Pq** Queantoweap Sandstone -- shown in cross section only

**Pp** Pakoon Dolomite -- shown in cross section only

PENNSYLVANIAN

**IPc** Callville Limestone -- shown in cross section only

MISSISSIPPIAN

**Mr** Redwall Limestone -- shown in cross section only

DEVONIAN

**Dm** Muddy Peak Dolomite -- shown in cross section only

## GEOLOGIC MAP SYMBOLS

Contact

Normal fault -- dashed where approximately located, dotted where concealed; bar and ball on down-thrown side

Thrust/reverse fault -- dotted where concealed; teeth on upper plate

Axial trace of folds, dotted where concealed, arrows show direction of plunge

Anticline

Syncline

Strike and dip of inclined bedding

Approximate strike and dip of inclined bedding determined from photogrammetry

Strike of near-vertical joint

Sand, gravel, or borrow pit

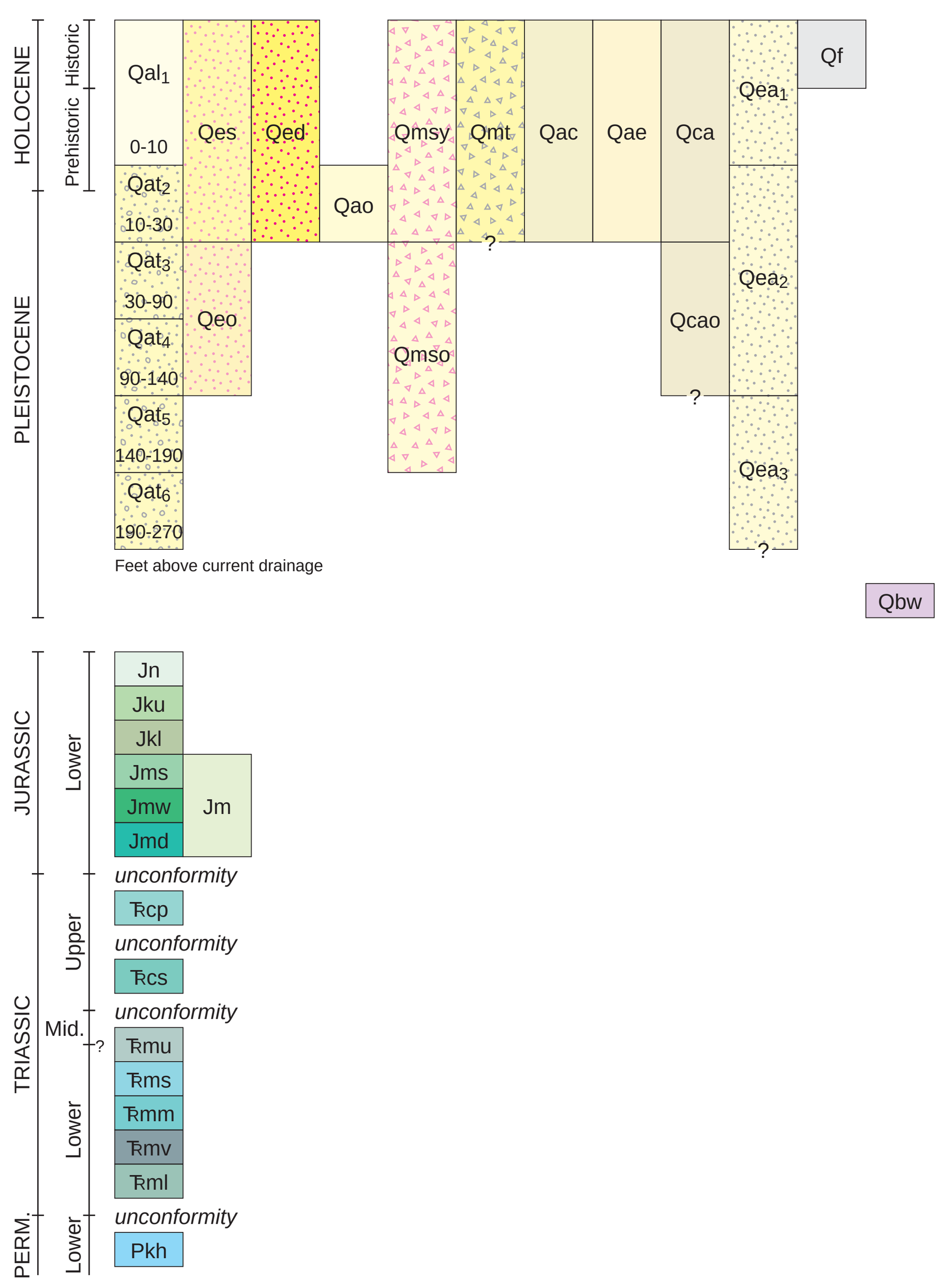
Prospect -- gypsum (no letter), uranium (u)

Adit

Oil exploration test hole, plugged and abandoned

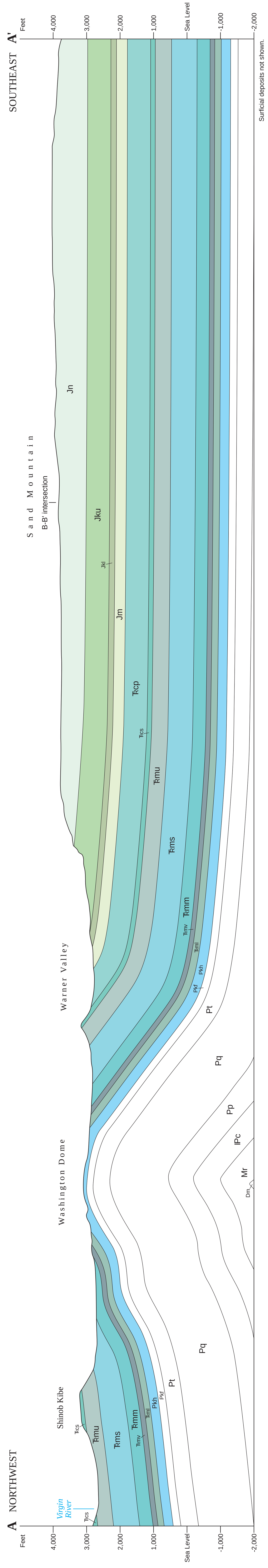
Spring

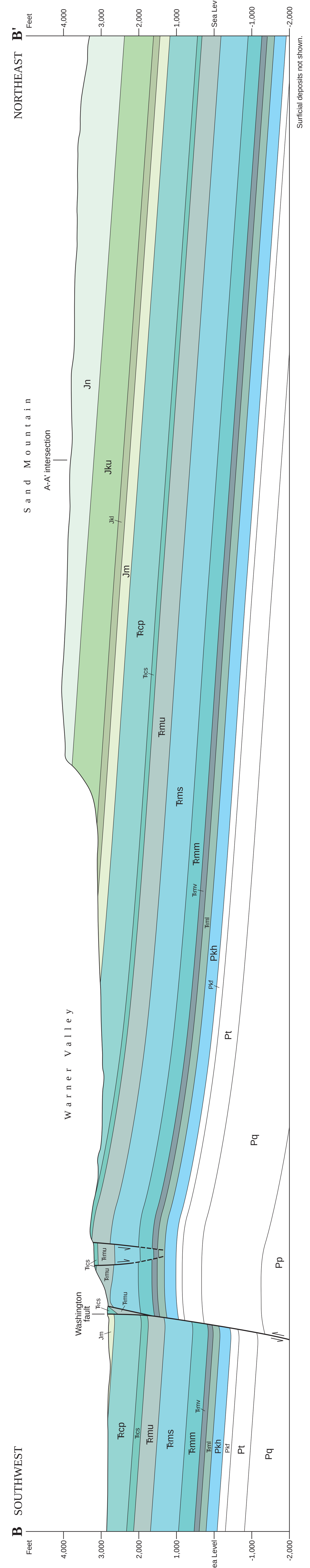
## CORRELATION OF GEOLOGIC UNITS




## LITHOLOGIC COLUMN

| SYSTEM | SERIES | FORMATION | MEMBER | SYMBOL | THICKNESS Feet (Meters) | LITHOLOGY |
|---|---|---|---|---|---|---|
| QUAT. | | | surficial deposits | Q | 0-70 (0-20) | |
| | | | Washington basalt flow | Qbw | 20-30 (6-10) | 0.98 ± 0.02 Ma, 0.87 ± 0.04 Ma (Biek (2003a)) |
| JURASSIC | Lower | | Navajo Sandstone | Jn | 1,000+ (300+) | Sand Mountain high-angle cross beds |
| | | Kayenta Formation | upper member | Jku | 700 (210) | |
| | | | lower member | Jkl | 145 (44) | gypsum |
| | | Moenave Formation | Springdale Ss. Mbr. | Jms (Jm) | 125 (38) | petrified wood |
| | | | Whitmore Point Mbr. | Jmw (Jm) | 30 (9) | *Semionotus kanabensis* (fish scales) |
| | | | Dinosaur Cyn. Mbr. | Jmd (Jm) | 155 (47) | |
| TRIASSIC | Upper | Chinle Formation | Petrified Forest Member | Ƭcp | 700 (210) | landslides; swelling clays; petrified wood |
| | | | Shinarump Conglomerate Member | Ƭcs | 5-200 (1.5-60) | "picture stone" |
| | Middle | Moenkopi Formation | upper red member | Ƭmu | 475 (145) | |
| | Lower | | Shnabkaib Member | Ƭms | 730 (220) | gypsum |
| | | | middle red member | Ƭmm | 400 (120) | |
| | | | Virgin Ls. Mbr. | Ƭmv | 25-115 (8-35) | *Composita* brachiopods; five-sided crinoid columnals |
| | | | lower red member | Ƭml | 25-200 (8-60) | structurally attenuated |
| PERMIAN | Lower | Kaibab Formation | Harrisburg Member | Pkh | 200+ (60+) | gypsum |




*Research supported by the Utah Geological Survey and U.S. Geological Survey, National Cooperative Geologic Mapping Program, under USGS STATEMAP award number 97AG01797. The views and conclusions contained in this document are those of the author and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S Government.*

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*by*

*Janice M. Hayden*

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**2005**

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# GEOLOGIC MAP OF THE WASHINGTON DOME QUADRANGLE, WASHINGTON COUNTY, UTAH

*by*

*Janice M. Hayden*

## ABSTRACT

The Washington Dome quadrangle in southwest Utah is in the transition zone between the Basin and Range Province to the west and the Colorado Plateau to the east. The quadrangle straddles two structural blocks separated by the Washington normal fault, which trends north-northwest along the west part of the quadrangle. Washington Dome, part of the northeast-trending Virgin anticline, a Late Cretaceous, Sevier-age structure, is in the northwest corner of the quadrangle. Two reverse faults cut both flanks of the south end of the dome and may extend to the north end.

The Permian Kaibab Formation, the oldest exposed unit in the quadrangle, forms the core of Washington Dome and has an exposed thickness of about 200 feet (60 m). The Triassic Moenkopi Formation unconformably overlies paleotopography eroded into the Kaibab Formation, and is about 1900 feet (575 m) thick; it, in turn, is unconformably overlain by the Chinle Formation, which is about 800 feet (240 m) thick. Within the quadrangle, Jurassic strata include the Moenave Formation, 310 feet (95 m) thick, the Kayenta Formation, 845 feet (255 m) thick, and the basal 1000 feet (300 m) of the Navajo Sandstone exposed on the southeast limb of the Virgin anticline.

Only one of several late Tertiary to Quaternary basaltic lava flows, erupted from vents to the north and east, reached the northwest corner of the Washington Dome quadrangle. Because of relative uplift and subsequent erosion of adjacent sedimentary rocks, this flow, like many others that once occupied drainages, now caps ridges, forming inverted topography. Downcutting is also documented by alluvial-terrace deposits and other elevated alluvial surfaces that have thick pedogenic carbonate development.

Stratigraphic displacement on the Washington fault decreases northward from about 1500 feet (455 m) at the Arizona-Utah state line to about 700 feet (210 m) at the northwest corner of the quadrangle. The Washington fault offsets Pleistocene colluvium and alluvium (Qcao) in the south-central part of the quadrangle (NE¼ section 13, T. 43 S., R. 15 W.), creating an 11.5-foot-high (3.5 m) fault scarp. Other normal faults in the quadrangle are near and trend subparallel to the Washington fault, except for the down-to-the-northwest faults near the southeast corner of the quadrangle, which are the most westerly of several parallel faults in that area.

Mineral resources in the Washington Dome quadrangle include gravel from alluvial terrace deposits, sand, gypsum, and stone, as well as mercury and gold. Water resources are increasingly important as population growth continues. Expansive, soluble, and collapsible soils that can adversely affect buildings, roads, and other structures are present and need to be considered by planners and builders. Other potential geologic hazards include earthquakes, blowing sand, flooding, debris flows, mass movements, radon gas, elevated levels of mercury and arsenic, and volcanoes.

## INTRODUCTION

The Washington Dome quadrangle is in south-central Washington County in the southwest corner of Utah (figure 1). Washington City, partly in the northwest part of the quadrangle, and St. George, just to the west, are two of the fastest growing communities in the state and many geologic concerns are arising as the population increases. Water supplies are limited and must be protected from contamination and misuse. Construction materials, particularly gravel, are in short supply.

Topographic relief in the quadrangle is over 1600 feet (245 m) from the Virgin River at about 2600 feet (788 m) above sea level to the highest point on Sand Mountain at 4227 feet (1280 m). Warner Valley bisects the quadrangle and is formed on the readily eroded Petrified Forest Member of the Chinle Formation and the slightly more resistant Moenave Formation. The valley separates two prominent ridges in the quadrangle: Warner Ridge, formed by the resistant Shinarump Conglomerate Member of the Chinle Formation, and Sand Mountain, formed by the Kayenta Formation and the basal part of the Navajo Sandstone. These ridge-forming strata create two steps on the "Grand Staircase" (Gregory, 1950) of rock that stretches across southern Utah and northern Arizona: the Chocolate Cliffs, capped by the Shinarump Conglomerate Member of the Chinle Formation; and the Vermilion Cliffs, capped by the Kayenta Formation and the base of the Navajo Sandstone.

The Virgin River lowland has the lowest elevation, warmest climate, and longest growing season in Utah. It receives about 8 inches (20 cm) of precipitation annually (Cordova and others, 1972). Natural vegetation includes sparse grasses, sagebrush, creosote bush, and several varieties of cactus and yucca. Pioneer settlers brought a wide variety of plants into the area including cotton, and fruit and nut trees.

Previous geologic studies in southwest Utah began with the U.S. Army Topographical Survey and U.S. Geological

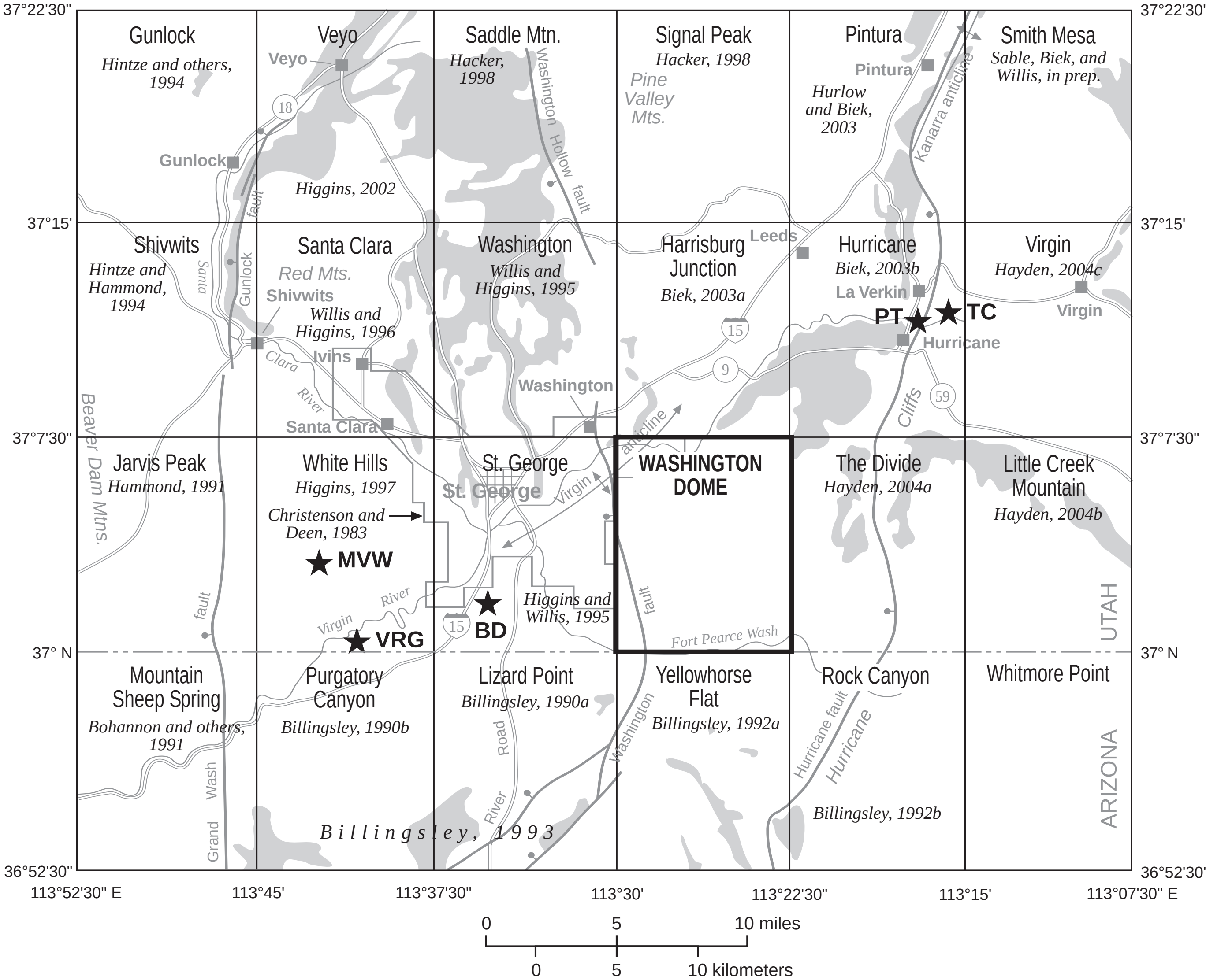



***Figure 1.*** *Geographic and geologic features and 7½′ quadrangles near the Washington Dome quadrangle. Basaltic flows are shaded. BD= Bloomington dome; MVW = Mountain Valley Wash; PT = Pah Tempe; TC = Timpoweap Canyon; VRG = Virgin River Gorge.*

Survey investigations during the latter half of the 19th century (Powell, 1875; Dutton, 1882). Dobbin (1939) produced a small-scale geologic map of the St. George area that focused on structural geology. Gregory (1950) mapped the Zion Canyon area to the east at a scale of 1:125,000 and established many of the geologic names in use today. Cook (1960) completed a map of Washington County at a scale of 1:125,000. Christenson and Deen (1983) mapped the surficial geology of the St. George area, including the west edge of the Washington Dome quadrangle, and focused on the engineering aspects of the geology. Eppinger and others (1990) compiled a 1:250,000-scale map of the Cedar City 1° x 2° quadrangle that includes the study area. Haynes' (1983) study of the geomorphic development of the Virgin River included the northeast corner of the quadrangle. Billingsley (1992a, b) mapped the Yellowhorse Flat and Rock Canyon quadrangles at a scale of 1:24,000, and Wolf Hole Mountain and vicinity (1993) at a scale of 1:31,680 in Arizona, all south of the Washington Dome quadrangle.

Due in large part to a focused effort by the Utah Geological Survey through the National Cooperative Geologic Mapping Program, the St. George area has some of the most complete 1:24,000-scale geologic map coverage in the state. Geologic maps of 7.5′ quadrangles completed at this scale through this and other mapping efforts are shown on figure 1. In addition, many topical studies have been done on stratigraphy, structure, volcanism, hazards, and economic and water resources of the area and are cited elsewhere in this report.

## STRATIGRAPHY

### Introduction

The Early Permian Kaibab Formation is the oldest rock unit exposed in the Washington Dome quadrangle and forms the exposed center of Washington Dome, the central one of three domes along the northeast-trending Virgin anticline. The Triassic section, including the Early Triassic Moenkopi and the Late Triassic Chinle Formations, is exposed along both flanks of the anticline. Early Jurassic strata, including the Moenave, Kayenta, and lower part of the Navajo Formations, are exposed within the quadrangle south of the anticline. Information for subsurface units, shown on cross sections only, is adapted from Biek (2003b) and Hammond (1991).

Only one of several basaltic lava flows in the area, erupted from vents north of the quadrangle, reached the northwest corner of the study area. Erosion has removed more than 360 feet (110 m) of strata since the flow solidified, leaving the resistant flow standing as a high linear ridge that forms a classic example of inverted topography (Hamblin, 1963, 1987). Continued uplift and erosion of the area is shown by four main levels of gravel terraces. Thin alluvial, colluvial, eolian, and mass-movement deposits cover much of the quadrangle.

Permian, Triassic, and Jurassic strata in the quadrangle were deposited in shallow-marine to low-level terrestrial conditions and lithologies strongly reflect sea-level fluctuations (figure 2a). Vail and others (1977), Mitchum (1977), and Van Wagoner and others (1990) recognized major cycles in the depositional record that are divisible into first-order megasequences through fifth-order parasequences, based on duration and extent of the cycle. Permian rocks exposed in the quadrangle were deposited near the end of the Paleozoic first-order megasequence, and the Triassic rocks mark the beginning of the Mesozoic/Cenozoic first-order megasequence. A Permian lowstand near the end of the Paleozoic megasequence exposed the Kaibab Formation to erosion. After the lowstand, sea level rose to near the record high where it fluctuated but remained high until the Early Jurassic, when it dropped to about 500 feet (150 m) below present sea level (Vail and others, 1977). These fluctuations in sea level define seven second-order sequences (Van Wagoner and others, 1990). However, only four of the seven are documented in rocks in the quadrangle (figure 2a).

## Permian

The Kaibab Formation, the only Permian rock exposed in the quadrangle, constitutes the upper part of a second-order cycle that began in the Early Permian (figure 2a). A subsequent Late Permian lowstand resulted in subaerial exposure and extensive erosion of the Kaibab Formation, which completely removed the Harrisburg Member in some areas west of the quadrangle (Jenson, 1984; Higgins, 1997).

### Kaibab Formation

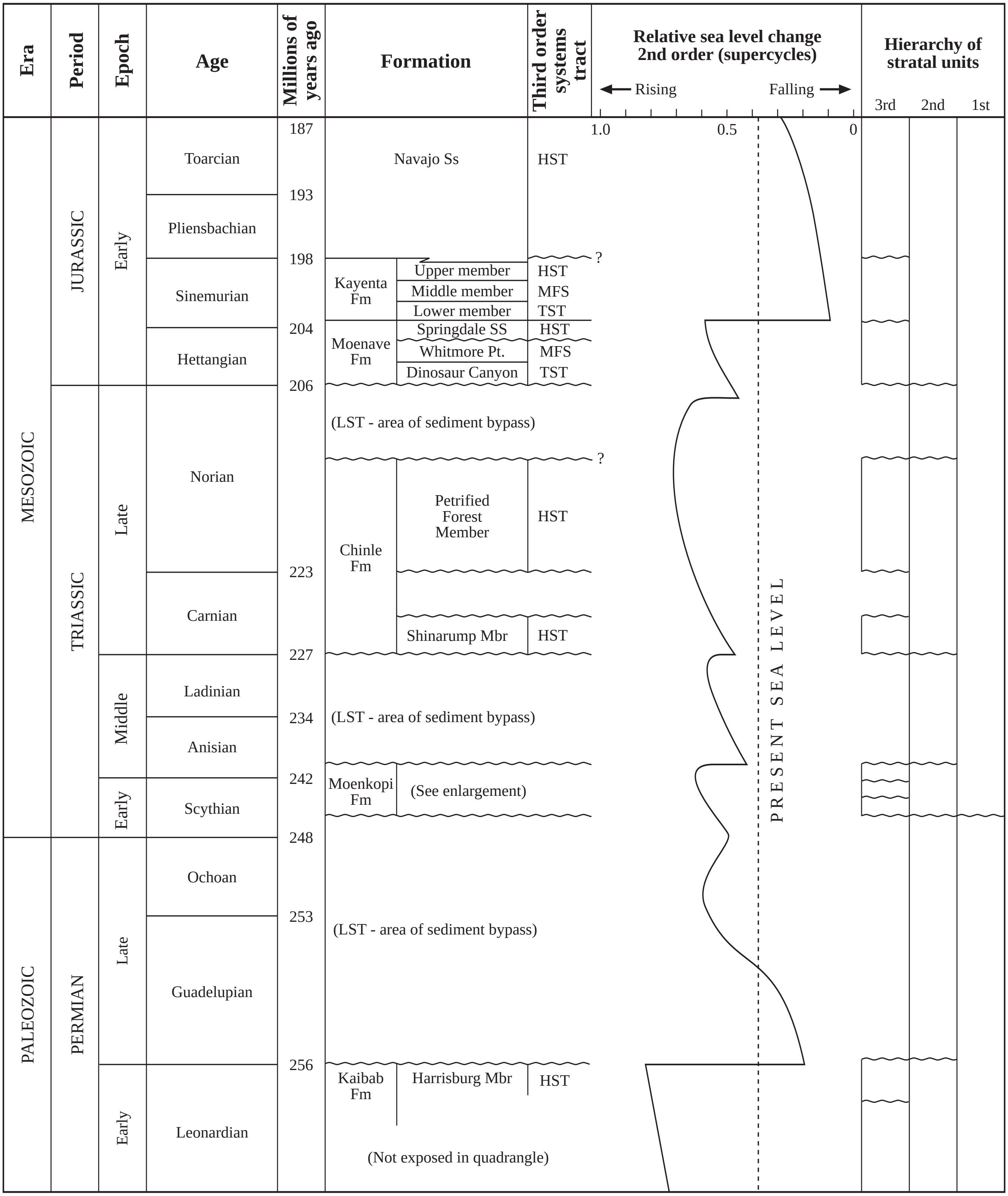
The Kaibab Formation consists of two members, the Fossil Mountain Member and the overlying Harrisburg Member (Sorauf, 1962). Only the Harrisburg Member is exposed in the Washington Dome quadrangle. The Kaibab Formation is late Early Permian in age (McKee, 1938; Rawson and Turner-Peterson, 1979; Sorauf and Billingsley, 1991).

**Harrisburg Member (Pkh):** The Harrisburg Member, named for a type section at Harrisburg Dome just north of the study area (Reeside and Bassler, 1921; Sorauf, 1962), is the oldest rock exposed in the quadrangle. Because Sorauf's type section is incomplete, Nielson (1981, 1986) established two reference sections that illustrate the rapid east-west facies changes of the Harrisburg Member. One section, located northeast of the quadrangle in Timpoweap Canyon (figure 1), is typical of eastern facies along the Hurricane Cliffs. A second section, west of the quadrangle in Mountain Valley Wash, is typical of western exposures including those of Washington Dome (figure 1). The Harrisburg Member is light-gray, fossiliferous, sandy, fine- to medium-grained limestone interbedded with red and gray gypsiferous siltstone and sandstone, and gray gypsum beds several feet thick. Dissolution of interbedded gypsum has locally distorted bedding. The Harrisburg Member forms a slope with limestone ledges. Beds of cherty limestone and sandy limestone about 30 feet (9 m) thick, informally referred to as the "medial limestone" (Nielson, 1981), form a resistant cliff in the upper part of the member. Only the upper part of the member, above and including the medial limestone interval, is exposed. In areas along the southeast side of Washington Dome, cherty limestone breccia overlies coarsely crystalline limestone that lacks chert. The chert occurs as very coarse sand- to pebble-sized angular fragments that form both clast- and matrix-supported limestone breccias. Most gypsum present in this interval farther west (Nielson, 1981; Higgins, 1997) appears to have been removed, or perhaps never deposited, in the Washington Dome quadrangle. These brecciated areas also generally coincide with areas of secondary silicification with some decalcification.

Several hundred feet of post-depositional, subaerial erosion during Late Permian and Early Triassic time completely removed the Harrisburg Member from the southwest part of the Price City Hills in the Bloomington dome portion of the Virgin anticline (Higgins and Willis, 1995). In the Beaver Dam Mountains 10 miles (16 km) to the west, Jenson (1984) and Higgins (1997) described karst topography having more than 500 feet (152 m) of relief that formed during this 15-million-year period of erosion (Sorauf, 1962; Nielson, 1981; Sorauf and Billingsley, 1991). However, the exposed thickness of the Harrisburg Member in the Washington Dome quadrangle seems fairly constant; neither the Rock Canyon Conglomerate Member nor the Timpoweap Member of the Moenkopi Formation exist as mappable units. The upper contact with the lower red member of the Moenkopi Formation is quite variable and unconformable. In this quadrangle, I placed the contact above the highest pinkish-gray, massive gypsum and below a light-reddish-brown to light-yellowish-orange gypsiferous siltstone. The incomplete exposed thickness of the Harrisburg Member is estimated at 200 feet (60 m) in the quadrangle. Nielson (1981) measured 280 feet (85 m) of Harrisburg strata near the southwest end of the Price City Hills in Bloomington dome and an incomplete section of 185 feet (56 m) near the northeast end of Bloomington dome, both to the southwest. Biek (2003a) described an incomplete section 250 feet (75 m) thick at Harrisburg Dome to the northeast.

## Triassic

The Lower Triassic Moenkopi (upper red member) and Upper Triassic Chinle Formations (Shinarump Conglomerate Member) are separated by an unconformity of about 10 million years (figure 2a). These formations denote two major second-order sequences of Vail and others (1977) separated by a smaller rise and subsequent fall of sea level during Middle Triassic time (Paull and Paull, 1994).




HST = highstand systems tract. MFS = maximum flooding stage. TST = transgressive systems tract. LST = lowstand systems tract.

***Figure 2A.*** *Sequence stratigraphy of Paleozoic and Mesozoic formations exposed in the Washington Dome quadrangle. See text for discussion. Modified from Vail and others (1977), Hintze (1988), and Dubiel (1994). Time scale from Palmer and Geissman (1999). Vertical scale is based on time of deposition, not on thickness.*

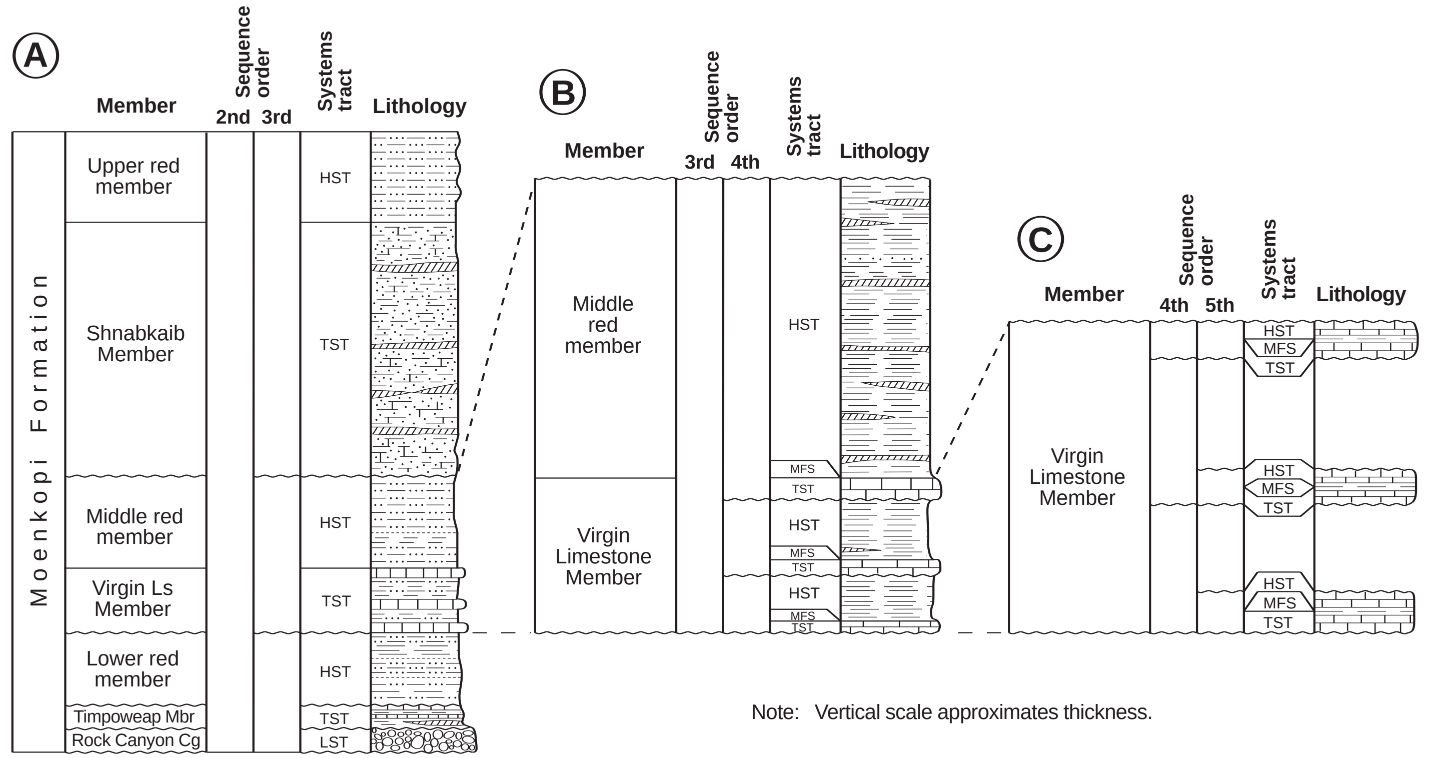



***Figure 2B.*** *Enlargement of figure 2A showing system tracts for the Moenkopi Formation. See text for discussion. Modified from Vail and others (1977), Hintze (1988), Dubiel (1994), and additional work in this project.*

## Moenkopi Formation

The Moenkopi Formation is divided into seven members (Stewart and others, 1972a), but only the upper five are mappable units in the Washington Dome quadrangle, where they reach a total thickness of 1900 feet (575 m). Although the Rock Canyon Conglomerate Member is exposed in the Hurricane Cliffs to the east where it is 0 to 130 feet (0-40 m) thick (Biek, 2003b; Hayden, 2004a), no channel-fill deposits of Rock Canyon Conglomerate are exposed in the Washington Dome quadrangle. Biek (2003a) reported neither Rock Canyon Conglomerate nor Timpoweap strata at Harrisburg Dome. Nielson (1981) also noted a lack of both these members at Harrisburg and Washington Domes. However, the uppermost Timpoweap Member may be exposed in two of the larger canyons that drain Washington Dome (SW¼NW¼ section 30, T. 42 S., R. 14 W. and SW¼NE¼ section 36, T. 42 S., R. 15 W.). In these drainages, a one-inch (2-cm) thick, medium-gray limestone bed is separated from Harrisburg Member gypsum by a few feet of dark-yellowish-orange to light-pinkish-gray gypsiferous siltstone with minor calcareous, gritty sandstone lenses. This thin limestone and clastic interval may belong to the Timpoweap Member, but is herein mapped as part of the lower red member due to limitations of map scale. Nielson (1981) noted that the Timpoweap and lower red contact is gradational and locally interfingering. The Moenkopi Formation is Early to Middle Triassic in age (late Scythian to early Anisian) (Dubiel, 1994).

The Moenkopi Formation was deposited on a very gentle slope where sea level changes of several feet translated into shoreline changes of many tens of miles (Morales, 1987; Blakey, 1989; Dubiel, 1994). It represents a second-order sequence that can be subdivided into three distinct third-order sequences, which depict smaller transgressive-regressive cycles in an overall sea level rise (figures 2a and 2b). Paull and Paull (1994) stated that the Early Triassic global rise in sea level from the Permian lowstand was greater than 660 feet (200 m). None of the lowstand systems tracts for these three third-order sequences are documented within the quadrangle. The transgressive systems tract of the lowest third-order sequence, which Dubiel (1994) correlated with a transgression that flooded this area from the northwest, is usually represented by the Timpoweap Member, which may be present but is unmapped in the study area as explained above. It is overlain by the highstand systems tract of the lower red member, correlated to continental sediments deposited during a time of regression, which completes the lowest third-order sequence. The Virgin Limestone Member and the middle red member make up the transgressive and highstand systems tracts, respectively, of the middle third-order sequence. The Shnabkaib Member and the upper red member form similar systems tracts for the uppermost third-order sequence in the Moenkopi Formation. Paleogeographic maps and time-rock stratigraphy charts in Blakey and others (1993) and Paull and Paull (1994) depict these changes.

**Lower red member (TRml):** The lower red member consists of interbedded siltstone, mudstone, and sandstone that form a narrow strike valley surrounding Washington Dome. It is best exposed along the northwest side and west end of the dome where intermittent streams eroded washes through surficial deposits that elsewhere cover the member. The siltstone and mudstone are moderate-reddish-brown, generally calcareous, commonly ripple marked, and exhibit small-scale cross-bedding. Dark-yellowish-orange, thin siltstone and mudstone beds are both interbedded with gypsum and crossed by stringers and thin veinlets of gypsum. The sandstone is reddish brown, calcareous, very fine grained, and thinly bedded. Locally, a one-inch (2-cm) thick, medium-gray limestone bed and the underlying few feet of dark-yellowish-orange to light-pinkish-gray gypsiferous siltstone beds with calcareous, gritty sandstone lenses usually indicative of the Timpoweap Member, is mapped at the base of the lower red member. The upper contact with the Virgin Limestone Member is generally placed at the base of the lowest of three 5- to 10-foot-thick (1.5-3 m) limestone ledges. The lower red member ranges in thickness from 25 to 200 feet (8-60 m) within the Washington Dome quadrangle. The thickness variation is probably due mostly to attenuation of the strata, especially in steeply dipping beds on the northwest side of Washington Dome. It may also be partially explained by stratigraphic thinning over small paleohills of the Kaibab Formation, although this thinning is not nearly as dramatic as it is to the west in the Beaver Dam Mountains (Jenson, 1984; Higgins, 1997).

**Virgin Limestone Member (TRmv):** The Virgin Limestone Member is best exposed at the south edge of the quadrangle, south of Fort Pearce Wash and east of the Washington fault, where it consists of three distinct, resistant, medium-gray to yellowish-brown, marine limestone ledges interbedded with nonresistant, moderate-yellowish-brown, muddy siltstone and pale-reddish-brown sandstone. The limestone ledges contain five-sided crinoid columnals. Poorly preserved *Composita* brachiopods (Billingsley, 1992a) are present in the upper part of the lowest limestone bed, which is also the thickest of the three limestone beds. Where this member resurfaces to the north at Punchbowl Dome, the limestone beds are grayish-yellow to dusky-yellow in color, perhaps indicating alteration due to hydrocarbons moving through the anticlinal area. This area also seems to be the southwest edge of the zone of gold, arsenic, and mercury mineralization described in the economic geology section of this report.

The Virgin Limestone Member, together with the middle red member, is a third-order sequence that can be subdivided into three fourth-order sequences (figure 2b). Each of the three limestone layers is a transgressive systems tract separated from an overlying muddy siltstone highstand systems tract by a maximum flooding surface. At least along the south edge of the quadrangle, the three limestone ledges, each 5 to 10 feet (1.5-3 m) thick, can be divided into distinct fifth-order parasequences (Van Wagoner and others, 1990). The lower part of each limestone is finer grained, muddy, and non-fossiliferous (transgressive systems tract), whereas the upper part is a coarser wackestone with birdseye structures, five-sided crinoid columnals, and bivalve shell fragments (highstand systems tract). The two limestone intervals are separated by about an inch (2.5 cm) of dark-grayish-brown shale (maximum flooding surface).

The Virgin Limestone Member is 115 feet (35 m) thick at the south border of the quadrangle just east of the Washington fault, in the NE¼SW¼ section 31, T. 43 S., R. 14 W. The thickness is an attenuated 25 feet (8 m) along the northwest, nearly vertical limb of Washington Dome where small bedding-plane faults are common. However, even with this thinning of incompetent beds, the three limestone ledges are preserved. The upper contact with the middle red member is drawn at the top of the highest limestone ledge.

**Middle red member (TRmm):** The middle red member forms slopes and a relatively broad strike valley on the flanks of Washington Dome and Punchbowl Dome. The member also forms low, reddish hills just north of Fort Pearce Wash, east of the Washington fault. The middle red member is composed of interbedded, moderate-red to moderate-reddish-brown siltstone, mudstone, and very fine grained, thin-bedded sandstone. Very thin interbeds and veinlets of gypsum that vary in color from greenish-gray to white are locally common. The middle red member maintains a relatively constant thickness of 400 feet (120 m) throughout the quadrangle. The upper contact is placed where the moderate-red siltstone of the middle red member gives way to predominantly light-gray, unfossiliferous, dolomitic limestone beds that mark the base of the Shnabkaib Member.

**Shnabkaib Member (TRms):** The Shnabkaib Member is extensively exposed east of the Washington fault and along both flanks of the Virgin anticline. The type section of this member is located at Shinob Kibe butte in the northwest corner of the quadrangle (section 24, T. 42 S., R. 15 W.) (Nielson, 1981) (figure 3). The member was originally named the Shnabkaib shale member by Reeside and Bassler (1921), who stated that the name *Shnabkaib* is probably a corruption of an old Indian name meaning *Coyote Mountain*. Gregory (1950), however, indicated that the name *Shnabkaib* may be a misspelling of the Piute *Shinob* (Great Spirit) and *Kaib* (mountain), loosely translated as *Mountain of the Lord*. The location was sacred to the Paiutes who retreated to the top of the butte for safety when Navajo raiding parties came up from the south in the 1800s.

The Shnabkaib Member consists of light-gray to pale-red gypsiferous siltstone with several thin interbeds of unfossiliferous, dolomitic limestone near the base. The alternating resistant and nonresistant beds form ledge-slope topography; the lower part is slightly more resistant to erosion than the upper part. The gypsiferous upper part weathers into a powdery soil and generally forms a valley except where it is held up by more resistant overlying units. Alternating light and dark colors give this member a "bacon-striped" appearance that shows up especially well on aerial photographs. The upper contact is gradational and is drawn where the greenish-gray, gypsiferous siltstone of the Shnabkaib Member grades into more resistant reddish-brown mudstone of the upper red member. This member is 730 feet (220 m) thick in the NW¼ section 32, T. 43 S., R. 14 W.

**Upper red member (TRmu):** The upper red member of the Moenkopi Formation is well exposed on both flanks of the Virgin anticline. It forms a steep slope with at least one prominent sandstone ledge beneath the resistant Shinarump Conglomerate Member of the Chinle Formation, which caps Shinob Kibe butte and Warner Ridge. The upper red member consists of moderate-reddish-brown, thin-bedded siltstone and very fine grained sandstone with some thin gypsum beds. Ripple marks are common in the siltstone. A massive, 50- to 70-foot-thick (15-20 m), pale-yellowish-orange, very fine grained sandstone with liesegang banding, which is informally called the “Purgatory sandstone” to the north in the Harrisburg Junction quadrangle (Biek, 2003a), forms a prominent ledge about 50 feet (15 m) up from the base of the member on the north and south flanks of the Virgin anticline. South of the anticline, beneath Warner Ridge, the sandstone persists but the color changes to the typical moderate-red-

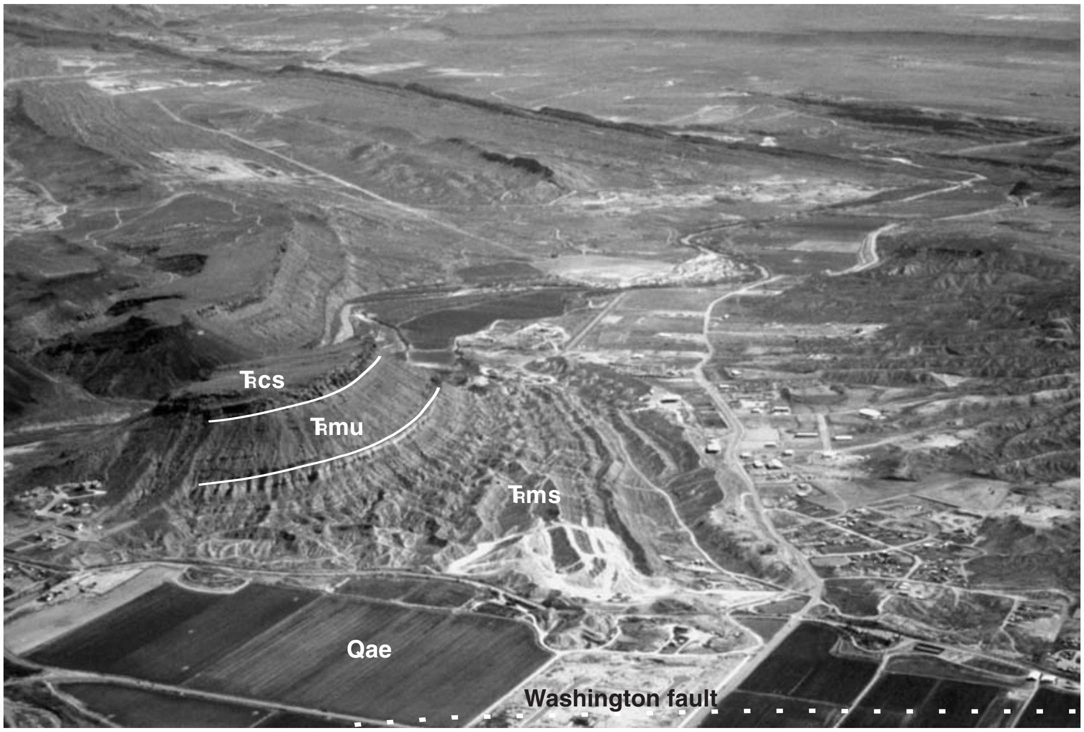



***Figure 3.*** *Aerial view northeast to Shinob Kibe butte, located in section 24, T. 42 S., R. 15 W., the type section of the Shnabkaib Member (Ŧms) of the Moenkopi Formation (Reeside and Bassler, 1921). The upper red member (Ŧmu) of the Moenkopi Formation and the Shinarump Conglomerate Member (Ŧcs) of the Chinle Formation are also visible. The north-trending Washington fault is concealed by mixed alluvial and eolian deposits (Qae) in the foreground.*

dish-brown, suggesting local reduction along the anticline, perhaps by hydrocarbons. The upper contact is unconformable, representing approximately 10 million years of Middle Triassic time (Dubiel, 1994), and is mapped at the base of the first coarse-grained, thick-bedded, pale-yellowish-brown conglomeratic sandstone, which fills shallow paleovalleys eroded into the upper red member. The upper red member is estimated to be 475 feet (145 m) thick.

## Chinle Formation

In the Washington Dome quadrangle, the Chinle Formation consists of the Shinarump Conglomerate and the Petrified Forest Members. The Chinle Formation averages 800 feet (245 m) thick but varies mostly due to changes in thickness of the Shinarump Conglomerate Member. The Chinle Formation is Late Triassic in age (Stewart and others, 1972a, b) based primarily on vertebrate and plant fossils. Dubiel (1994) assigned it to the early Carnian to late Norian with an unconformity of several million years separating the two members.

The Chinle Formation represents the youngest Triassic second-order supercycle (figure 2a) (Vail and others, 1977) and can be subdivided into two distinct third-order cycles. The lower third-order cycle consists of the Shinarump Conglomerate Member derived from the ancestral Uncompahgre highlands to the northeast and from a magmatic arc near the continental margin to the southwest (Blakey and others, 1993). The basal Shinarump was deposited in the lowest parts of paleovalleys cut into the upper red member of the Moenkopi Formation (Dubiel, 1994) and signifies the beginning of base-level rise. The Shinarump grades upward from very thick bedded conglomerate and tabular-planar stratified sandstone to medium-grained, trough cross-stratified sandstone (a highstand systems tract) formed by hinterland braided-stream deposits. This change is evident near Fort Pearce Wash along the south edge of the quadrangle. The Petrified Forest Member is the highstand systems tract of another third-order cycle. The Petrified Forest Member's fluvial systems mimicked paleoflow of the Shinarump system except that these stream deposits were of much higher sinuosity as shown by abundant flood-plain mudstone (Dubiel, 1994). Bentonitic mudstone in the Petrified Forest Member indicates that volcanic ash formed a significant component of the sediment supply, most of which was derived from the magmatic arc at the continental margin to the southwest (Blakey and others, 1993).

**Shinarump Conglomerate Member (Ŧcs):** The Shinarump Conglomerate Member is very resistant and forms the moderate-brown pebbly conglomerate grading to a dark-brown to moderate-yellowish-brown sandstone cuesta of Warner Ridge. This ridge stretches the length of the quadrangle on the south limb of the Virgin anticline. The Shinarump Conglomerate Member is also exposed on the west edge of the quadrangle due to down-to-the-west movement on the Washington fault, and also caps Shinob Kibe butte, Nichols Peak, and smaller hills on the north flank of the anticline in the northwest corner of the quadrangle. It is mostly thick to very thick bedded with both planar and low-angle cross-stratification, although thin, platy beds are present locally. In some areas, the more coarsely grained sandstone contains fragments of poorly preserved petrified wood that is commonly partly replaced by iron-manganese oxides. Locally, the finer grained sandstone has well-developed Liesegang bands that give rise to the nicknames "picture rock" and "landscape stone" (Bugden, 1993).

The Shinarump Conglomerate is 5 to 200 feet (1.5-60 m) thick in the Washington Dome quadrangle. It is highly variable in composition and thickness because it fills paleotopography and was deposited in braided stream channels. Thickness variations may also be due to unrecognized Quaternary slumping. Slickensides having multi-directional lineations at the base of the sandstone and along joints indicate that it commonly slides on the upper red member of the Moenkopi Formation. Northwest of the study area, Hintze and Hammond (1994) described several masses of Shinarump in the Shivwits quadrangle that slumped or slid. The upper contact appears sharp and is placed at the base of the first variegated, bentonitic shale of the Petrified Forest Member; Dubiel (1994) reported that the contact is unconformable. Biek (2003a) and Willis and Higgins (1996) reported a gradational contact to the north and northwest, respectively.

**Petrified Forest Member (TRcp):** The Petrified Forest Member of the Chinle Formation forms the prominent strike valley of Warner Valley, which extends north-south across the quadrangle. Due to down-to-the-west movement on the Washington fault, the Petrified Forest Member is also exposed in south Washington Fields. It consists of light-brownish-gray to grayish-red-purple bentonitic shale and siltstone with several resistant lenticular interbeds of pale-yellowish-brown, cross-bedded, thick-bedded sandstone up to 10 feet (3 m) thick. Shaly beds weather to a "popcorn" surface due to swelling and shrinking of bentonitic clay. These swelling clays are responsible for many foundation problems in the region and form the slip surface for numerous rotational slumps, such as those at the southwest end of Washington Black Ridge in the northwest corner of the quadrangle. Petrified wood, locally well silicified and brightly colored, is common. The Petrified Forest Member is well exposed as low hills next to the Shinarump Conglomerate Member cuesta, especially where the more resistant sandstone interbeds are present near the base. One particularly resistant sandstone interbed is near the middle of the member and forms small resistant hogbacks that protrude though the Quaternary deposits in Warner Valley. Although the member is usually covered by Quaternary deposits, the Petrified Forest Member is nearly entirely exposed at both the north and south ends of Warner Valley. The upper contact is placed at the top of the highest purplish-gray shale and below reddish-brown siltstone of the Dinosaur Canyon Member of the Moenave Formation. A thin chert-pebble conglomerate typically marks this contact throughout the greater St. George area (James I. Kirkland, Utah Geological Survey, verbal communication, November 19, 2004). This contact is unconformable and represents a period of about 10 million years (Dubiel, 1994). Within the quadrangle, the member is about 700 feet (210 m) thick as estimated from map relationships, but it is only 408 feet (124 m) thick in excellent exposures at East Reef to the north (Stewart and others, 1972b).

## Jurassic

Three Early Jurassic formations are present in the quadrangle: the Moenave, Kayenta and Navajo Formations (figure 4). They form the youngest second-order supercycle in

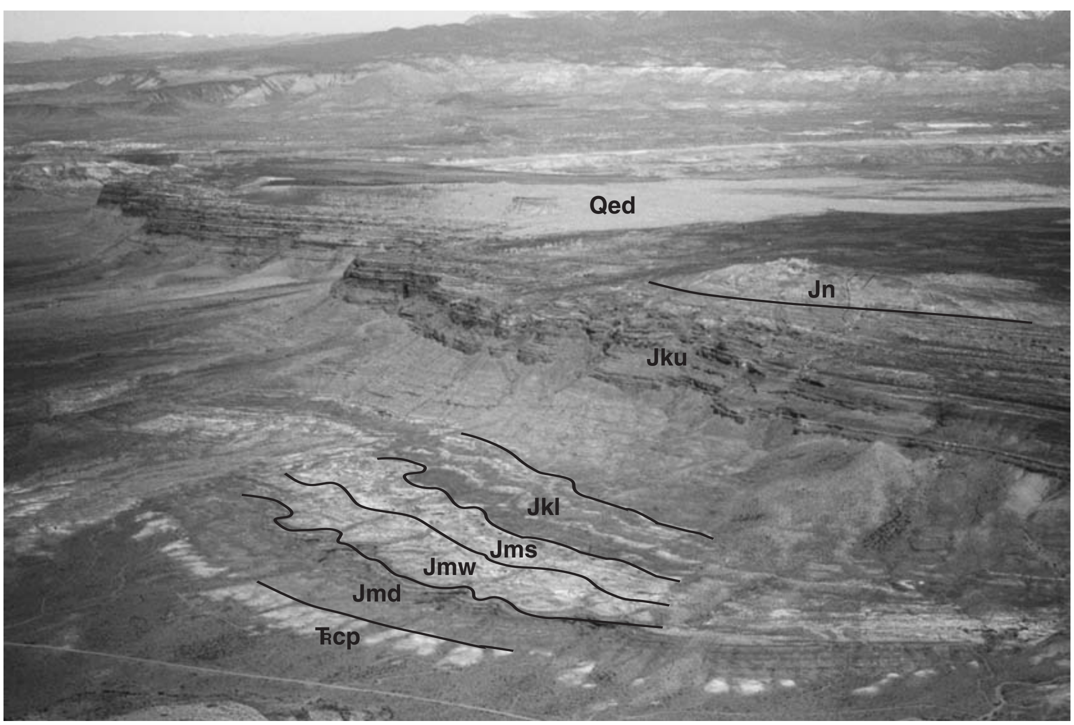



*Figure 4. Aerial view to the northwest of the complete Jurassic section within the Washington Dome quadrangle in south Warner Valley in section 26, T. 43 S., R. 14 W. Petrified Forest (TRcp), Dinosaur Canyon (Jmd), Whitmore Point (Jmw), Springdale Sandstone (Jms), lower Kayenta (Jkl), upper Kayenta (Jku), and lower Navajo Sandstone (Jn) strata are visible. Sand weathered from the Navajo Sandstone and upper member of the Kayenta Formation accumulates as transverse dunes (Qed) on the top of Sand Mountain.*

the Washington Dome quadrangle, and were deposited after sea level dropped dramatically from somewhat higher, to 500 feet (150 m) lower, than current sea level (figure 2a) (Vail and others, 1977).

The Early Jurassic rocks can be further divided into two and possibly three third-order sequences. The oldest third-order sequence is represented by the three members of the Moenave Formation. The Dinosaur Canyon Member is the transgressive systems tract, the Whitmore Point Member represents the maximum flooding stage, and the Springdale Sandstone Member comprises the highstand systems tract. The middle third-order sequence is represented by the Kayenta Formation. The lower member of the Kayenta is the transgressive systems tract with freshwater dolomite beds near the top of this member designated as the maximum flooding stage; the upper member forms the highstand systems tract. Strata above a possible unconformity in the basal Navajo Sandstone, perhaps at the top of an eolian tongue within fluvial sediments, may be the highstand systems tract of another third-order sequence.

## Moenave Formation

Miller and others (1989) assigned this formation to the Lower Jurassic rather than the Upper Triassic largely because of the presence of fish scales from the holostean fish, *Semionotus kanabensis* (Hesse, 1935; Schaeffer and Dunkle, 1950). Lucas and Heckert (2001) assigned it specifically to Hettangian age due to its globally rare tetrapod assemblage. This formation is divided into three members: Dinosaur Canyon, Whitmore Point, and Springdale Sandstone. The formation is 310 feet (94 m) thick at the south end of Warner Valley, in the NE¼ section 26, T. 43 S., R. 14 W.

**Dinosaur Canyon Member (Jmd):** The Dinosaur Canyon Member is completely exposed at the north and south ends of Warner Valley. Dinosaur Canyon strata are also partially exposed in the hanging wall of the Washington fault (NE¼ section 13 and SE¼ section 12, T. 43 S., R. 15 W.), in fault contact with the Shnabkaib Member of the Moenkopi Formation. The Dinosaur Canyon Member consists of interbedded, ledge- and slope-forming, moderate-red-brown siltstone and very fine grained, thin-bedded, pale-reddish-brown to grayish-red sandstone and mudstone. Planar, low-angle, and ripple cross-stratification are common. Isolated outcrops are difficult to distinguish from the Kayenta Formation. The upper contact is conformable and is placed between the highest reddish-brown sandstone of the Dinosaur Canyon Member and the base of a 6-inch-thick (15 cm), light-gray dolomitic limestone with algal structures that weathers to mottled colors of yellowish-gray, white, and grayish-orange-pink and contains dark-reddish-brown chert nodules. Measured thickness of the Dinosaur Canyon Member at the south end of Warner Valley in the NE¼ section 26, T. 43 S., R. 14 W. is 155 feet (47 m).

**Whitmore Point Member (Jmw):** The Whitmore Point Member is well exposed at the north and south ends of Warner Valley and partially exposed in the hanging wall of the Washington fault in the NE¼ section 13 and SE¼ section 12, T. 43 S., R. 15 W. It is composed of pale-red-purple to greenish-gray claystone interbedded with pale-brown to pale-red, thin-bedded siltstone. Several 2- to 6-inch-thick (5-15 cm) beds of light-greenish-gray, dolomitic limestone contain algal structures and fossil fish scales of *Semionotus kanabensis* (Hesse, 1935; Schaeffer and Dunkle, 1950). Unlike exposures to the west in the St. George quadrangle, about 5 feet (2 m) of red beds that look like the Dinosaur Canyon Member are present above the basal light-gray dolomitic limestone (Higgins and Willis, 1995). These red beds are here assigned to the Whitmore Point Member, similar to what Biek (2003a) reported in the Harrisburg Junction quadrangle. The unconformable upper contact is mapped at the base of the massive, cross-bedded Springdale Sandstone Member. At the south end of Warner Valley in the NE¼ section 26, T. 43 S., R. 14 W., the Whitmore Point Member is 30 feet (9 m) thick.

**Springdale Sandstone Member (Jms):** The Springdale Sandstone Member is beautifully exposed at the north and south ends of Warner Valley and partially exposed just west of the Washington fault in the NE¼ section 13 and SE¼ section 12, T. 43 S., R. 15 W. It is pale-reddish-brown to grayish-yellow, medium- to very thick bedded, fine- to medium-grained, cross-bedded, ledge-forming quartzose sandstone with interbedded light-purple-gray siltstone near the middle. The sandstone weathers to pale pink, pinkish gray, yellowish gray, and pale reddish purple, and forms rounded cliffs and ledges that commonly have Liesegang banding. Some of the sandstone layers are characterized by small, resistant, 0.13-inch-diameter (2 mm) concretions that give weathered surfaces a pimply appearance. In some areas the member also includes minor, thin, discontinuous lenses of intraformational conglomerate with mudstone rip-up clasts. Poorly preserved petrified wood is locally abundant. More than 7 million ounces (220,000 kg) of silver was produced from the Springdale Sandstone prior to 1900 at the Silver Reef mining district about 8 miles (13 km) north of the quadrangle (see, for example, Proctor and Shirts, 1991). The upper contact is drawn at the top of the massive sandstone and at the base of slope-forming, moderate-reddish-brown mudstone of the lower Kayenta Formation. This member is 125 feet (38 m) thick at the south end of Warner Valley in the NE¼ section 26, T. 43 S., R. 14 W., and also near the Virgin River in the NE¼NW¼ section 28, T. 42 S., R. 14 W.

## Kayenta Formation

The Kayenta Formation is divided into two informal members that collectively display a general coarsening upward sequence. Because of its transitional nature, the upper contact with the Navajo Sandstone is not consistent in the literature. In southwest Utah, generally west of the Hurricane fault, this transition zone can be several hundred feet thick (Tuesink, 1989; Sansom, 1992). Hintze and Hammond (1994) divided this formation into three members northwest of the Washington Dome quadrangle by putting the upper contact above the uppermost fluvial sequence, thus including a significant amount of eolian sand in the upper Kayenta. In this and adjacent quadrangles, I chose to use the Kayenta-Navajo contact from published work to the east (Moore and Sable, 1994; Doelling and Davis, 1989) that places it above the major break in topography created by the fluvial siltstone beds below the first major eolian sandstone, above which the sequence remains predominantly eolian. Thus, my upper Kayenta member is roughly equivalent to the middle member of Hintze and Hammond (1994) and their upper member is herein included in the Navajo Sandstone. The Kayenta Formation is late Pliensbachian to early Toarcian in age (Early Jurassic) (Imlay, 1980). Total thickness of the formation is 845 feet (256 m).

**Lower member (Jkl):** A complete section of the lower member of the Kayenta Formation is exposed at the base of Sand Mountain at the north and south ends of Warner Valley. This slope-forming unit consists of interbedded, pale-reddish-brown to moderate-reddish-brown, thin-bedded siltstone; very fine grained, moderately well-sorted, thin-bedded, planar to lenticular sandstone with climbing ripple marks; moderate-purplish-red mudstone that has sericite on some bedding surfaces; and very thin-bedded gypsum. The thin sandstone layers generally pinch out laterally, are typically calcareous, and their upper surface is locally bioturbated and mottled. Immediately east of the quadrangle, dinosaur footprints are present near the base of the lower member (Hayden, 2004a). Three thinly laminated beds of light-pinkish-gray to light-olive-gray micritic dolomite that weather to small blocks about 6 inches (15 cm) in diameter are present in the upper half of the member. They are separated by interbedded siltstone, mudstone, and sandstone. The top of the uppermost dolomite bed marks the conformable contact with the upper member of the Kayenta Formation. The lower member is 145 feet (44 m) thick at the south end of Warner Valley in the NE¼ section 26, T. 43 S., R. 14 W.

**Upper member (Jku):** The upper member comprises most of the Sand Mountain cliff face. It consists of moderate-reddish-brown siltstone and pale-reddish-brown to light-purplish-red mudstone with interbedded pale-reddish-brown to pale-red sandstone. Planar bedding of these mudstone and siltstone layers, along with small-scale cross-bedding of the sandstone, suggests alluvial deposition. The mudstone and siltstone are generally slope forming, but the very fine grained, usually calcareous sandstone forms thin ledges in the lower part and considerably thicker ledges near the top of the member. The upper surfaces of the sandstone ledges in the lower part of the upper member are locally bioturbated and mottled, varying in color from light-greenish-gray to moderate-reddish-brown. The upper member is 700 feet (210 m) thick at the base of Sand Mountain at the south end of Warner Valley, in the NE¼ section 26 and SE¼ section 23, T. 43 S., R. 14 W. The upper contact with the Navajo Sandstone is transitional and difficult to trace across the quadrangle. It is drawn at the top of the topographic break created by planar, water-lain siltstone and sandstone. Above this break the sandstone is a massively cross-bedded, slightly lighter in color, eolian deposit, above which the strata are predominantly eolian.

### Navajo Sandstone (Jn)

The Navajo Sandstone is the youngest Mesozoic rock in the quadrangle. Although it is about 2000 feet (600 m) thick in southwest Utah, only the basal 1000 feet (300 m) is exposed within the Washington Dome quadrangle. It forms the upper part of the cliff face as well as the top of Sand Mountain. The basal transition zone is characterized by massive, resistant, cross-bedded sandstone whose layers are separated by planar bedded, silty, fine-grained sandstone with thin mudstone interbeds. In addition to wavy bedding and dark, flaser-like laminae, soft-sediment deformation features such as diapiric and load structures, and bioturbation are present (Sansom, 1992). Except for the basal transition zone, this massive, cross-bedded, eolian sandstone is pale to moderate reddish brown and consists of fine- to medium-grained, well-rounded, well-sorted, frosted quartz grains. It weathers to sand that is locally blown into dune form.

## Quaternary

### Basaltic Lava Flow

Only one of several late Tertiary to Quaternary basaltic lava flows, which are present in the area as part of the western Grand Canyon basaltic field, reached the Washington Dome quadrangle (Hamblin and Best, 1970). The flows in this part of the field erupted from volcanic vents north of the quadrangle and flowed southward along tributary streams of the Virgin River (Hamblin, 1963; Willis and Higgins, 1995). Due to relative uplift of the area, downcutting of the streams along the sides of the resistant basalt flows created "inverted" valleys (Hamblin, 1970a, 1987; Hamblin and others, 1981). Hamblin (1970a, 1987) mapped flows in the region as stages I to IV, based on the amount of topographic inversion and erosion of the flows (stage I are high remnants that bear no apparent relation to the present topography, whereas stage IV are very young flows with little or no topographic inversion). Because downcutting has been the dominant geomorphic process during the late Cenozoic, the relative height of flows above drainages provides a way of estimating their relative age, and, coupled with radiometric dating, allows determination of a downcutting rate for the area. Hamblin and others (1981) first calculated a downcutting rate of 300 feet (90 m) per million years for the area between the Hurricane and Grand Wash/Gunlock faults, which includes the Washington Dome quadrangle. However, whereas stage designations are useful for comparison of flows within individual, large, fault-bounded blocks, Willis and Biek (2001) found that the complex downcutting history across major faults in southwestern Utah, including the Washington fault, can render stage designations misleading. They reported average long-term incision rates of 200 feet/million years (60 m/Ma) for the St. George block (between the Grand Wash/Gunlock and Washington faults) and 360 feet/million years (110 m/Ma) for the Hurricane block (between the Washington and Hurricane faults). Hamblin (1963), Best and others (1966), Hamblin (1970a), Lowder (1973), Best and Brimhall (1970, 1974), Best and others (1980), Hamblin and others (1981), Hamblin (1987), Biek (2003a, b and references therein) and Hayden (2004a) described the flows in this area. Best and Brimhall (1974), Best and others (1980), and Smith and others (1999) discussed the petrogenesis and tectonic setting of the flows.

**Washington lava flow (Qbw):** Only a small part of the Washington lava flow, which forms a prominent inverted valley called Washington Black Ridge, is exposed in the northwest corner of the quadrangle. Washington Black Ridge is composed of only one cooling unit (cooling units are lava pulses from the same eruption separated by short time intervals, whereas flows are from different eruptions and are separated by enough time for weathering to occur) in the Washington Dome quadrangle, but just north of the quadrangle in the SW¼ section 18, T. 42 S., R. 14 W. and the SE¼ section

13, T. 42 S., R. 15 W., three cooling units of the flow are exposed that have a cumulative thickness of about 40 feet (12 m) (Biek, 2003a). The flow's source is a deeply dissected cinder cone located 4 miles (6.5 km) north of the quadrangle at the common border of sections 25 and 36, T. 41 S., R. 15 W. The flow trends south-southeast, apparently along the course of the ancestral Grapevine Pass Wash, until it is deflected to the southwest, then west, by the cuesta of the Shinarump Conglomerate Member of the Chinle Formation along the north edge of the Virgin anticline. The total flow length is 5.5 miles (8.8 km) and the average gradient is about 150 feet per mile (27 m/km) (Biek, 2003a). The change in flow direction probably indicates where the flow entered the ancestral Virgin River channel; the flow locally overlies well-cemented ancestral Virgin River gravel (Biek, 2003a).

Within the Washington Dome quadrangle, the Washington Flow now lies up to 360 feet (110 m) above the Virgin River near the north edge of section 24, T. 42 S., R. 15 W. The end of the flow, in the St. George quadrangle to the west, is only about 220 feet (67 m) above the river. This difference in height above the river is due in part to paleotopography and the paleogradient of the Virgin River, Quaternary offset on splays of the Washington fault, and slumping of the basalt on the weak, clay-rich Petrified Forest Member of the Chinle Formation (Higgins and Willis, 1995). The Washington flow is classified as stage IIb, indicating that it was deposited on a surface that has a similar slope and gradient to, but that now lies 200 to 500 feet (60-150 m) above, the current drainage (Hamblin, 1970a).

The Washington flow is a very dark-greenish-gray basanite to borderline picrobasalt using the classification system of LeBas and others (1986), and petrographically it is classified as an ankaramite (an olivine-bearing basalt containing abundant clinopyroxene and olivine phenocrysts) (Best and Brimhall, 1974; Best and others, 1980; Biek, 2003a). It is the most mafic of the St. George basin flows. It is very fine grained with abundant small phenocrysts of clinopyroxene and olivine up to about 0.1 inch (3 mm) in diameter; the groundmass is plagioclase and titaniferous magnetite (Best and Brimhall, 1974). Best and others (1980) reported a K-Ar age of 1.7 ± 0.1 Ma for this flow. However, Biek (2003a) reported two $^{40}Ar/^{39}Ar$ ages of 0.98 ± 0.02 Ma and 0.87 ± 0.04 Ma for the Washington flow. The flow is strongly jointed and has been quarried for landscaping and building foundation stone just north of the quadrangle (Biek, 2003a). The thickness of the Washington Flow within the quadrangle ranges from 20 to 30 feet (6-10 m).

## Alluvial Deposits

**Older alluvial deposits (Qao):** Remnants of older, mostly locally derived, moderately sorted clay- to boulder-sized sediments are present above many minor drainages, especially between Punchbowl and Washington Domes. They are incised by active drainages 10 to 20 feet (3-6 m), thus forming a higher bench and remnants near Punchbowl Dome. The deposits are 0 to 20 feet (0-6 m) thick.

**Stream-terrace deposits ($Qat_2$-$Qat_6$):** Gravel- to cobble-size clasts in a muddy to coarse-sand matrix form a poorly sorted, indurated conglomerate at several levels above the modern flood plains of the Virgin River and Fort Pearce Wash. Many of the clasts are well-rounded basalt, quartz monzonite, and quartzite which are exotic to the quadrangle, indicating a source several miles upstream. Most terraces have a thick pedogenic carbonate (caliche) with up to a stage VI carbonate development using the classification system of Birkeland and others (1991). The sediments were deposited in paleochannels of rivers and streams. The terrace gravels are combined into five groups for mapping: level 2 deposits are 10 to 30 feet (3-10 m), level 3 deposits are 30 to 90 feet (10-27 m), level 4 deposits are 90 to 140 feet (27-42 m), level 5 deposits are 140 to 190 feet (42-57 m), and level 6 deposits are 190 to 270 feet (57-82 m) above present channels. These stream-terrace deposits range from 0 to about 40 feet (0-12 m) thick, except at the northeast end of Washington Dome in the N½NE¼ section 30 and the S½SE¼ section 19, T. 42 S., R. 14 W., where deformed $Qat_6$ deposits may exceed 70 feet (20 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 (2001) 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 major faults. Thus, whereas the subscripts 2 to 6 also denote the relative age of terrace deposits (youngest to oldest) west or east of the Washington fault, correlation across the fault is not intended. Indeed, based on long-term incision rates of 0.43 feet/1,000 years (0.13 mm/yr) east of the Washington fault and 0.20 feet/1,000 years (0.06 mm/yr) west of the fault, level 4 deposits west of the fault may be correlative with level 6 or older deposits east of the fault. If these long-term incision rates are correct, level 2 and level 3 terraces west of the Washington fault may be middle Pleistocene and level 4 terraces west of the fault may be lower Pleistocene. Similarly, level 2 deposits east of the Washington fault are likely upper Pleistocene to Holocene, level 3 deposits are middle to upper Pleistocene, and level 4, level 5, and level 6 deposits are lower Pleistocene. Thus, when comparing deposits on both sides at the Washington fault, the subscripts 2 through 6 denote only the elevation above modern drainages and cannot be used to compare relative ages across the fault. Conversely, the subscripts do indicate relative age when comparing deposits restricted to the hanging wall or footwall.

Level 6 terrace deposits are unusually thick at the northeast end of Washington Dome, south of the Virgin River, in the N½NE¼ section 30 and the S½SE¼ section 19, T. 42 S., R. 14 W. In this area, the Harrisburg Member of the Kaibab Formation and the lower red member of the Moenkopi Formation, as well as the overlying terrace gravels, are severely distorted. Anderson and Christenson (1989) proposed faulting to separate these oppositely dipping strata from those of Washington Dome. But they also recognized that the limited extent of the gravels dictated a highly localized depocenter that was probably the result of subsidence accompanying dissolution of subsurface evaporites. They recognized one and possibly two angular unconformities in the gravels, which suggests syndepositional deformation. The underlying units are highly altered by decalcification, silicification, and bleaching. Red and yellow limonitic stains are prominent in beds of the Harrisburg Member that are exposed in drainages. It is possible that breccia pipes originating in the deeply buried Mississippian Redwall Limestone might cause this type of deformation and mineralization (Wenrich, 1985). Solution-collapse breccia pipes originating in the Redwall are commonly uranium-rich, but also host other mineral assemblages (Wenrich and Sutphin, 1989). Kennecott Exploration, Inc. drilled three holes in this area as part of their gold exploration program on Washington Dome in 1990-91 and reportedly encountered Queantoweap Sandstone at a depth of 460 feet (140 m). Removal of section by decalcification of limestone and dissolution of gypsum would allow for the deposition of this unusually thick sequence of river gravel.

**Stream deposits ($Qal_1$):** Stream deposits consist of moderately to well-sorted clay to fine gravel in large, active drainages, including the Virgin River and Fort Pearce Wash. These deposits include river-channel and flood-plain sediment and minor terraces up to 10 feet (3 m) above the modern streams. The deposits are generally 0 to 20 feet (0-6 m) thick, although deposits along the Virgin River are locally greater than 50 feet (15 m) thick (Wayne Rogers, Applied Geotechnical Engineering Consultants, Inc., verbal communication, Oct. 9, 2003).

## Eolian Deposits

**Older eolian sand and caliche deposits (Qeo):** These deposits form planar surfaces with abundant pedogenic carbonate (caliche) (stage IV of Birkeland and others, 1991) and lesser eolian sand. They are mapped on the Navajo Sandstone of Sand Mountain where planar surfaces are of higher relief than the surrounding sandstone. They generally range from 0 to 10 feet (0-3 m) thick.

**Eolian dune sand deposits (Qed):** These deposits consist of well- to very well sorted, very fine to medium-grained, well-rounded, usually frosted, mostly quartz sand blown into dunes on Sand Mountain and in Warner Valley. The sand was derived from weathering of the Navajo Sandstone and the upper member of the Kayenta Formation. Some of the transverse dunes on Sand Mountain are 40 feet (12 m) high in the NE¼ section 10, T. 43 S., R. 14 W. (figure 5). Thickness varies from 0 to 40 feet (0-12 m).

**Eolian sand deposits (Qes):** These deposits of well- to very well sorted, very fine to medium-grained, well-rounded, usually frosted, mostly quartz sand accumulate in irregular hummocky mounds on the lee side of ridges as well as on Sand Mountain and in Warner Valley. In many areas, the blowing sand is partially stabilized by sparse vegetation. Most of the sand was probably derived from weathering of the Navajo Sandstone and the upper member of the Kayenta Formation. Locally, it forms poorly developed dunes. Thickness varies from 0 to 50 feet (0-15 m).

## Mass-Movement Deposits

**Landslide deposits (Qmsy, Qmso):** Several landslide deposits are mapped in the quadrangle and are divided into younger (Qmsy) and older (Qmso) landslides based on degree of preservation of landslide features. The deposits consist of very poorly sorted debris ranging in size from clay to blocks several hundred feet across, and form chaotic, hummocky mounds. Basal slip surfaces are within the Petrified Forest Member of the Chinle Formation and the upper red member of the Moenkopi Formation. The landslides involve overlying bedrock formations, talus, and basalt.

The largest landslide, partially within the northwest corner of the quadrangle and extending in to the St. George quadrangle to the west, formed on steep slopes of Washington Black Ridge, where the Petrified Forest Member of the Chinle Formation is capped by the Washington flow. It is

***Figure 5.*** *View northwest to the Pine Valley Mountains on the skyline from the SW¼ section 11, T. 43 S., R. 14 W. Transverse sand dunes form on Sand Mountain from the weathering of the Navajo Sandstone and upper member of the Kayenta Formation.*

mapped as Qmsy and is characterized by chaotic bedding, hummocky topography, and numerous subdued internal scarps and thus should be considered capable of renewed movement. The deposit is partially covered by blocks of basalt from the Washington flow. Smaller slide masses involving the upper red member of the Moenkopi Formation and the overlying Shinarump Conglomerate Member of the Chinle Formation are present on the north side of Shinob Kibe butte. To the south along the Washington fault, in the SW¼SE¼ section 12, T. 43 S., R. 15 W., a chaotic block of Shinarump Conglomerate that sits unconformably on tilted beds of the Moenave Formation is mapped as an older slide mass (Qmso). The thickness of landslide deposits in the quadrangle is highly variable.

**Talus deposits (Qmt):** Talus deposits are very poorly sorted, angular boulders with minor fine-grained interstitial sediments that have accumulated on and at the base of steep slopes. Most talus deposits consist of blocks of the Shinarump Conglomerate Member of the Chinle Formation that accumulate on the upper red member of the Moenkopi Formation. Similarly, jointed blocks of basalt have moved down slopes of Washington Black Ridge as the supporting softer beds of the Petrified Forest Member of the Chinle Formation erode; blocks of upper Kayenta strata similarly rest on the lower slopes of Sand Mountain. Only the larger talus deposits were mapped, but talus boulders are common on all steep slopes in the quadrangle. Talus ranges from about 0 to 20 feet (0-6 m) thick.

### Mixed-Environment Deposits

**Mixed alluvial and eolian deposits (Qae):** These deposits consist of moderately to well-sorted clay- to sand-sized sediment of alluvial origin that locally includes abundant eolian sand and minor fluvial gravel. The deposits are in large, open, nearly flat areas, are generally finer grained than other surficial deposits, and have minor pedogenic carbonate (caliche) development. In the Washington Fields area they consist primarily of silt- and clay-sized particles (Christenson and Deen, 1983), but are slightly coarser in south Washington Fields and in the valley area between Shinob Kibe butte and Washington Dome. The deposits are typically 0 to 30 feet (0-9 m) thick, but locally may be thicker.

**Mixed alluvial and colluvial deposits (Qac):** These deposits of poorly to moderately sorted clay- to boulder-sized sediment are present in minor drainages throughout the quadrangle. The alluvial deposits are transported along washes during heavy rainstorms whereas colluvial material is derived from side slopes along the washes. These deposits locally include stream deposits ($Qal_1$) and stream-terrace deposits ($Qat_2$) too small to map separately. The deposits are 0 to 10 feet (0-3 m) thick.

**Mixed eolian and alluvial deposits ($Qea_1$-$Qea_3$):** These deposits are differentiated based on degree of incision and pedogenic carbonate development; level 1 deposits are the youngest and level 3 deposits are the oldest. $Qea_1$ deposits are composed mostly of well-sorted eolian sand but locally include minor alluvial clay, sand, and gravel. They have been locally reworked by alluvial processes and are starting to develop a pedogenic carbonate horizon. These deposits cover much of Warner Valley and are 0 to 20 feet (0-6 m) thick.

$Qea_2$ deposits are similar to $Qea_1$ deposits in that they are mostly well-sorted eolian sand that includes minor alluvial clay to gravel. However, level 2 deposits are older; they have a stage I pedogenic carbonate horizon and are dissected by modern drainages, forming a higher bench. $Qea_2$ deposits are heavily dissected at the north end of Warner Valley and are being eroded in south Warner Valley, exposing the Petrified Forest Member of the Chinle Formation. $Qea_2$ deposits are 10 to 30 feet (3-10 m) above current drainages and are 0 to 20 feet (0-6 m) thick.

$Qea_3$ deposits are also composed of well-sorted eolian sand and minor alluvial clay, sand, and gravel, but these deposits have a thick stage V to VI pedogenic carbonate horizon that forms a resistant cap. $Qea_3$ deposits cap the elevated surface of the "racetrack" (old landing strip) area in the southwest part of the quadrangle. They are 20 to 40 feet (6-12 m) above current drainages and are 0 to 20 feet (0-6 m) thick.

**Mixed colluvial and alluvial deposits (Qcao, Qca):** These deposits consist of poorly sorted, angular to rounded, fine-grained to boulder-sized sediment on broad, low to moderate slopes. Locally, they include talus, eolian, and alluvial deposits too small to map separately. They are weakly consolidated to unconsolidated, exhibit well-developed desert pavement, and were deposited mainly by debris-flow, slope-creep, and sheet-wash processes. Older deposits (Qcao) are dissected by current drainages and lie at higher elevations than younger (Qca) deposits. The older deposits are deeply dissected by washes on the north side of Washington Dome and are offset by the Washington fault in the SE¼ section 12 and the E½ section 13, T. 43 S., R. 15 W. Anderson and Christenson (1989) reported that fault rupture of these sediments occurred during late Pleistocene time. Younger deposits (Qca) are along Fort Pearce Wash and south of Washington Dome. Similar deposits that have a larger alluvial component and are confined to modern channels are mapped as mixed alluvial and colluvial (Qac) deposits. Both older and younger mixed colluvial and alluvial deposits are 0 to 30 feet (0-10 m) thick.

**Artificial fill (Qf):** Artificial fill, used for dams and levees, is present throughout the quadrangle. It consists of engineered fill and general borrow material. Although only a few deposits are mapped, fill should be anticipated in all developed areas, many of which are shown on the topographic base map. Thickness is highly variable.

## STRUCTURE

### Regional Setting

The Washington Dome quadrangle is in the transition zone between the Colorado Plateau and the Basin and Range physiographic provinces and contains structural elements of both regions (Hamblin, 1970b; Hintze, 1986). The transition zone coincides with the leading edge of the Late Cretaceous Sevier orogenic thrust belt. Strata in the quadrangle are involved in folds and minor faults in front (east) of the main thrust belt, and a basal detachment is postulated in underlying Cambrian strata. At the frontal portion of most thrust belts, a detachment at depth transfers the waning displacement of the thrust belt through a triangle zone characterized by a reverse fault, which helps create an anticline commonly tens of miles in length. The development of the fold effectively uses up the remaining displacement of the thrust belt. In the St. George area, the basal detachment is believed to lie within the Cambrian Bright Angel Shale and the frontal fold is the Virgin anticline (Davis, 1999).

The transition zone is also part of the active southern segment of the Intermountain seismic belt, which here coincides with the boundary between relatively thin lithosphere of the Basin and Range Province and thicker, more stable lithosphere of the Colorado Plateau (Arabasz and Julander, 1986). The transition zone consists of a series of late Cenozoic, north-trending, down-to-the-west normal faults that bound fault blocks that "step down" from the Colorado Plateau into the Basin and Range Province. The Washington Dome quadrangle straddles one of these faults, the Washington fault, and so includes parts of the Hurricane and St. George fault blocks. The Hurricane block is bounded on the east by the Hurricane fault, which has about 3600 feet (1100 m) of tectonic displacement at the latitude of St. George (Anderson and Christenson, 1989). Displacement increases to the north to 4800 feet (1460 m) near "Noah's Ark" in The Divide quadrangle (Hayden, 2004a). The Washington fault, which bounds the west side of the Hurricane block (and the east side of the St. George block), has about 700 to 1650 feet (210-500 m) of stratigraphic displacement in the quadrangle as described below.

The regional dip of the strata in the St. George and Hurricane blocks is 5 to 10 degrees northeast. During the Sevier orogeny, strata in the blocks were compressed into the broad, northeast-trending St. George syncline, the axis of which lies northwest of the quadrangle, and the much tighter Virgin anticline, which cuts across the northwest corner of the quadrangle.

## Folds

### Virgin Anticline

The dominant structure in the quadrangle is the northeast-trending Virgin anticline. The generally symmetrical anticline is about 30 miles (48 km) long and is colinear with the Kanarra anticline to the north. The Virgin anticline includes the Bloomington, Washington, and Harrisburg Domes, of which only the Washington Dome lies within the quadrangle. At present levels of exposure, each of the three domes is cored by the Permian Kaibab Formation, with the lower Fossil Mountain Member only exposed at Bloomington Dome. A hogback formed by the Shinarump Conglomerate Member of the Chinle Formation delineates the main part of the Virgin anticline around a central core of the Moenkopi and Kaibab Formations.

In the Washington Dome quadrangle, the Virgin anticline also contains two smaller, subsidiary domes, both exposing the Virgin Limestone Member of the Moenkopi Formation. Both trend roughly parallel to Washington Dome. Punchbowl Dome is to the south. The dome to the north (section 25, T. 42 S., R. 15 W.) is unnamed and is cut by a down-to-the-west normal fault.

**Washington Dome:** The Harrisburg Member of the Kaibab Formation forms the exposed core of Washington Dome. Much of the apparent internal deformation of the Harrisburg Member is likely due to pre-Triassic dissolution of gypsum.

The southwest part of Washington Dome is structurally complex (figures 6 and 7). A southeast-dipping reverse fault is present where the lower members of the Moenkopi Formation are nearly vertical, and a northwest-dipping out-of-the-syncline thrust repeats resistant limestone beds of the Virgin Limestone Member of the Moenkopi Formation. These faults create a syncline and a broad shoulder of Kaibab Formation at depth that supports another broad anticline, seen as an unnamed dome in the Virgin Limestone and the shallow dips of the middle red member farther out in the valley toward Shinob Kibe butte (figure 6). At the southeast end of Washington Dome, a steeply southeast-dipping reverse fault repeats the Harrisburg Member of the Kaibab Formation.

Although exposures are limited, these major and minor structures seem to die out to the northeast so that the northern part of the dome appears to be an unfaulted symmetrical anticline with some attenuation of incompetent beds. Previously, an area of thick gravel ($Qat_6$) was assumed to occupy a small structural low separating Washington and Harrisburg Domes (Anderson and Christenson, 1989), through which the Virgin River was able to breach the anticline (figure 8). However, Kennecott Exploration, Inc. drilled three holes in this area as part of their gold exploration program in 1990-91 and encountered Queantoweap Sandstone at a shallower-than-expected depth of 460 feet (140 m) (Kenneth A. Krahulec, Kennecott Exploration, Inc., verbal communication, May 27, 1998). This area is thus a structural high and must be part of Washington Dome. Alternatively, it may be structurally high from a blind backthrust. About 300 to 540 feet (90-165 m) of section has been removed by some combination of erosion, faulting, or dissolution and subsequent collapse. Lack of exposure in the Virgin River valley does preclude choosing a preferred alternative.

**Punchbowl Dome:** Punchbowl Dome, in the NE1/4 section 1, T. 43 S., R. 15 W., exposes a core of the Virgin Limestone Member of the Moenkopi Formation (figure 9). Part of the west limb of this fold is modified by normal drag on the Washington fault.

**Unnamed dome:** To the north of and roughly parallel to Washington Dome in the center of section 25, T. 42 S., R. 15

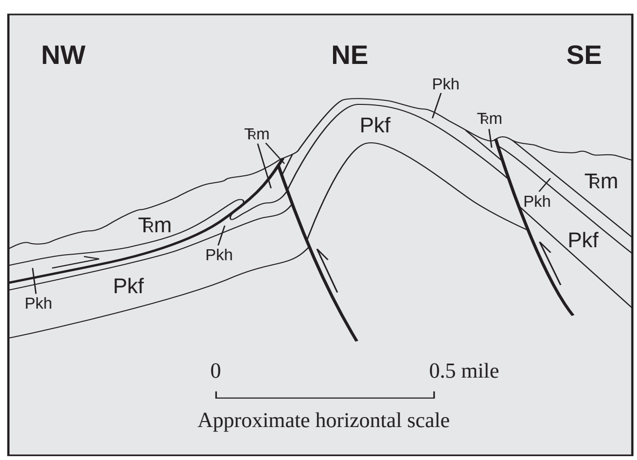



*__Figure 6.__ Cross section across the south end of Washington Dome showing faulting and associated asymmetrical folding. Pkf = Fossil Mountain Member of the Kaibab Formation; Pkh = Harrisburg Member of the Kaibab Formation; TRm = Moenkopi Formation, undivided.*

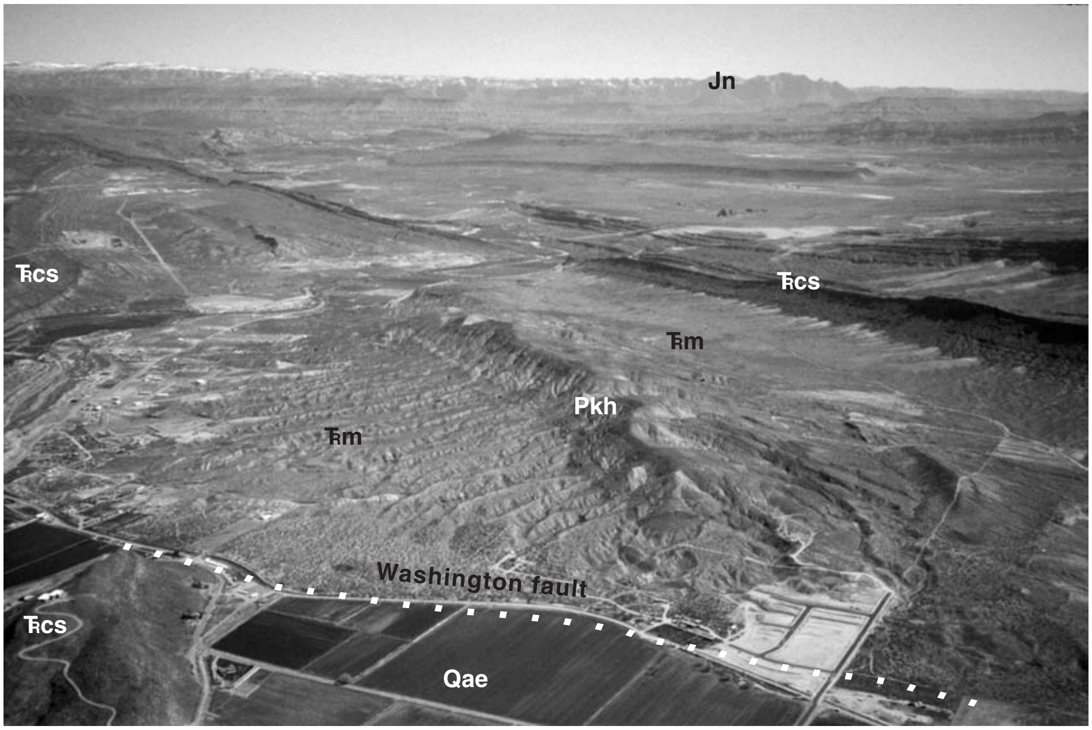



***Figure 7.*** *Aerial view northeast to Washington Dome from near the west edge of the quadrangle. Pkh = Harrisburg Member of the Kaibab Formation; TRm = Moenkopi Formation, undivided; TRcs = Shinarump Conglomerate Member of the Chinle Formation; Qae = mixed alluvial and eolian deposits. The Washington fault trends across the bottom of the photo near the St. George and Washington Canal at the edge of the cultivated area. The towering cliffs of Navajo Sandstone (Jn) on the horizon are in Zion National Park.*

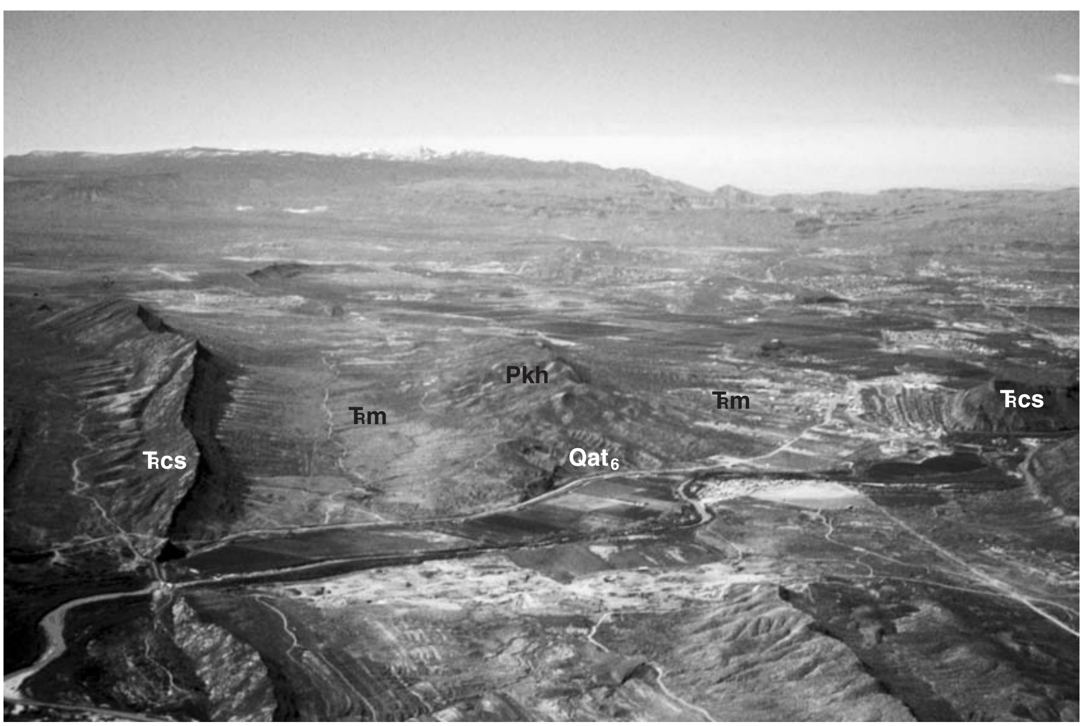



***Figure 8.*** *Aerial view southwest to Washington Dome. Unusually thick river-terrace gravels ($Qat_6$) of the ancestral Virgin River are at the northeast-plunging end of Washington Dome. Speculation as to the origin of this localized depocenter has produced several different alternatives, all complicated by Kennecott's drill hole that shows the area is a structural high, instead of a structural low as was previously postulated by Anderson and Christenson (1989). Prominent hogback on left and Shinob Kibe butte on the right are capped by the Shinarump Member of the Chinle Formation (TRcs). In the middle of the dome, the Harrisburg Member of the Kaibab Formation (Pkh) is exposed, flanked by the Moenkopi Formation (TRm).*

W., is a broad dome defined by gentle dips in the Virgin Limestone Member of the Moenkopi Formation. This broad dome may have resulted from reverse and thrust faulting on the northwest side of Washington Dome. The western extension of this dome is truncated by a down-to-the-west normal fault, likely a splay of the Washington fault, with approximately 300 feet (90 m) of stratigraphic displacement. This fault places the middle red member in the hanging-wall block against the Virgin Limestone Member to the east.

## Faults

### Thrust and Reverse Faults

Two northeast-trending thrust or reverse faults related to folding during the Sevier orogeny are exposed, one on each side of the structurally complex south end of Washington Dome, and a third such fault is inferred (figure 6). The larger fault, on the southeast side of the dome, dips steeply southeast and places Harrisburg Member strata over lower red through middle red Moenkopi strata. On the northwest side of the dome, an inferred, steeply southeast-dipping fault creates nearly vertical beds in the lower members of the Moenkopi Formation, and is in turn truncated by a northwest-dipping, out-of-the-syncline thrust that duplicates resistant limestone beds of the Virgin Limestone Member.

### Normal Faults

**Washington fault:** The Washington fault is a 42-mile-long (68-km), down-to-the-west, high-angle normal fault that trends north from northern Arizona into southern Utah, where it passes along the west side of the Washington Dome quadrangle (Cook, 1960; Peterson, 1983; Billingsley, 1992a). The fault terminates in the Washington quadrangle to the northwest where it bifurcates into a series of smaller northwest- to northeast-trending faults (Willis and Higgins, 1995).

The amount of offset on the Washington fault decreases northward. According to Peterson (1983), the fault reaches a maximum stratigraphic separation of 2200 feet (660 m) about 6 miles (10 km) south of the Utah-Arizona state line; Billingsley (1992a) reported 1650 feet (500 m) of stratigraphic separation at the state line. The best place to calculate stratigraphic separation of the fault in the Washington Dome quadrangle is just south of the road that cuts across Warner Ridge into Warner Valley in the NW¼NE¼ section 13, T. 43 S., R. 15 W. There, the Dinosaur Canyon Member of the Moenave Formation is in fault contact with the upper red member of the Moenkopi Formation, resulting in 1500 feet (455 m) of stratigraphic separation. Stratigraphic separation decreases to about 700 feet (210 m) where the fault cuts across the northeast corner of the St. George quadrangle, based on tenuously projecting the Springdale Sandstone Member of the Moenave Formation from outcrops about 2 miles (3.2 km) west of the fault, and by projecting a marker bed in the upper member of the Kayenta Formation in the Washington quadrangle (Willis and Higgins, 1995).

Normal drag along the Washington fault creates beautifully displayed, narrow, faulted anticlinal drag folds in the members of the Moenkopi Formation and the Shinarump Conglomerate Member of the Chinle Formation from Wash-

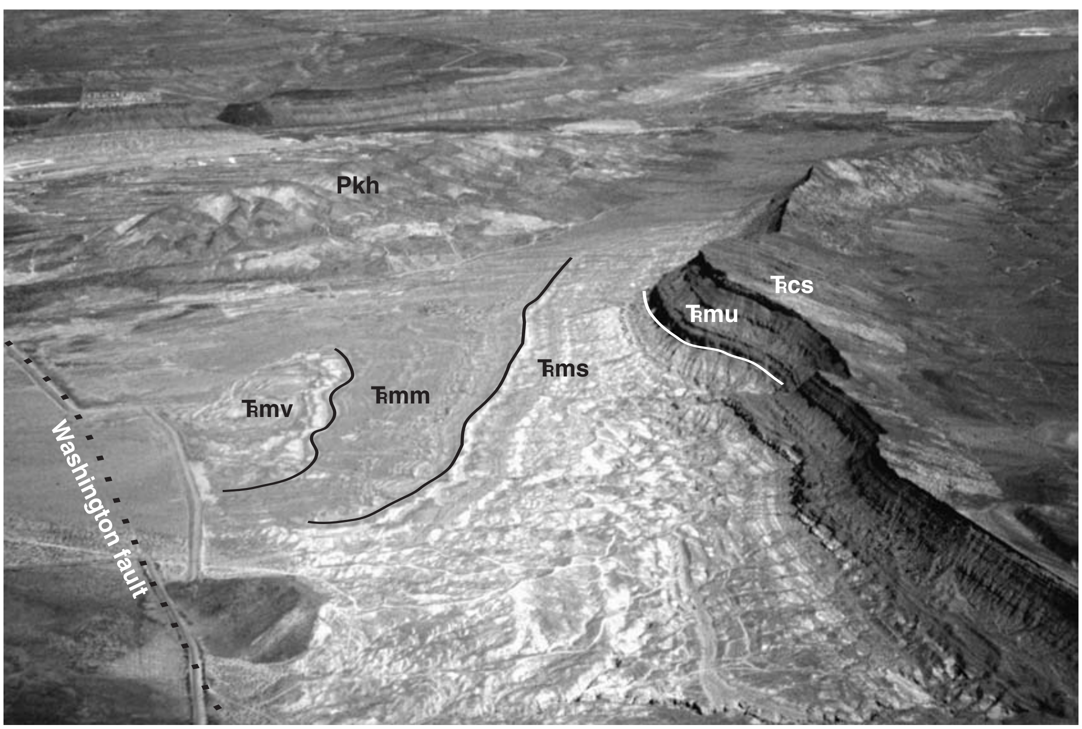



***Figure 9.*** *Aerial view north to Punchbowl Dome. The prominent east-dipping ridge on the right (east) side of the photo is Warner Ridge, capped by the Shinarump Conglomerate Member (TRcs) of the Chinle Formation. Members of the Moenkopi Formation exposed beneath the ridge are upper red member (TRmu), Shnabkaib Member TRms), middle red member (TRmm), and Virgin Limestone Member (TRmv). The Virgin Limestone forms the center of Punchbowl Dome. The Washington fault trends northward near the west edge of the photo while the Harrisburg Member of the Kaibab Formation (Pkh) forms Washington Dome.*

ington Dome south into Arizona. One of the largest and best defined of these drag features, formed in the middle red member of the Moenkopi Formation on the upthrown side of the fault, is Beehive Dome in section 30, T. 43 S., R. 14 W., just north of Fort Pearce Wash (figure 10). Steeply west-dipping normal drag on the hanging wall is also evident in the few areas where bedrock is exposed, particularly in the Shinarump Conglomerate Member of the Chinle Formation in sections 12 and 13, T. 43 S., R. 15 W., just south of the road intersection to Warner Valley.

The dip of the main splay of the Washington fault varies from 80° west to nearly vertical where it is exposed well enough to be measured. Smaller subsidiary faults, which join the main fault and bound blocks of rock in the fault zone, have dips that vary from 50° to 80° west. These blocks of rock are composed of the Chinle Formation and the upper red member of the Moenkopi Formation.

Three fault scarps in the quadrangle provide data to bracket ages of movement on the Washington fault: one scarp on the main fault cuts highly dissected, gently sloping Quaternary sediments (Qcao), and two scarps on different splays of the fault cut the 900,000-year-old Washington flow (Qbw) (Biek, 2003a) in the northwest corner of the quadrangle. Other prominent scarps in the quadrangle seem to be the result of differential erosion, a conclusion reached by Peterson (1983) and Anderson and Christenson (1989). Anderson and Christenson's (1989) profile of the scarp in Quaternary sediment (Qcao) indicated a scarp height of 11.5 feet (3.5 m) and a maximum slope angle of 17 degrees, with tabular rock fall slabs in the gravel clasts rotated into approximate conformity with the steeply dipping fault. A comparison of these data with those for Bonneville shoreline scarps indicates that this Washington fault scarp is probably latest Pleistocene in age, about 15,000 years old (Anderson and Christenson, 1989). The Washington fault should thus be considered an active fault having late Quaternary displacement. The two scarps in the 900,000-year-old Washington flow are about 800 feet (240 m) east of the main fault trace where the basalt is displaced vertically 5 feet (2 m), and about 2000 feet (600 m) east of the main fault trace where the basalt is displaced vertically 15 feet (4.5 m). Anderson and Christenson (1989) estimated that the age of this faulting is middle to late Pleistocene.

**Other normal faults:** All other mapped normal faults in the quadrangle are near to and associated with the Washington fault, except for the two in south Warner Valley along the edge of Sand Mountain. They are the westernmost of several northeast-trending faults in that area. The southernmost of these two faults has 200 feet (60 m) of down-to-the-northwest stratigraphic separation. The largest of the faults associated with the Washington fault, just east of and parallel to it, cuts the unnamed dome north of Washington Dome and shows about 300 feet (90 m) of down-to-the-west stratigraphic separation, placing middle red against Virgin Limestone strata. This fault may extend beneath valley alluvium and be continuous with the easternmost fault that cuts the Washington flow; both are about 2000 feet (600 m) east of the Washington fault. The only other mapped normal faults in the quadrangle also lie just east of the Washington fault, south of the road that cuts across Warner Ridge into Warner

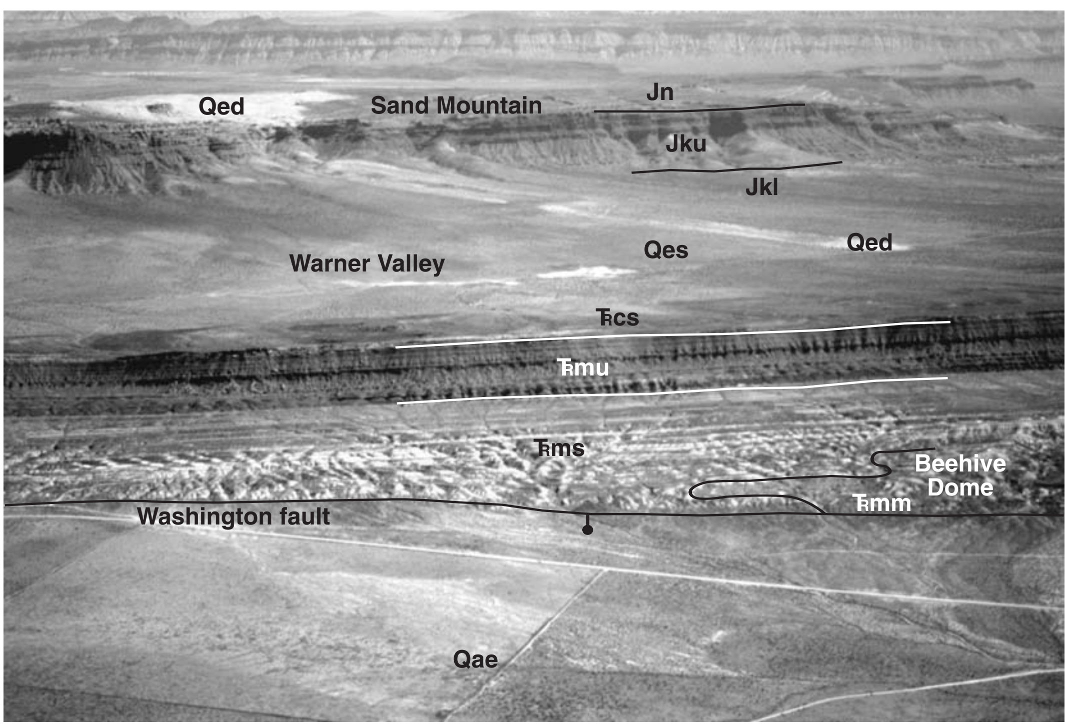



***Figure 10.*** *Aerial view eastward toward Sand Mountain and the Washington fault in the W½ sections 19 and 30, T. 43 S., R. 14 W. Here, normal drag in the footwall of the fault created Beehive Dome, cored by the middle red member of the Moenkopi Formation (TRmm). Warner Ridge, Warner Valley, and Sand Mountain are visible in the distance. TRms = Shnabkaib Member and TRmu = upper red member of the Moenkopi Formation; TRcs = Shinarump Conglomerate Member of the Chinle Formation. The Kayenta Formation (Jkl and Jku) and Navajo Sandstone (Jn) form the cliffs of Sand Mountain where weathered sand accumulates and is blown into dune form (Qed). In some areas the sand is blown off of Sand Mountain into Warner Valley (Qes) where it may take dune form. In front of the fault, the valley is filled with Quaternary alluvial/eolian sediment (Qae).*

Valley in the NW¼NE¼ section 13, T. 43 S., R. 15 W. There, two small grabens within the large anticlinal structure formed by normal drag are developed in the Shinarump Conglomerate Member of the Chinle Formation.

### Joints

All competent bedrock units in the quadrangle are jointed, but the most prominent joints are in the massive sandstone beds of the upper Kayenta Formation and Navajo Sandstone at Sand Mountain, and in the Shinarump Conglomerate Member of the Chinle Formation at Warner Ridge. The joints in the Shinarump Conglomerate Member are generally a few feet to a few tens of feet apart and form a conjugate set subparallel to the strike and dip of bedding. The joints control Liesegang banding of iron-manganese oxides, commonly forming “picture stone.”

Willis and Higgins (1995) recognized three main types of joints in the extensive exposures of Navajo Sandstone in the Washington quadrangle to the northwest. Two of them are recognized in the Washington Dome quadrangle where the Navajo crops out from beneath the sand that covers much of Sand Mountain. The first type are generally parallel, high-angle, open joints. Spacing is generally uniform over large areas although there are areas of higher joint density. They form a very prominent joint pattern and trend generally north to slightly northeast. In several areas these joints form a conjugate set with northeast-trending joints. Joints in this category are generally not healed or recemented and in many areas they are differentially weathered, forming straight, narrow gaps in the rock a few inches to several feet wide and locally more than 50 feet (15 m) deep.

The second type of joints are very prominent, widely spaced, high-angle, parallel, mostly northeast trending, and are clearly visible on aerial photographs. They are distinguished by strong siliceous and calcareous recementation that is generally more resistant than the country rock, causing them to weather out in relief to form prominent linear ridges. Generally some brecciation is present near the joints (deformation shear bands), and in a few cases cross-beds in the sandstone are offset up to a few feet.

## ECONOMIC GEOLOGY

Several geologic resources have been used from the Washington Dome quadrangle. Gravel, sand, road fill, and riprap are currently in high demand because of rapid growth in the area. Stone is used for construction and ornamental uses, and there has been extensive gypsum exploration. Finely disseminated gold, mercury, arsenic, antimony, and thallium are reported at Washington Dome, although not in economic concentrations. Also, the Springdale Sandstone Member of the Moenave Formation, host to the silver, copper, and uranium mineralization in the Silver Reef mining district, is present in the quadrangle (Proctor and Brimhall, 1986; James and Newman, 1986).

### Gravel, Road Fill, Riprap, and Sand

Gravel, essential for construction, is presently the most important geologic resource in the quadrangle. The primary deposits are near the Virgin River and Fort Pearce Wash, with most active pits north of the Virgin River near the north edge of the quadrangle. Most gravel-pit operations along Fort Pearce Wash are just west of the quadrangle. Many older gravel deposits are cemented with thick pedogenic carbonate (caliche) so most active pits are in lower terrace deposits ($Qat_3$), which contain less carbonate. The Utah Department of Highways Material Inventory of Washington County contains analytical information on aggregate resources in the quadrangle (Utah Department of Highways, 1964). Blackett and Tripp (1998) discussed issues affecting development of sand and gravel and aggregate resources in Washington County.

Road fill was acquired from gravel locations described above and from deposits mapped as Qea and Qao. A few other small excavations are scattered throughout the quadrangle. Large boulders from Shinarump Conglomerate talus and the Washington basalt flow are used as riprap, especially along the St. George and Washington Canal diversion dam on the Virgin River.

Sand for local uses has been obtained from eolian sand deposits (Qes) near Fort Pearce Wash, north Warner Valley, and north of Washington Dome. Active sand pits are north of Washington Dome where wind-blown sand covers older colluvial and alluvial deposits (Qcao).

### Building Stone

Blocks of sandstone from the Kayenta Formation are taken from talus in the south end of Warner Valley and used for landscaping and retaining walls (Larry Gore, U.S. Bureau of Land Management, verbal communication, May 27, 1998). No quarries for building stone have been developed in the Washington Dome quadrangle; however, outcrops of flagstone in the Kayenta Formation are extensive. Also, large rock-fall blocks of Shinarump Conglomerate excavated during construction of homes on hillsides are reused to build retaining walls and as landscape stone.

### Ornamental Stone

Petrified wood from the Petrified Forest Member of the Chinle Formation is used to construct monuments, decorate rock gardens and fireplace mantles, and is sold as curiosities in gift shops. "Picture rock" or "landscape stone" from the sandstone beds of the Shinarump Conglomerate Member of the Chinle Formation is polished into spheres, coasters, and clock bases, and is cut into slabs that are mounted in picture frames. Currently, there are no quarries for this stone in the quadrangle, but several outcrops of picture rock exist. Picture rock is well-cemented sandstone with extensive Liesegang banding that imparts alternating light-brown, dark-brown, and orangish-brown swirls, bands, and other patterns in the rock. In cut pieces, these complexly intertwined bands resemble landscape silhouettes.

### Gypsum

Although the Harrisburg Member of the Kaibab Formation has been extensively explored for gypsum, no gypsum has been mined from the quadrangle. Henry Chemical, while exploring for food-grade gypsum, found anomalous amounts of mercury and arsenic associated with the gypsum of the Harrisburg Member (Cliff Phillips, independent prospector, verbal communication, May 27, 1998). The gypsum is pale gray to white with bands of clay and limestone. Gypsum intervals within the Harrisburg Member vary in thickness due to secondary flowage, but outcrops are typically 10 to 30 feet (3-9 m) thick. The Shnabkaib Member of the Moenkopi Formation also has bedded gypsum, but beds are thin and contain abundant claystone and sandstone contaminants.

## Metals

Several metals are found in highly disseminated deposits in the Harrisburg Member of the Kaibab Formation in the Washington Dome quadrangle. In the 1950s, a small, unrecorded mercury mine operated in the NW¼ section 30, T. 42 S., R. 14 W. The mine workings consist of dozer scrapes and one adit into the hillside. Mercury was processed from metacinnabar. Mercury concentrations in some areas reach 200 ppm (Cliff Phillips, independent prospector, verbal communication, May 27, 1998). Energy Fuels drilled the same locality for uranium but results of those tests are not available. Arsenic levels in some areas commonly reach 5000 to 6000 ppm (Cliff Phillips, verbal communication, May 27, 1998), but have been known to be as high as 10,000 ppm, in the form of scorodite, an arsenic oxide mineral (Kenneth A. Krahulec, Kennecott Exploration, Inc., verbal communication, May 27, 1998).

Kennecott Exploration, Inc., in a joint venture with High Frontier Resources, Ltd., drilled 115 holes into a 50- to 100-foot-thick (15-30 m), highly altered, silty limestone in the upper part of the Harrisburg Member of the Kaibab Formation, mostly on the southeast side of Washington Dome (Larry Gore, BLM, verbal communication, May 27, 1998). The alteration in the limestone consists of silicification with minor decalcification and the formation of jarosite. An area of widespread low-grade gold mineralization, primarily along the southeast side of the dome, was found that includes three zones having modest gold values (Engineering and Mining Journal, 1991). The mineralization has the classic alteration and geochemical trace element patterns of a typical sediment-hosted gold system that includes gold, arsenic, antimony, mercury, and thallium. The mineralized area is 7000 feet (2100 m) long northeast to southwest with widths of 1000 to 2000 feet (300-600 m). Typically, the rock is not obviously altered, but geochemical sampling and close inspection shows evidence of hydrothermal alteration. There is no aeromagnetic signature of an intrusion (Kenneth A. Krahulec, verbal communication, May 27, 1998).

In addition, the Springdale Sandstone Member of the Moenave Formation, which is extensively exposed in the quadrangle, produced more than 7 million ounces (220,000 kg) of silver prior to 1900 at the Silver Reef mining district near Leeds, Utah, about 8 miles (13 km) north of the quadrangle (James and Newman, 1986; Proctor and Brimhall, 1986). Locally, significant copper and uranium concentrations are also present in the Springdale Sandstone at Silver Reef (James and Newman, 1986). In the Washington Dome quadrangle, the Springdale Sandstone is exposed in Warner Valley along the south limb of the Virgin anticline. Anomalous concentrations of silver are locally present in the Springdale Sandstone well beyond the boundaries of the mining district and some gold has been reported, but none of ore grade (Proctor and Brimhall, 1986).

## Oil and Natural Gas

There has been no production of oil or gas in the Washington Dome quadrangle. The nearest production was from the Virgin oil field, which is about 10 miles (16 km) northeast of the quadrangle, adjacent to Zion National Park. With the drilling of the first well in 1907, the Virgin oil field has the distinction of being the oldest oil field in Utah (Heylmun, 1993). The discovery well was probably drilled in an attempt to locate the down-dip source of the oil seeps observed in Timpoweap Canyon and its tributaries, about 3 miles (5 km) southwest of the field (Richardson, 1908). The trapping mechanism is generally held to be stratigraphic due to the lack of significant structural closure, the depressured nature of the field at discovery, interpretations of the depositional environment, the variability of porosity and permeability over relatively short distances, and the differences in pay thickness which varies from 1 to 12 feet (0.3-3 m) but averages only 4 feet (1.2 m) thick (Blakey, 1979). Production is primarily from the Timpoweap Member of the Moenkopi Formation (Gregory, 1950) with a possible contribution from the subjacent Kaibab Formation (Brandt, 1989). Productive depths range from 475 to 800 feet (145-244 m) with an average of 550 feet (168 m) (Bahr, 1963). The brown to black oil ranges from 22° API sour crude at the shallow south end of the field, to 32° API sweet crude at the deeper north end and has a mixed paraffin-asphalt base (Heylmun, 1993). Field development and production occurred intermittently with the last production report dated April, 1985 (Christopher J. Kierst, Division of Oil, Gas and Mining, verbal communication, Oct. 29, 2004). Cumulative production of over 206,000 barrels of oil is estimated since production records were not preserved prior to 1927 (Christopher J. Kierst, verbal communication, Oct. 29, 2004). The productive area included about 200 acres (0.8 $km^2$) (Heylmun, 1993). All known wells have now been plugged and abandoned (Christopher J. Kierst, verbal communication, Oct. 29, 2004).

Of eight oil and gas exploration wells drilled in Washington Dome quadrangle, only three penetrated more than 2500 feet (750 m) of strata. The deepest well, Dixie State No. 1 drilled by Energy Associates, was drilled in 1977 in the NE¼SW¼NE¼ section 32, T. 43 S., R. 14 W. It penetrated 2880 feet (870 m) of strata, from the middle of the Shnabkaib Member of the Moenkopi Formation to the Queantoweap Sandstone. It is the only well for which a well log is available from the Utah Division of Oil, Gas and Mining. Most of the wells were drilled along the anticline created by normal drag on the Washington fault, including Beehive Dome; however, two wells drilled by Arrowhead Oil Company tested Punchbowl Dome in 1932 and 1936, where bleached Virgin Limestone forms the exposed core of the dome. The 1932 well was drilled to a total depth of 1185 feet (359 m). The 1936 test well was drilled to a total depth of 2590 feet (785 m), also in the Queantoweap Sandstone, with a show of oil at a depth of 2190 feet (664 m). Both wells were plugged and abandoned and no logs are available. Washington Dome itself has not been drilled for petroleum.

## Geothermal Resources

The Washington Dome quadrangle is in an area with geothermal potential (Mabey and Budding, 1985; Budding and Sommer, 1986; Blackett and Wakefield, 2004). Quaternary basalt vents in the area, some possibly as young as about 10,000 years, could be an indicator of geothermal potential. However, basalts are believed to ascend through relatively small conduits from depths of several miles (Budding and Sommer, 1986). The hydrothermal alteration of and emplacement of minerals into the Permian Harrisburg Member of the Kaibab Formation is, perhaps, another indicator of geothermal potential. No hot springs are known in the quadrangle, but hot springs are present within 8 miles (13 km). The highest recorded spring water temperature in the area is 108°F (42°C) at Pah Tempe Hot Springs between Hurricane and LaVerkin (Budding and Sommer, 1986).

# WATER RESOURCES

Water is of great importance in the St. George basin because the population is rapidly increasing and much of the area receives less than 8 inches (20 cm) of precipitation per year (Cordova and others, 1972; Cordova, 1978; Clyde, 1987; Horrocks-Carollo Engineers, 1993; Utah Division of Water Resources, 1993). A study by the Utah Geological Survey, Utah Division of Water Resources, and U.S. Geological Survey Water Resources Division evaluated major aquifers in detail (Hurlow, 1998). Only a brief overview is given here.

## Surface Water

Cordova and others (1972) and Sandberg and Sultz (1985) summarized flow data for perennial streams and surface-water quality in the upper Virgin River basin. The Virgin River, with an average annual flow at the Virgin gaging station of 130,610 acre-feet (170,430,000 $m^3$) (Cordova, 1978), flows across the northwest corner of the quadrangle. Fort Pearce Wash enters the quadrangle near the southeast corner and extends along the south edge, joining the Virgin River a few miles west of the quadrangle. It has an estimated average annual flow of 2000 acre-feet (2,440,000 $m^3$), although it is dry much of the year, except in the vicinity of the spring that issues near the site of old Fort Pearce at a rate of 0.03 cfs (0.85 L/sec) (K. Michael Hebertson, Utah Division of Water Rights, verbal communication, March 1998). A few springs mapped in the north part of the quadrangle create a small perennial flow down their drainages for short distances.

Water from the Virgin River is diverted into the St. George and Washington Canal where the river crosses the Shinarump Conglomerate Member of the Chinle Formation. The U.S. Fish and Wildlife Service requires a minimum flow in the river of the lesser of 86 cfs (2435 L/sec) or the natural flow during all months of the year to protect endangered fish species (Washington County Water Conservancy District [WCWCD], 1997). Much of the water diverted into the canal is used for irrigation, but a significant portion of the water belonging to the WCWCD is used for culinary water.

Part of the 960-acre (384-hectare) Sand Hollow Reservoir floods a portion of Sand Mountain in the northeast corner of the quadrangle. It is operated by the WCWCD as an off-line reservoir; water is pumped into the reservoir during peak runoff months and then allowed to re-enter the Quail Lake system by gravity flow during the summer months. An estimated 10,000 acre-feet (12,200,000 $m^3$) is used annually from the 28,000 acre-foot (34,150,000 $m^3$) reservoir, and each year an additional 5000 acre-feet (6,100,000 $m^3$), provided by recharge from Sand Hollow Reservoir to the Navajo Sandstone aquifer, will be recovered (WCWCD, 1997).

## Ground Water

The Virgin River controls base level in the quadrangle and the unconfined potentiometric surface slopes toward the river from both the north and the south (Cordova and others, 1972; Cordova, 1978; Clyde, 1987). Important aquifers in the quadrangle are in the Chinle, Moenave, Kayenta, and Navajo Formations, and in thin unconsolidated deposits (Cordova and others, 1972; Clyde, 1987). Of these, the Navajo aquifer (which includes the upper part of the Kayenta Formation) is the most important. Regionally, the Navajo aquifer consists of about 2000 feet (600 m) of porous, well-sorted, fine- to medium-grained sandstone, but ground water is primarily transmitted through the formation along fractures (Hurlow, 1998). Only the lower 1000 feet (300 m) of Navajo Sandstone is exposed in the northeast part of the quadrangle. Regionally, the primary recharge area for the Navajo aquifer is limited to the Navajo outcrop area (Freethey, 1993) because the overlying Temple Cap and Carmel Formations form an impervious barrier that effectively seals the Navajo from infiltration. Regionally, recharge is from precipitation on the Navajo and from streams crossing the Navajo that originate in the Pine Valley and Bull Valley Mountains to the north and northwest. Wells in the Navajo aquifer north and northwest of the quadrangle are a major source of domestic water for the St. George area (Horrocks-Carollo Engineers, 1993; Willis and Higgins, 1996; Hurlow, 1998).

In the Washington Dome quadrangle, the Navajo dips to the northeast, forming the upper part of Sand Mountain, which is isolated from important recharge areas. No streams cross the aquifer on Sand Mountain so the only recharge comes from precipitation; however, under full reservoir conditions Sand Hollow Reservoir is expected to recharge the Navajo aquifer at a rate of 6 to 15 cfs (170-340 L/sec) or 4500 to 11,000 acre-feet (5,500,000-13,400,000 $m^3$) annually. Six to ten wells downgradient from the reservoir are expected to recover 5000 acre-feet (6,100,000 $m^3$) of ground water annually, which will be fed directly into the St. George City water system (WCWCD, 1997).

Sand spring, the only spring in the Navajo aquifer in the quadrangle, issues from near the Navajo-Kayenta contact near the north edge of the quadrangle; it has an average flow of 0.015 cfs (0.4 L/sec) (K. Michael Hebertson, Utah Division of Water Rights, verbal communication, March 1998). Springs along this horizon are common on the north limb of the Virgin anticline where south-flowing water "spills" over this natural threshold (Higgins and Willis, 1995). The two largest springs in the Washington Dome quadrangle both emanate from the Dinosaur Canyon Member of the Moenave Formation near the Virgin River: Warner Springs with a flow of 0.44 cfs (12 L/sec), and an unnamed spring nearby that flows at 0.32 cfs (9.0 L/sec). Several small springs are also present in the Chinle Formation (Keith Hebertson, verbal communication, March 1998). Spring water in the quadrangle is primarily used for irrigation and stock watering.

The water quality in many springs and wells in the quadrangle is reported in Cordova and others (1972), Cordova (1978), Clyde (1987), and Freethey (1993). In general, water is fresh and of high quality in the Navajo aquifer, but older formations generally have higher total dissolved solids. Water quality in unconsolidated valley-fill aquifers varies considerably depending upon local conditions.

## GEOLOGIC HAZARDS

The Washington Dome quadrangle is in a tectonically active area with several faults that could generate large earthquakes. The quadrangle contains many steep slopes with landslide and rock-fall hazards, and flash floods and debris flows are also important geologic hazards. Other potential hazards in the quadrangle include formations that contain expansive, soluble, or collapsible materials; blowing sand; radon-producing uranium and potentially toxic levels of arsenic and mercury; and volcanism.

### Earthquakes

The Washington Dome quadrangle is within the Intermountain seismic belt and the area has experienced several historical earthquakes of magnitude 4 or greater (Christenson and Deen, 1983; Anderson and Christenson, 1989; Christenson and Nava, 1992; Hecker, 1993). Historical earthquakes have not exceeded magnitude 6.5 in southwest Utah, but geological studies indicate that faults in the region could produce earthquakes of magnitude 7 to 7.5 (Arabasz and others, 1992). The largest historical earthquake was an estimated magnitude 6.3 event in 1902 with the epicenter about 20 miles (32 km) north of the quadrangle near the Pine Valley Mountains (Arabasz and others, 1979; Christenson and Deen, 1983). The most recent large earthquake was a magnitude 5.8 event on September 2, 1992, with the epicenter located in the Washington Dome quadrangle in the NE¼NW¼ section 1, T. 43 S., R. 15 W. (Pechmann and others, 1995). Ground shaking was strongly felt in the St. George and Washington City area and caused damage as far as 95 miles (153 km) from the epicenter (Olig, 1995). Seismologic data indicate that the earthquake originated at a depth of 9 miles (15 km) and was caused by dominant normal faulting on a north-south-trending fault (Pechmann and others, 1995). Distribution of limited aftershocks implies a west-dipping slip plane, possibly a subsurface part of the Hurricane fault (Pechmann and others, 1995). Ground accelerations in the St. George and Washington City area were not measured, so an empirical relationship (Campbell, 1987) was used to estimate a peak horizontal ground acceleration of 0.21 g for the area (Black and others, 1994). Ground shaking triggered a landslide that destroyed homes and utilities in Springdale, 27 miles (44 km) east of the epicenter (Jibson and Harp, 1996), and caused liquefaction, lateral spreads, and sand blows in poorly graded sand along the Virgin River (Black and Christenson, 1993; Black, 1994; Black and others, 1994). It also caused a change in flow of Pah Tempe Hot Springs near Hurricane and triggered many rock falls, at least two of which caused property damage (Black and others, 1995). No surface fault rupture was reported (Black and Christenson, 1993). Total losses from direct damage, response costs, and lost property values in the 1992 St. George earthquake approached $1 million, but this value is likely a minimum (Carey, 1995). The Washington Dome quadrangle is in an area of moderate seismic risk (Christenson and Nava, 1992) and buildings should be constructed in accordance with the seismic provisions of the International Building Code (2003).

Three large fault zones in the area have documented Quaternary movement and a few smaller faults have possible Quaternary movement (Christenson and Deen, 1983; Anderson and Christenson, 1989; Lund and others, 2001; Black and others, 2003). The Washington fault cuts rocks along the west side of the Washington Dome quadrangle. It displaces late Pleistocene sediments 11.5 feet (3.5 m) in the NW¼ section 13, T. 43 S., R. 15 W. (Anderson and Christenson, 1989). Basalt in the northeast corner of the quadrangle, dated at about 900,000 years old (Biek, 2003a), is displaced about 20 feet (6 m) by two splays of the Washington fault. The Hurricane fault is about 3 miles (5 km) east of the quadrangle (see Biek, 2003b; Hayden, 2004a ; and references therein), and the Grand Wash, Reef Reservoir, and Gunlock faults form a zone about 15 miles (24 km) west of the quadrangle (figure 1) (Hammond, 1991; Hintze and Hammond, 1994; Hintze and others, 1994).

Future earthquakes in the area could generate groundshaking and related hazards such as surface fault rupture, slope failure, liquefaction, flooding, and tectonic subsidence (Christenson and Nava, 1992). Poorly consolidated soil, such as is present in parts of the Washington Dome quadrangle, can amplify ground motions relative to sites on bedrock, thereby increasing the potential for damage. Liquefaction and related ground failure is most likely along the Virgin River and Fort Pearce Wash flood plains and other areas of shallow ground water. Flooding may result from failure of nearby dams; diversion or destruction of canals, aqueducts, water lines, or streams; increased ground-water discharge; seiches (large waves) in lakes and reservoirs; or tectonic subsidence in areas of lakes, reservoirs, or shallow ground water. Ground shaking, liquefaction, and surface fault rupture associated with future earthquakes will likely damage structures, especially older, unreinforced masonry buildings, and may rupture underground utilities. Rock falls caused by ground shaking are of increasing concern as development encroaches on steep slopes capped by basalt flows and resistant bedrock units.

### Flooding and Debris Flows

Floods are probably the most frequent and consistently destructive natural hazard in the greater St. George area. Most of the historical record of flooding published by Wooley (1946), Butler and Marsell (1972), and the Utah Division of Comprehensive Emergency Management (1981) was summarized by Christenson and Deen (1983). Since these publications, two major and several smaller flood events have occurred in the area. In February 1995, rain and snow melt combined to produce flooding of the Ivins area west of the quadrangle, including damage to buildings in the Tuachan ampitheater. Perhaps the most remarkable flooding occurred in January 2005 along the Santa Clara River and, to a lesser degree, the Virgin River. During 3 days following an extended period of unusually high rain and snow fall, combined with warm temperatures that extended up to higher elevations, the Santa Clara River swelled from its usual flow of 5 cubic feet per second (0.14 $m^3/s$) to an estimated 7000 cubic feet per second (200 $m^3/s$) (Dean Cox, Washington County Emergency Management Agency, verbal communication, March 5, 2005). This increase in volume caused the river to migrate laterally into $Qat_2$ deposits, undermining and destroying 28 homes and infrastructure and resulting in nearly $200 million in damages (Stories of Hope Volunteer Committee, 2005). The Virgin River, which crosses the northwest part of the Washington Dome quadrangle, rose from an average of 40 cubic feet per second (1.1 $m^3/s$) to an estimated 29,000 cubic feet per second (820 $m^3/s$) (Dean Cox, Washington County Emergency Management Agency, verbal communication, March 5, 2005). Within the Washington Dome quadrangle damage was minor because the Virgin River is in a more confined channel and development is limited near the river. The flood hazard results from the complex interaction of the area's rugged topography and seasonal weather patterns (Lund, 1992). Although the conditions that cause flooding are not controllable, the relative hazard posed by flooding is generally manageable through preservation of natural flood plains and discouraging channelization and development within the 100-year flood plain. However, it is important to note that during the January 2005 event, some damage did occur outside of the unofficial 100-year flood plain. Most was a result of undercutting and collapse of riverbanks on the outside bends of the migrating river channel.

The Virgin River and Fort Pearce Wash provide drainage for large areas through the Washington Dome quadrangle, so flooding within the quadrangle is influenced by snowmelt and storms in the region. More locally, levees and dams were built on many smaller drainages to inhibit flooding of farmland; however, most of these structures are not designed to adequately provide protection for subdivisions or more extensive development.

Debris flows are poorly sorted masses of clay- to boulder-sized materials that flow in a muddy slurry. They generally develop during or after a period of unusually high precipitation as colluvium and other loose deposits become saturated with water and begin to flow. They are a concern in gullies and washes and in some areas near moderate and steep slopes in many parts of the quadrangle.

## Slope Failures

Many ridges and benches bounded by steep slopes in the quadrangle have landslide and rock-fall hazards. The stability of natural slopes is dependent on slope steepness, lithology, ground-water conditions, and attitude of bedding and jointing (Christenson and Deen, 1983). The most common causes of slope destabilization are loss of support at the base of the slope due to stream erosion or excavations for construction, increasing pore pressure by adding water, increasing the load at the top of the slope, ground shaking resulting from earthquakes, and strong vibrations caused by construction.

### Landslides

Slip surfaces of landslides within the quadrangle develop primarily in the clay-rich Petrified Forest Member of the Chinle Formation, which absorbs moisture, forming a weak, pasty substance (Harty, 1992). Most large landslides in these areas probably last moved during Pleistocene time when conditions were wetter than they are today (Christenson, 1992), but could reactivate if slope-stability conditions change.

The largest landslide, partly within the northwest corner of the quadrangle, is on a steep slope along the edge of Washington Black Ridge. The ridge is composed of the Petrified Forest Member of the Chinle Formation capped by the Washington basaltic flow. The landslide is characterized by chaotic bedding, hummocky topography, and numerous, subdued internal scarps and thus should be considered capable of renewed movement. The deposit is partially covered by talus blocks of basalt from the Washington flow. Smaller slide masses involving the upper red member of the Moenkopi Formation and the overlying Shinarump Conglomerate Member of the Chinle Formation are present on the north side of Shinob Kibe butte. To the south, in the SW¼SE¼ section 12, T. 43 S., R. 15 W., a chaotic block of Shinarump Conglomerate Member that sits unconformably on tilted beds of the Moenave Formation next to the Washington fault is mapped as a slide mass that is apparently much older than other landslides in the quadrangle.

### Rock Falls

Rock falls are common in the quadrangle, as demonstrated by abundant rock debris both on and at the base of steep slopes. Rock falls occur naturally when less resistant rock layers are eroded from beneath more resistant, fractured layers. They may also result from ground shaking caused by earthquakes. Human activities that artificially increase the natural slope of a hillside, introduce significant moisture to hilltops, or add substantial weight to the edge of hilltops also increase the potential for rock falls. Buildings at the top of steep slopes are at risk of damage by rock falls as their foundation is undermined, whereas those near the base of slopes are at risk of damage by impact.

Currently, the areas of basalt-capped Washington Black Ridge and Shinarump-capped Shinob Kibe butte and Nichols Peak have the greatest potential for damage due to rock fall because of nearby development. Rock falls from the basalt-capped ridges are particularly dangerous since the basalts are dense, jointed, and form equidimensional blocks that roll well and do not break up during descent. Major rock-fall hazards also exist on the southeast limb of the Virgin anticline and involve the upper member of the Kayenta Formation along Sand Mountain, and hills capped by the Shinarump Conglomerate that form Warner Ridge and hills in the southwest corner of the quadrangle. Massive sandstone beds of the upper member of the Kayenta Formation and of the Shinarump Conglomerate have intersecting joints, making it common for blocks of these rocks to detach and roll. Several blocks fell from these cliffs during the 1992 St. George earthquake (Black and others, 1995).

Although a rock-fall hazard exists near the base of all slopes, site-specific investigations indicate that the local degree of hazard varies significantly and is dependent upon several variables. These include the distance of the site from the base of the slope, the nature and stability of slope debris, the local protection provided by previous rock-fall blocks, and the presence of erosional gullying in the slope which may deflect falling rocks (Christenson, 1992).

## Problem Soil and Rock

Several highly publicized incidents of structural damage due to problem soil and rock in southwest Utah prompted litigation that has increased local public awareness of such potential problems (Daily Spectrum newspaper, various issues from 1990 to 1998). Washington City officials, responding to the concern, now require site evaluations and laboratory reports for new subdivisions. Hazards are of three types: expansive soil and rock, soluble soil and rock, and collapsible soil.

### Expansive Soil and Rock

Bentonitic clay, derived from altered volcanic ash in the mudstone and shale intervals of the Petrified Forest Member of the Chinle Formation and commonly known as "blue clay," which swells when moistened, is responsible for most expansive soil and rock problems in the area, along with the clays of the Whitmore Point Member of the Moenave Formation. Since the Petrified Forest Member lies stratigraphically above the ridge-forming Shinarump Conglomerate Member, valleys up-dip from the ridge are formed in these swelling clays and are usually thinly covered by sediment. In the Washington Dome quadrangle, these valley areas are quite extensive, including Warner Valley and south Washington Fields on the south side of the Virgin anticline. Bentonitic clay is also present on the north side of the anticline. In swell tests using a 60-pounds-per-square-foot (psf) (293 kg/m$^2$) surcharge load, expansion greater than 12 percent is classified as critical (Rick Chesnut, Kleinfelder, verbal communication, May 28, 1998). Clay from the Petrified Forest Member is highly variable but typically swells 15 to 20 percent and some samples have tested as high as 38 percent swell. Based on Atterburg-limits test results, the clay is classified as CH soil using the Unified Soil Classification System, or a "lean to fat clay," with a plasticity index of 15 to 30 and liquid limit of 30 to 55. Even in some tests that apply pressures of 3000 to 5000 pounds per square foot (14,640-24,400 kg/m$^2$), the clay can still swell 2 to 5 percent (Rick Chesnut, verbal communication, May 28, 1998). Thick overburden or other measures are necessary to protect a structure from this amount of swelling.

The Shnabkaib Member of the Moenkopi Formation, which is well exposed in the quadrangle just west of Warner Ridge and also at the base of Shinob Kibe butte, also has expansive clays. To a lesser degree, mudstone intervals in the Virgin Limestone Member and the three red members of the Moenkopi Formation, as well as the Whitmore Point Member of the Moenave Formation, can create problems due to expansion (Christenson and Deen, 1983). In addition, easily eroded, fine-grained soil with moderate swell potential (4 to 8 percent) is common on flat to very gentle slopes on flood plains, alluvial lowlands, and benches (Christenson and Deen, 1983).

Common signs of expansive soils are cracked foundations, heaving and cracking of floor slabs and walls, and failure of wastewater disposal systems (Mulvey, 1992). Even if engineering precautions are taken to protect buildings, expansive soils can damage sidewalks, roads, porches, garages, driveway and patio slabs, and underground utilities. Damage can occur quickly. Thompson (1992) found an average time lapse of two years and seven months from construction to repairs in similar settings in the Denver, Colorado area.

### Soluble Soil and Rock

Soluble soil and rock, deposits that contain minerals that dissolve in water, are common in the quadrangle. These include gypsiferous deposits, limestone, and pedogenic and ground-water-deposited calcium carbonate (water rock) (Christenson, 1992). The Shnabkaib Member, and to a lesser degree, the red members of the Moenkopi Formation and the lower member of the Kayenta Formation, are subject to settlement, collapse, and piping due to dissolution of gypsum (Christenson and Deen, 1983). Piping can also occur in the Petrified Forest Member of the Chinle Formation. Solubility tests run by Kleinfelder on the Shnabkaib Member show an average of 3 to 8 percent of the sample is dissolvable. As development continues around Washington Dome, weathered limestone and gypsum of the Kaibab Formation could pose a major problem. Decalcification of limestone and dissolution of gypsum may be responsible for the unusually thick gravel terraces on the north end of Washington Dome.

Pedogenic carbonates in terrace gravels and older geomorphic surfaces are common in the quadrangle and impede water percolation if undisturbed. However, construction may fracture the seal and increase weathering (Christenson, 1992). Honeycomb gypsum and solution cavities as much as 2 feet (0.6 m) wide are sometimes encountered in the area during excavation (Dave Black, Black, Miller and Associates, verbal communication, 1995).

### Collapsible Soil

Hydrocompaction, which causes subsidence, may occur in certain geologically young materials present in the quadrangle (Mulvey, 1992). Subsidence occurs in loose, dry, low-density deposits that decrease in volume or collapse when they are saturated or loaded for the first time since deposition (Costa and Baker, 1986). To measure collapse potential, a sample is weighted with 1000 psf (4880 kg/m$^2$) and then saturated with water. The percent of volume change, which averages 2 to 6 percent in the St. George-Washington City area, is then calculated (Rick Chesnut, Kleinfelder, verbal communication, May 28, 1998). Alluvial-fan deposits commonly contain collapsible soils. Other low-density deposits, such as eolian silt and sand, mainly derived from the upper member of the Kayenta Formation and the Navajo Sandstone, are commonly poorly consolidated and require compaction prior to construction.

## Blowing Sand

As development continues, blowing sand may become a concern in the area. Currently, sand dunes must be periodically removed from the Warner Valley road to keep the road passable. The development of facilities around Sand Hollow

Reservoir will require special efforts to keep unwanted sand from encroaching into areas such as the ball fields, camping areas, and the paved road to the off-highway vehicle (OHV) staging area.

## Elemental Geohazards

### Mercury and Arsenic

Several potentially toxic elements are found highly disseminated in the Harrisburg Member of the Kaibab Formation and the lower members of the Moenkopi Formation on and around Washington Dome. Mercury concentrations in some areas reach 200 ppm (Cliff Phillips, independent prospector, verbal communication, May 27, 1998). Arsenic levels in some areas commonly reach 5000 to 6000 ppm (Cliff Phillips, verbal communication, May 27, 1998), but have been known to be as high as 10,000 ppm, in the form of scorodite, an arsenic oxide mineral (Kenneth A. Krahulec, Kennecott Exploration, Inc., verbal communication, May 27, 1998). There is a potential for increased exposure to these toxic elements as development in these areas continues.

### Radon

Radon gas forms as a product of three different radioactive decay series, but is derived primarily from the decay of uranium-238 (Solomon, 1992a). Alpha particles, emitted by atoms as they decay, are the main danger. Outside the body, alpha particles pose no danger because they cannot penetrate the skin. If radon gas is inhaled, however, these particles can cause serious damage to sensitive cells, eventually causing lung cancer (Wilbraham and others, 1990). The U.S. Environmental Protection Agency estimated that 8000 to 40,000 Americans die each year from lung cancer caused by long-term radon inhalation (Schmidt and others, 1990).

In homes and offices that are built on soil and rock rich in uranium, radon can enter through porous building materials, cracks in basement floors, walls or slabs, or other openings below grade. If the home is well insulated, the gas may be trapped inside and inhaled by the occupants. Because radon gas is colorless, odorless, and causes no pain when it is inhaled, most people are never aware of its presence.

Indoor-radon levels measured in the southern St. George basin during a 1988 statewide survey conducted by the Utah Division of Radiation Control (UDRC) indicated local high radon levels (Sprinkel and Solomon, 1990). A map of potential radon hazards in Utah, modified from Sprinkel (1987), showed the St. George area as having a general elevated indoor radon concentration of 4 to 10 picocuries per liter (pCi/L) of air (Solomon, 1992a), well above the action level of 4 pCi/L specified by the U.S. Environmental Protection Agency and U.S. Department of Health and Human Services (1986). Above this level, hazard-reduction procedures are recommended. The average ambient outdoor radon level is 0.2 pCi/L (Monroe and Wicander, 1998).

The primary geologic prerequisite for elevated indoor-radon levels is uranium in the soil around building foundations. Solomon (1992b) measured uranium levels in the southern St. George basin using gamma-ray spectrometry and found that high uranium levels originate from three distinct sources. A local primary source where levels were highest (up to 6.7 parts per million [ppm]) is the tuffaceous, fine-grained rock and residual bentonitic soil of the Petrified Forest Member of the Chinle Formation. Levels were also high (up to 3.4 ppm) in granular soils of the Virgin River flood plain, which are derived in part from Miocene intrusive igneous rocks eroded from the Pine Valley Mountains to the north (Cook, 1957). Secondary uranium mobilization, suggested by high uranium/thorium ratios, has resulted in uranium enrichment in local areas of rock and soil.

Two important geologic factors inhibit the ability of radon to migrate into buildings: shallow ground water, since pore water effectively traps radon, and impermeable soil, since there must be soil pathways through which the gas can migrate. Solomon (1992b) contoured a map of the southern St. George basin showing depth to ground water using well data from Cordova and others (1972), and a map of soil permeability using data from a soil survey made by Mortensen and others (1977). He then used a combination of all three factors (uranium concentration, ground-water level, and soil permeability) to derive a map showing the relative potential for elevated indoor-radon levels in the southern St. George basin.

Solomon's (1992b) map, which includes the west part of the Washington Dome quadrangle, indicates the most extensive areas of high hazard potential are in the small hills underlain by the Petrified Forest Member of the Chinle Formation and in the alluvial deposits of the Virgin River flood plain. The factor common to areas of high hazard potential is a uranium concentration greater than 3 ppm. Permeability varies considerably in these areas, from relatively high in the flood plain to relatively low in the shale of the Petrified Forest Member, and ground water is seldom less than 10 feet (3 m) deep (Solomon, 1992b). The area of the Washington Dome quadrangle that was included in his study is of moderate radon-hazard potential.

Because of the many non-geologic factors that influence indoor-radon levels, a quantitative relationship between geologic factors and indoor-radon levels does not exist. However, the relative hazard potential can be used to prioritize indoor testing and to evaluate the need for radon-resistant new construction (Solomon, 1996).

## Volcanism

Volcanic hazards in the area are of two main types: ash and lava flows from local sources, and wind-blown ash from distant sources (Mabey, 1985; Bugden, 1992). Only hazards from local sources are discussed here. Volcanic activity in southwest Utah during mid-Cenozoic time was characterized by violent eruptions of large volumes of felsic pyroclastic material, but late Cenozoic eruptions resulted in smaller, mafic cinder cones and flood basalts. The most recent basalt flow in the area, the Santa Clara flow, is 8 miles (13 km) west of the quadrangle. Luedke and Smith (1978) suggested that this flow is less than 1,000 years old. However, Willis and Higgins (1996) believe it is 10,000 to 20,000 years old based on the amount of incision next to the flow and degree of weathering of the basalt. Such relatively young flows and geothermal activity in the region suggest that additional eruptions will occur. Future eruptions can be expected to follow a similar pattern, producing relatively small cinder cones and slow-moving flows that follow topographic lows. Flows from future eruptions would likely follow drainages into populated areas. Eruptions would likely be preceded by earthquake swarms, which could provide some advance notice of an impending eruption. Hazards from future eruptions include damage and injuries from molten lava, explosively ejected cinders and volcanic gas, blockage of transportation corridors and rivers, disruption of utilities, and fires (Mabey, 1985).

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