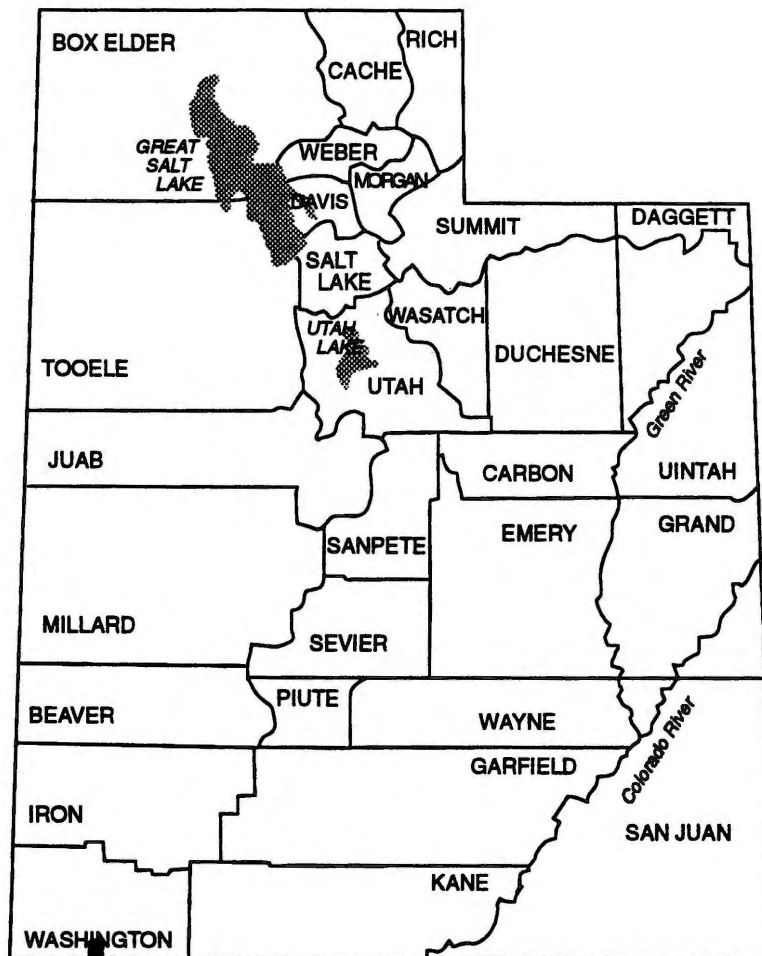


# INTERIM GEOLOGIC MAP OF THE ST. GEORGE QUADRANGLE, WASHINGTON COUNTY, UTAH

by  
*Janice M. Higgins and Grant C. Willis*



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## **ABSTRACT**

The St. George quadrangle in southwestern Utah is located in the transition zone between the Basin and Range Province to the west and the Colorado Plateau Province to the east and is famous for its scenic panoramas and recreational opportunities. It sits on an intermediate structural block bounded by down-to-the-west faults, the Grand Wash-Gunlock fault to the west, and the Hurricane fault to the east. The Bloomington dome portion of the northeast-trending Virgin anticline, a late Cretaceous and Paleocene structure, is in the center of the quadrangle. The Permian Kaibab Formation, with a thickness of 368 feet (113 m), is partially exposed in the center of the dome and is the oldest unit in the quadrangle. The Triassic Moenkopi and Chinle Formations unconformably overlie paleotopography eroded into the Kaibab Formation, and are 2,150 feet (650 m) and 800 feet (245 m) thick, respectively. A Jurassic section consisting of the Moenave Formation, 420 feet (127 m) thick, the Kayenta Formation, 1,170 feet (355 m) thick, and the basal 200 feet (61 m) of the Navajo Sandstone, is exposed on the north limb of the anticline.

Four Late Tertiary to Quaternary sequences of basalt and basaltic andesite flowed down stream drainages from quadrangles to the north. Because of continued uplift and subsequent erosion of adjacent sedimentary rocks, these flows now cap ridges, forming inverted valleys. Uplift and downcutting are also documented by alluvial-terrace deposits and other elevated alluvial surfaces that have thick pedogenic carbonate development.

Several normal faults displace the rocks in the St. George quadrangle. Only two north-trending faults have more than a few tens of feet of offset. The Washington fault offsets strata about 750 feet (229 m) where it crosses the northeast corner of the quadrangle. The St. George fault offsets strata about 450 feet (138 m) and cuts across the north-central part of the quadrangle. Both of these are considered late Cenozoic extensional faults, but neither offsets surficial deposits in the quadrangle. Most other faults in the quadrangle trend north-northwest, roughly perpendicular to the Virgin anticline. These small faults generally developed in pairs, forming grabens.

Economic resources include gravel from alluvial terrace deposits, gypsum, and stone. Water resources are increasingly important as population growth continues. Flooding; slope failures, including rock falls, landslides, and slumps; expandable, soluble, and collapsible rock and soil; earthquakes, volcanic eruptions and radon are of concern as development increases.

## CONTENTS

ABSTRACT .....	i
INTRODUCTION .....	1
DESCRIPTION OF MAP UNITS .....	3
Permian .....	4
Kaibab Formation .....	4
Fossil Mountain Member (Pkf) .....	4
Harrisburg Member (Pkh) .....	5
Triassic .....	6
Moenkopi Formation .....	7
Rock Canyon Conglomerate (TRmr) .....	8
Timpoweap Member (TRmt) .....	9
Lower red member (TRml) .....	10
Virgin Limestone Member (TRmv) .....	11
Middle red member (TRmm) .....	12
Shnabkaib Member (TRms) .....	13
Upper red member (TRmu) .....	13
Chinle Formation .....	14
Shinarump Conglomerate (TRCs) .....	15
Petrified Forest Member (TRcp) .....	16
Jurassic .....	17
Moenave Formation .....	18
Dinosaur Canyon Member (Jmd) .....	18
Whitmore Point Member (Jmw) .....	19
Springdale Sandstone Member (Jms) .....	19
Kayenta Formation .....	20
Lower member (Jkl) .....	20
Middle member (Jkm) .....	21
Upper member (Jku) .....	22
Navajo Sandstone (Jn) .....	22
Quaternary and Tertiary .....	23
Basaltic Flows .....	23
West Black Ridge flow (Tbwb) .....	25
Washington flow (Tbw) .....	25
Airport flow (Qba) .....	26
Middleton flow (Qbm) .....	27
Alluvial Deposits .....	28
Alluvial gravel beneath basalt flows (Tag, Qag) .....	28
Older stream-terrace deposits (Qato) .....	29
Stream terrace deposits (Qat <sub>3</sub> -Qat <sub>5</sub> ) .....	29
Pediment-mantle deposits (Qap) .....	31

Older alluvial deposits near Washington (Qaow) . . . . .	31
Older alluvial deposits (Qao) . . . . .	32
Stream deposits (Qal <sub>1</sub> -Qal <sub>2</sub> ) . . . . .	32
Eolian Deposits . . . . .	32
Eolian sand (Qe) . . . . .	32
Mass-Movement Deposits . . . . .	33
Slump and landslide deposits (Qms) . . . . .	33
Talus deposits (Qmt) . . . . .	33
Mixed-Environment Deposits . . . . .	34
Eolian and alluvial deposits with thick carbonate soil on basalt flows (QTeca, Qeca) . . . . .	34
Mixed older eolian and alluvial deposits (Qeao) . . . . .	34
Mixed older alluvial and eolian deposits (Qaeo) . . . . .	35
Mixed eolian and alluvial deposits (Qea) . . . . .	35
Mixed colluvial and alluvial deposits (Qca) . . . . .	35
Mixed alluvial and eolian deposits (Qae) . . . . .	36
Mixed alluvial and colluvial deposits (Qac) . . . . .	36
<b>STRUCTURE . . . . .</b>	<b>37</b>
Regional setting . . . . .	37
Folds . . . . .	38
Virgin Anticline and Bloomington Dome . . . . .	38
St. George Syncline . . . . .	39
Faults . . . . .	40
Washington Fault Zone . . . . .	40
St. George Fault . . . . .	40
Other High-Angle Faults . . . . .	41
Joints and Fractures . . . . .	41
<b>ECONOMIC GEOLOGY . . . . .</b>	<b>42</b>
Gravel, Roadfill, Riprap, and Sand . . . . .	43
Building Stone . . . . .	44
Ornamental Stone . . . . .	45
Gypsum . . . . .	46
Metals . . . . .	46
Oil and Natural Gas . . . . .	47
Geothermal Resources . . . . .	48
<b>WATER RESOURCES . . . . .</b>	<b>49</b>
Surface Water . . . . .	49
Ground Water . . . . .	50
<b>GEOLOGIC HAZARDS . . . . .</b>	<b>51</b>
Earthquakes . . . . .	52

Slope Failures . . . . .	54
Slumps and Landslides . . . . .	55
Rock Falls . . . . .	56
Problem Soil and Rock . . . . .	58
Expansive Soil and Rock . . . . .	58
Soluble Soil and Rock . . . . .	59
Collapsible and Compressible Soil . . . . .	61
Flooding and Debris Flows . . . . .	61
Radon . . . . .	62
Volcanism . . . . .	65
 SCENIC AND RECREATIONAL RESOURCES . . . . .	 66
ACKNOWLEDGEMENTS . . . . .	67
REFERENCES . . . . .	68

## INTRODUCTION

The St. George quadrangle is located in south-central Washington County in the southwest corner of Utah (figure 1). St. George, located in the northern part, is one of the fastest growing communities in the nation 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. Expansive and collapsible soils that adversely affect buildings, roads, and other structures are present and need to be mapped. Other geologic hazards include volcanoes, active earthquake faults, blowing sand, flooding, debris flows, and mass movements.

[figure 1 near here]

Maximum topographic relief is just over 800 feet (245 m) from the base of the Virgin River drainage at 2,500 feet (765 m) above sea level to the top of West Black Ridge north of Devil's Saddle at 3,317 feet (1,014 m). Several groups of hills exceeding altitudes of 3,000 feet (917 m) dot the quadrangle, including: Red Hills, Webb Hill, Price City Hills, White Hills, and the north edge of Little Black Mountain in the southeast corner. Strata that comprise these hills form two risers or steps on the "Grand Staircase" of rock (Gregory, 1950) that stretches across southern Utah and northern Arizona, the Chocolate Cliffs, capped by the Shinarump Member of the Chinle Formation, and the Vermilion Cliffs, capped by the Kayenta Formation.

The area has the lowest elevation, warmest climate, and the 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.

The U.S. Army Topographical Survey and U.S. Geological Survey regionally investigated southwestern Utah geology 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 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 that is still the most detailed map available for much of the county. Christenson and Deen (1983) mapped the surficial geology of the St. George area, focusing on engineering aspects of the geology. Eppinger and others (1990) compiled a 1:250,000-scale map of the Cedar City 1°x2°-quadrangle that includes the St. George quadrangle. Hintze and others (1994) mapped the Motoqua and Gunlock quadrangles to the northwest that cover many of the same formations exposed in the St. George quadrangle (figure 1). Billingsley (1993) mapped four quadrangles south and southwest of the quadrangle at a scale of 1:31,680. Willis and Higgins (1995) mapped the Washington quadrangle to the north at a scale of 1:24,000. Many topical studies have been done on structure, stratigraphy, volcanism, hazards, and economic and water resources of the area.

## DESCRIPTION OF MAP UNITS

The oldest rock exposed in the St. George quadrangle, the Late Permian Kaibab Formation, forms the Price City Hills in the center of the Bloomington dome, the southern-most of three domes in 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 north of the anticline.

Four basaltic flows, derived from sources north of the quadrangle, are 2.24 million to less than 1 million years old (Best and others, 1980; Hamblin and others, 1981). Erosion has removed more than 600 feet (181 m) of strata since the oldest flows solidified, leaving the resistant flows standing as high linear ridges that form classic examples of inverted topography (Hamblin, 1963, 1987). The oldest flow caps the highest black ridge. Continued uplift and erosion of the area is confirmed by three main levels of gravel terraces. Thin alluvial, colluvial, eolian, and mass movement deposits cover much of the quadrangle.

Permian and Mesozoic strata in the quadrangle were deposited in shallow marine to low-level terrestrial conditions and lithologies strongly reflect sea-level fluctuations (figure 2). 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, according to duration and extent of the cycle. Permian rocks exposed in the quadrangle were deposited

near the end of the Paleozoic megasequence and the Triassic rocks mark the beginning of the Mesozoic/Cenozoic megasequence (figure 2a). 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 five supercycles (second-order sequences) (Van Wagoner and others, 1990). However, only two of the five are documented in rocks in the quadrangle (figure 2a).

[figure 2 near here]

### **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 places (Jenson, 1984). The Kaibab Formation is late Early Permian to early Late Permian in age.

### **Kaibab Formation**

**Fossil Mountain Member (Pkf):** The Fossil Mountain Member, the oldest rock exposed in the quadrangle, is exposed in the northeast portion of Bloomington dome and in the bottom of a few deep washes along the southwest edge of the Price City

Hills. It consists of yellowish-gray, abundantly fossiliferous, cherty limestone that forms a prominent cliff. The fossils, including corals, brachiopods, crinoids, and bryozoan, are silicified. The outcrop appears black banded because of reddish-brown and black chert that forms irregularly bedded nodules. The base of the member is not exposed. Nielson (1981) measured an incomplete thickness of 68 feet (21 m) in sections 8 and 9, T. 43 S., R. 15 W., near River Road. Four feet (1.2 m) is exposed beneath the Rock Canyon Member of the Moenkopi Formation in a wash on the southwest side of the dome (in and near SE1/4 NE1/4, section 24, T. 43 S., R. 16 W.). The top contact is conformable and is drawn at the base of the first thick gypsum bed.

**Harrisburg Member (Pkh):** The Harrisburg Member is well-exposed in the Bloomington dome. It 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. Beds of cherty limestone and sandy limestone about 20 feet ( 6 m) thick form resistant cliffs in the upper part of the member. Dissolution of interbedded gypsum has locally distorted the member. It forms a slope with limestone ledges. The excellent exposure in the Bloomington dome is unusual since the member is generally poorly exposed (Billingsley, 1993).

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 (figure 3). Jenson (1984) described karst topography with more than 594 feet (180 m) of relief formed during this 20-million

year period of erosion in the Beaver Dam Mountains. The Rock Canyon Conglomerate Member of the Moenkopi Formation was locally deposited on the Fossil Mountain Member of the Kaibab Formation where the Harrisburg Member was previously removed by erosion (figure 4). Elsewhere, the Harrisburg Member is overlain by the Timpoweap Member of the Moenkopi Formation. The upper contact, which is poorly exposed, highly variable, and unconformable, is placed above the last pinkish-gray, massive gypsum and below alternating, light-yellowish-orange, gypsiferous siltstone, light-reddish-brown siltstone and very thin-bedded, medium-gray limestone. Thickness of the Harrisburg Member varies from 0 to about 300 feet (0-91 m) in the quadrangle. Nielson (1981) measured 280 feet (85 m) near the southwest end of the Price City Hills and an incomplete section of 185 feet (56 m) near the northeast end.

[figure 3 near here]

### **Triassic**

The Lower Triassic Moenkopi and Upper Triassic Chinle Formations are separated by an unconformity of about ten million years (figure 2a). These formations denote two major second-order supercycles of Vail and others (1977) separated by a smaller rise and subsequent fall of sea level during middle Triassic time (Paull and Paull, 1994).

## **Moenkopi Formation**

The Moenkopi Formation is divided into seven members with a total thickness of 2,150 feet (650 m). The lower three members, Rock Canyon Conglomerate, Timpoweap, and lower red, were measured along the west side of Bloomington dome in the NE 1/4, section 24, T. 43 S., R 16 W. while the Virgin Limestone Member was measured in the SE 1/4, section 13, T. 43 S., R. 16 W. The upper three members, middle red, Shnabkaib, and upper red were measured in a south-to-north line starting in the NE 1/4, section 18 and ending in the NE 1/4, section 7, T. 43 S., R.15 W., between the Price City Hills and Webb Hill. This formation is early to middle Triassic in age (late Scythian to early Anisian).

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. It represents a second-order supercycle that can be subdivided into three distinct third-order sequences depicting smaller transgressive-regressive cycles in an overall sea level rise (figures 2a, 2b). Paull & Paull (1994) stated that the Early Triassic global rise in sea level from the Permian lowstand was greater than 660 feet (200 m). Only the lowest of the three third-order sequences includes a lowstand systems tract that is documented within the quadrangle (represented by the Rock Canyon Conglomerate). Above the Rock Canyon Conglomerate is the transgressive systems tract of the Timpoweap Member, which Dubiel (1994) correlated to the Smithian-age transgression that flooded this area from the northwest. It is overlain by the highstand systems tract of the lower red member, correlated to Smithian-Spathian age regression of Dubiel (1994), which completes the lowest third-order sequence.

The Virgin Limestone Member and the middle red member, respectively make up the transgressive and highstand systems tracts of the middle third-order sequence, while the Shnabkaib Member and the upper red member form similar systems tracts for the top third-order sequence in the Moenkopi Formation. These two third-order sequences are correlated to the early to late Spathian transgressions and regressions of Dubiel (1994). Paleogeographic maps and time-rock stratigraphy charts in Blakey and others (1993) and Paull & Paull (1994) depict these changes.

**Rock Canyon Conglomerate (TRmr):** The Rock Canyon Conglomerate fills paleocanyons eroded into the Kaibab Formation (figures 3 and 4). The only outcrop in the quadrangle is along the southwest edge of the Price City Hills where the Harrisburg Member of the Kaibab Formation was removed by erosion and the conglomerate directly overlies the Fossil Mountain Member and abuts the Harrisburg Member. This member is composed of yellowish-gray to light-olive-gray, poorly to moderately sorted conglomerate with angular to subrounded clasts. Thick beds, some of which are lenticular and indurated, form a cliff with a rough, angular surface. The basal layers include limestone rip-up clasts and blocks eroded from the Harrisburg Member as large as 14 inches (35 cm) in diameter that have been healed with sparry calcite during several episodes. The basal layers weather into angular, brecciated clasts. Rounding in the conglomerate varies from mostly angular in the lower part to sub-angular to sub-rounded toward the top. Clasts are pebble- to cobble-sized and composed primarily of chert weathered from the Kaibab Formation. The conglomerate is clast supported. The unit grades upward into calcareous, gritty,

pebble conglomerate that is poorly sorted and includes some sandstone lenses. The upper contact is conformable where exposed along the west side of the outcrop and is gradational with dark-yellowish-orange to light-pinkish-gray, gritty siltstone beds of the Timpoweap Member. We measured a thickness of 35 feet (10 m) in the NE1/4 SE1/4 NE1/4, section 24, T. 43 S., R. 16 W. Nielson (1981) measured 38 feet (11 m) nearby.

[figure 4 near here]

**Timpoweap Member (TRmt):** The Timpoweap Member generally overlies the Harrisburg Member of the Kaibab Formation but locally overlies the Rock Canyon Conglomerate Member of the Moenkopi Formation (figure 3). In most exposures it consists of thin siltstone and limestone with very fine-grained lenticular sandstone near the base. Typically, five distinct 0.25- to 2-inch-thick (0.5-5 cm) beds of medium-gray limestone and bedded gypsum are separated by alternating bands of dark-yellowish-orange and moderate-reddish-brown gypsiferous siltstone. This alternating sequence can be traced along the north side of Bloomington dome to River Road where alluvial deposits cover the rocks. The sandstone generally fines upward. The bedded gypsum is punky and weathers to form a slope covered with cryptogamic soil. The unit does not contain limestone where it overlies the Rock Canyon Conglomerate Member. There the dark-yellowish-orange to light-pinkish-gray, calcareous and friable sandstone is thin-bedded and includes interbeds of

medium- to very coarse-grained sandstone with abundant chert granules. Exposures on the southern side of the dome are poor.

The thickness of the Timpowep Member decreases dramatically as the siltstone beds between the limestone intervals thin. Nielson (1981) measured 272 feet (83 m) in the NW1/4 NE1/4 NE1/4, section 24, T. 43 S., R. 15 W., but we only measured 110 feet (32 m) in the same area. We measured 75 feet (23 m) in the SW1/4 SW1/4 SW1/4, section 18, T. 43 S., R 15 W. The difference is probably due to local thinning and to selection of different upper contacts. We place the upper contact at the top of a dark-yellowish-orange, friable sandstone, and below the predominantly light-reddish-brown mudstone of the lower red member. Locally, very thin beds of dark-yellowish-orange siltstone, widely separated by light- to moderate-reddish-brown mudstone and siltstone, are included in the lower red member.

**Lower red member (TRml):** The lower red member consists of interbedded siltstone, mudstone, and sandstone that form a strike-valley around the edge of the Price City Hills. It is best exposed along the north and west sides of the hills. The siltstone and mudstone are moderate-reddish-brown, generally calcareous, commonly ripple marked, and exhibit small-scale cross-bedding. Dark-yellowish-orange, thin siltstone beds are interbedded and crossed by stringers and thin veinlets of gypsum. The sandstone is reddish brown, calcareous, very fine grained, and thinly bedded. The upper contact with the Virgin Limestone Member is placed at the base of the lowest thick limestone ledge. The lower red member varies in thickness from 25 feet (8 m) to 300 feet (91 m), probably due to attenuation faulting, especially in steeply

dipping beds on the north side of the Virgin anticline. The thickness variation is probably not due to stratigraphic thinning over paleohills of the Kaibab Formation, as is the case to the west in the Beaver Dam Mountains (Jenson, 1984), because the Timpoweap Member, which fills most of the paleo-topography, is prevalent throughout the quadrangle.

**Virgin Limestone Member (TRmv):** The Virgin Limestone Member is well exposed along the west and south sides of Bloomington dome where it consists of four distinct, resistant, medium-gray to yellowish-brown, marine limestone ledges interbedded with nonresistant, moderate-yellowish-brown, muddy siltstone and pale-reddish-brown sandstone. This member, together with the middle red member, is a third-order sequence that can be subdivided into four fourth-order sequences (figure 2b). Each of the four limestone layers are transgressive systems tracts that are separated from an overlying muddy siltstone highstand systems tract by a maximum flooding surface.

The four limestone beds, each about 5 feet (1.5 m) thick, can be further 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), while the upper portion is a coarser wackestone with birdseye structures, five-sided crinoid columnals, and bivalve shell fragments (highstand systems tract). The two limestone portions are divided by about an inch (2.5 cm) of dark-grayish-brown shale (maximum flooding surface).

This member is 134 feet (41 m) thick in SE1/4 SW1/4 SE1/4, section 13 ,T. 43 S., R. 15 W. The thickness varies from 225 feet (68 m) on the southwest edge of the Price City Hills to an attenuated 25 feet (7.5 m) along the north side of the nearly vertical limb of the Virgin anticline where small bedding plane faults are common. However, even with this thinning of incompetent beds, the four 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 is a slope-forming member that is generally not well exposed. The best exposures within the quadrangle are along the northwest side of Bloomington dome and next to the White Hills near the south edge of the quadrangle where the member forms low reddish-colored hills. It 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 thickness is relatively consistent throughout the quadrangle. We measured 372 feet (113 m) along the northeast side of Bloomington dome in the NW1/4 NE1/4, section 18, T. 43 S., R. 15 W. 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 exposed between the Price City Hills and Webb Hill near the center of the quadrangle and in the White Hills near the south edge of the quadrangle. It 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 and make the lower portion slightly more resistant to erosion than the upper portion. The gypsiferous upper portion 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 reddish-brown mudstone of the upper red member. This member is 996 feet (302 m) thick in the SW1/4 SE1/4 and the SW1/4 NE1/4, section 37, T. 43 S., R 15 W.

**Upper red member (TRmu):** The upper red member of the Moenkopi Formation is well exposed along both the north and south flanks of the Virgin anticline as a steep slope with at least one prominent sandstone ledge beneath the resistant ledge formed by the Shinarump Conglomerate. It consists of moderate-reddish-brown, thin-bedded siltstone and very fine-grained sandstone with some thin gypsum beds. Ripplemarks are common in the siltstone. A massive, pale-reddish-orange, very fine-grained sandstone forms a prominent ledge near the top. The upper contact is unconformable, representing approximately 10 million years of middle Triassic time, and is mapped at the base of the first coarse-grained, thick-bedded, pale-yellowish-

brown sandstone caprock. It is 363 feet (110 m) thick on the south side of Webb Hill in the SW1/4 NW14 NE1/4, section 7, T. 43 S., R. 15 W.

### **Chinle Formation**

The Chinle Formation consists of the Shinarump Conglomerate and the Petrified Forest Members in the quadrangle. The Shinarump forms a prominent cuesta in the middle and eastern parts of the quadrangle while the Petrified Forest is nonresistant and forms low hills at the base of a broad dip slope. The Chinle Formation varies in thickness mostly because of changes in the basal Shinarump Member, but it averages 800 feet (245 m). It is assigned to the late Carnian to early Norian in the Late Triassic epoch (Hintze, 1988); however, Dubiel (1994) assigned it an early Carnian to late Norian age with an unconformity of several million years separating the two members.

The formation represents the last 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 Member sourced from the ancestral Uncompahgre highlands to northeast and from a magmatic arc near the continental margin to the southeast (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) which signifies the beginning of base level rise. The Shinarump grades upward from massive conglomerate and tabular-planar stratified sandstone to medium-grained, trough cross-stratified sandstone (a highstand systems tract) formed by hinterland braided stream deposits. The Petrified Forest

Member is the highstand systems tract of a separate third-order cycle. Its fluvial systems mimicked paleoflow in the lower Shinarump system except that these stream deposits were of much higher sinuosity as evidenced by ample floodplain mudstone (Dubiel, 1994). Abundant bentonitic mudstone intervals indicate 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 (TRcs):** The Shinarump Conglomerate is very resistant and forms a dark-brown to moderate-yellowish-brown sandstone cuesta that stretches east-west across the middle of the quadrangle on the north limb of the Virgin anticline, and in the southeast quadrant on the south limb of the anticline. It is grayish-orange to moderate-yellowish-brown, medium- to coarse-grained sandstone with intermittent gravel conglomerates across most of the quadrangle, but is moderate-brown, chert pebble and gravel conglomerate in the extreme southeast corner of the quadrangle. The sandstone contains fragments of petrified wood in some areas. Locally, it has well-developed liësegang bands that give rise to the nicknames of "picture rock" or "landscape stone" (Bugden, 1993).

The Shinarump Conglomerate is 5 to 200 feet (1.5-61 m) thick in the St. George quadrangle. It is highly variable in composition and thickness because it backfills paleotopography and was deposited in braided stream channels. Measured thickness variations may also be due to unrecognized slumping. Slickensides with multi-directional lineations at the base of the sandstone indicate that it commonly

slides on the upper red member of the Moenkopi Formation and Hintze and Hammond (1994) described several masses of Shinarump that slumped or slid in the Shivwits quadrangle, west of the study area. Similar unmapped slump blocks may be on the steeply dipping north limb of the Virgin anticline, such as at Webb Hill. The upper contact is placed at the base of the first variegated, bentonitic shale of the Petrified Forest Member.

**Petrified Forest Member (TRcp):** The Petrified Forest Member of the Chinle Formation forms well-developed strike valleys that extend east-west across the quadrangle, adjacent to the more resistant cliffs of the Shinarump Conglomerate. It is well exposed only where it is protected from erosion by stream terraces. It consists of light-brownish-gray to grayish-red-purple bentonitic shale and siltstone with several lenticular interbeds of pale-yellowish-brown, cross-bedded, thick-bedded, resistant sandstone up to 10 feet (3 m) thick. Shaly beds weather to a "popcorn" surface due to swelling and shrinking of bentonitic clay. Petrified wood is common. 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. This contact is unconformable and represents about ten million years. The member is 700 feet (215 m) thick as estimated from map relationships.

## **Jurassic**

Three Early Jurassic formations of Sinemurian, Pliensbachian, and Toarcian age are present in the quadrangle. They form the youngest second-order supercycle in the St. George 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). There is no evidence of a relatively small second-order base level rise commonly placed by sequence stratigraphers in the Late Triassic to earliest Jurassic in the St. George quadrangle because Hettangian age rocks are not present (figure 2a).

The Early Jurassic rocks can be further divided into two and possibly three third-order sequences. The lowest one is comprised of 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 designated as the maximum flooding stage; the middle and upper members form the highstand systems tract. The strata above a possible unconformity in the upper member of the Kayenta Formation (perhaps at the top of an eolian tongue), 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* (Hamilton, 1984), and because of Jurassic palynomorphs found in the Moenave Formation of northern Arizona (Olsen and Galton, 1977). Dinosaur footprints from Warner Valley, just east of the study area, indicate a relatively advanced stage of dinosaur development, which also appears suggestive of an Early Jurassic age (Miller and others, 1989) although no dinosaur footprints have been found within the St. George quadrangle. This formation is divided into three members. The lower Dinosaur Canyon and Whitmore Point Members are Sinemurian in age while the upper Springdale Sandstone Member is lower Pliensbachian. The formation is 420 feet (127 m) thick in the drainage east of Middleton Black Ridge, near the center of section 28, T. 42 S., R. 15 W.

**Dinosaur Canyon Member (Jmd):** The Dinosaur Canyon Member is exposed in the northwest corner of the quadrangle where it is protected from erosion by stream terraces and in the drainages east and west of Middleton Black Ridge. Much of the section is also exposed in excavations below basalt talus along Bluff Street in St. George. It is comprised of interbedded ledge- and slope-forming, moderate-red-brown siltstone and very fine-grained, thin-bedded, pale-reddish-brown to grayish-red sandstone with laminated cross-beds. 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 purplish-gray-green claystone of the Whitmore Point Member. Measured thickness of the member east of Middleton Black Ridge, in the E1/2 SW1/4, section 28, T. 42 S., R. 15 W., is 250 feet (76 m).

**Whitmore Point Member (Jmw):** This member is exposed only in drainages next to Middleton Black Ridge, beneath a few protective stream terraces, and in excavations along Bluff Street. 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- (0.05-0.15-m-) thick beds of light-greenish-gray, dolomitic limestone contain algal structures and fossil fish scales of *Semionotus kanabensis* (Hamilton, 1984). The conformable upper contact is mapped at the base of the massive, cross-bedded Springdale Sandstone Member. In the drainage east of Middleton Black Ridge, in the NE1/4 NE1/4 SE1/4, section 28, T. 42 S., R. 15 W., this member is 55 feet (17 m) thick.

**Springdale Sandstone Member (Jms):** Because of its resistance to erosion, the Springdale Sandstone Member of the Moenave Formation forms isolated outcrops that protrude from beneath basalt talus along the slopes of the black ridges and is completely exposed east and west of Middleton Black Ridge (figure 5). It is pale-reddish-brown to grayish-yellow, fine- to medium-grained, cross-bedded, ledge-forming sandstone with interbedded light-purple-gray siltstone near the middle. 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 115 feet (35 m) thick east of Middleton Black Ridge, in the SE1/4 SE1/4 NW1/4, section 28, T. 42 S., R. 15 W.

[figure 5 near here]

## **Kayenta Formation**

The Kayenta Formation is divided into three members that display a general coarsening upward sequence. It is upper Pliensbachian to lower Toarcian in age (Early Jurassic) (Hintze, 1988). Total thickness is 1,170 feet (355 m).

**Lower member (Jkl):** A complete section of the lower member of the Kayenta Formation is exposed in drainages in the northeast part of the quadrangle, west and east of Middleton Black Ridge. Most of the section is also exposed in excavations along Bluff Street between 600 South and 200 South. Several other small outcrops protrude from under the talus along West Black Ridge and Middleton Black Ridge and where more resistant terrace deposits have protected the member from erosion.

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 ripplemarks, and moderate-purplish-red mudstone that has sericite on some bedding surfaces. The thin sandstone layers generally pinch out laterally and are typically calcareous. Their upper surface is typically bioturbated and mottled. Three thinly laminated beds of light-pinkish-gray to light-olive-gray, micritic dolomite that weather in blocky chips

about 6 inches (15 cm) in diameter are present 85 feet (26 m), 105 feet (31 m), and 110 feet (33 m) above the base 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 middle member of the Kayenta Formation. The member is 110 feet (33 m) thick just east of Middleton Black Ridge in NE1/4 NW1/4, section 28, T. 42 S., R. 15 W.

**Middle member (Jkm):** The middle member is exposed at the base of the Red Hills along the north edge of the quadrangle and in small outcrops near West Black Ridge and Middleton Black Ridge. It consists of moderate-reddish-brown siltstone, light-purplish-red mudstone, and thin ledges of sandstone. The mudstone and siltstone are generally poorly exposed but the very fine-grained, generally calcareous sandstone forms thin ledges. The sandstone is commonly mottled and varies in color from light-greenish-gray to moderate-reddish-brown. The upper surface of the sandstone ledge is commonly bioturbated.

It is difficult to measure a complete section of this member, but piecing together the top and bottom sections across Interstate 15 at Middleton Black Ridge gives a thickness of 700 feet (212 m). Just northwest of the study area in the Santa Clara and Washington quadrangles, this member is 677 feet (205 m) thick (Willis and Higgins, 1995). The upper contact is tenuous and difficult to correlate across the quadrangle. It is placed at the base of the first thick, blocky sandstone ledge of the upper member and is best exposed west of Bluff Street at about 700 North in St. George. A marker bed (mapped as dashed line m,) of orangish-red, planar, blocky

sandstone 10 to 20 feet (3-6 m) thick is about 20 feet (6 m) above the contact in the upper member.

**Upper member (Jku):** The upper member of the Kayenta Formation forms the cliff face and top of the Red Hills along the north central edge of the quadrangle (figure 6). It consists mostly of pale-reddish-brown to pale-red sandstone but includes thin interbeds of pale-reddish-brown mudstone and siltstone. The planar bedding of these mudstone and siltstone layers, along with small-scale cross-bedding of the sandstone, indicates alluvial deposition. However, there is a prominent interval of massively cross-bedded, pale-grayish-orange sandstone up to 40 feet (13 m) thick that signifies eolian deposition near the middle of the section (figure 6). The top of this eolian tongue is mapped as dashed line  $m_3$  on the map. The upper contact with the Navajo Sandstone is gradational and is drawn at the top of the highest water-lain sandstone, above which the sandstone is a massively cross-bedded, eolian deposit. Measured thickness just north of St. George in the Washington quadrangle is 382 feet (116 m) (Willis and Higgins, 1995).

[figure 6 near here]

### **Navajo Sandstone (Jn)**

The Navajo Sandstone is the youngest bedrock unit in the quadrangle. Although it is about 2,000 feet (606 m) thick in southwestern Utah, only the basal 200 feet (61 m) are preserved in the St. George quadrangle. It forms the jointed cliffs and

slopes of the upper Red Hills (figure 6). 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 accumulates on outcrops and that is locally blown into crude dune forms.

## **Quaternary and Tertiary**

### **Basaltic Flows**

Basaltic lava flows cap four prominent mesas in the quadrangle, West Black Ridge (West Black Ridge flow), "airport ridge" (airport flow), Middleton Black Ridge (Middleton flow), and Washington Black Ridge (Washington flow). The cap on Middleton Black Ridge is composed of at least three flows (Hamblin and Best, 1970); the others may also be composed of multiple flows. Most flows consist of more than 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).

Flows 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 regional 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). The oldest inverted valleys are now at the highest elevations above present drainages. Since downcutting has been the dominant geomorphic process during the late Cenozoic, the relative height above drainages

provides a way of estimating relative age of the flows, and, coupled with radiometric dating, allows determination of a downcutting rate for the area (figure 8). Hamblin and others (1981) calculated a downcutting rate of 300 feet (90 m) per million years for the St. George structural block. Hamblin (1970, 1987) mapped flows in the region as stages I to IV, based on the amount of inversion and erosion of the basalts (stage I are very young flows with little or no inversion, while stage IV are high remnants that bear no apparent relation to the present topography). All flows in the St. George quadrangle are stage II flows (figure 7). We mapped individual flows and groups of flows based on source, relative age, and composition (Willis and Higgins, 1995).

[figure 7 near here]

[figure 8 near here]

Hamblin (1963), Best and others (1966), Hamblin (1970a), Lowder (1973), Best and Brimhall (1970, 1974), Best and others (1980), Hamblin and others (1981), and Hamblin (1987) described the flows. Best and Brimhall (1974) and Best and others (1980) discussed the petrogenesis and tectonic setting of the flows. The composition of the flows varies from quartz-bearing, basaltic andesite to tephrite basanite (table 1 and figures 9 and 10).

[table 1 near here]

[figure 9 near here]

[figure 10 near here]

**West Black Ridge flow (Tbwb):** This flow caps the inverted valley that now forms West Black Ridge. It is dark-gray to dark-greenish-gray, quartz-bearing, basaltic andesite (table 1 and figures 9 and 10) (Best and Brimhall, 1974). Rocks are dark-gray to dark-brownish-gray and porphyritic with large plagioclase phenocrysts, quartz phenocrysts (some bipyramidal) with brown glassy reaction rims, and small olivine phenocrysts. The intergranular groundmass consists of plagioclase, olivine, augite, magnetite, and ilmenite (Best and Brimhall, 1974). The flow is strongly columnar jointed and weathers to form large, angular, blocky rubble. It is the oldest flow in the quadrangle and has been K-Ar dated at  $2.3 \pm 0.1$  Ma (Best and others, 1980) and at  $2.24 \pm 0.11$  Ma (Hamblin and others, 1981). It is currently about 660 feet (200 m) above the present Virgin River and varies from 20 to 80 feet (6-24 m) thick.

**Washington flow (Tbw):** Only a small part of the Washington flow is exposed in the northwest corner of the quadrangle. It can be traced northeast of the quadrangle about a mile (1.6 km) where it makes a sharp bend and continues north about a mile (1.6 km). The change in flow direction probably indicates where the flow entered the Virgin River channel. This flow is very dark-greenish-gray tephrite basanite (table 1 and figures 9 and 10), and petrographically is an ankaramite (an olivine-bearing basalt containing abundant clinopyroxene and olivine phenocrysts) (Best and Brimhall, 1974; Best and others, 1980). It has a uniform seriate texture with abundant small phenocrysts of clinopyroxene and olivine that range from about 0.1 inches (3 mm) down to the groundmass. The groundmass is plagioclase and titaniferous magnetite (Best and Brimhall, 1974). This flow was dated at  $1.7 \pm 0.1$  Ma

(Best and others, 1980). It is 360 feet (110 m) above the Virgin River about 0.5 miles (0.8 km) east of the quadrangle (near the north edge of section 24, T. 42 S., R. 15 W., in the Washington Dome quadrangle). The part within the St. George quadrangle is only about 280 feet (85 m) above the river. We attribute 20 to 30 feet (6-9 m) of this to Quaternary offset on a splay of the Washington fault, which cuts the flow, and the remaining 50 feet (15 m) to slumping and settling of the basalt on the weak, clay-rich Petrified Forest Member of the Chinle Formation. It is strongly jointed and has been quarried for building construction just outside of the quadrangle. The thickness varies from 5 to 30 feet (2-10 m).

**Airport flow (Qba):** The airport flow caps a long, narrow ridge in the northwest part of the quadrangle upon which the St. George airport has been constructed. It is dark-greenish-gray to dark-brownish-gray, phenocryst-poor basalt to trachybasalt (table 1 and figures 9 and 10) (Best and Brimhall, 1974). It has sparse phenocrysts of plagioclase and olivine in an aphanitic groundmass. As mapped it may include part of a quartz-bearing, basaltic andesite flow. It is strongly weathered along joints, giving samples a mottled "patchwork" texture. Columnar jointing is prevalent, although not as well developed as it is in the older, West Black Ridge flow. Two cooling units are well exposed along the east side of the flow near the airport. The flow is 330 feet (97 m) above larger active drainages and was K-Ar dated at  $1.07 \pm 0.04$  Ma (Hamblin and others, 1981). This age is inconsistent with calculated ages on other basalts in the area (figure 8). For example, the Middleton flow is dated at  $1.5 \pm 0.1$  Ma (Best and others, 1980) and yet is only about 200 feet (60 m) above

active drainages and the Gunlock basalt (Embree, 1970; Hintze and others, 1994) is dated at  $1.6 \pm 0.1$  Ma (Best and others, 1980) but is only 300 feet (90 m) above active drainages near Gunlock (figure 1). One or more of the ages are in error. This flow varies from 10 to 50 feet (3-15 m) thick.

**Middleton flow (Qbm):** The Middleton flow caps a two-mile (3.2 km) long, straight, narrow inverted valley in the northern part of the quadrangle where it was confined in a narrow channel and forms a broad "foot" where it entered the more open channel of the Virgin River (figure 7). The Middleton flow actually consists of three flows near the north end of the quadrangle (in a road cut on Middleton Drive near the intersection with Red Rock Road in NE1/4 NE1/4, section 20, T. 42 S., R. 15 W.) (Hamblin and Best, 1970), whereas a nearby roadcut on Interstate 15 reveals only one. In the Middleton Drive cut the oldest flow overlies alluvial gravel deposited on bedrock and is about 5 feet (1.5 m) thick (figure 11). It is overlain by another well-developed alluvial gravel, a basalt flow about 20 feet (6 m) thick, another gravel and then an upper basalt flow about 15 feet (4.5 m) thick. The older flow appears to be more mafic than the other two.

[figure 11 near here]

The main flow is composed of moderate- to dark-gray to brownish-gray, quartz-bearing, basaltic andesite (Best and Brimhall, 1974). It contains very large (up to 0.4 inch, 1 cm) phenocrysts of plagioclase, large quartz phenocrysts, and small olivine

phenocrysts. It is moderately jointed and weathers to a slightly more rounded form than other flows in the quadrangle. Table 1 and figures 9 and 10 give analyses of two samples from the Middleton flow that indicate SiO<sub>2</sub> content of 48.6 and 51.1 percent. This is considerably less than the 53.6 percent SiO<sub>2</sub> average on seven analyses reported by Best and Brimhall (1970). We consider the higher numbers to be more representative of the main flow because of the presence of quartz phenocrysts. The sample with 48.6 percent had 2.6 percent loss on ignition, suggesting possible weathering or contamination. The Middleton flow stands about 200 feet (61 m) above the river and has been dated at 1.5±0.1 Ma (Best and others, 1980). This age conflicts with the ages on the other flows as previously discussed (figure 8).

### **Alluvial Deposits**

**Alluvial gravel beneath basalt flows (Tag, Qag):** Small, isolated outcrops of stream deposited, poorly to moderately sorted, clay- to boulder-sized sediment are exposed beneath basalt flows. Most of the clasts are well-rounded cobbles and small boulders that are exotic to the quadrangle, including igneous rocks derived from the Pine Valley Mountains. In the Middleton Black Ridge basalt flows, gravel too thin to map are also exposed between two flows (Hamblin and Best, 1970). The best exposures are typically in road cuts. Thickness varies from 0 to 20 feet (0-6 m). The deposits are obviously slightly older than the basalt flows that cover them, the ages of which are discussed above.

**Older stream-terrace deposits (Qato):** Three 0- to 10-foot-thick (0-3-m) outcrops of high-level, stream-terrace deposits are preserved near the northern edge of the quadrangle. The terrace deposits are small and isolated and cannot be clearly related to the current drainage network. An outcrop on the north end of West Black Ridge stands about 450 feet (136 m) above the current drainage. It is bracketed in elevation and thus in age between the West Black Ridge and airport flows. Several nearby terraces, too small to map, were deposited at slightly lower levels as streams cut down from the level of West Black Ridge flows to that of the airport flow. A few were briefly exposed during construction of homes in the W1/2, section 24, T. 42 S., R. 16 W. during this mapping project.

An outcrop in NW1/4, section 20, T. 42 S., R. 15 W., west of Middleton Black Ridge, is about 200 feet (60 m) above current drainages at about the same elevation as the Middleton flow. It overlies the St. George fault but we were unable to determine if it had been offset by fault movement since it has been disturbed by quarrying of gravel.

The easternmost of the three outcrops is in the NE1/4 NW1/4, section 22, T. 42 S., R. 15 W., near the north edge of the quadrangle. It is not near a major drainage but its elevation above present drainages is estimated at 120 feet (36 m). The unit is at the elevation of Qat<sub>4</sub> deposits and correlates up slope with an old surface in the Washington quadrangle (Willis and Higgins, 1995).

**Stream terrace deposits (Qat<sub>3</sub>-Qat<sub>5</sub>):** Gravel- to cobble-size clasts in a muddy to coarse sand matrix form a poorly sorted, indurated conglomerate at several levels

above the present floodplains of the Santa Clara River, Virgin River, Fort Pearce Wash, and Atkinville Wash. The clasts are well-rounded and many 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 (figure 12) (Birkeland and others, 1991). The deposits correlate with paleo-channels of modern rivers and streams, unlike older stream terrace deposits (Qato). We combined the terrace gravels into three groups for mapping. Level 3 deposits are 40 to 90 feet (12-27 m); level 4 deposits are 90 to 140 feet (27-42 m); and level 5 deposits are 140 to 190 feet (42-57 m) above present channels. Thickness varies from 0 to about 40 feet (0-12 m), except in an area near Fort Pearce Wash where deposits may exceed 100 feet (30 m). Using a downcutting rate of 300 feet (90 m) per million years (Hamblin and others, 1981), level 3 deposits are 130,000 to 300,000 years old, level 4 are 300,000 to 470,000 years old, and level 5 are 470,000 to 630,000 years old. These are approximate ages because downcutting rates probably varied and because of the uncertain ages of the basalts used to determine the downcutting rate (see figure 8 and discussion of airport flow).

[figure 12 near here]

Terraces are most extensive near the Santa Clara River. The river is in a strike valley developed on the dip slope of the resistant Shinarump Conglomerate and cut into the non-resistant Petrified Forest Member. As the river cut down, it consistently shifted northeast, cutting the softer unit and leaving terrace deposits on

the southeast side of the river. In contrast, the Virgin River has meandered back and forth near its present channel, cutting away many older terraces.

Fort Pearce Wash terraces are unusually thick in the area where they overlie the gypsiferous Shnabkaib Member of the Moenkopi Formation. We hypothesize that as the fresh stream water flowed over the member, it dissolved the gypsum, causing the area to subside. Over 100 feet (30 m) of stream gravel then accumulated in the depression.

**Pediment-mantle deposits (Qap):** An indurated conglomerate of poorly sorted, subangular- to rounded-clasts, ranging in size from gravel to small boulders, caps a broad northward-inclined bench in the south part of the quadrangle. Clasts include small boulders of petrified wood presumably derived from the Petrified Forest Member of the Chinle Formation, small rounded boulders of basalt derived from older flows south of the quadrangle, and limestone. Thickness increases southward from 0 to 80 feet (0-24 m).

**Older alluvial deposits near Washington (Qaow):** A poorly to moderately well-sorted alluvial-fan deposit with clay- to small boulder-sized clasts covers part of an inclined surface in the northeast part of the quadrangle (E1/2, section 32, T. 42 S., R. 15 W.). It contains a thick pedogenic carbonate (caliche) as well as a variety of rounded basalt and sedimentary clasts. The surface is about 60 feet (18 m) above the current drainages and correlates with level 3 terrace deposits. It slopes

southward toward the Virgin River. Thickness of the alluvial deposit varies from 0 to 20 feet (0-6 m).

**Older alluvial deposits (Qao):** Remnants of older, mostly locally derived, moderately sorted clay- to boulder-sized materials are mapped in many minor drainages. Current drainages incise the deposits 10 to 30 feet (3-10 m). The deposits are 0 to 10 feet (0-3 m) thick.

**Stream deposits (Qal<sub>1</sub>-Qal<sub>2</sub>):** Moderately to well-sorted clay to small gravel deposits are mapped in large active drainages, including the Virgin and Santa Clara Rivers, Cotton Mill Creek, and Fort Pearce and Atkinville Washes. Qal<sub>1</sub> includes deposits in, and up to 20 feet (6 m) above, current channels and is 0 to 20 feet (0-6 m) thick. Qal<sub>2</sub> deposits are adjacent to and dissected by drainages containing Qal<sub>1</sub> deposits and are up to 40 feet (12 m) above active channels. They are also 0 to 20 feet (0-6 m) thick.

### **Eolian Deposits**

**Eolian sand (Qe):** Well- to very well-sorted, fine- to very fine-grained, well-rounded, mostly quartz sand has accumulated in irregular hummocky mounds on the lee side of ridges along the top of the Red Hills. Much of the sand was probably derived from weathering of the Navajo Sandstone and the upper member of the Kayenta Formation, which it now covers. Locally, it forms poorly developed dunes. Thickness varies from 0 to 50 feet (0-15 m).

## **Mass-Movement Deposits**

**Slump and landslide deposits (Qms):** Several large landslides and slumps formed on steep slopes capped by basalt flows. The slump and landslide deposits consist of very poorly sorted debris ranging in size from clay to blocks several hundred feet across, and form chaotic, hummocky mounds. Basal detachments are on the Petrified Forest Member of the Chinle Formation and the lower member of the Moenave Formation. The mass-movements involve overlying bedrock formations, talus, and basalt.

A semi-coherent mass of basalt and sandstone in and near the NE1/4, section 35, T. 42 S., R. 16 W. slumped about 330 feet (100 m). The slide movement opened joints in the basalt, forming 5- to 10-foot (1.5-3-m) blocks. Early settlers quarried the blocks of basalt, slung them under wagons, hauled them along Temple Trail to the marshy site of the St. George Mormon temple, and pounded them into the ground with the town cannon to form the footings for the temple (DeMille, 1976). The thickness of these deposits is highly variable, but is generally 30 to 40 feet (6-12 m).

Most slumps and landslides are late Pleistocene to early Holocene, but a few small slumps moved historically. Christenson (1992) reported two slumps induced by construction activity in Green Valley. Temple Trail is displaced by small slumps in a few places, indicating historical movement.

**Talus deposits (Qmt):** Talus deposits are very poorly sorted, angular boulders with minor fine-grained interstitial materials that have accumulated on and at the base of steep slopes. Most talus deposits consist of blocks of basalt that roll down slopes as

the supporting softer red beds of the Kayenta and Moenave Formations erode away. Similarly, blocks of the Shinarump Member of the Chinle Formation accumulate on the upper red member of the Moenkopi Formation and blocks from the Virgin Limestone Member rest on the lower red member. Only large deposits were mapped, but talus boulders are common on all steep slopes in the quadrangle. Thickness varies from 0 to 20 feet (0-6 m).

### **Mixed-Environment Deposits**

**Eolian and alluvial deposits with thick carbonate soil on basalt flows (QTeca, Qeca):** These deposits are eolian clay, silt, and sand and alluvial gravel with a very thick pedogenic carbonate soil deposited on the three main basalt flows. After the flows solidified, streams flowed over the top of the basalts and deposited boulder gravels. As regional downcutting continued, the streams shifted to the sides of the flows where the softer Jurassic sedimentary rock was easier to erode. Once isolated, only eolian clay, silt, and sand continued to accumulate on the flows. Over time, thick pedogenic carbonate soil developed in the deposits to Stage VI (Birkeland and others, 1991), with the highest stage on the oldest flows. The stage VI carbonates have laminar layers and platy structures with multiple generations of incipient brecciation and recementation, and pisoliths. The thickness varies from 0 to 15 feet (0-18 m).

**Mixed older eolian and alluvial deposits (Qeao):** These deposits are similar to Qea deposits in that they are both composed of well-sorted eolian sand that includes

a minor clay to gravel component; however these deposits are older and have developed a thick Stage V to VI pedogenic carbonate horizon that is resistant to erosion. This resistant cap preserved the elevated surface of the racetrack (old landing strip) area in the southeast part of the quadrangle. They are 0 to 20 feet (0-6 m) thick.

**Mixed older alluvial and eolian deposits (Qaeo):** These deposits are moderately to well-sorted, clay- to sand-sized material of alluvial origin that locally include abundant eolian sand and minor gravel. They are similar to Qae in composition but are older and have a better developed pedogenic carbonate (caliche) horizon. They are mapped on the same surface as Qaow near Washington and in St. George where they form broad, sloping benches dissected by current drainages. They are mapped in broad, nearly flat areas north of the Virgin River and are from 0 to 30 feet (0-9 m) thick.

**Mixed eolian and alluvial deposits (Qea):** These deposits are composed mostly of well-sorted eolian sand but locally include a minor alluvial clay to gravel component and contain a thick pedogenic carbonate horizon. They have been locally reworked by alluvial processes. They are preserved on surfaces that have been protected from erosion for long periods of time and are 0 to 20 feet (0-6 m) thick.

**Mixed colluvial and alluvial deposits (Qca):** Poorly sorted, angular to rounded, fine-grained to boulder-sized materials on broad low to moderate slopes are mapped

as mixed colluvial and alluvial deposits. They were deposited mainly by debris flow, slope-creep, and sheet wash processes and lack well-defined drainage patterns. However, they are locally dissected by washes. Locally, they include talus, eolian, sand and silt, or alluvial deposits that are too small to be mapped separately. They are 0 to 30 feet (0-18 m) thick. Similar deposits that have a larger alluvial component and are confined to channels were mapped as mixed alluvial and colluvial (Qac) deposits.

**Mixed alluvial and eolian deposits (Qae):** These deposits consist of moderately to well-sorted, clay- to sand-sized material of alluvial origin that locally include abundant eolian sand and minor gravel. They are deposited in large, open, nearly flat areas, are 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). The deposits are typically 0 to 30 feet (0-9 m) thick, but locally may be thicker.

**Mixed alluvial and colluvial deposits (Qac):** Poorly to moderately sorted clay- to boulder-sized material is mapped in minor drainages throughout the quadrangle. The alluvial deposits are transported along washes during heavy rainstorms while colluvial material is derived from side slopes along the washes. These deposits are gradational with colluvial deposits and include level 1 and 2 alluvial deposits (Qal<sub>1</sub>, Qal<sub>2</sub>) too small to map separately. They vary in thickness from 0 to 10 feet (0-3 m).

a minor clay to gravel component; however these deposits are older and have developed a thick Stage V to VI pedogenic carbonate horizon that is resistant to erosion. This resistant cap preserved the elevated surface of the racetrack (old landing strip) area in the southeast part of the quadrangle. They are 0 to 20 feet (0-6 m) thick.

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**Mixed colluvial and alluvial deposits (Qca):** Poorly sorted, angular to rounded, fine-grained to boulder-sized materials on broad low to moderate slopes are mapped

George syncline and the much tighter Virgin anticline, which includes the Bloomington, Washington, and Harrisburg domes.

## **Folds**

### **Virgin Anticline and Bloomington Dome**

The dominant structure in the quadrangle is the northeast-trending Virgin anticline, which affects most of the bedrock in the quadrangle. The anticline is about 30 miles (48 km) long and has three structural culminations, the Harrisburg, Washington, and Bloomington domes. Only the southernmost Bloomington dome is in the quadrangle.

The Bloomington dome is asymmetrical; beds on the north side are near-vertical while those on the south side dip at low to moderate angles (cross section B-B'). The Timpoweap, lower red, and Virgin Limestone Members of the Moenkopi Formation thin dramatically along the north side, but none of the competent beds are missing from these thinned strata. There is also evidence of local thickening in the same area. Low-angle reverse faults in incompetent beds locally ramp up into limestone ledges, repeating about half the thickness of the ledge. Closure around the dome is in the middle red member of the Moenkopi Formation, although the Shnabkaib Member probably closes around the north end beneath the valley alluvium (younger beds flank the anticline, but do not close around each dome). The Kaibab Formation is exposed in the center of the dome where beds are involved in complex secondary folding. Deformed gypsum beds in the Kaibab, which are incompetent

under stress, complicate the structure. Subsurface interpretations suggest the core of the structure is cut by a small back-thrust, opposite the regional southeast-directed thrusting (cross section B-B'). This fault has 900 feet (275 m) of displacement where the Mississippian Redwall Limestone and Devonian Muddy Creek Formations are repeated in the California Company #1 well (Munger, 1963). Another fault zone at the top of the first Redwall encountered in the well suggests the presence of another fault, interpreted by Spence Reber (unpublished data, 1994) as an antithetic fault (cross section B-B').

### **St. George Syncline**

Strata in the northern part of the quadrangle are folded into a very broad, poorly defined syncline that Cordova (1978) called the St. George syncline (it is called the Pine Valley Mountain syncline in some publications—for example Hintze, 1986). The fold is best indicated on the map by the change in strike of the cliffs of the Shinarump Conglomerate north of the Virgin anticline. The axis trends roughly northeastward through Bloomington, beneath the airport flow, and through the Red Hills, but is not shown on the map because its location is so poorly constrained. A small, low-angle reverse fault in the trough of the syncline near the corner of sections 1, 2, 11, and 12, T. 43 S., R. 16 W. places beds of the Petrified Forest Member at a high angle on top of gently dipping strata of the same member. This fault may have formed by compression in the trough of the syncline.

## **Faults**

### **Washington Fault Zone**

The Washington fault zone is a major down-to-the-west, high-angle normal fault that generally trends north in northern Arizona and southern Utah (Cook, 1960; Peterson, 1983; Billingsley, 1993). Willis and Higgins (1995) mapped the northern terminus just north of the quadrangle where it bifurcates into a series of smaller northwest- to northeast-trending faults. According to Peterson (1983), the fault reaches a maximum displacement of 2,200 feet (660 m) about six miles (10 km) south of the Utah-Arizona state line.

The Washington fault zone has about 700 feet (214 m) of offset where it cuts across the northeast corner of the St. George quadrangle, based on a tenuous projection of 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 (Willis and Higgins, 1995). A splay of the fault zone cuts the Washington flow in the northeast corner of the quadrangle and late Pleistocene sediments are offset south of the quadrangle (discussed in Anderson and Christenson, 1989; Hecker, 1993), indicating that the Washington fault should be considered an active fault with late Quaternary offset.

### **St. George Fault**

The St. George fault is a north-trending, high-angle, down-to-the-west normal fault that is poorly exposed in a rock quarry near the center of the northern border of the quadrangle where it offsets the upper Kayenta and Navajo Formations (Willis and

Higgins, 1995). Just north of the quadrangle, the St. George fault appears beneath two basalt flows that are well exposed but are not offset, indicating that latest movement was at least 1 million years ago. We found no evidence of Quaternary offset in the St. George quadrangle. This fault has about 400 feet (122 m) of offset based on projections of the  $m_1$  marker bed in the upper member of the Kayenta Formation.

### **Other High-Angle Faults**

Several sets of north-northwest-trending, high-angle normal faults with opposing offset form small grabens with a few tens of feet of displacement. Most are mapped in outcrops of the Shinarump Conglomerate, but two sets are mapped in the Kaibab Formation. A single high-angle normal fault is mapped in the Red Hills on the north edge of the quadrangle. This fault has about 10 feet (3 m) of offset and is probably down-to-the-east, though projection of beds across the fault is difficult. Cordova (1978) showed this fault with down-to-the-west offset and W.K. Hamblin (unpublished mapping) showed two faults in this location with opposing offsets, forming a small graben similar to other fault sets in the quadrangle. We found no evidence of Quaternary movement on these faults.

### **Joints and Fractures**

All competent bedrock units in the quadrangle are fractured, but the most prominent joints are in the massive sandstone beds of the upper Kayenta and Navajo Formations. Willis and Higgins (1995) recognized three main types in more extensive

exposures of Navajo in the Washington quadrangle. We recognize two of them in the St. George quadrangle. The first type are generally parallel, high-angle, open joints. Spacing is uniform over large areas, forming a very prominent pattern in the rock. The joints generally trend north but they swing slightly northeast or northwest in broad swatches. They are best exposed in the Navajo in the Red Hills, but they are also locally prominent in outcrops of the Shinarump Conglomerate. In a few areas these joints form a conjugate set with northwest- or northeast-trending joints. Joints in this category are generally not healed or recemented and in many areas they are differentially weathered, forming repeated 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 fractures are less prominent, but a few are exposed near the northern quadrangle border. These joints are widely spaced, high-angle, parallel joints that mostly trend northwest. 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. There is generally some brecciation near the fracture and in a few cases cross-beds in the sandstone are offset up to a few feet.

## **ECONOMIC GEOLOGY**

A variety of geologic resources have been used from the St. George quadrangle. Gravel, sand, road fill, and riprap are currently in high demand because of rapid growth in the area. Stone has been quarried for construction and ornamental uses, and gypsum has been mined. No metallic resources are known from the

quadrangle, but the Springdale Sandstone Member of the Moenave Formation, a known host of silver, copper, and uranium, is present (James and Newman, 1986).

### **Gravel, Roadfill, Riprap, and Sand**

Gravel, essential for construction, is the most important resource in the quadrangle. The primary deposits in the quadrangle are near the Santa Clara River, Fort Pearce Wash, and Atkinville Wash. Small deposits are present along the Virgin River. Many gravel deposits are cemented with thick pedogenic carbonate (caliche). Most active pits are in the lowest terrace deposits (Qat<sub>3</sub>), which contain less carbonate.

Several large terrace remnants (Qat<sub>3</sub>-Qat<sub>5</sub>) are present on the Chinle Formation dip-slope north of the Santa Clara River near the western edge of the quadrangle and a few large pits have been excavated in the deposits. The gravel has less silt and clay than most other deposits in the quadrangle but is higher level and is strongly cemented with pedogenic carbonate. Several deposits have been covered by recent construction and are no longer accessible.

Several terrace-gravel deposits were mapped along the Virgin River, but they are smaller than the Santa Clara terraces because the meandering Virgin River removed most older deposits.

Most active gravel pits in the quadrangle are along Fort Pearce Wash where terrace gravels exceed 100 feet (30 m) in thickness. The gravels are thick only where they overlie the Shnabkaib Member of the Moenkopi Formation. We

hypothesize that fresh water from Fort Pearce Wash dissolved gypsum in the Shnabkaib, causing local subsidence that was then filled with gravel from the wash. The gravel contains a large percentage of silt and clay compared to the river terrace gravels, but has less pedogenic carbonate cement. It requires extensive screening and washing for most uses.

Some gravel is present along Atkinville Wash in the southern part of the quadrangle. However, in that area the deposits are typically less than 10 feet (3 m) thick. They contain large percentages of fine-grained materials similar to Pearce Wash. Other minor deposits are present in Qato and Qaow deposits in the northern part of the quadrangle.

Roadfill has been acquired from the previously described gravel locations and from deposits mapped as Qc and Qca. A few other small excavations for limited uses are scattered through other parts of the quadrangle. Large boulders from basalt and Shinarump Conglomerate talus is used as riprap along the rivers and washes. Several pits have been opened adjacent to the basalt-capped ridges. However, like the gravel, many of these sources are being blocked by construction. Sand for local uses has been obtained from eolian sand deposits (Qe) near the northern edge of the quadrangle.

### **Building Stone**

Blocks of sandstone from the Kayenta Formation were quarried from near the north edge of the quadrangle in section 19, T. 42 S., R. 15 W. and from just north of

the quadrangle (Willis and Higgins, 1995) by early settlers to construct the walls of the LDS (Mormon) temple, tabernacle, and several other historic buildings. Flagstone and crushed stone for landscaping and retaining walls are quarried from the Kayenta Formation in the SW 1/4, section 17, T. 42 S., R. 15 W., where the rock has been fractured by the St. George fault. Early settlers excavated basalt from a slump block in the NE 1/4, section 35, T. 42 S., R. 16 W. for the foundation of the Mormon temple. Slumping had opened many fractures, allowing for easy removal of the blocks. Large rock-fall blocks of Shinarump Conglomerate excavated during construction of homes on hillsides are reused to build retaining walls.

### **Ornamental Stone**

Petrified wood from the Petrified Forest Member of the Chinle Formation are used to construct monuments, decorate rock gardens and fireplace mantles, and to sell as curiosities in gift shops. "Picture rock" or "landscape stone" from 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 within 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**

An inactive gypsum quarry is located in NW1/4 NW1/4, section 19, T. 43 S., R. 15 W. on the south side of the Price City Hills where gypsum was mined from the Harrisburg Member of the Kaibab Formation. The gypsum is pale gray to white with bands of clay and limestone. Thicknesses vary 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.

## **Metals**

No metal mines or mineralization are known in the St. George quadrangle. However, the Springdale Sandstone Member of the Moenave Formation, which is 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 15 miles (24 km) northeast of St. George (James and Newman, 1986; Proctor and Brimhall, 1986). In the quadrangle, the sandstone is exposed along the northeast-trending Virgin anticline, a setting similar to the Silver Reef district. At Silver Reef, however, there are two subsidiary folds to the west and the ore zone of the sandstone is repeated three times by flank thrust faults (Proctor and Brimhall, 1986). Anomalous concentrations of silver are 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). Locally, significant copper and uranium concentrations are also present in the Springdale Sandstone at Silver Reef (James and Newman, 1986).

### **Oil and Natural Gas**

There has been no production of oil or gas in the St. George quadrangle. The nearest production was from the Virgin oil field, which was first developed in 1907. It is 20 miles (32 km) northeast of St. George, adjacent to Zion National Park. Production through 1963 was 195,000 barrels (31,000 m<sup>3</sup>) of oil from 30 wells, although over 200 wells were drilled (Eppinger and others, 1990). Oil was derived from a sandstone and vuggy limestone interval 1 to 8 feet (0.3-2.4 m) thick in the uppermost part of the Timpoweap Member of the Triassic Moenkopi Formation, with minor production from the Pennsylvanian Calville Limestone. The brown to black oil from the Virgin field ranges from 22° to 32° API, and has a mixed paraffin-asphalt base (Heylmun, 1993). The field lies in a small synclinal pocket near the axis of a broad, low-relief anticline that plunges gently northward. After erosion caused the reservoir pressure to dissipate, the oil drained into small synclinal pockets on the nose. The accumulations were also controlled by local porosity and fracturing (Heylmun, 1993). Similar structures exist around Bloomington dome. The productive stratigraphic interval in the Virgin field, the Timpoweap Member, flanks the Bloomington dome in the St. George quadrangle, but no shows of oil or asphaltic material have been found (Eppinger and others, 1990). Of nine or ten wells drilled on

Bloomington dome, only three penetrated more than 1,000 feet (300 m) (table 2). The deepest well, California Oil Co. #1, was drilled in 1951 in the NW1/4 NW1/4 NE1/4, section 19, T. 43 S., R. 15 W. It penetrated 6,347 feet (1,923 m) of strata and ended 95 feet (29 m) below the top of the Devonian Muddy Peak Dolomite, after repeating the Mississippian Redwall Limestone (Munger, 1963). Drill stem tests recovered only mud and fresh water, and no oil shows were noted. Another oil or gas possibility in or near the quadrangle involves the Kaibab Formation. During the Late Permian sea-level lowstand, canyons were eroded into the Kaibab Formation and a shelf-margin wedge was deposited basinward. These coarse sediments would be sealed by shales of the lowstand systems tract, creating a possible stratigraphic trap.

[table 2 near here]

### **Geothermal Resources**

The quadrangle is in an area with geothermal potential (Mabey and Budding, 1985; Budding and Sommer, 1986). Quaternary basalt vents in the area, some as young as about 10,000 years old, also indicate that the area has geothermal potential. However, basalts are believed to ascend through relatively small pipes from depths of several miles. No hot springs are known in the quadrangle, but hot springs are present within 30 miles (48 km) (Budding and Sommer, 1986). A well drilled near the cinder cone in Big Sand flats was reported to have encountered

steam at about 900 feet (Pete Tolman, personal communication, 1995), but no actual testing has been reported.

## **WATER RESOURCES**

Water is of great importance in the St. George area since the population is rapidly increasing and much of the valley 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 begun in July 1995 by the Utah Geological Survey, the Utah Division of Water Resources, and the U.S. Geological Survey Water Resources Division will study major aquifers in greater detail. Only a brief overview is given here.

### **Surface Water**

Cordova and others (1972) and Sandberg and Sultz (1985) summarized flow data on the three main perennial streams in the quadrangle and reported on surface-water quality in the upper Virgin River basin. The Virgin River, with an average local annual flow of 145,600 acre-feet (179 hectares<sup>3</sup>), flows diagonally across the quadrangle. The Santa Clara River enters the quadrangle near the northwest border and flows into the Virgin River near the center of the quadrangle. It has an average annual flow of 14,600 acre-feet (18 hectares<sup>3</sup>) as measured just west of the quadrangle. Fort Pearce Wash, with an estimated average annual flow of 2,000 acre-

feet (2.5 hectares<sup>3</sup>), enters the quadrangle near the southeast corner and also flows into the Virgin River. A few creeks in the northern part of the quadrangle have small perennial spring-fed flows.

## **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 Moenkopi, 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, it consists of about 2,000 feet (610 m) of porous, well-sorted, fine- to medium-grained sandstone, but only the lower few hundred feet extend into the northern part of the quadrangle. The primary recharge area for the Navajo aquifer is limited to the Navajo outcrop area (Freethey, 1993) since the overlying Temple Cap and Carmel Formations form an impervious barrier that seals the Navajo from surface waters. 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 area (Horrocks-Carollo Engineers, 1993; Willis and Higgins, 1995).

Several small springs issue near the contact between the middle and upper members of the Kayenta Formation in the northern part of the quadrangle. This gradational contact separates underlying, low-porosity, muddy siltstone and sandstone from overlying, porous sandstone and forms the base of the Navajo aquifer. The springs issue where south-flowing water "spills" over this natural threshold. The spring water is primarily used for irrigation. Many small springs are also present in sandy intervals in the lower and middle members of the Kayenta Formation and in the Dinosaur Canyon Member of the Moenave Formation.

The water quality in many springs and wells in the quadrangle is reported in Cordova and others (1972), Cordova (1978), Clyde (1987), and Freethy (1993). In general, water is fresh and of high quality in the Navajo and Kayenta aquifers, and generally has higher total dissolved solids ranging up to salty in older formations. Quality in unconsolidated sediment aquifers varies considerably depending upon local conditions.

## **GEOLOGIC HAZARDS**

The quadrangle is in a tectonically active area with several faults that could generate large earthquakes. The quadrangle also has many steep slopes with landslide and rock fall hazards, and it has formations that contain expansive, soluble, or compactible materials and radon-producing uranium. Flash floods and debris flows are also concerns. The St. George Community Development Department created a general plan that addresses many of these hazards and geologic hazard maps

covering particular areas of the city are available to the public through the city engineer's office.

### **Earthquakes**

The St. George quadrangle is within the Intermountain Seismic Belt and the area has experienced several historic 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 southwestern Utah, however 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 St. George near the Pine Valley Mountains (Arabasz and others, 1979; Christenson and Deen, 1983). The most recent large earthquake was a 5.8 magnitude event on September 2, 1992 with the epicenter about 5 miles (8 km) east of St. George (Black and Christenson, 1993). Ground shaking was strongly felt in St. George and caused damage as far as 95 miles (153 km) from the epicenter. Preliminary seismologic data indicate that the earthquake originated at a depth of 9 miles (15 km) and was caused by dominantly normal faulting on a north-south trending fault, possibly a subsurface part of the Hurricane fault (Arabasz and others, 1992). Ground acceleration could not be measured, so an empirical relationship was used to estimate peak horizontal ground acceleration (PHA) of 0.21 g for St. George (Black and others, 1992). Ground shaking probably triggered landslides that destroyed homes and utilities in Springdale and caused

liquefaction in poorly graded sand along the Virgin River (Black and Christenson, 1993). It also caused a change in flow of Pah Tempe Hot Springs near Hurricane (figure 1) and triggered many rock falls, at least two of which caused property damage. No surface rupture was reported (Black and Christenson, 1993). The quadrangle is in the Uniform Building Code seismic zone 2B, an area of moderate earthquake risk with expected PHA of 0.1 to 0.2 g (International Conference of Building Officials, 1991; Christenson and Nava, 1992).

Three large faults 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; Hecker, 1993). The Washington fault crosses through the northeastern part of the quadrangle (figure 1). The Hurricane fault is about 10 miles (16 km) east of the quadrangle and the Grand Wash, Reef Reservoir, and Gunlock faults form a zone about 10 miles (16 km) west of the quadrangle (figure 1) (Hammond, 1991; Hintze and Hammond, 1994; Hintze and others, 1994).

The Washington fault offsets 10,000- to 25,000-year-old Quaternary sediments up to 3 feet (1 m) south of the quadrangle (Earth Science Associates reported in Christenson and Deen, 1983; and Hecker, 1993). Basalt in the northeast corner of the quadrangle, dated at 1.7 Ma (Best and others, 1980), is offset about 20 feet (6 m) by a branch of the Washington fault. However, the basalt is deposited on the landslide-prone Petrified Forest Member of the Chinle Formation and some of the offset may be attributed to sliding or slumping.

Earthquakes generate ground shaking and related hazards such as surface rupture, slope failure, liquefaction, flooding, and tectonic subsidence (Christenson and Nava, 1992). Poorly consolidated soil, such as is present in parts of the St. George quadrangle, amplifies waves that cause ground shaking, increasing damage.

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. Movement on a fault sufficient to cause surface rupture would likely damage many 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 flanking basalt flows and resistant bedrock units.

### **Slope Failures**

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

1992, St. George City enacted a hillside ordinance in an effort to reduce hazards near steep slopes and to protect the hillsides.

### **Slumps and Landslides**

Basal detachments of slumps and 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). Landslides are common where the Petrified Forest Member forms bluffs held up by gravel-terrace deposits along the Virgin and Santa Clara Rivers and on unstable slopes at the southern ends of the black ridges. Most landslides in these areas last moved during Pleistocene time when conditions were wetter than they are today (Christenson, 1992). Although these slopes are apparently stable, they may reactivate if material is removed from the base, or if additional water or fill is added by construction on top of the slide mass.

A large slump on the west side of West Black Ridge involves the West Black Ridge basalt flows, the lower member of the Kayenta Formation, and the Moenave Formation. The mass has rotated along a detachment plane in the Petrified Forest Member and slumped about 330 feet (100 m) so that the West Black Ridge basalt flows at the top of the block are almost equal in elevation with the Airport basalt flows.

We are aware of three landslides or slumps in the quadrangle with historic movement. One slump displaces the Temple Trail, constructed to quarry the West Black Ridge basalts at the top of the rotational block described above (SE 1/4, SW

1/4, section 25, T 42 S., R. 16 W). Christenson (1992) reported two recent landslides in the Petrified Forest Member within the quadrangle, both of which have been mitigated. One occurred in a road cut near Green Valley and the other is in SW 1/4 SW 1/4, section 26, T. 42 S., R. 16 W. Both were the result of human activity.

Developments on landslides suffered extensive damage in the St. George area as a result of the 1992 magnitude 5.8 earthquake. Damage included shifting of numerous retaining walls, foundation cracks, separated interior walls, and cracks in sheet rock (Summer Roe, resident, personal communication, July, 1992).

### **Rock Falls**

Significant rock falls are common in the quadrangle, as evidenced by abundant rock debris both on and at the base of steep slopes. Rocks fall naturally when less resistant rock layers are eroded from beneath more resistant, fractured caprock. 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 constructed at the base or top of steep slopes are in danger of damage by rock falls (figure 13).

[figure 13 near here]

Major rock-fall hazards involve basalt-capped ridges, the upper member of the Kayenta Formation along the Red Hills, and hills capped with the Shinarump

**Conglomerate Member of the Chinle Formation in the central part of the quadrangle. The Virgin Limestone Member of the Moenkopi is also a candidate for rock falls, but presently there is only minor development at the base of these slopes. However, there is a proposal to build a new airport in that area (American Public Works Association, 1995).**

**Rock falls from the basalt-capped ridges are particularly dangerous since the basalts are dense, jointed, and form equidimensional blocks that roll well and don't break up during descent. The area immediately west of West Black Ridge is in the process of being subdivided and new excavations are being cut into the hillside on the east side of West Black Ridge along Bluff Street. Christenson (1992) discussed a basalt boulder that narrowly missed an office building on Bluff Street as it rolled down the hill in 1984 and emphasized that cutting back into the base of the slope increased the vulnerability of the building. Extensive development is also in progress near Middleton Black Ridge and the Washington basalt flow.**

**Massive sandstone beds of the upper member of the Kayenta Formation that form the Red Hills along the north edge of the quadrangle and of the Shinarump Conglomerate are jointed in two directions making it easier for blocks of this rock to detach and roll (figure 13). Several blocks fell from these cliffs during the 1992 earthquake, damaging retaining walls and other developments.**

**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 prompted litigation that has increased local public awareness of potential problem (Daily Spectrum newspaper, various issues from 1990 to 1995). 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 or compressible soil.

### **Expansive Soil and Rock**

Bentonitic clay from volcanic ash in the mudstone and shale intervals of the Petrified Forest Member of the Chinle Formation (commonly known as "blue clay"), which swells when moistened, is responsible for most of the expansive soil and rock problems. In swell tests using a 60-pounds-per-square-foot (psf) (293 kg/m<sup>3</sup>) surcharge load, expansion greater than 12 percent is classified as critical. Clay from the Petrified Forest Member is highly variable but typically swells 20 percent and some samples have tested as high as 38 percent (Joel Myers, Kleinfelder, personal communication, 1995). It is classified as cH soil, or "fat clay" using an Atterburg limit with a plastic index of 7 to 30 and liquid limit of 15 to 40 (Roy J. Rushing, Delta

Geotech, personal communication, 1995). Thick overburden or other measures are necessary to protect a structure from this amount of swelling.

The Shnabkaib Member, and, to a lesser degree, mudstone intervals in the Virgin Limestone Member and the three red members of the Moenkopi Formation, and the Whitmore Point Member of the Moenave Formation (Christenson and Deen, 1983) also have expansive clays. In addition, easily eroded, fine-grained soil with moderate swell potential (4 to 8%) 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 the building, expansive soils can damage neglected 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 when exposed to water, are common in the quadrangle. These include gypsiferous deposits, weathered limestone, and pedogenic and ground-water calcium carbonate. 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, piping, and local heaving problems due to dissolution of gypsum

(Christenson and Deen, 1983). Sinkholes probably caused by piping are present east and west of West Black Ridge. In some cases, dissolution has created beneficial results. We attribute unusually thick gravel-terrace deposits near Pearce Wash to infilling of depressions caused by dissolution of gypsum in the Shnabkaib Member. These gravel deposits are a primary source of gravel for construction in the St. George area. However, there are dissolution caverns up to several feet across under the gravel. In one instance a bulldozer broke through the roof of a cavern and was suspended by its front blade and back ripper bar (the company filled the cavern beneath the bulldozer and was able to drive the machine off, J and J Construction Company, personal communication, 1995). Honeycomb gypsum and solution cavities as much as two feet (0.6 m) wide were reported during recent excavation for a swimming pool in central St. George (Dave Black, Black, Miller and Associates, personal communication, 1995). As development surrounds the Price City Hills, weathering limestone and gypsum of the Kaibab Formation could pose a problem.

Pedogenic carbonates developed in terrace gravel and older geomorphic surfaces impede water percolation if undisturbed. However, construction damage may fracture the seal and increase weathering (Christenson, 1992). Another common foundation problem is "water rock", strongly cemented gypsum and calcium carbonate layers in unconsolidated deposits in the shallow subsurface. These layers generally mark the top of the water table and locally form a confining layer. Blasting during construction may result in artesian flow that requires a drainage system (Christenson, 1992). This problem has been encountered in a construction area east of Middleton Black Ridge (Black, Miller and Associates, personal communication, 1995).

## **Collapsible and Compressible Soil**

The problem of hydrocompaction occurs in geologically young material (Mulvey, 1992). Subsidence occurs in loose, dry, low-density deposits that decrease in volume or collapse when they are saturated or loaded. To measure collapsibility, a sample is weighted with 1,000 pounds per square foot and then saturated with water. The percent of volume change is then calculated. Debris flows deposited at the mouth of drainages during flash floods commonly contain collapsible soils. Other low-density deposits, such as eolian silt and sand, mainly derived from the middle and upper members of the Kayenta Formation and the Navajo Sandstone, are commonly poorly consolidated and require compaction prior to construction.

## **Flooding and Debris Flows**

Floods are probably the most frequent and consistently destructive natural hazard in the St. George area. Most of the historical record of flooding published by Utah Division of Comprehensive Emergency Management (1981) has been summarized by Christenson and Deen (1983). The high 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 they pose is generally manageable with wise planning. The recently developed St. George City General Plan (1994) calls for development that encourages preservation of natural flood plains and discourages man-made channelization and development within the 100-year flood plain.

The most extensive flood of the 1995 spring flood season, which occurred on March 13, involved most drainages in the area and resulted from an extensive rainstorm coupled with high meltwater runoff. Damage was most extensive along the Virgin and Santa Clara Rivers. The Santa Clara River eroded 120 feet (36 m) into adjacent property, and broke through a rip-rap wall protecting townhomes only 10 feet (3 m) from the river's edge (figure 14). The preliminary damage assessment by the Utah Division of Comprehensive Emergency Management (May 20, 1995) for St. George was \$1,184,000. The cost of damage to private property was not included.

[figure 14 near here]

Debris flows are masses of clay- to boulder-sized materials that flow in a muddy slurry. They generally develop 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.

### **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 8,000 to 40,000 Americans die each year from lung cancer caused by long-term radon inhalation (Schmidt and others, 1990).

Radon can enter homes that are built on soil and rock rich in uranium 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 in their homes.

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), shows the St. George area as having a general elevated indoor radon concentration of 4 to 10 pico curies per liter (pCi/L) of air (Solomon, 1992a), well above the maximum of 4 pCi/L advised 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 level of radon is 0.2 pCi/L (Monroe and Wicander, 1992).

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 groundwater level, 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.

His map indicated the most extensive areas of high hazard potential occur 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, with small areas of high hazard potential scattered throughout the southern portion of the study area. It is interesting to note that the factor common to areas of high hazard potential is a uranium level 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, but ground water is nowhere less than 10 feet (3 m) deep (Solomon, 1992b).

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, to indicate the urgency with which homeowners should reduce the potential hazard in existing buildings, and to evaluate the need for radon-resistant new construction (Solomon, 1992b).

## **Volcanism**

Volcanic hazards in the St. George area are of two main types, ash and lava flows from local sources, and wind-blown ash and dust 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 violent felsic-eruptions of large volumes of pyroclastic material but late Cenozoic eruptions resulted in smaller, less violent mafic cinder cones and flood basalts. The toe of the most recent basalt flow in the St. George area, the Santa Clara flow, is just west of the quadrangle. Luedke and Smith (1978) indicated this flow is less than 1,000 years old. However, we believe it is 10,000 to 20,000 years old based on amount of downcutting next to the flow and amount of weathering of the basalt. It is likely that flows from future eruptions would follow drainages into populated areas. Hazards from future eruptions include damage and injuries by molten lava, explosively ejected cinders and

volcanic gas, blockage of transportation corridors and rivers, disruption of utilities, and fires (Mabey, 1985).

## **SCENIC AND RECREATIONAL RESOURCES**

The St. George quadrangle is in the "red rock" country of southwestern Utah and is surrounded by buttes and mesas of red sandstone. Many are capped by black basalt, creating a striking visual contrast. The quadrangle is also near the lowest elevation in the state and has the warmest climate. The combination of the striking scenery and warm climate make the area a popular recreation and retirement destination. It is near several popular recreation sites, including Snow Canyon State Park and Zion National Park.

Several roads along the mesas within the quadrangle and along Red Cliffs, north of St. George are popular for their vistas of the valley and of the towering cliffs of Zion National Park. Red Hills City Park, on the Red Cliffs, is built around large rounded boulders of Kayenta Sandstone. Their exotic weathering patterns, complete with narrow joint systems or "chimney cracks" make them popular for exploring and rock climbing. Other popular sites include Temple Trail, a near-level 0.75-mile (1.2 km) trail west of the airport that follows a haul-road constructed by pioneers to a basalt quarry, and bicycle trails between Green Valley and Bloomington and along the Virgin and Santa Clara Rivers. Several short but strenuous climbs up basalt talus on

the west side of West Black Ridge lead to a close-up view of Anasazi petroglyphs etched in basalt.

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## Captions

Figure 1. Geographic and geologic features and 7 1/2' quadrangles near the St. George quadrangle. Basaltic flows are shaded.

Figure 2a. Deposition of strata in the quadrangle was strongly influenced by world wide sea-level fluctuations and rocks correlate well with the global sequence stratigraphic framework. Of the four recognized first-order megadepositional sequences (Archeozoic, Proterozoic, Paleozoic, and Triassic - Cenozoic), the strata cover the end of the Paleozoic and the beginning of the Triassic - Cenozoic megasequences. Vail and others (1977) showed seven second-order supercycles during the interval represented by strata exposed in the quadrangle (only part of the first and last are represented). The St. George area underwent erosion and/or sediment bypass during three of the second-order sequences, so sea-level fluctuations during the late Permian, Middle Triassic, and earliest Jurassic (shown by the sea level curve) are not documented by rock in the quadrangle. The four documented second-order cycles are divided into nine third-order cycles that reflect smaller relative changes in sea level. Systems tracts are listed for the third-order cycles. Figure 2b shows fourth- and fifth-order sequences of part of the Moenkopi Formation. Modified from Vail and others (1977), Hintze (1988), and Dubiel (1994). Time scale from Palmer (1983). Vertical scale is based on time of deposition, not on thickness.

Figure 2b. (A) The second-order sequence of the Moenkopi Formation is divided into three third-order sequences indicating three smaller transgressive-regressive sequences. (B) Similarly, the third-order sequence of the Virgin Limestone and middle red member is divided into four fourth-order sequences with transgressive system tracts (TST) of the limestone ledges separated from the muddy siltstone interbeds of the highstand systems tract (HST) by a maximum flooding surface (MFS). (C) Each limestone ledge is itself a fifth-order parasequence. The lower portion of each ledge is finer, more muddy, and non-fossiliferous, signifying a transgressive systems tract (TST), while the upper portion is a coarser wackestone with birdseye structures and fossils, signifying a highstand systems tract (HST). The two portions are divided by about 1 inch (2.5 cm) of dark-grayish-brown shale, indicative of a maximum flooding surface. Modified from Vail and others (1977), Hintze (1988), Dubiel (1994), and additional work in this project.

Figure 3. Schematic cross section across the southwest end of Bloomington dome showing depositional setting of the Rock Canyon Conglomerate and the Timpoweap Members of the Moenkopi Formation. The Rock Canyon was deposited in a paleo-canyon up to 300 feet (90 m) deep eroded through the Harrisburg Member of the Kaibab Formation and into the top of the Fossil Mountain Member. Kaibab Formation: Pkf-Fossil Mountain Member, Pkh-Harrisburg Member; Moenkopi Formation: TRmr-Rock Canyon Conglomerate, TRmt-Timpoweap Member, TRml-lower red member, TRmv-Virgin Limestone, TRmm-middle red member.

**Figure 4.** The Rock Canyon Conglomerate (massive cliff) sits unconformably on the Fossil Mountain Member of the Kaibab Formation (thin, smooth bed in lower part of photograph). The Harrisburg Member, which is completely cut out by the unconformity at this location, is 300 feet (91 m) thick directly behind the photographer. Outcrop is in the NW 1/4, section 19, T. 43 S., R. 15 W.

**Figure 5.** The Springdale Sandstone typically forms a resistant, rounded ledge and is an important marker bed throughout the St. George basin. This outcrop is on the east side of Middleton Black Ridge.

**Figure 6.** View northward toward Red Cliffs in northern part of quadrangle. The water tank is on the contact between the middle and upper members of the Kayenta Formation. The lowest planar ridge is the  $m_1$  marker bed and the light-colored, rounded, knobby ledge is the  $m_3$  marker bed. The Navajo Sandstone is exposed in the middle distance beneath several basalt-capped ridges. The Pine Valley Mountains are in the far distance.

**Figure 7.** The Middleton basaltic andesite flow caps Middleton Black Ridge, forming an inverted valley. It flowed directly south along a fracture-controlled canyon and spread out into a "foot" where it entered the Virgin River. The river and its tributaries have cut down about 200 feet (60 m) since the flow was emplaced.

**Figure 8.** Plotting ages of basalt flows (points A-G) versus relative height in feet above major rivers and streams allows calculation of a downcutting history for the St. George basin. The rates were calculated using radiometric ages of several basalt flows reported in Best and others (1980) (B, C, D, E, and F) and Hamblin and others (1981) (A and G), combined with the amount of inversion of drainages near the flows. The solid lines represent two alternative (and conflicting) down-cutting histories. Hamblin and others (1981) used points A and G to estimate an average downcutting rate of 300 feet (90 m) per million years. A conflicting downcutting history is indicated by points A, B, C, D, E, and F. The dashed line indicates a consistent rate using only points A and B. Additional data is needed to evaluate the accuracy of either downcutting history. Points: A and B-West Black Ridge flow, C-Washington flow, D-Gunlock flow, E-Middleton flow, F-Cedar Bench flow (sits directly on Middleton flow north of quadrangle; Willis and Higgins, 1995), G-airport flow. See original references for sample locations and analytical data.

**Figure 9.** Geochemical classification of basaltic rocks in the St. George and Washington quadrangles. The West Black Ridge (Tbwb), Washington (Tbw), Airport (Qba), and Middleton (Qbm) flows are present in the St. George quadrangle. The Washington flow data (\*) is an average of five analyses on ankaramite flows reported in Best and Brimhall (1974). See table 1 for other sources of data. Classification system from Le Bas and others (1986).

Figure 10. Ratios of major oxides of basaltic rocks in the St. George and Washington quadrangles. See figure 9 for key to symbols. The West Black Ridge (Tbwb), Washington (Tbw), Airport (Qba), and Middleton (Qbm) flows are present in the St. George quadrangle. The Washington flow data (\*) is an average of five analyses on ankaramite flows reported in Best and Brimhall (1974). See table 1 for other sources of data.

Figure 11. Road cut through the Middleton flow in NE1/4 NE1/4, section 20, T. 42 S., R. 15 W. reveals two basalt flows sandwiched between alluvial gravel. The lower flow is just above the road. A third flow (not seen here) overlies a gravel deposited on the second flow (Hamblin and Best, 1970).

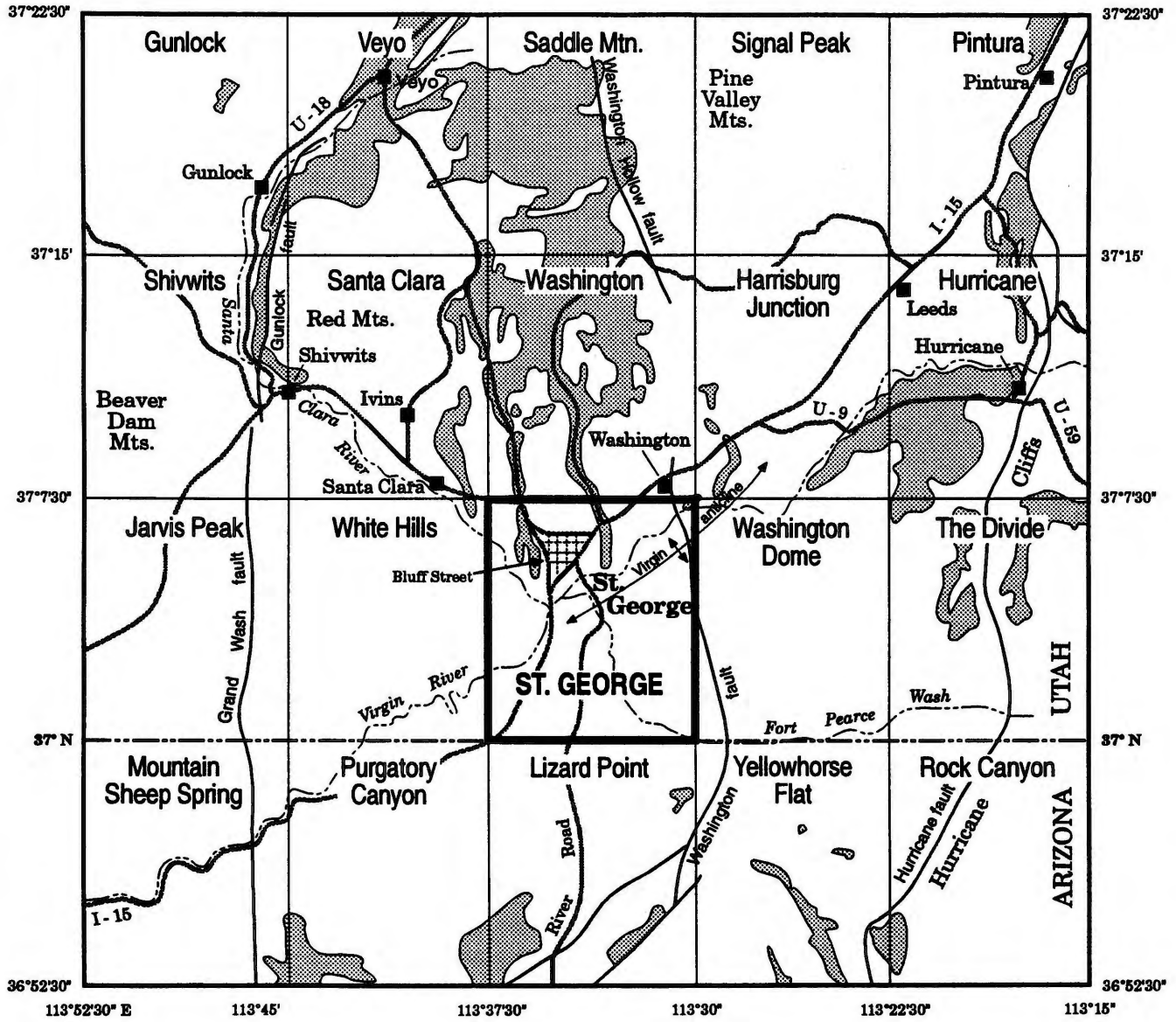
Figure 12. Gravel-terrace deposit near Green Valley with thick pedogenic carbonate cement. Carbonate is thickest in the highest terraces.

Figure 13. Rock falls are an increasing threat as development encroaches on steep hill sides. This outcrop of Shinarump Conglomerate in the Bloomington Hills is the source of many huge boulders.

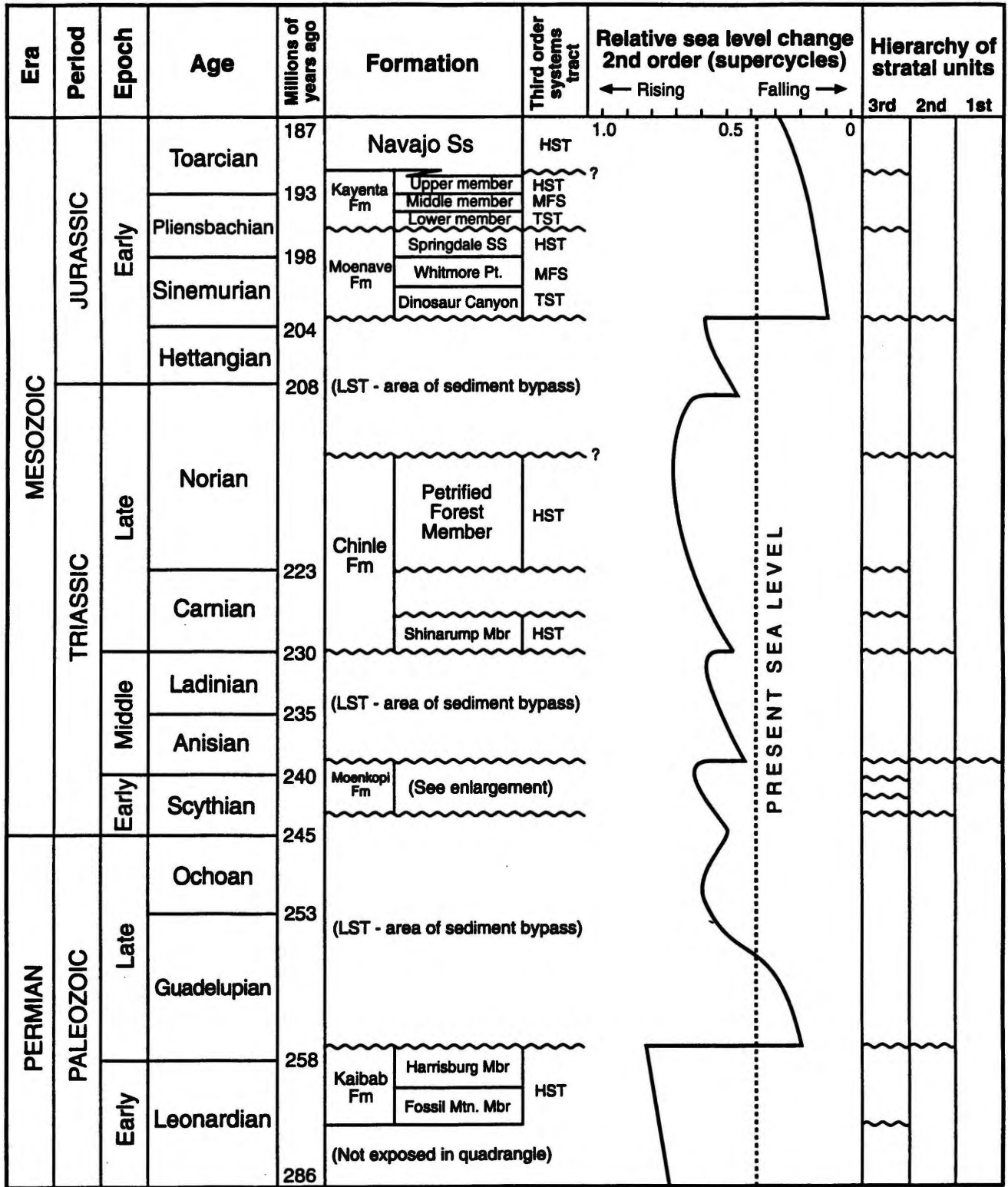
Figure 14. Flooding is of increasing concern as development expands onto river floodplains. On March 13, 1995 the Santa Clara River abandoned a meander bend and cut through a riprap wall, threatening this subdivision. Photograph courtesy of Rosenberg Associates.

**Table 1. Chemical analyses and normative calculations of basaltic rocks in and near the St. George quadrangle.  $\text{Fe}_2\text{O}_3$  data in all samples is recalculated as total iron. Sample ANK-av is the average of five analyses of ankaramite flows in the St. George area reported in Best and others (1974). Samples with WA and SG prefix were collected by authors for this study. Samples with SC prefix were collected by Miriam Bugden and Douglas Sprinkel of the Utah Geological Survey. Samples with 92 and 94 prefix were collected by Robert Nusbaum of the College of Charleston, South Carolina. Latitude and longitude based on North American datum of 1983.**

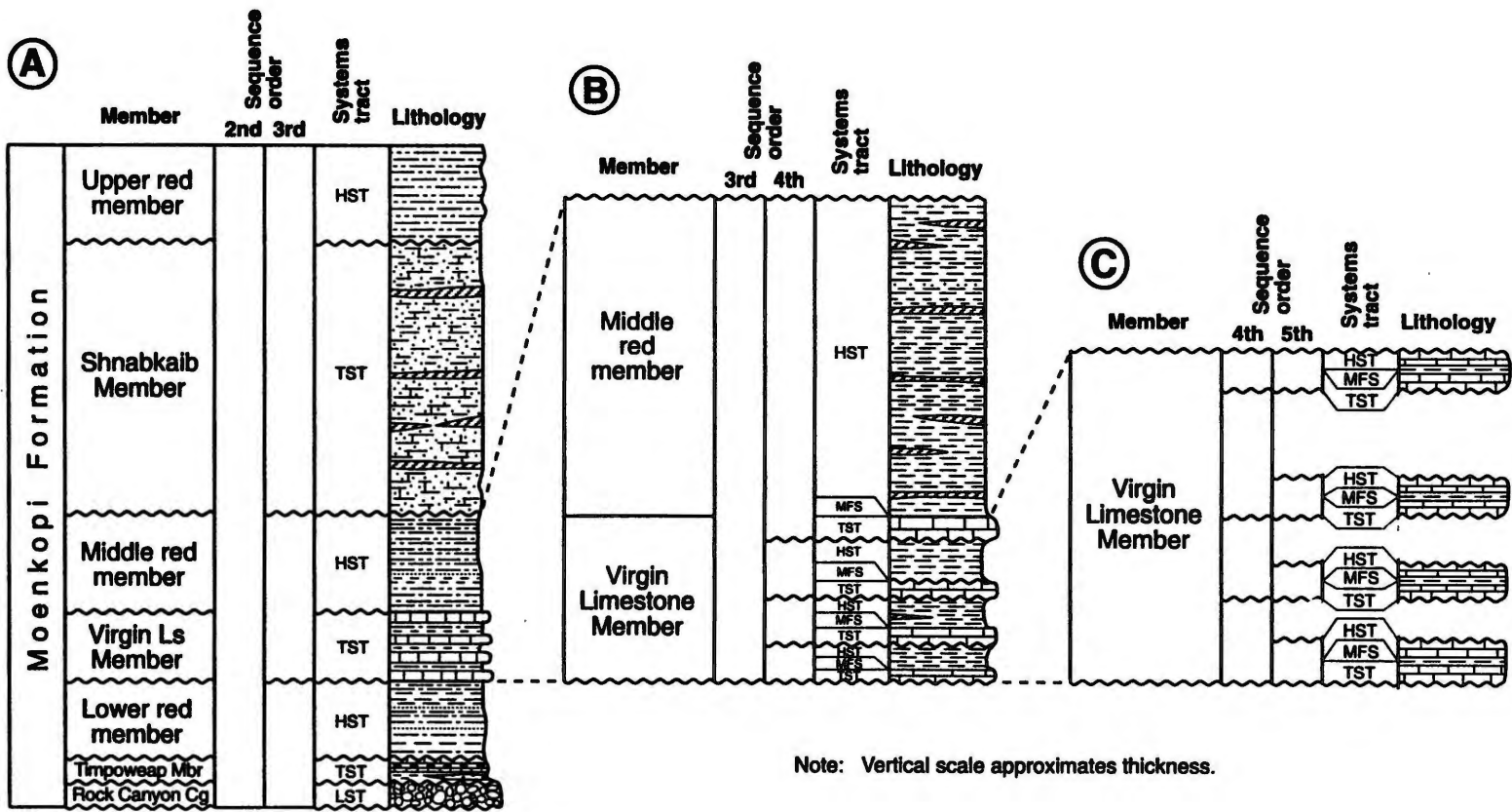
**Table 2. Petroleum exploration drill holes in the St. George quadrangle. Numbers are keyed to numbers on map.**



St. George Figure 1

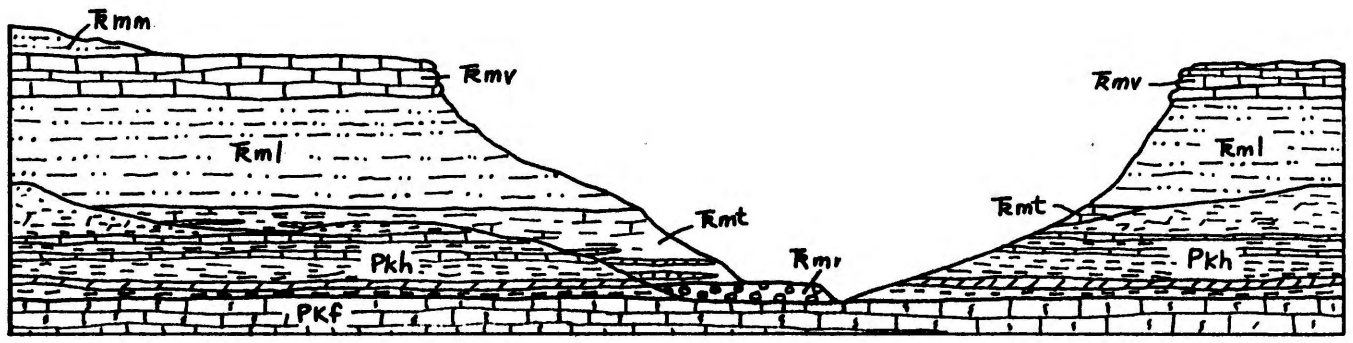


HST = highstand systems tract. MFS = maximum flooding stage. TST = transgressive systems tract. LST = lowstand systems tract.

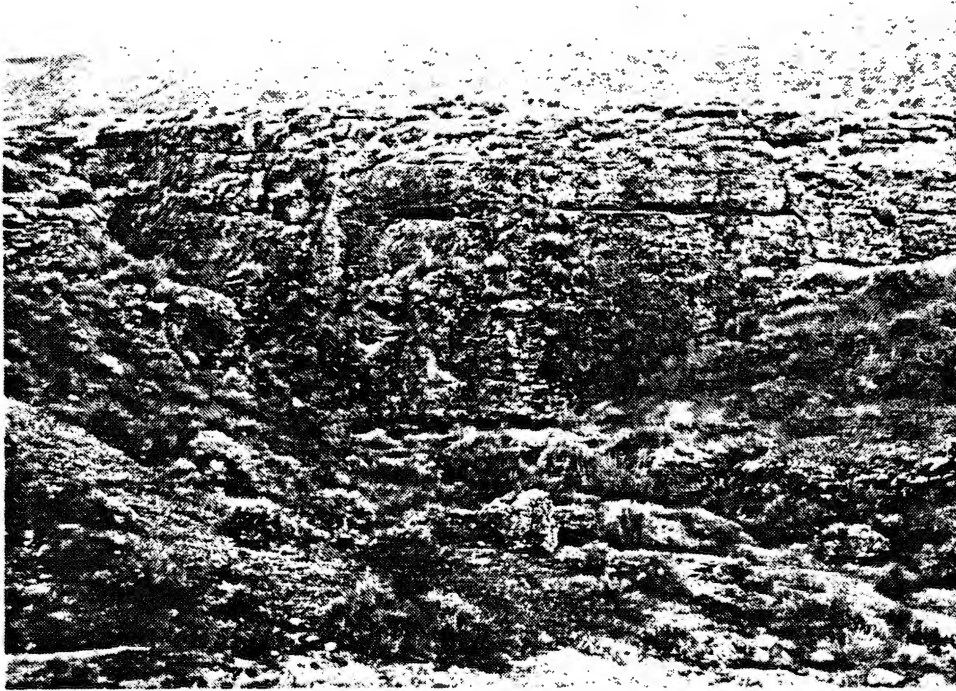


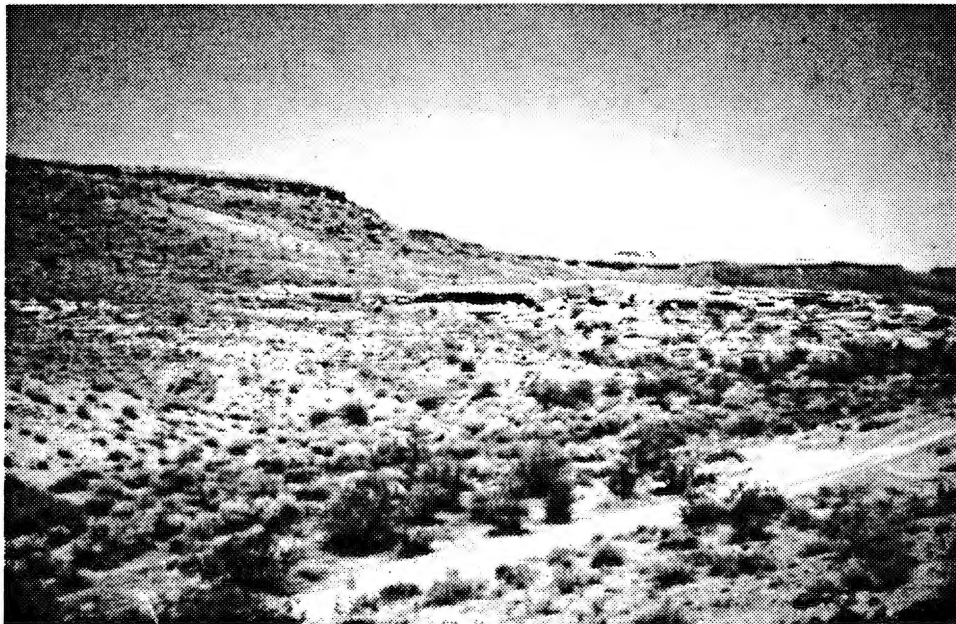
Note: Vertical scale approximates thickness.

St. George Figure 2b



St. George Figure 1



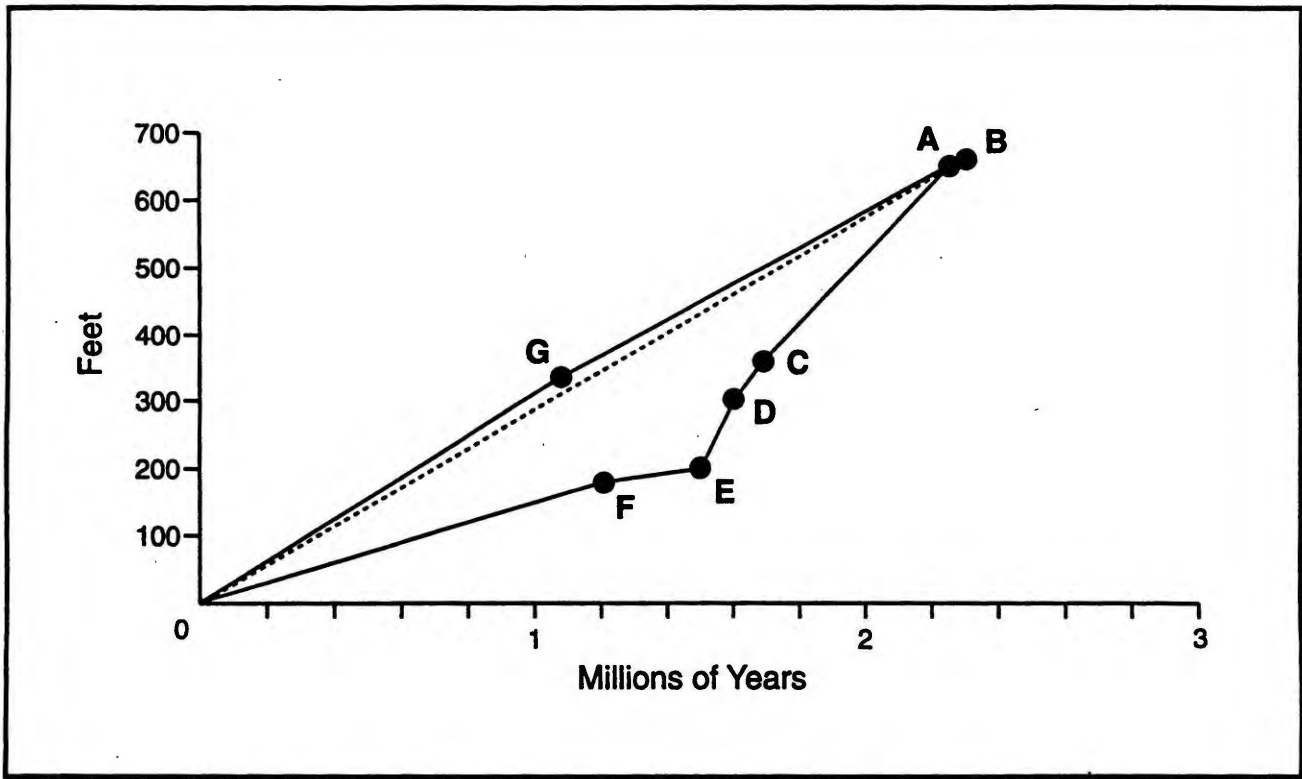




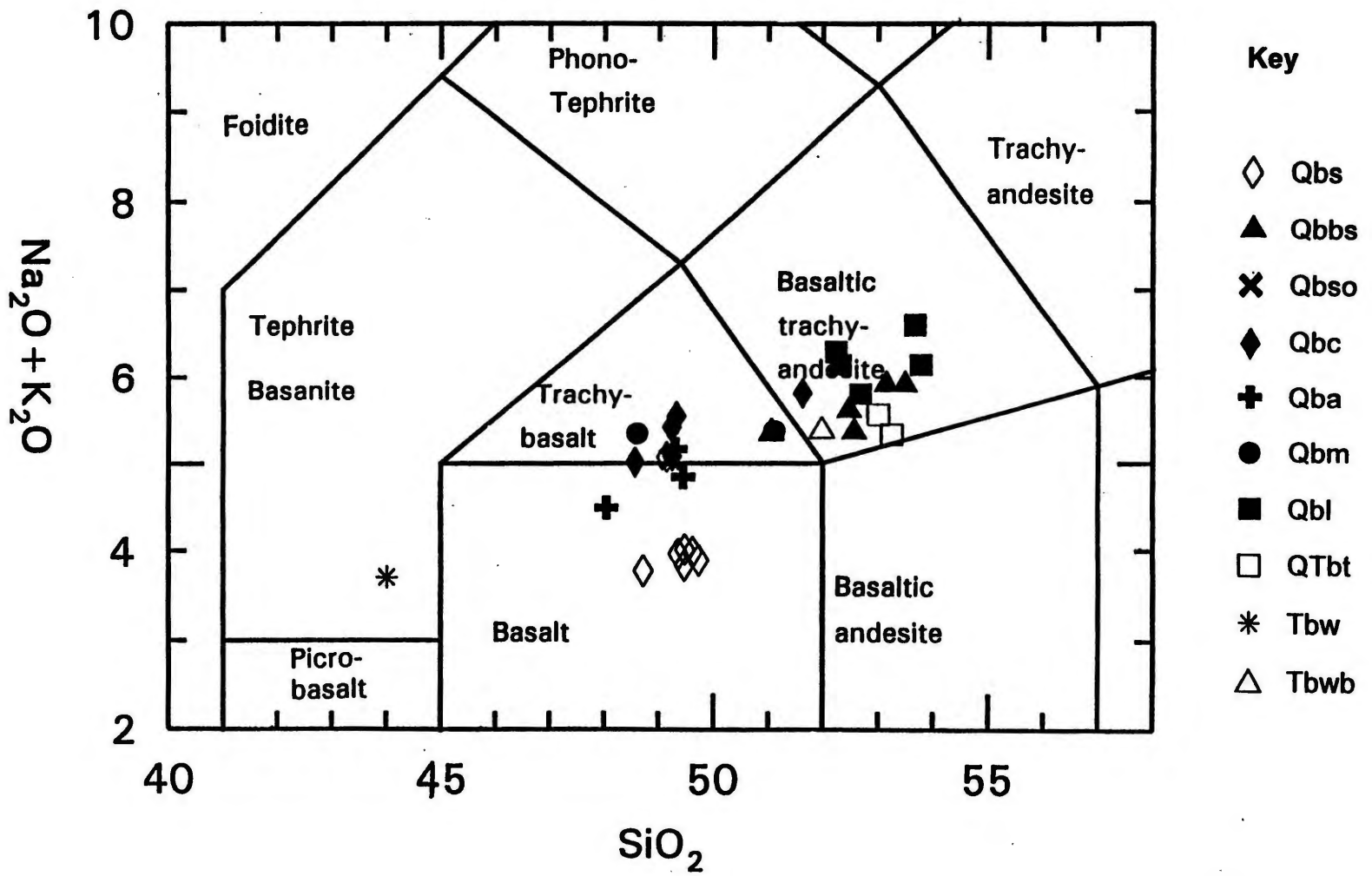
St. George Figure 6

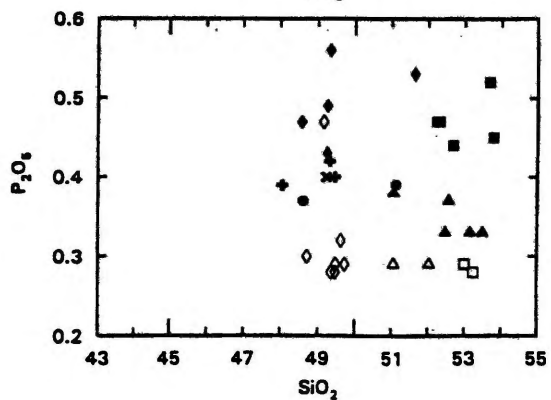
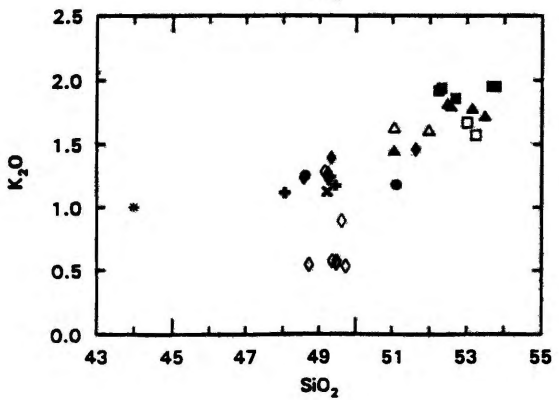
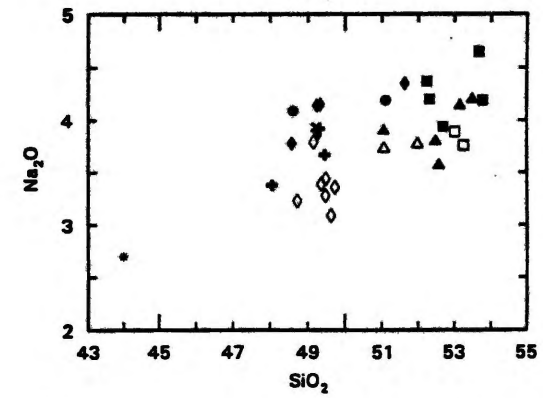
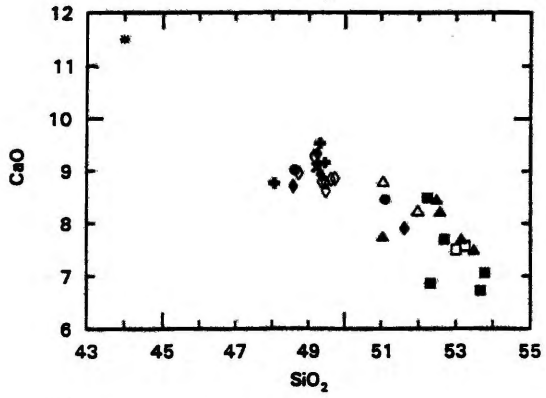
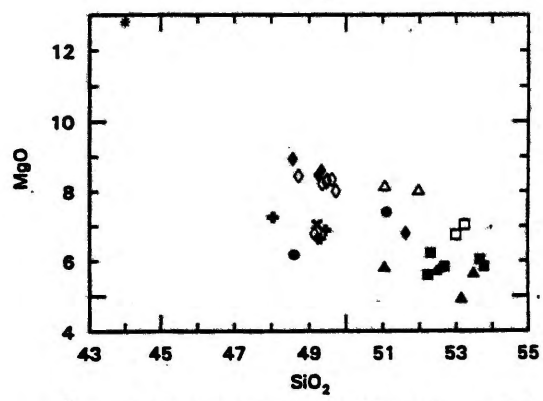
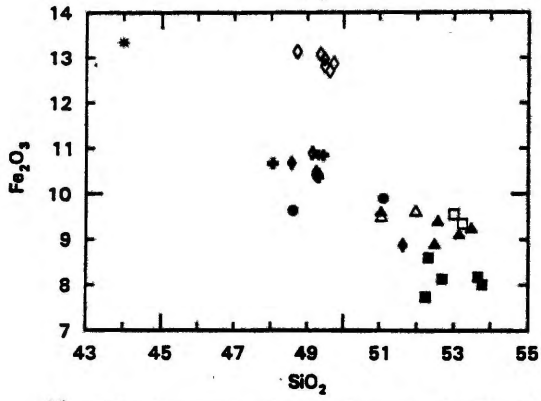
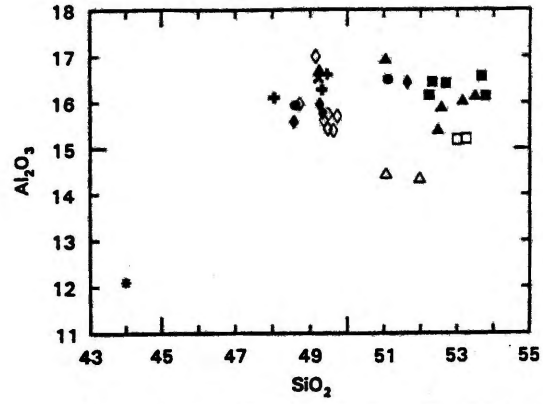
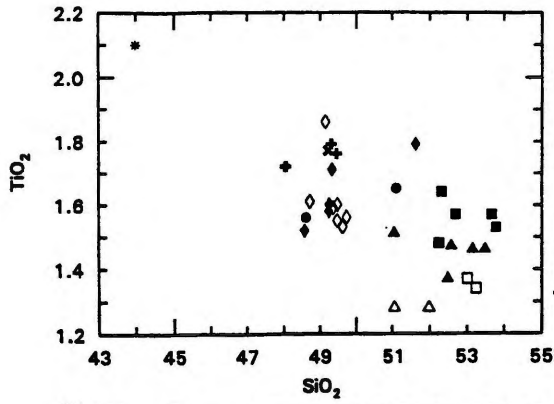


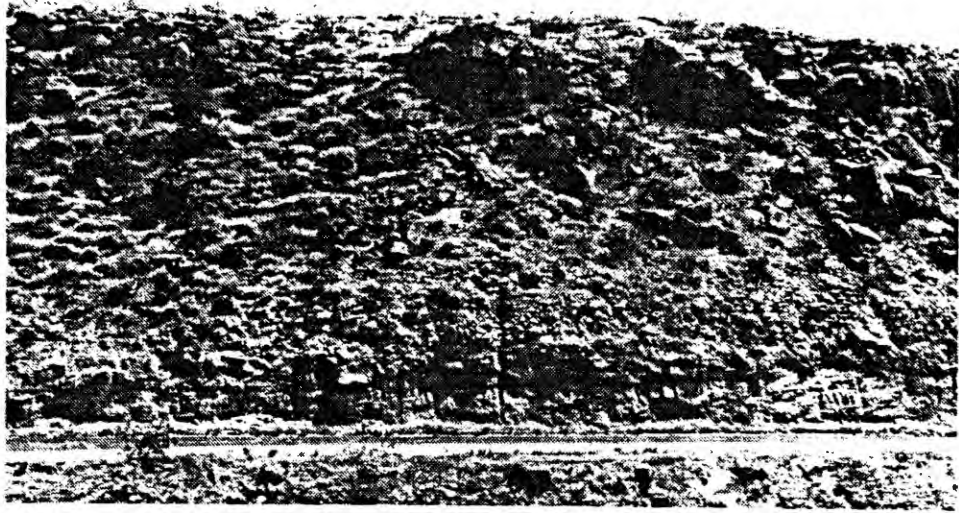
St. George Figure 7



St. George Figure 8













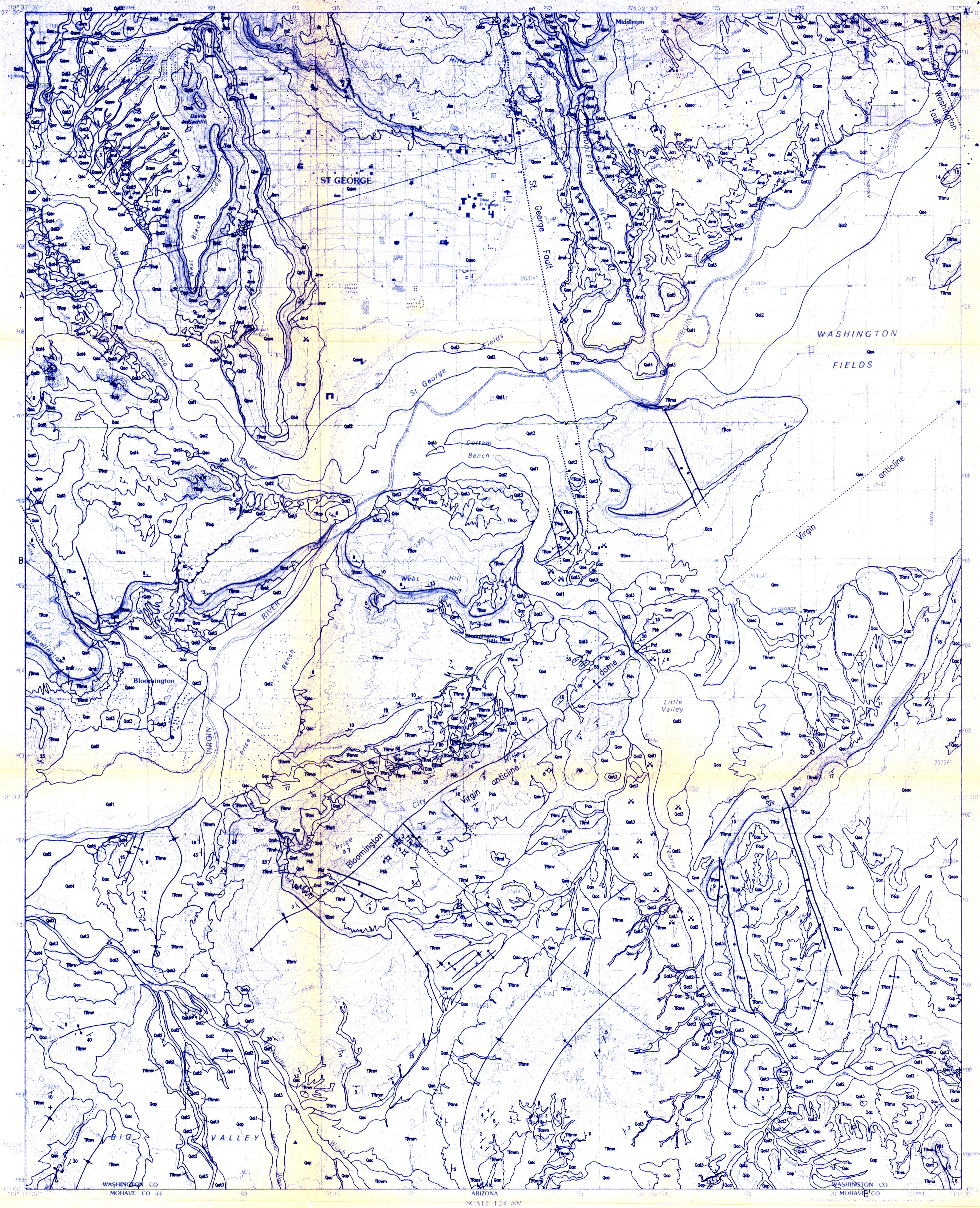
Sample Map Unit Latitude Longitude	94N1 Tbwb 37°06'24" 113°35'47"	94N2 Tbwb 37°06'24" 113°35'47"	Ank-av Tbw — —	SG0801 Qbm 37°06'48" 113°33'03"	94N12 Qbm 37°06'46" 113°32'55"	WA1104 Qba 37°07'58" 113°36'15"
SiO <sub>2</sub>	51.06	51.98	44.00	48.61	51.11	48.05
TiO <sub>2</sub>	1.28	1.28	2.10	1.56	1.65	1.72
Al <sub>2</sub> O <sub>3</sub>	14.42	14.33	12.10	15.93	16.50	16.10
Fe <sub>2</sub> O <sub>3</sub>	9.47	9.59	13.34	9.63	9.89	10.66
MnO	0.13	0.12	0.00	0.13	0.13	0.14
MgO	8.11	7.99	12.80	6.18	7.40	7.25
CaO	8.78	8.22	11.50	9.02	8.46	8.77
Na <sub>2</sub> O	3.73	3.77	2.70	4.09	4.19	3.38
K <sub>2</sub> O	1.62	1.60	1.00	1.25	1.18	1.11
P <sub>2</sub> O <sub>5</sub>	0.29	0.29	0.00	0.37	0.39	0.39
LOI	0.59	0.39	0.00	2.58	0.26	2.29
Total	99.51	99.39	98.20	99.39	101.19	99.90
Nb	20	17	0	14	16	24
Zr	158	154	0	168	215	156
Y	15	17	0	20	22	22
Sr	499	495	0	642	655	614
Rb	29	30	0	18	19	12
Th	0	0	0	0	0	0
Pb	0	0	0	0	0	0
Ga	0	0	0	0	0	0
Zn	0	0	0	0	0	0
Cu	0	0	0	0	0	0
Ni	0	0	0	0	0	0
Co	0	0	0	0	0	0
Cr	0	0	0	0	0	0
La	0	0	0	0	0	0
Ba	663	553	0	445	440	510
Sc	0	0	0	0	0	0
V	0	0	0	0	0	0
%An	36.09	35.36	74.73	41.39	39.07	47.12
Q	0.00	0.00	0.00	0.00	0.00	0.00
or	9.75	9.60	6.00	7.69	6.96	6.77
ab	32.13	32.39	6.15	31.55	35.38	29.54
an	18.14	17.72	18.21	22.28	22.68	26.32
ne	0.00	0.00	9.22	2.41	0.00	0.00
di	19.46	17.46	31.73	17.50	13.34	12.86
hy	0.47	6.81	0.00	0.00	0.36	4.11
ol	12.78	8.77	19.35	9.97	12.70	11.27
mt	4.10	4.09	5.30	4.62	4.56	4.82
il	2.48	2.47	4.05	3.08	3.13	3.37
ap	0.68	0.68	0.00	0.89	0.9	0.93

Sample	WA0803	94N3
Map Unit	Qba	Qba
Latitude	37°08'32"	37°05'06"
Longitude	113°36'22"	113°35'25"

SiO <sub>2</sub>	49.45	49.31
TiO <sub>2</sub>	1.76	1.79
Al <sub>2</sub> O <sub>3</sub>	16.60	16.27
Fe <sub>2</sub> O <sub>3</sub>	10.84	10.35
MnO	0.14	0.14
MgO	6.88	6.65
CaO	9.16	9.53
Na <sub>2</sub> O	3.67	3.92
K <sub>2</sub> O	1.17	1.24
P <sub>2</sub> O <sub>5</sub>	0.40	0.42
LOI	0.02	0.01
Total	100.12	99.65

Nb	22	26
Zr	153	183
Y	20	30
Sr	600	623
Rb	14	12
Th	0	0
Pb	0	0
Ga	0	0
Zn	0	0
Cu	0	0
Ni	0	0
Co	0	0
Cr	0	0
La	0	0
Ba	680	540
Sc	0	0
V	0	0
%An	44.96	43.71
Q	0.00	0.00
or	6.96	7.41
ab	31.27	30.13
an	25.54	23.39
ne	0.00	1.85
di	14.17	17.39
hy	0.89	0.00
ol	12.11	10.60
mt	4.76	4.82
il	3.37	3.44
ap	0.93	0.98

<b>No.</b>	<b>Location (Sec.-T.-R.)</b>	<b>Operator and Well Name</b>	<b>Completion Date</b>	<b>Total Depth (feet)</b>	<b>Formation at TD</b>
1.	NESENW 17-43S-15W	Escalante Exploration (Mid American) Escalante 1	05/04/31	2532	Queantoweap Sandstone
2.	NENE 19-43S-15W	Uzona Oil Co Uzona 1A	10/10/27	43	Kaibab Formation
3.	NWNWNE 19-43S-15W	California Oil St. George Unit 1	09/22/51	6347	Muddy Peak Dolomite
4.	NWNWNE 19-43S-15W	Arrowhead Petroleum Arrowhead 1	06/06/36	4114	Callville Limestone
5.	NENW 19-43S-15W	Uzona Oil Co Uzona 1	08/01/27	265	Kaibab Formation
6.	NENW 19-43S-15W	Uzona Oil Co Bloomington 1	02/01/28	625	Kaibab Formation?
7.	NESWNE 32-43S-15W	Escalante Exploration Escalante 1	03/05/35	969	Kaibab Formation
8.	CNNWNE 17-43S-15W	unlabeled standpipe identification unknown			
9.	NWSWSE 17-43S-15W location in state records seems unreasonable - not shown on map	Uzona Oil Government 1	03/15/27	387	Kaibab Formation
10.	SWSE 17-43S-15W location in state records seems unreasonable - not shown on map	Utah Parks Pet Government 1	00/00/28	50	Kaibab Formation



Base from U.S. Geological Survey,  
St. George 7.5-minute provisional quadrangle, 1986

Field work by Higgins, 1991-1995;  
by Willis, 1994-1995.

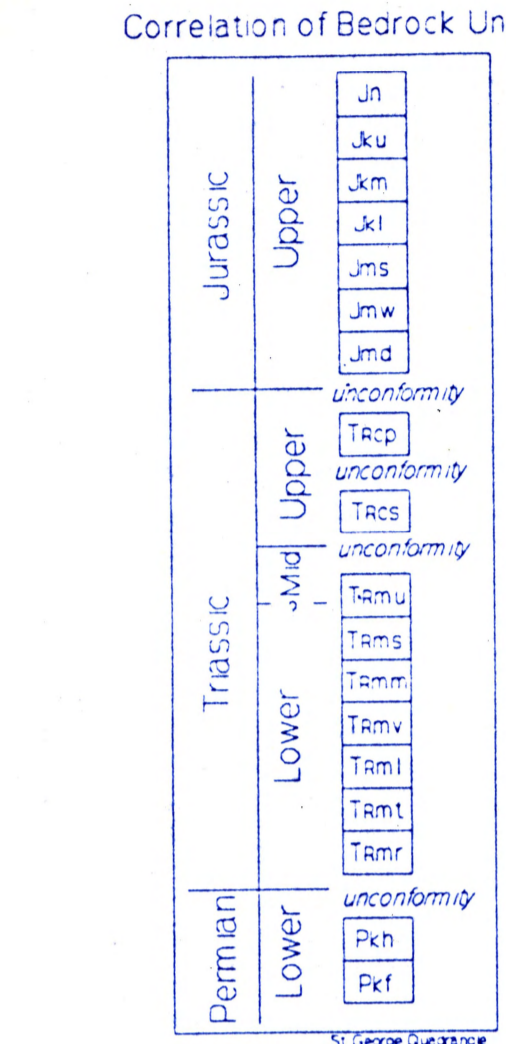
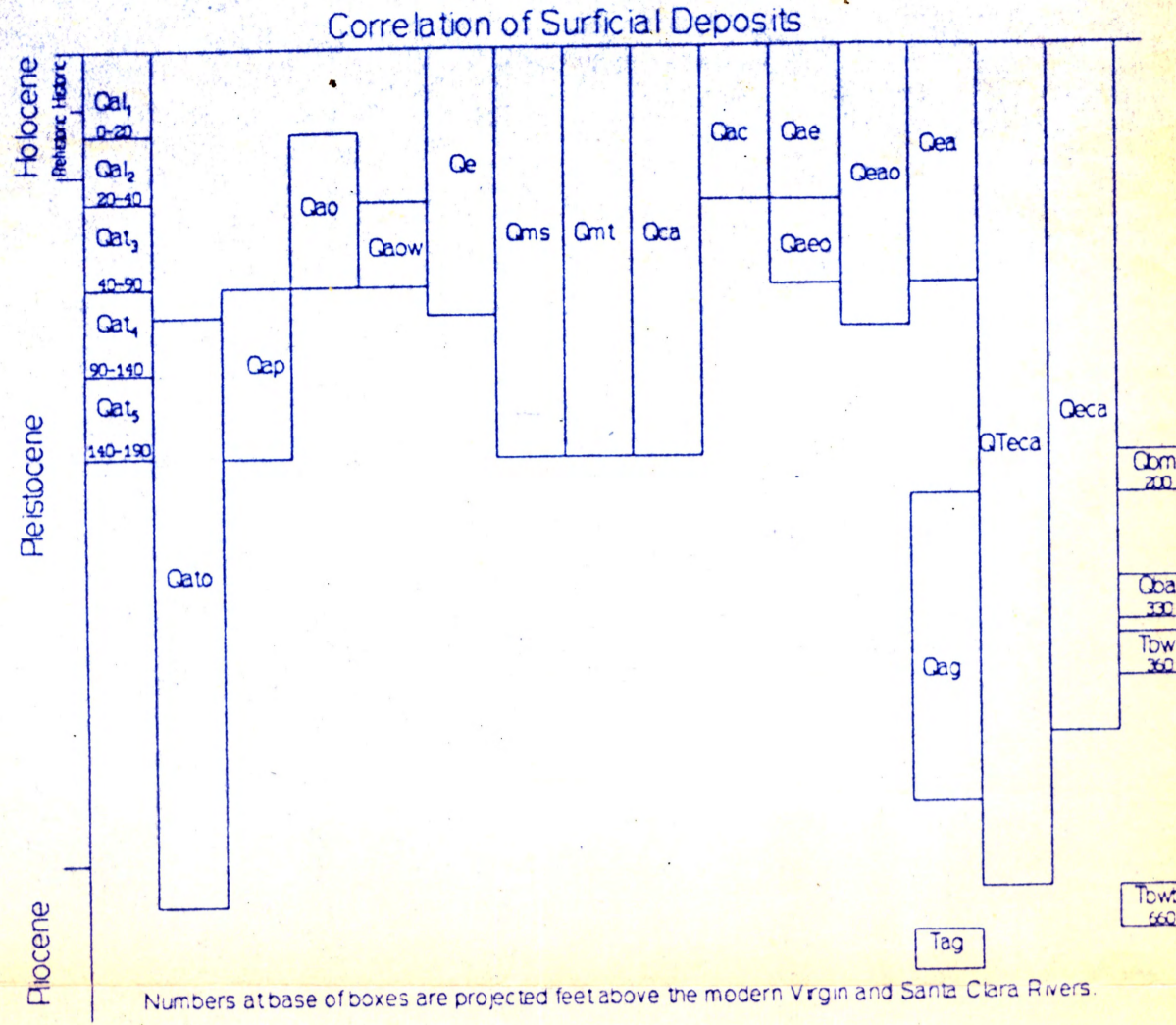
CONTOUR INTERVAL 20 FEET  
SUPPLEMENTAL CONTOUR INTERVAL 10 FEET

### Interim Geologic Map of the St. George Quadrangle, Washington County, Utah

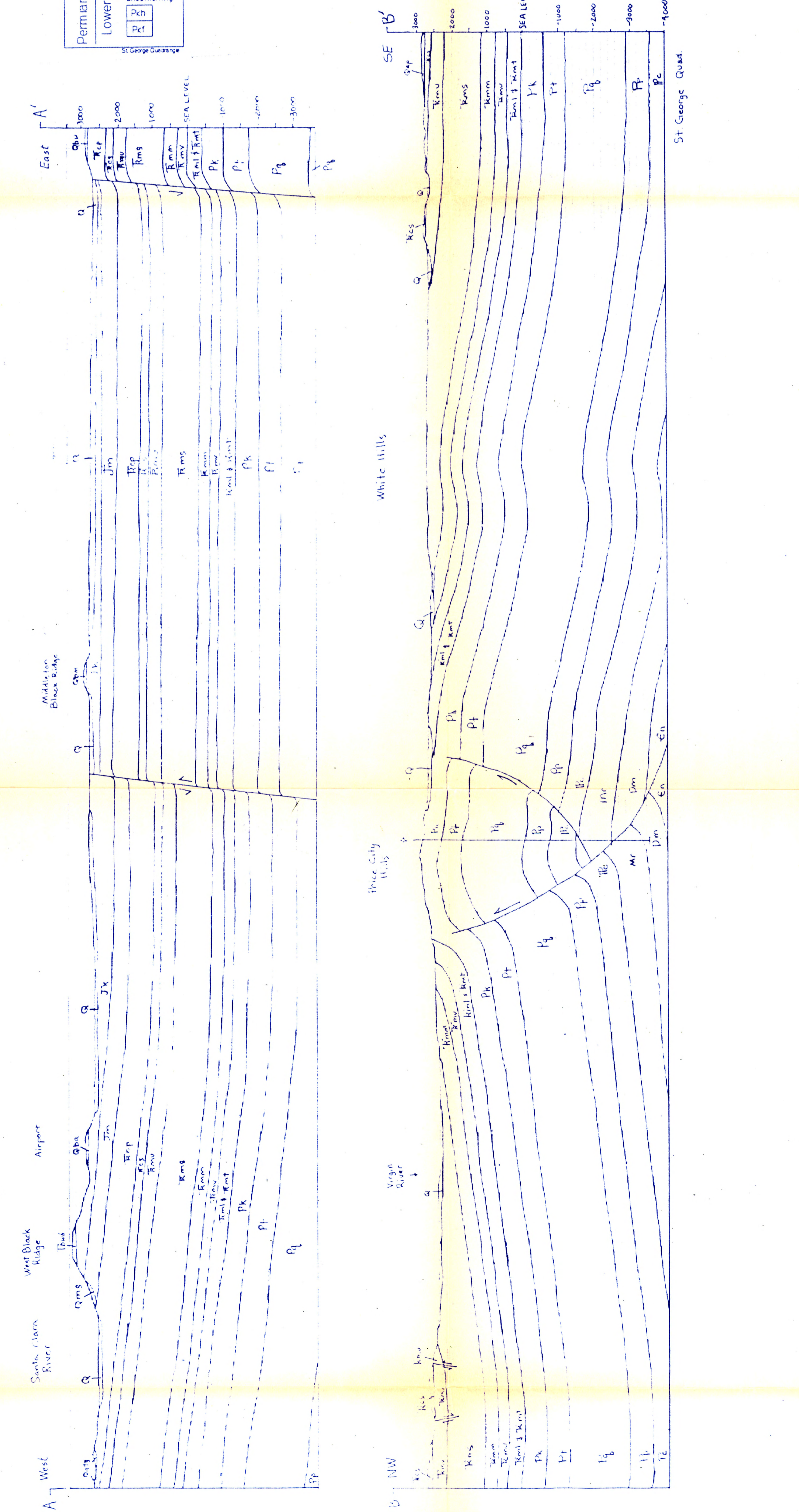
by  
Janice M. Higgins and Grant C. Willis  
1995

- SYMBOLS FOR STRATA
- 1. Sandstone
  - 2. Shale
  - 3. Limestone
  - 4. Conglomerate
  - 5. Sandstone
  - 6. Shale
  - 7. Limestone
  - 8. Conglomerate
  - 9. Sandstone
  - 10. Shale
  - 11. Limestone
  - 12. Conglomerate
  - 13. Sandstone
  - 14. Shale
  - 15. Limestone
  - 16. Conglomerate
  - 17. Sandstone
  - 18. Shale
  - 19. Limestone
  - 20. Conglomerate
- SYMBOLS FOR STRUCTURAL FEATURES
- 1. Fault
  - 2. Anticline
  - 3. Syncline
  - 4. Unconformity
  - 5. Fold
  - 6. Thrust
  - 7. Strike-slip
  - 8. Normal
  - 9. Inverse
  - 10. Overthrust
  - 11. Fault zone
  - 12. Fault zone
  - 13. Fault zone
  - 14. Fault zone
  - 15. Fault zone
  - 16. Fault zone
  - 17. Fault zone
  - 18. Fault zone
  - 19. Fault zone
  - 20. Fault zone
- SYMBOLS FOR OTHER FEATURES
- 1. Alluvium
  - 2. Alluvium
  - 3. Alluvium
  - 4. Alluvium
  - 5. Alluvium
  - 6. Alluvium
  - 7. Alluvium
  - 8. Alluvium
  - 9. Alluvium
  - 10. Alluvium
  - 11. Alluvium
  - 12. Alluvium
  - 13. Alluvium
  - 14. Alluvium
  - 15. Alluvium
  - 16. Alluvium
  - 17. Alluvium
  - 18. Alluvium
  - 19. Alluvium
  - 20. Alluvium

ST. GEORGE, UTAH  
PROVISIONAL EDITION, 1986



Interim Geologic Map of the St. George Quadrangle, Washington County, Utah  
by  
Janice M. Higgins and Grant C. Willis  
1995

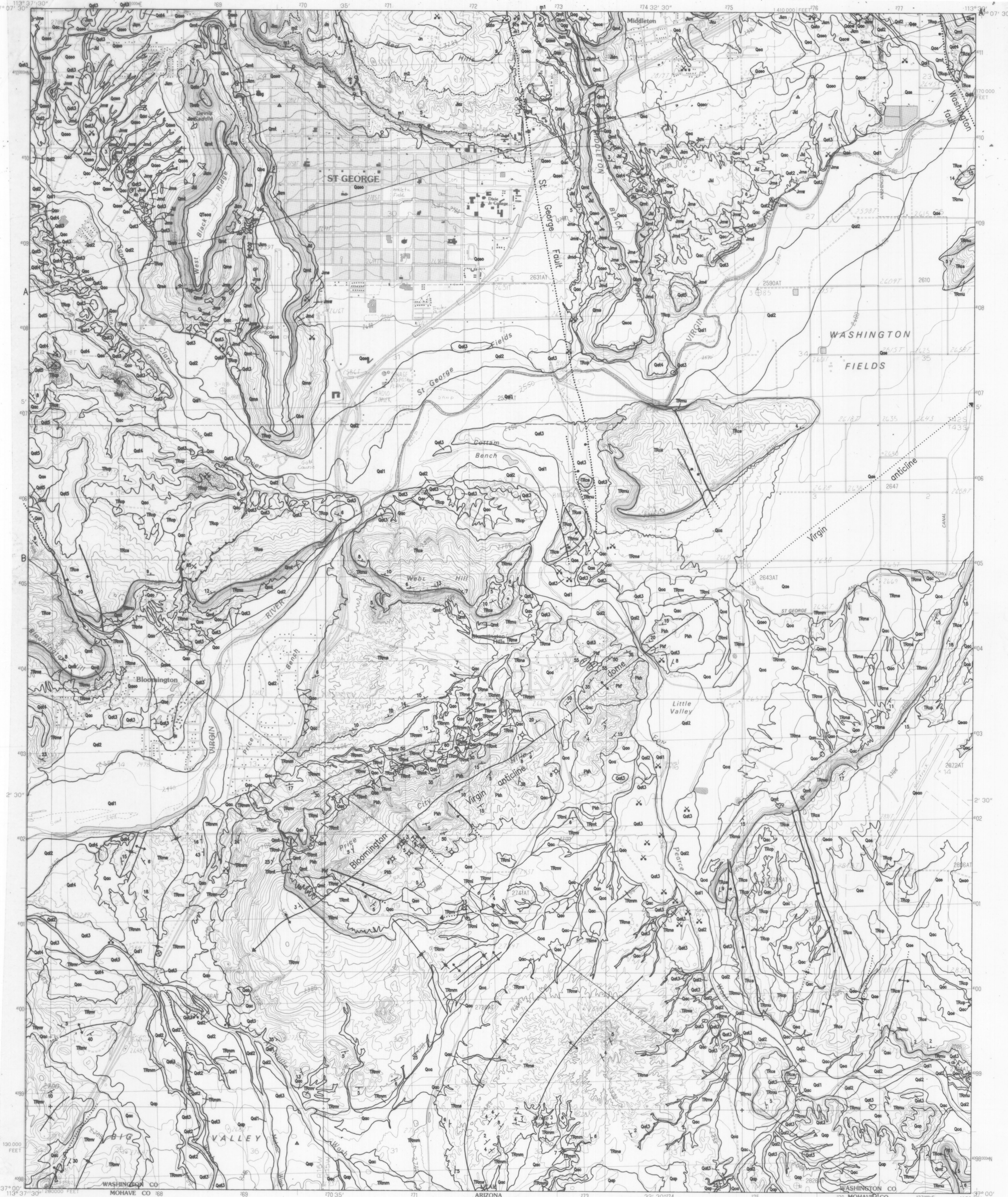


- QUATERNARY**
- Qu** Undivided Quaternary deposits - Shown in cross sections only.
  - Aluvial Deposits**
  - Qal<sub>1</sub>** Younger alluvial-stream deposits - Moderately to well-sorted clay to small gravel deposits in large active drainages; includes benches up to 20 feet (6 m) above current channels; 0-20 feet (0-6 m) thick.
  - Qal<sub>2</sub>** Older alluvial-stream deposits - Moderately to well-sorted clay to small gravel deposits adjacent to and dissected by Qal<sub>1</sub>; upper surface up to 40 feet (12 m) above active channels; 0-20 feet (0-6 m) thick.
  - Qal<sub>3</sub>** 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 floodplain; clasts are well-sorted and many are exotic to the quadrangle, indicating a source several miles upstream; pedogenic carbonate (caliche) thicker in older deposits; subscripts denote relative heights above the current drainage (and approximate ages); level 3 deposits are 40-80 feet (12-27 m); level 4 are 80-140 feet (27-42 m); and level 5 are 140-190 feet (42-57 m) above present channels, typically 0-40 feet (12 m) thick; near Fort Pearce Wash may exceed 100 feet (30 m) thick.
  - Qao** Older alluvial deposits - Remnants of older, locally derived and moderately sorted clay- to gravel-sized alluvial deposits; are 10-30 feet (3-10 m) higher than, and dissected by minor drainages; 0-10 feet (0-3 m) thick.
  - Qap** Pediment-mantle deposits - Poorly sorted, sub-angular to rounded clasts that range in size from gravel to small boulders; form an indurated conglomerate that caps a broad northward-trending bench in the south part of the quadrangle; thickness increases southward from 0-80 feet (0-24 m).
  - Qaow** Older alluvial deposits near Washington - Poorly to moderately well-sorted, clay- to small boulder-sized deposit that caps an older cut surface in the northeast part of quadrangle; contains a thick pedogenic carbonate (caliche); slopes southward toward the Virgin River; 0-20 feet (0-6 m) thick.
  - Eolian Deposits**
  - Qe** Eolian sand - Well- to very well-sorted, fine- to very fine-grained, well-sorted, mostly quartz sand; commonly deposited in irregular hummocky mounds on the lee side of ridges; locally forms poorly developed dunes; 0-50 feet (0-15 m) thick.
  - Mass Movement Deposits**
  - Qms** Slump and landslide deposits - Very poorly sorted clay- to boulder-size debris in chaotic, hummocky mounds; form on steep slopes beneath lava flows; basal detachments developed on Petrified Forest Member; displaces bedrock formations; talus and basalt flows; 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; 0-10 feet (0-3 m) thick.
  - Mixed-Environment Deposits**
  - Qac** Alluvial and colluvial deposits - Poorly to moderately sorted clay- to boulder-sized material in minor drainages; gradational with colluvial deposits; includes terrace outcrops too small to map separately; 0-10 feet (0-3 m) thick.
  - Qae** 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; 0-30 feet (0-9 m) thick.
  - Qaoo** Older alluvial and eolian deposits - Similar to Qae but is being dissected by current drainages; forms higher bench and has strong pedogenic carbonate (caliche); mapped in broad, sloping areas north of the Virgin River; 0-30 feet (0-9 m) thick.
  - Qca** Colluvial and alluvial deposits - Poorly sorted, angular to rounded, fine-grained to boulder-sized material deposited on moderate slopes; lacks well-defined drainage pattern; deposited by sheet wash, debris flow, and slope-creep processes; locally includes talus, eolian, or alluvial deposits; dissected by washes with Qac deposits; 0-30 feet (0-9 m) thick.
  - Qea** Eolian and alluvial deposits - Well-sorted eolian sand with minor alluvial clay to gravel; locally reworked by alluvial processes; 0-20 feet (0-6 m) thick.

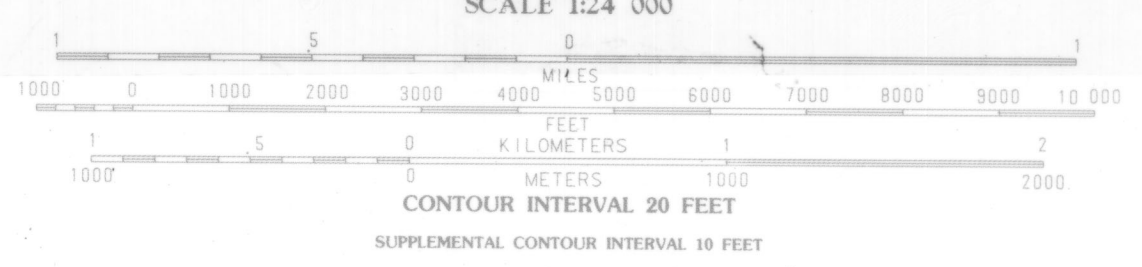
- Key to Map Symbols**
- Contact
  - Marker bed
  - High-angle fault - dashed where approximately located, dotted where concealed, bar and ball on down-thrown side
  - Low-angle reverse fault - teeth on hanging wall block
  - Axial trace of folds - dotted where concealed, arrows on trace show direction of plunge
  - Anticline
  - Syncline
  - Strike and dip of bedding
  - Inclined
  - Vertical
  - Horizontal
  - Strike and dip of joints
  - Inclined
  - Near-vertical
  - Gravel or road-fill pit
  - Quarry - gypsum (g), building stone (s)
  - Petroleum exploration drill hole - dry and abandoned, numbers refer to table 2 in text
  - Spring

System	Series	Formation	Member	Symbol	Thickness (feet/meters)	Lithology	
Tertiary-Quaternary-Recent	Unconsolidated Surficial Deposits	Basalt Flows				0-45/0-150	
		Navajo Sandstone				200+ (61+)	
Jurassic	Early	Kayenta Formation	Upper Member	Jku	380 (116)		
			Middle Member	Jkm	680 (207)		
			Lower Member	Jkl	110(34)		
			Springdale Sandstone Mbr.	Jms	115(35)		
	Moenave Formation	Whitmore Point Member	Jmw	55(17)			
		Dinosaur Canyon Member	Jmd	250 (76)			
	Late	Chinle Formation	Petrified Forest Member	Jcp	700 (213)		
			Shinarump Cg Member	Jcs	5-200 (15-61)		
		Moenkopi Formation	Upper Red Member	Jrmu	360 (110)		
			Shnabkaib	Jrms	1000 (305)		
Triassic	Early	Moenkopi Formation	Middle Red Member	Jrmm	375 (114)		
			Virgin Ls Member	Jrmv	25-225 (8-69)		
			Lower Red Member	Jrml	25-300 (8-91)		
			Timpoweap Mbr.	Jrmt	10-200? (3-61?)		
	Late	Kaibab Formation	Rock Canyon Cg	Jrcr	0.35(0-11)		
			Harrisburg Member	Pkh	0-300 (0-91)		
			Fossil Mtn. Mbr.	Pkf	70+(21+)		
			Permian	Permian	Permian	Permian	Permian

- Qca** Eolian and alluvial deposits with thick carbonate soil on basalt flows - Eolian clay, silt, and sand and alluvial gravel deposited on basalt flows; very thick pedogenic carbonate soil dominates unit; deposited in areas where streams flowed on top of congealed flows; 0-20 feet (0-6 m) thick.
- Basalt Flows and Related Deposits**
- Qbm** Middleton flow - Moderate- to dark-gray to moderate-brownish-gray, quartz-bearing, basaltic trachyandesite; has large plagioclase and quartz, and small olivine phenocrysts; consists of multiple flows of differing mineralogy; main flow is probably sourced at Lava Ridge cinder cone, about 200 feet (60 m) above larger active drainages; K-Ar dated at 1.5±0.1 Ma (Best and others, 1980), but this age is inconsistent with calculated ages on other flows in area (see text).
- Qba** Airport flow - Dark-greenish-gray to dark-brownish-gray trachybasalt; small olivine phenocrysts; as mapped may also include parts of a quartz-bearing, basaltic trachyandesite flow; strongly jointed; weathering along fractures imparts a "bathtub" appearance; multiple cooling units exposed, about 330 feet (97 m) above larger active drainages; K-Ar dated at 1.07±0.04 Ma (Hamblin and others, 1981) but this age is inconsistent with calculated ages on other flows (see text).
- Qag** Alluvial gravel beneath basalt flows - Small isolated remnants of poorly to moderately sorted clay- to boulder-sized alluvial materials exposed beneath and between basalt flows; 0-20 feet (0-6 m) thick.
- QUATERNARY-TERTIARY**
- QTea** Eolian and alluvial deposits with thick carbonate soil on basalt flows - Eolian clay, silt, and sand and alluvial gravel deposited on basalt flows; very thick pedogenic carbonate soil dominates unit; deposited in areas where streams flowed on top of congealed flows; 0-20 feet (0-6 m) thick.
- QTato** Older stream-terrace deposits - Three outcrops, 0 to 10 feet (3 m) thick, of stream terrace deposits, similar to those described above but not associated with the current drainage system; near northern edge of the quadrangle, outcrop on north end of West Black Ridge is about 450 feet (136 m) above current drainage, outcrop west of Middleton Black Ridge is about 200 feet (60 m) above current drainage and probably is similar in age to Middleton basalt flow; outcrop near Middleton is about 100 feet above current drainages and may correlate with Qay deposits; 0-40 feet (0-12 m) thick.
- TERTIARY**
- Tbw** Washington flow - Dark-greenish-gray tephritic basaltic (ankaramite), has abundant small clinopyroxene and olivine phenocrysts in a seriate groundmass; dense, strongly jointed; caps ridge 300 feet (110 m) above the adjacent Virgin River; K-Ar dated at 1.7±0.1 Ma (Best and others, 1950).
- Tbw** West Black Ridge flow - Dark-gray to dark-brownish-gray, quartz-bearing, basaltic trachyandesite; large plagioclase and small quartz, clinopyroxene and olivine phenocrysts; strongly columnar jointed; about 650 feet (200 m) above the active drainage; K-Ar dated at 2.3±0.1 Ma (Best and others, 1980) and 2.24±0.11 Ma (Hamblin and others, 1981); 20-80 feet (6-24 m) thick.
- Tag** Alluvial gravel beneath basalt flows - Small isolated remnants of poorly to moderately sorted clay- to boulder-sized alluvial materials exposed beneath oldest basalt flow; 0-20 feet (0-6 m) thick.
- unconformity**
- JURASSIC**
- Jn** Navajo Sandstone - Pale- to moderate-reddish-brown, massively bedded, eolian sandstone; forms cinder cone; 2,000 feet (606 m) thick but only basal 200 feet (61 m) in the quadrangle.
- Jku** Upper member of the Kayenta Formation - Moderate- to dark-reddish-brown, fine-grained, thin planar bedded, sandstone and mudstone in lower part; pale- to moderate-reddish-brown, thick cross-bedded sandstone with planar bounding surfaces 1-5 feet apart in upper part; upper part is entirely fine- to medium-grained, well-sorted, frosted quartz sand; resembles Navajo Sandstone except has fewer sedimentary structures; forms prominent ledges and cliffs; 380 feet (115 m) thick.
- Jkm** Middle member of the Kayenta Formation - Interbedded reddish-brown siltstone, purplish-red to reddish-brown mudstone, and fine-grained, calcareous, slightly modeled sandstone; punky gypsum in some intervals near the base; cross-cutting gypsum stringers are common; generally coarsens upward; forms slopes and small ledges; 680 feet (206 m) thick.
- Jkl** Lower member of the Kayenta Formation - 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 dolomite, each about 6 inches (0.15 m) thick, are present near the top; 110 feet (33 m) thick.
- Jms** Springdale Sandstone Member of the Moenave Formation - Pale-reddish-brown to grayish-yellow, fine- to medium-grained, cross-bedded sandstone with interbedded light-purple-gray siltstone near the middle; weathers to rounded ledges; 115 feet (35 m) thick.
- Jmw** Whitmore Point Member of the Moenave Formation - Greenish-gray claystone interbedded with pale-brown to pale-red, thin-bedded siltstone with several 2-6 inch (0.05-0.15 m) thick beds of light-greenish-gray dolomitic limestone that contain algal structures and fossil fish scales of *Semionotus hanabensis* (Hamblin, 1984); non-resistant and thus poorly exposed; about 55 feet (17 m) thick.
- Jmd** Dinosaur Canyon Member of the Moenave Formation - Interbedded moderate-red-brown siltstone and fine-grained, thin-bedded, pale-reddish-brown to grayish-red sandstone with laminated crossbeds; very similar to the steep-slope appearance of the middle member of the Kayenta Formation; 250 feet (76 m) thick.
- unconformity**
- TRIASSIC**
- Jcp** Petrified Forest Member of the Chinle Formation - Light-brownish-gray to grayish-purple bentonitic shale and siltstone with several intervals of pale-yellowish-brown, cross-bedded sandstone up to 10 feet (3 m) thick; petrified wood is common; shales weather to a "popcorn" surface with abundant mudcracks due to bentonitic clay swelling and shrinking with moisture; forms well-developed strike valleys adjacent to the more resistant cliffs of the Shinarump Conglomerate Member; 700 feet (215 m) thick.
- unconformity**
- Jcs** Shinarump Conglomerate Member of the Chinle Formation - Varies from a grayish-orange to moderate-yellowish-brown, medium- to coarse-grained sandstone with locally well-developed limonite bands ("picture rock" or "landscape stone") across most of the quadrangle to a moderate-brown, chert pebble conglomerate in the southwest corner of the quadrangle; forms a dark-brown to moderate-yellowish-brown caprock above the Moenkopi Formation; variable in composition and thickness because it represents stream channel deposition; ranges from 5-200 feet (1.5-61 m) thick.
- unconformity**
- Jrmu** Upper red member of the Moenkopi Formation - Moderate-reddish-brown, thin-bedded siltstone and sandstone with some thin gypsum beds and abundant discordant gypsum stringers; ripplemarks common in the siltstone; forms a slope with a few minor sandstone ledges; 360 feet (109 m) thick.
- Jrms** Shnabkaib Member of the Moenkopi Formation - Light-gray to pale-red, "bacon-stripe", gypsiferous siltstone with several thin interbeds of dolomitic, unfossiliferous limestone near the base; upper portion is very gypsiferous and weathers into a powdery soil; forms a valley except where held up by more resistant overlying units; 1,000 feet (303 m) thick.
- Jrmm** Middle red member of the Moenkopi Formation - Interbedded moderate-red to moderate-reddish-brown siltstone, mudstone, and thin-bedded sandstone; forms a slope and is generally not well exposed within the quadrangle; 375 feet (114 m) thick.
- Jrmt** Virgin Limestone Member of the Moenkopi Formation - Four distinct medium-gray to yellowish-brown marine limestone ledges interbedded with moderate-reddish-brown, muddy siltstone and pale-reddish-brown sandstone; limestone beds average 5 feet (1.5 m) in thickness and contain five-sided echinoderms and shell fragments; total thickness varies from 25 feet (8 m) at the southwest edge of the Pine City Hills to 25 feet (7.5 m) because of attenuation faulting on steeply dipping north side of Bloomington dome.
- Jrml** Lower red member of the Moenkopi Formation - Moderate-reddish-brown siltstone, mudstone, and fine-grained, slope-forming sandstone; generally calcareous and has interbeds and stringers of gypsum; ripple marks and small-scale cross-beds are common in the siltstone; thickness varies considerably from 25-300 feet (8-91 m) probably because of attenuation faulting.
- Jrmt** Timpoweap Member of the Moenkopi Formation - Dark-yellowish-orange to light-pinkish-gray, thin- to very thin-bedded, calcareous siltstone with thin limestone beds and very fine-grained sandstone near the base; gypsiferous near the top with lenses of gypsum and sandstone; gypsum forms punky surface; poorly jointed and forms slope; varies from 0-200 feet (0-61 m) thick due to deposition over paleotopography.
- Jrcr** Rock Canyon Conglomerate Member of the Moenkopi Formation - Yellowish-gray to light-olive-gray, clast-supported conglomerate with pebble- and cobble-sized clasts; basal layers are limestone rip-up clasts and brecciated blocks from Harrisburg Member; locally cemented with stony calcite; rounding increases upward to sub-rounded; most chert clasts near top; grades upward to calcareous, gritty, poorly sorted, pebble conglomerate with coarse sandstone lenses; thick, locally lenticular bedding; indurated; chert forms; field paleoconchylons eroded into the Kaibab Formation; thickness 0.35 feet (0-10 m).
- unconformity**
- PERMIAN**
- Pkh** Harrisburg Member of the Kaibab Formation - 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 about 20 foot-thick (6 m), resistant ledges near upper middle; solution of interbedded gypsum causes local collapse; forms slope with limestone ledges; thickness varies greatly due to subaerial erosion; 0-300 feet (0-91 m) thick.
- Pkf** Fossil Mountain Member of the Kaibab Formation - Yellowish-gray, abundantly fossiliferous, cherty limestone that forms a prominent cliff; studied fossils include corals, brachiopods, crinoids, and bryozoans; reddish-brown and black chert forms irregularly bedded nodules and causes the outcrop to appear black-banded; base is not exposed; incomplete exposed thickness is 70 feet (21 m).
- Subsurface Units**
- Pt** Toroweap Formation - shown in cross section only
- Pq** Quantowep Sandstone - shown in cross section only
- Pp** Pakoon Dolomite - shown in cross section only
- PENNSYLVANIAN**
- lPc** Callville Limestone - shown in cross section only
- MISSISSIPPIAN**
- Mr** Redwall Limestone - shown in cross section only
- DEVONIAN**
- Dim** Muddy Peak Dolomite - shown in cross section only
- CAMBRIAN**
- Cr** Nopah Dolomite - shown in cross section only



Base from U.S. Geological Survey,  
 St. George 7.5-minute provisional quadrangle, 1986



Field work by Higgins, 1991-1995;  
 by Willis, 1994-1995.

**Interim Geologic Map  
 of the St. George Quadrangle,  
 Washington County, Utah**

by  
 Janice M. Higgins and Grant C. Willis  
 1995

1	2	3	4	5	6	7	8
1	2	3	4	5	6	7	8

ADJOINING 7.5' QUADRANGLE NAMES

ST. GEORGE, UTAH  
 PROVISIONAL EDITION 1986