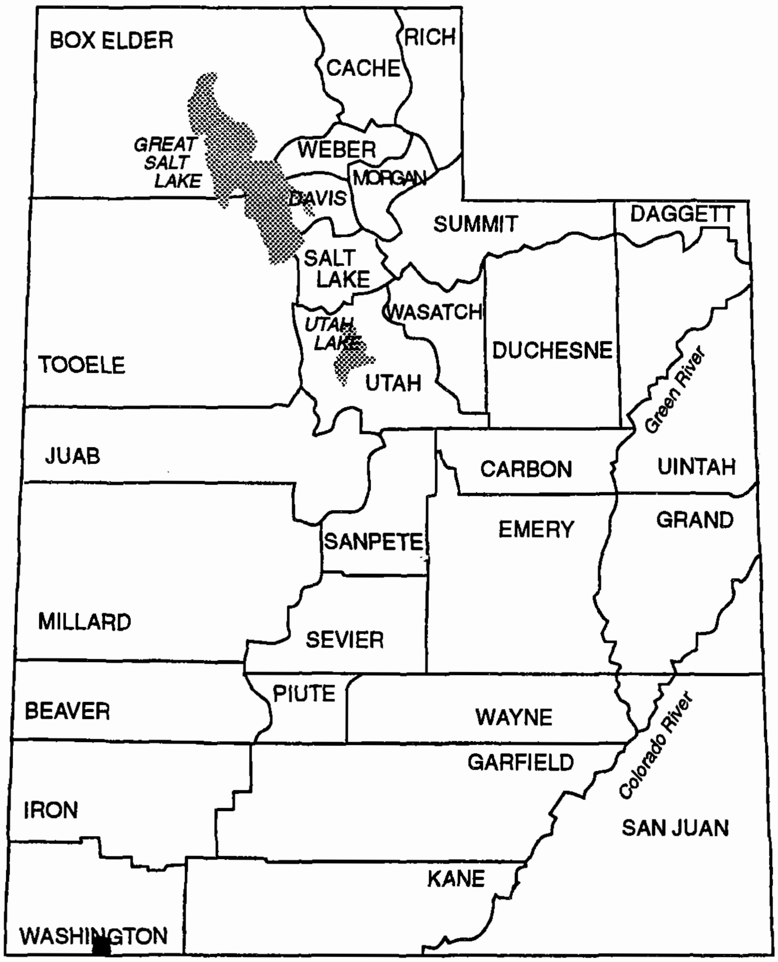
INTERIM GEOLOGIC MAP OF THE WASHINGTON QUADRANGLE, WASHINGTON COUNTY, UTAH

by
Grant C. Willis and Janice M. Higgins



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ABSTRACT

The Washington quadrangle is in the St. George basin near the southwest corner of Utah. Strata are exposed in a gently northward- to northeastward-dipping homocline overprinted by a broad syncline. The upper 300 feet (91 m) of the Upper Triassic Petrified Forest Member of the Chinle Formation are the oldest exposed strata. The Lower Jurassic includes the Moenave Formation, which is mapped in three members and is 420 feet (128 m) thick, the Kayenta Formation, which is also divided into three members and is 1,170 feet (357 m) thick, and the Navajo Sandstone, which is about 2,000 feet (610 m) thick. Middle Jurassic strata include the Temple Cap Formation, which is 200 feet (61 m) thick, and the Carmel Formation, which is about 300 feet (91 m) thick. A regional unconformity has cut out much of the Carmel Formation, leaving only the Co-op Creek Member and scattered remnants of the Crystal Creek Member. About 50 feet (15 m) of upper Cretaceous bentonitic beds overlie the unconformity. They are overlain by the Upper Cretaceous Iron Springs Formation, of which only the lower 400 feet (122 m) are preserved in the quadrangle.

Several Late Tertiary and Quaternary basalt and basaltic andesite flows and three cinder cones that range in age from 2.3 million years to about 10,000 years old cover much of the quadrangle. At least three source vents are within the quadrangle and others are located to the north, northwest, and east. The flows are typically 10

to 40 feet (3-12 m) thick, but thicken to over 100 feet (30 m) where they filled washes. *Surficial deposits consist mostly of scattered eolian sand, colluvium,* alluvium, and talus.

Geologic resources include cinders, gypsum, clay, gravel, building stone, and sand. Massive red sandstone cliffs capped by black basalt flows form spectacular scenic vistas that attract many visitors each year. The quadrangle contains important bedrock aquifers, primarily in the Navajo Sandstone, and to a lesser extent in the Kayenta and Iron Springs Formations, that are of increasing importance as the local population increases. Geologic hazards include earthquake faults, volcanic eruptions, blowing sand, flash floods and debris flows, problem soils, landslides, and slumps. Faults with probable Quaternary offset are present within the quadrangle.

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INTRODUCTION

Setting

The Washington quadrangle is located in the St. George basin of southwestern Utah (figure 1). It extends from the south flank of the Pine Valley Mountains southward to just north of the Virgin River. The City of Washington is in the southeast corner of the quadrangle and the northern part of Middleton and St. George extend into the southern part. Snow Canyon State Park extends into the western side of the quadrangle and the northern part is within the Dixie National Forest. Much of the central part is managed by the Bureau of Land Management. Private and state trust lands are scattered throughout the quadrangle. A large part of the quadrangle is under consideration as a protected area for the endangered Desert Tortoise. Interstate 15 crosses the southwestern part of the quadrangle and Utah Highway 18 extends northward near the western edge. Paved roads provide access to the southern parts of the quadrangle and many small dirt roads allow access to the northern part.

[figure 1 near here]

Altitude ranges from about 2,700 feet (644 m) above sea level in the valley near the southern border to 5,410 feet (1,650 m) in the mountainous northeastern part. Pinyon-juniper forests and sagebrush dominate the northern part of the quadrangle while creosote bushes, black brush, cactus, and yucca dominate the southern part.

Previous Works

The U.S. Army Topographical Survey and U.S. Geological Survey conducted regional geologic investigations of southwestern Utah during the later 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 1:125,000-scale map of Washington County that still is the most detailed map available for much of the county. Christenson and Deen (1983) mapped the surficial geology of the populated parts of the St. George area, including the southern part of the quadrangle, at the 1:31,250-scale, focusing on engineering aspects of the geology. Houser and others (1988) produced a generalized 1:24,000-scale map that included the northeastern part of the quadrangle as part of a wilderness study area. Eppinger and others (1990) compiled a 1:250,000-scale map of the Cedar City 1°x 2° quadrangle that includes the Washington 7 1/2' quadrangle. Hintze and others (1994) mapped the Motoqua and Gunlock quadrangles to the west that expose many of the same bedrock formations found in the Washington quadrangle. Higgins and Willis (1995) mapped the St. George quadrangle to the south at a scale of 1:24,000 and D.B. Hacker is mapping the Saddle Mountain quadrangle to the north. Many topical studies have also been done on structure, stratigraphy, volcanism, geologic hazards, and economic and water resources of the area.

STRATIGRAPHIC UNITS

Triassic

Chinle Formation

Petrified Forest Member (TRcp): The Petrified Forest Member of the Chinle Formation is poorly exposed beneath alluvium and landslides in the southeast corner of the quadrangle. It consists of purple, reddish-brown, pale-greenish-gray, and pale-gray claystone, mudstone, siltstone, and minor sandstone. It has a large component of volcanic-derived bentonitic clay that swells when moistened, causing many problems for building and road foundations.

The upper contact is unconformable but it is generally poorly exposed because the overlying Dinosaur Canyon Member of the Moenave Formation is also nonresistant. It is placed at the change from purplish bentonitic beds to reddish-brown mudstone and siltstone beds. The Petrified Forest Member is Late Triassic in age. It is about 700 feet (213 m) thick in the area (Higgins and Willis, 1995) but only about 300 feet (91 m) are exposed.

Jurassic

Moenave Formation

The Moenave Formation consists of three members, in ascending order, the Dinosaur Canyon, Whitmore Point, and Springdale Sandstone, which are exposed near the east quadrangle boundary in Washington City. The Moenave has been variously placed in the Upper Triassic (Cook, 1960) or Lower Jurassic (Hintze and others, 1994). 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 in Warner Valley, just east of the study area, indicate a relatively advanced stage of dinosaur development suggestive of an Early Jurassic age (Miller and others, 1989). The formation is 420 feet (127 m) thick east of Middleton Black Ridge, just south of the quadrangle (Higgins and Willis, 1995).

Dinosaur Canyon Member (Jmd): The Dinosaur Canyon Member is well exposed only in a small wash in section 14, T. 42 S., R. 15 W. Elsewhere, its presence is indicated by a reddish-brown soil. It is interbedded moderate-reddish-brown siltstone and very fine-grained, thin-bedded, pale-reddish-brown to grayish-red, laminated to cross-bedded sandstone. It weathers to form low ledgy slopes. 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 purplish-gray-green claystone of the Whitmore Point Member. It is 250 feet (76 m) thick just south of the quadrangle in the E1/2 SW1/4, section 28, T. 42 S., R. 15 W. (Higgins and Willis, 1995).

Whitmore Point Member (Jmw): This member is only exposed in a cut bank near the parking lot of the Washington City swimming pool and in a shallow wash to the east. It is composed of pale-reddish-purple to greenish-gray claystone interbedded with pale-brown to pale-red, thin-bedded siltstone. Several 2- to 6-inch-thick (0.05-0.15 m) 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. It is 55 feet (17 m) thick just south of the quadrangle in NE1/4 NE1/4 SE1/4, section 28, T. 42 S., R. 15 W. (Higgins and Willis, 1995).

Springdale Sandstone Member (Jms): The Springdale Sandstone Member of the Moenave Formation forms bare sandstone knolls in the eastern part of the quadrangle. Because it is much more resistant than any adjacent map unit, it is an important marker bed. It is well exposed near the local elementary school and in isolated outcrops that have been incorporated into the landscaping of many houses. It is pale-reddish-brown to grayish-yellow, fine- to medium-grained, medium- to thick-bedded, cross-bedded, ledge-forming lenticular sandstone interbedded with pale-purplish-gray siltstone near the middle of the member.

The upper contact is placed at the top of the uppermost thick, pale-reddish-gray sandstone ledge and at the base of moderate- to dark-reddish-brown, slope-forming, silty mudstone of the Kayenta Formation. This member is 115 feet (35 m) thick east of Middleton Black Ridge, SE1/4 SE1/4 NW1/4, section 28, T. 42 S., R. 15 W., just south of the quadrangle (Higgins and Willis, 1995).

Kayenta Formation

Wilson and Stewart (1967) divided the Kayenta into two informal members in the St. George area (working mostly east and northeast of the quadrangle) and Hintze and others (1994) divided the formation into three members to the west in the Gunlock area. We follow the mapping of Hintze and others (1994) and also map three members. However, the contacts between the middle and upper members and between the Kayenta and the overlying Navajo are difficult to map and may differ slightly from their contacts. The Kayenta Formation is exposed in the southern part of the quadrangle where it forms a broad, mostly obscured slope that grades up into ledges and small cliffs of the upper member. The best exposure of the upper member is west of Halfway Wash near the western edge of the quadrangle where northeast-dipping strata form a cuesta ridge. Parts of the formation are well-exposed northeast of Washington City. The Kayenta Formation is Early Jurassic in age.

Lower member (Jkl): The lower member of the Kayenta Formation is exposed in the quadrangle only near the east boundary in the northeast part of Washington City. It consists of slope-forming, moderate- to dark-reddish-brown, thin-bedded, silty mudstone and very fine-grained, moderately well-sorted, planar- to lenticular-bedded sandstone with climbing ripplemarks. Sericite is common on bedding surfaces. Some beds are bioturbated and mottled. Three thinly laminated beds of light-pinkish-gray to light-olive-gray, micritic dolostone about 6 inches (0.15 m) thick are commonly present 85 feet (26 m), 105 feet (31 m), and 110 feet (33 m) above the base of the member (Hintze and others, 1994; Higgins and Willis, 1995). The dolostone commonly weathers into distinct pale-gray angular fragments covered by dendrites. The top of the uppermost dolostone forms the upper contact of the member. We were unable to locate the three dolostone beds because construction of houses and roads has obscured most outcrops in the quadrangle. However, we do believe they are present beneath the fill of Interstate 15 near the east border of the quadrangle since they are exposed near Middleton Black Ridge just south of the quadrangle. The lower member is 110 feet (33 m) thick near Middleton Black Ridge in the St. George quadrangle (Higgins and Willis, 1995).

Middle member (Jkm): The middle member is exposed north of Washington and near Halfway Wash in the southwest corner of the quadrangle where it forms a broad slope cut by shallow washes. It consists of interbedded moderate-reddish-brown to purplish-brown, slope-forming siltstone and mudstone, and moderate-reddish-brown to light-greenish-gray, very fine-grained, silty sandstone. Resistant, very fine-grained channel sandstone lenses are locally present. Sandstone beds increase upward and the member is more ledgy near the top. The member is typically calcareous and bioturbation is common. Punky gypsiferous soil indicates gypsum is common in some intervals, though it is rarely exposed. The upper contact is placed at the base of the lowest thick, blocky, ledge-forming sandstone. A marker bed (mapped as dashed line m_1) in the upper member about 20 feet (6 m) above the top helps to identify the contact. The member is 677 feet (205 m) thick in sections 10 and 11, T. 42 S., R. 16 W.

Upper member (Jku): The upper member forms a broad band of ledges and cliffs across the southern part of the quadrangle. It is a transitional unit between the fluvial-dominated silty and muddy sandstone of the Kayenta and the eolian sand dune deposits of the Navajo Sandstone. The lower part of the member consists of interbedded, moderate- to dark-reddish-brown, very fine-grained sandstone, mudstone, and siltstone. The sandstone forms resistant blocky, planar to lenticular ledges and cross-bedded channel sandstone lenses are locally prominent. A prominent bed of orangish-brown, thick-bedded, planar, blocky sandstone about 20 feet (6 m) above the base is mapped as marker bed m_1.

Two prominent tongues of pale-orangish-gray sandstone in the middle of the member are similar in gross appearance to the main body of the Navajo Sandstone. One tongue (mapped as marker bed m_2) is thickest in the eastern part of the quadrangle and pinches out near the middle. The other tongue (mapped as marker bed m_3) is thickest in the western part of the quadrangle and pinches out in the eastern part (plate 1). The base of these tongues marks a distinct lithologic change. Sand in and above the tongues is very well-sorted, fine- to medium-grained, well-rounded, frosted quartz and outcrops are pale orangish gray instead of reddish brown, similar to the Navajo Sandstone. The rock is cross-bedded with planar cross-set boundaries and forms rounded massive cliffs and knolls.

Above the massive tongues, the unit is cross-bedded in low-angle sets bounded by prominent planar surfaces a few inches to a few feet apart that give the interval a horizontally bedded appearance. Sand grains are entirely fine- to medium-grained, frosted, well-rounded quartz, and the outcrop maintains a pale-orangish-gray color similar to the underlying tongues and to the overlying Navajo Sandstone. The thickness between planar surfaces gradually increases and high-angle cross-bedding becomes more common in the upper part of the member. The upper contact is gradational and is placed at the change from sandstone with small-scale, low-angle cross-beds and planar cross-bed bounding surfaces to massive sandstone with 10- to 30-foot (3-9 m) thick, high-angle cross-beds. This contact is difficult to locate in many areas due to an extensive mantle of windblown sand, but it can be fairly well constrained in section 12, T. 42 S., R. 16 W. The upper Kayenta member is 380 feet (116 m) thick in section 2, T. 42 S., R. 16 W. It is too poorly exposed to determine a thickness in the Washington area.

Navajo Sandstone (Jn)

The Navajo Sandstone is extensively exposed throughout the southern two thirds of the quadrangle where outcrops vary from rubbly knolls mostly buried by eolian sand to high cliffs. It consists entirely of grayish-yellow, pale-reddish-gray, and pale-brownish-orange, well-rounded, fine- to medium-grained sandstone. Grains are frosted quartz. Cementation is generally poor to moderate and varies from calcareous to siliceous. It is strongly jointed and is locally brecciated (figure 2). Locally, abundant iron and manganese oxides form dark-brown to brownish-black desert varnish and rounded concretions. The iron and manganese oxides are also commonly concentrated in fractures and joints near overlying basalt flows in the southwestern part of the quadrangle and weather out in relief to form resistant dikes up to 4 feet (1.2 m) thick. They may be related to leaching of the basalts. The Navajo is locally strongly bleached and has prominent interfingering pale-grayish-yellow and moderate-reddish-brown color bands (figure 2). These dissolution bands follow cross-beds and cross-bed bounding surfaces locally but they also crosscut bedding features in many places. In general, the upper part of the formation is more pale-yellowish-gray and the lower part is more grayish-red. The formation weathers easily, forming loose sand that is commonly mobilized by wind and water, forming dunes and sand sheets that choke stream beds and washes, and that blanket much of the outcrop area.

[figure 2 near here]

In the SE1/4, section 32, T. 41 S., R. 15 W., the massive eolian Navajo Sandstone contains a lens of moderate-reddish-gray, thin, planar-bedded, well-cemented sandstone. This lens is exposed across an area of about 200 feet (61 m). It provides the only control on bedding inclination in the middle part of the formation.

The upper contact is an unconformity and is marked by a sharp break between underlying pale-yellowish-orange, cliff-forming sandstone and overlying pale-reddish-gray, slope-forming, gypsiferous mudstone. The broad width of the Navajo outcrop and the lack of planar beds on which to measure dips makes it difficult to determine an accurate thickness for the formation, but it is estimated at 2,000 feet (610 m). It is Early Jurassic in age.

Temple Cap Formation (Jtc)

The Temple Cap Formation consists of two members at its type locality in Zion National Park, a thin Sinawava Member and a thick White Throne Member (Peterson and Pipiringos, 1979). Due to facies changes the Sinawava Member thickens westward toward the Washington quadrangle and the White Throne Member thins westward, pinching out near the Hurricane fault. Only the Sinawava Member is present in the Washington quadrangle.

The Temple Cap forms prominent reddish-gray slopes and benches in the northern part of the quadrangle (figure 3). It is interbedded, pale-reddish-gray to pale-greenish-gray gypsum, claystone, siltstone, and minor sandstone. Rare good exposures reveal thin, biotite-bearing, volcanic ash layers. The gypsum is in distorted beds, nodules, and lenses up to 10 feet (3 m) thick that weather to form punky, pale-gray slopes. The claystone is thin bedded and easily weathered. Sandstone beds contain fine- to coarse-grained sand and range from thin, lenticular, channel deposits to planar sheet sands.

[figure 3 near here]

The upper contact is placed at the top of the highest gypsum bed and at the base of the first pale-yellowish-gray limestone ledge of the Carmel Formation. The Temple Cap Formation is 199 feet (61 m) thick in NE 1/4, section 11, T. 41 S., R. 15 W. It is early to middle Bajocian (early Middle Jurassic) in age (Peterson and Pipiringos, 1979).

Carmel Formation

The Carmel Formation is exposed in two areas near the northern border of the quadrangle where it forms a pale-greenish-gray to pale-yellowish-gray ridge overlain by a gentle dip-slope (figure 3). The Carmel Formation was deposited in a restricted marine basin and therefore has many interfingering lithologic units (Blakey and others, 1983). Because of the lithologic variety, names of member subdivisions are complex and inconsistently applied (Cashion, 1967; Thompson and Stokes, 1970; Peterson and Pipiringos, 1979; Blakey and others, 1983; and Doelling and Davis, 1989). The Carmel Formation has four members at the type locality, 50 miles (80 km) east of the quadrangle (Gilluly and Reeside, 1926; Gregory and Moore, 1931). Of the four members, only the lower two, a limestone member and a banded member, are preserved in Washington County because a regional unconformity (the K-1 unconformity of Pipiringos and O'Sullivan, 1978) cuts out the upper members of the formation. Thompson and Stokes (1970) named the banded member the Crystal Creek Member, which name is consistently used in Washington County (Blakey and others, 1983; Doelling and Davis, 1989; Hintze and others, 1994).

Most controversy concerns the limestone member. Phoenix (1963) applied the term Judd Hollow Member to a thin interval of strata in central and eastern Kane County (about 100 miles [160 km] east of the quadrangle) considered equivalent to the limestone member at the type locality. Workers continued to use the informal term "limestone member" for the lower part of the Carmel Formation in exposures west of the type area, including in Washington County (Peterson and Pipiringos, 1979). However, Blakey and others (1983) extended the term Judd Hollow Member to western Utah where they applied it to all Carmel strata below the Crystal Creek Member. This usage was followed by Rigby (1986) and Hintze and others (1994). However, Doelling and Davis (1989) showed that the type Judd Hollow is equivalent to Co-op Creek, Crystal Creek, and Paria River Members in Kane County and proposed the name Co-op Creek Member for the original limestone member with the type section in western Kane County. We agree with their interpretation and use the term Co-op Creek Member for the limestone unit in the Washington quadrangle. The Carmel Formation in the quadrangle is Bajocian to Bathonian (Middle Jurassic) in age (Imlay, 1980).

Co-op Creek Member (Jcco): The Co-op Creek Member consists of pale-yellowish-gray to pale-greenish-gray, interbedded, muddy limestone, thin-bedded, very fine-grained sandstone, and muddy shale. Its weathers to form uniform thin, blocky ledges. The lower part is primarily limestone while the upper part is limestone interbedded with light-olive-brown sandstone and pale-greenish-brown mudstone. Near the top is an interval of mudstone with abundant crumbly, nodular, dark-red, jasperoid chert. Certain horizons are abundantly fossiliferous with *pentacrinus* columnals, bivalves, and mollusks. The upper contact is placed at the change from pale-greenish-brown mudstone to dark-reddish-brown mudstone where the Crystal Creek Member is present and to pale-gray bentonitic mudstone elsewhere. The member is 285 feet (87 m) thick in the SW 1/4, section 2, T. 41 S., R. 15 W. Wright and others (1979) measured 258 feet (79 m) at approximately the same location.

Crystal Creek Member (Jccc): The Crystal Creek Member is preserved only as thin isolated slivers beneath a regional unconformity. It is easily recognized because it is moderate- to dark-reddish-brown and contrasts sharply with the adjacent pale-yellowish Co-op Creek Member and pale-gray Cretaceous strata. It consists of thin-bedded, slope-forming, silty mudstone and very fine-grained sandstone. It is not well-exposed, but isolated outcrops are present in a few washes. It varies from 0 to 50 feet (0-15 m) thick in the quadrangle. We measured 48 feet (87 m) in the SW 1/4, section 2, T. 41 S., R. 15 W. Wright and others (1979) measured 50 feet (15 m) in approximately the same location.

Cretaceous

Bentonitic Bed (Kb)

A thin interval of pale-gray bentonitic mudstone forms a slope above the Jurassic strata throughout the northern part of the quadrangle. It forms a soft, deeply weathered, "popcorn" surface. Quartz crystals give the slope a sparkly sheen in the sunlight. We tentatively correlate this interval with "bentonitic beds" mapped by Hintze and others (1994) in the Gunlock area to the west. The correlation is questionable because outcrops are discontinuous between the two areas. Hintze and others (1994) described the bed as moderate red whereas the outcrop in the Washington quadrangle is pale gray. In addition, they described sparse barite nodules which we did not find. However, both beds are in the same stratigraphic position overlying an unconformity cut into the Jurassic strata. The bentonitic beds are overlain by the Dakota Conglomerate in the Gunlock area (Hintze and others, 1994) but the Dakota is discontinuous in southwestern Utah (Cook, 1960) and is not present in the Washington quadrangle. The upper contact is mapped at the base of thick-bedded sandstone in the Iron Springs Formation. Hintze and others (1994) reported a fission-track age of 80±5 Ma (Campanian) on zircon extracted from the bentonitic beds in the Gunlock area. Maximum thickness is near Diamond Valley where we measured about 90 feet (27 m).

Iron Springs Formation (Ki)

The uppermost bedrock formation exposed in the quadrangle is the Iron Springs Formation, which forms steep ledgy ridges in the northern part of the quadrangle. The Iron Springs is interbedded resistant, ledge-forming sandstone, and non-resistant, slope-forming mudstone and sandstone. Pale-yellowish-brown, pale-gray, moderate-reddish-brown, dark-brown and other colored outcrops characterize the unit. The sandstones are mostly medium to coarse grained, but range from fine grained to pebbly. Most beds are well cemented but some are friable and bleached. Ledge-forming beds are up to about 15 feet (4.6 m) thick. The slope-forming intervals are mostly covered by colluvium but where exposed they are pale-greenish-gray to moderate-reddish-gray mudstone and thin-bedded sandstone. The formation is 3,500 to 4,000 feet (1,067-1,220 m) thick in the area (Cook, 1960; Hintze and others, 1994) but only about 400 feet (122 m) are preserved in the Washington quadrangle. Hintze and others (1994) reported pollen analyses that suggested a Turonian to Cenomanian age (90-100 Ma) for the Iron Springs. This age conflicts slightly with the Campanian age for the underlying bentonitic beds. Therefore, the age of the Iron Springs can only be bracketed to early Late Cretaceous.

Quaternary and Tertiary

Basaltic Flows and Cinder Cones

The Washington quadrangle is within the Western Grand Canyon basaltic field, a large area of Late Tertiary and Quaternary basaltic volcanism in southwestern Utah, northern Arizona, and eastern Nevada (Hamblin, 1963, 1970a; Best and Brimhall, 1970; 1974). Regionally, most basalts are less than 6 million years old and the youngest is less than 500 years old (Best and others, 1980). The area is noted for inverted valleys, which formed as stream erosion cut down along the sides of the basalt flows, leaving the flows as elevated basalt caps on ridges (Hamblin, 1970a, 1987). Since downcutting is the dominant geomorphic process of the late Cenozoic, the relative height above drainages provides a way of estimating the relative age of the flows, and, coupled with radiometric dating, allows determination of a downcutting rate for the area (figure 4). Hamblin and others (1981) calculated a downcutting rate of 300 feet (90 m) per million years for the St. George structural block. Hamblin (1970a, 1987) mapped flows in the region as stages I to IV, based on the amount of downcutting and erosion (stage I are high flow remnants that bear no apparent relation to the present drainage system; stage IV are young flows with little or no downcutting or alteration). Flows in the quadrangle are stage II and IV.

[figure 4 near here]

Within the quadrangle there are at least 20 flows, 3 source vents with associated cinder cones, and a small part of a fourth cone. Other vents may be obscured by younger flows. The flows originated in the northern part of the map area and in nearby areas and flowed generally south toward the Virgin River. The flows are typically 10 to 40 feet (3-12 m) thick, but reach thicknesses in excess of 100 feet (30 m) where they filled canyons. They range in age from about 2.3 million years (Best and others, 1980; Hamblin and others, 1981) to about 10,000 years old. 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). We mapped the flows in ten map units, most of which consist of two or more closely related flows. (Though they may be composed of more than one flow, each map unit is referred to as a "flow" for simplicity.)

Several factors affect mapping of the flows:

(1) Inverted valleys are well-developed near the large rivers, but erosive processes are much slower along small tributaries farther away. Thus, in many areas downcutting did not have time to "invert" the topography between eruptions. Thus, some younger flows that are inverted (lower than an older flow) in the southern part of the quadrangle overlie the older flow in the northern part of the quadrangle. Relationships are complex where flows cross inflection points.

(2) In some areas flows split into multiple lobes that followed different paths with different elevations. Later erosion then left nearby remnants of the

same flows at significantly different elevations, which could be interpreted as different flows of different ages.

(3) Older and younger paleodrainages commonly cross each other. For example, part of the Lava Ridge flow followed a southeast canyon, the Cedar Bench flow flowed almost straight south, and part of the Twin Peaks flow moved generally southwest, all intersecting near the middle of the quadrangle.

(4) In some areas, such as at Black Gulch, flows from a second and third eruption flowed down the same canyon, stacking directly on top of each other.

(5) Many flows have similar compositions, making them difficult to distinguish in outcrop or chemically.

(6) Surficial sedimentary deposits and younger flows have obscured older flows in many places.

We differentiated flows using litholoigc and geochemical characteristics, by studying slopes and drainages on aerial photographs and topographic maps, using stretched vesicles and other flow-direction indicators, and using relative heights of adjacent flows. Degree of weathering and stage of pedogenic calcium carbonate on flow surfaces were evaluated in some areas, but they generally were not as useful because of differences due to local conditions. Carbonate evaluation is also hindered by the sparsity of adequate exposures.

The flows were described in Hamblin (1963, 1970a, 1987), Best and others (1966, 1980), Best and Brimhall (1970, 1974), Lowder (1973), and Hamblin and others (1981). Best and Brimhall (1974) and Best and others (1980) discussed *petrogenesis and tectonic setting of the flows*: Analyses of 32 samples collected in and near the quadrangle, and data from Best and Brimhall (1970, 1974) cluster into four groups (table 1 and figures 5 and 6). These groups are also apparent in outcrops and hand samples.

[table 1 near here]

[figure 5 near here]

[figure 6 near here]

The first group are quartz-bearing, basaltic trachyandesites. Rocks are gray to dark-brownish-gray, porphyritic, and have an aphanitic groundmass. They contain abundant large plagioclase phenocrysts up to 0.4 inches (1 cm) in diameter, large embayed 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 Big Sand, Lava Ridge, Twin Peaks, and Middleton flows are of this type.

The second group are trachybasalts and alkaline basalts (figure 5) that Best and Brimhall (1974) described as Hawaiites. They are dark-greenish-gray to almost black, dense, aphanitic, and have abundant small olivine phenocrysts. The Cedar Bench, Snow Canyon Overlook, and airport flows are of this type.

The third type are similar to the second type, and are also called Hawaiites (Best and Brimhall, 1974) but samples consistently have a higher iron content and plot as subalkaline basalts (figure 5). The Santa Clara flow is of this type.

The fourth group plot in the tephrite basanite field (table 1 and figure 5) and are called ankaramites (an olivine-bearing basalt containing abundant clinopyroxene and olivine phenocrysts) by Best and Brimhall (1974). They are dark greenish gray to very dark gray and have a uniform seriate texture with abundant small phenocrysts of clinopyroxene and olivine that range from about 0.1 inch (3 mm) down to the groundmass. The groundmass is plagioclase and titaniferous magnetite (Best and Brimhall, 1974). The Washington flow is of this type.

Older flows (Tbo): Two high-elevation basaltic caps are mapped as older flows. One is in and near section 1, T. 42 S., R. 16 W., and the other caps T-bone hill in section 18, T. 42 S., R. 15 W. Both are isolated remnants separated from other flows of similar level by more than 2 miles (3.2 km). The flow in section 1 stands at least 600 feet (183 m) above modern drainages. The T-Bone Hill flow caps a hill about 160 feet (49 m) above the Middleton flow, which in turn is about 200 feet (61 m) above the Virgin River. However, the T-Bone Hill flow is not near a major drainage and we are uncertain if the combined elevation of 360 feet (110 m) can be used to determine a reliable relative age for this flow. It is about 400 feet (122 m) lower than the flow in section 1, but it is also 1.5 miles (2.4 km) downslope. The flows are about 20 to 30 feet (6-9 m) thick.

No chemical analyses of these flow remnants are available, but hand-sample descriptions suggest they are quartz-bearing, basaltic trachyandesite, described above (table 1 and figures 5 and 6). They are strongly jointed and weather to form large, angular, blocky rubble. They are similar in composition and at about the same level as the West Black Ridge flow in the St. George quadrangle (Higgins and Willis, 1995), which was K-Ar dated at 2.3±0.1 Ma (Best and others, 1980) and at 2.24+0.11 Ma (Hamblin and others, 1981). We believe these flow remnants originated from an early eruption at Twin Peaks in the northern part of the quadrangle.

Washington flow (Tbw): Only a small part of the Washington flow is exposed in the southeast corner of the quadrangle. It can be traced northeast of the quadrangle about one 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, described above (table 1 and figures 5 and 6) (Best and Brimhall, 1974; Best and others, 1980). It is strongly jointed and is about 30 feet (9 m) thick. This flow was dated at 1.7±.1 Ma (Best and others, 1980) which seems to correlate well with amount of adjacent downcutting and the age of other flows in the area. 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 and Harrisburg Junction quadrangles). The part within the St. George and Washington quadrangles is only about 280 feet (85 m) above the river. We attribute about 20 to 30 feet (6-9 m) of this to Quaternary offset on a splay of the Washington fault, which cuts the flow. The remaining 50-foot (15-m) difference is due to slumping and settling of the basalt on the weak, heavily-weathered, clay-rich Petrified Forest Member, which was probably saturated with river water at one time. It has been quarried for building stone just outside of the quadrangle.

__Twin Peaks flows (QTbt) and cinder cones (QTbtc)__: Twin Peaks, in the northern part of the quadrangle, consists of two to four partially overlapping cinder cones. The cones are moderately eroded and expose cores of welded spatter and flow breccia. The Twin Peaks flows are dark-gray to dark-greenish-gray, quartz-bearing, basaltic trachyandesite, described above, (table 1 and figures 5 and 6), and are difficult to distinguish from the Lava Ridge flows. Several flows erupted from this source. The older basalt remnants described above (Tbo) may have been from early eruptions. Later flows followed several paths to the south and southwest. One lobe flowed almost due south and now caps a large inverted valley in the east-central part of the quadrangle. A side-lobe from this flow topped over a saddle in section 20, T. 41 S., R. 15 W. and cascaded into a narrow linear valley eroded along a large fracture or older fault near East Knolls. It then followed this valley south for about 3 miles (4.8 km). These two lobes are at slightly different elevations in section 32. Another lobe of the Twin Peaks flows cascaded down a draw in sections 17, 18, and 19, T. 41 S., R. 15 W. that was probably an earlier canyon of Black Gulch. This flow is about 50 feet (15 m) higher than the Cedar Bench and the Middleton flows, and formed a resistant ridge that deflected the later flows. This lobe may be an upper part of the older basalt flows (Tbo) that cap West Black Ridge in the St. George quadrangle

(Higgins and Willis, 1995), or it may be a source of the lower Black Knolls caps near T-Bone Hill.

Basaltic flows cap several knolls of slightly different elevations near Middleton Wash in section 32, T. 41 S., R. 15 W. and section 5, T. 42 S., R. 15 W. Relations are unclear in the area, but the caps represent at least three different eruptions from the Twin Peaks area, including some of those described above.

No radiometric ages have been determined for the Twin Peaks flows. However, the 2.24 and 2.3 Ma ages on the West Black Ridge flow, discussed above, may be the age of early eruptions from this source. All Twin Peaks flows seem to be older than the Middleton flows and the Cedar Bench flows, dated at 1.5±0.1 Ma and 1.2±0.1 Ma, respectively, (Best and others, 1980) suggesting an age range of 2.3 to 1.5 million years.

Lava Ridge flow (Qbl) and cinder cone (Qblc): The Lava Ridge cinder cone is near the upper end of Lava Ridge in section 12, T. 41 S., R. 16 W. It consists of a single cinder cone that is partially eroded but that still has a cone-shape, and three main bodies of welded spatter. The rock is moderate- to dark-gray to dark-brownish-gray, quartz-bearing, basaltic trachyandesite, described above (table 1 and figures 5 and 6), and is similar to the Twin Peaks flows. The vent was the source of three or more flow lobes or cooling units that moved south, southeast, and west from the source. Stacked flows or cooling units are exposed in Black Gulch, about 1.5 miles (2.4 km) south of the cones. The main flow moved almost due south down a broad valley that gradually narrowed toward the south end. Our mapping indicates that part of this flow continued to the southeast as the Middleton flow, which we mapped separately.

Several small lobes also flowed westward from the side of the main flow into Big Sand. Apparently, the Big Sand area was part of a low valley (continuous with Diamond Valley via a connection approximately in the position of Utah Highway 18 near the west quadrangle border) separated from the valley followed by the main flow by a narrow sandstone ridge. The side lobes flowed through notches or passes in the sandstone ridge and cascaded into the deeper valley. The most impressive lava cascade is in the E 1/2, section 14, T. 41 S., R. 16 W. near the Winchester Hills housing development, where a cascade descended 600 feet (183 m) in 0.25 miles (0.4 km). The distal end of the cascade is near the present elevation of Big Sand, indicating that the Big Sand flat has undergone almost no downcutting since the cascade was emplaced. This is probably because another lobe of the flow blocked the valley between Diamond Valley and Big Sand (just west of the quadrangle), forcing the main drainage to the west into the present position of Snow Canyon, and protecting the cut-off valley from future erosion. (There is almost no downcutting east of the Snow Canyon overlook flow and near the upper part of the Big Sand flow for the same reason).

Best and others (1980) determined the age of the Middleton flow, which we traced into the Lava Ridge flow, of 1.5±0.1 Ma, using the K-Ar method. This correlates well with an age of 1.2±0.1 Ma they determined for the Cedar Bench flow, which directly overlies the Middleton flow. However, because the Lava Ridge sequence is composed of multiple flows, parts may be considerably younger or older. This age conflicts with the age of the airport flow, discussed later.

Middleton flow (Qbm): The Middleton flow forms a long thin "finger" that extends southward through most of the Washington quadrangle and about two miles (3.2 km) into the St. George quadrangle (Higgins and Willis, 1995). In the northern part of the St. George quadrangle it consists of three flows of slightly differing mineralogy (Hamblin and Best, 1970; Higgins and Willis, 1995). The Middleton flow is a quartz-bearing, basaltic trachyandesite, described above. Table 1 and figures 5 and 6 give analyses of two samples from the Middleton flow that indicate SiO_2 contents of 48.6 and 51.1 percent. This is considerably less than the 53.6 percent SiO_2 average on seven analyses reported by Best and Brimhall (1970). We consider the higher numbers to be more representative of the main flows 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.

Outcrops of the Middleton flow are complexly intermixed with outcrops of the Cedar Bench and Twin Peaks flows in the central part of the quadrangle. Apparently, all of these flows followed the same valley at different times. The Cedar Bench flow sits directly on top of the Middleton flow; locally, there is a thin alluvial gravel layer between, but in most areas the two basalts are in direct contact. The Middleton flow is consistently 50 to 100 feet (15-30 m) lower in elevation that the Twin Peaks flows. The source of the Middleton flow has generally been attributed to the cinder cone complex at Twin Peaks (for example Hamblin, 1987); however, we followed the flow to the Lava Ridge source area. This source seems to fit better with the relative elevations of the different flows in the middle part of the quadrangle.

The Middleton flow stands about 200 feet (61 m) above the Virgin River and has been dated at 1.5±.1 Ma (Best and others, 1980). This age is inconsistent with the ages of other flows in the area (figure 4, also see discussion of airport flow).

Snow Canyon Overlook flow (Qbso): The Snow Canyon Overlook flow is exposed only in a few small outcrops west of Big Sand near the western quadrangle boundary. These outcrops are part of a large flow remnant about two miles (3.2 km) long and 0.25 miles (0.4 km) wide that caps a bench overlooking Snow Canyon just west of the quadrangle. This flow is a trachybasalt, described above (table 1 and figures 5 and 6). It is dense and strongly jointed, and weathers to a very dark brown with small phenocrysts that weather out in relief. There are no additional exposed remnants of this flow to the south or north for several miles, making relations to other flows unclear. It is likely that the source is in the Veyo or Saddle Mountain quadrangle. It is geochemically similar to the Cedar Bench flow (table 1 and figure 5 and 6), and there is a reasonable flow path from that source, but we have not investigated that possibility. This flow may be a separate remnant of the airport flow since they are chemically similar (table 1, and figures 5 and 6), but the distance between these remnants makes that correlation uncertain. The age of this flow has not been determined, but it directly overlies the Lava Ridge flow in section 15, T. 41 S., R. 16 W., just west of the quadrangle, which we estimate is about 1.5 million years old for reasons discussed above.

Cedar Bench flow (Qbc): This flow forms a broad sloping bench in the north-central part of the quadrangle. It consists of trachybasalt (table 1 and figures 5 and 6) and is dark greenish gray, phenocryst poor, and very brittle. It is moderately jointed and weathers to form angular blocks with smooth surfaces that break with a conchoidal fracture. It apparently was more fluid than other flows and formed a relatively smooth upper surface. It is sourced in the hills north of the quadrangle and flowed southward. At least four flows or cooling units are exposed in Black Gulch in the NE 1/4, section 16, T. 41 S., R. 15 W., where two are separated by gravel deposits. One of the flows continued several miles to the south. In the Black Gulch area it was confined between older ridges of the Lava Ridge and Twin Peaks flows and flowed down a canyon floored by the slightly older Middleton flow. It flowed on top of the Middleton flow and on a thin alluvial cover on the Middleton flow for about four miles (6.4 km) to near Black Knolls Reservoir. The composite thickness in the Black Gulch area is about 150 feet (46 m), but to the south the single flow maintains a uniform thickness of only 5 to 10 feet (1.5-3 m) thick. Best and others (1980) determined a K-Ar age of 1.2±0.1 Ma for this flow.

Airport flow (Qba): The airport flow caps a long, narrow bench followed by Utah Highway 18 in the southwestern part of the quadrangle and forms the base for the St. George airport in the St. George quadrangle (Higgins and Willis, 1995). This flow is dark-greenish-gray to dark-brownish-gray, phenocryst poor, basalt to trachybasalt (table 1 and figures 5 and 6). It is strongly weathered along joints and fractures, giving it a patch-work appearance. Columnar jointing is moderately developed in some exposures. Two cooling units are well exposed along the east side of the flow near the airport. As mapped it may include part of a quartz-bearing, basaltic andesite flow.

The flow is 330 feet (97 m) above larger active drainages (Higgins and Willis, 1995) and was K-Ar dated at 1.07±0.04 Ma (Hamblin and others, 1981). This age is inconsistent with calculated ages of other basalts in the area (figure 4). For example, the Middleton flow was dated at 1.5±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) was dated at 1.6±0.1 Ma (Best and others, 1980) but is only 300 feet (90 m) above active drainages. Additional data is needed to resolve the inconsistent ages. This flow varies from 10 to 50 feet (3-15 m) thick.

The airport flow seems to grade directly into the Big Sand flow without an obvious contact. However, analyses of the two flows show a sharp difference (table 1 and figures 5 and 6), supporting our mapping of the airport flow beneath the Big Sand flow. The location of the mapped contact between the two flows is tenuous.

Big Sand flow (Qbb) and cinder cone (Qbbc): A prominent, well-formed cinder cone, here called the Big Sand cone, is present on the boundary between sections 25 and 26, T. 41 S., R. 16 W. A flow is exposed in several outcrops around the cinder cone that we map as an outflow facies of the cone. Analyses of the cinder cone and the basalt flow indicate the two are almost identical, confirming this interpretation (table 1 and figures 5 and 6). They are quartz-bearing, basaltic trachyandesites, described above. The flow consists of dense rock and abundant "rafts" of scoria and cinders that were apparently transported in the flow. The flow spread out in Big Sand and then narrowed into a channel that generally followed the path of the older airport flow. The distal end of the flow is difficult to distinguish from the airport flow, but is tentatively mapped near Miller Spring.

The Big Sand flow has not been dated and the complex downcutting history near Big Sand makes it difficult to estimate an age. The morphology of the cinder cone, which is mostly unaltered by weathering and the abundant scoria on the flow surface suggest it is younger than other nearby flows. It does have a thick stage V to VI pedogenic carbonate (Birkeland and others, 1991). Halfway Wash, which is not well graded to the Santa Clara River, is incised about 200 feet (61 m) on the west side of the flow. It overlies the airport flow, dated by Hamblin and others (1981) at 1.07±0.04 Ma; however, this age is questionable (see discussion of airport flow). Therefore, we postulate that the Big Sand flow and cone are between 0.75 and 1.2 million years old.

Santa Clara flow (Qbs) and cinder cone (Qbsc): The Santa Clara flow and cinder cone are mostly in adjacent quadrangles, but extend into the Washington quadrangle near the northwest corner. The quadrangle boundary just "clips" the edge of a well-shaped cinder cone and a second cone of similar age is a few hundred feet north of the quadrangle. These very young, well-shaped cones are some of the favorite tourist attractions of Snow Canyon State Park. They are composed of subalkaline basalt and have a distinctly higher iron content than other flows in the area (table 1 and figures 5 and 6). The flow consists of dark-reddish-black aa lava with a very jagged upper surface. The iridescent sheen typical of very young flows has been mostly weathered away and can only be found on a few protected surfaces. There is no significant buildup of soil on the flow, but some windblown sand has collected in pockets and depressions. Downcutting of a few tens of feet is locally present where streams forced out of equilibrium by the flow quickly readjusted, but overall the flow is near the present land surface. Luedke and Smith (1978) and Hamblin (1987) estimated this flow is as young as 1,000 years old. We estimate it is 10,000 to 20,000 years old.

Alluvial Deposits

Alluvial gravel beneath lava flows (QTag, Qag): Small, isolated outcrops of stream deposited, poorly to moderately sorted, clay- to boulder-sized sediment are locally exposed beneath and between lava flows. Most of the clasts are well-rounded cobbles and small boulders that are exotic to the quadrangle, including Tertiary igneous and sedimentary rocks derived from the Pine Valley Mountains, and late Tertiary or Quaternary basaltic clasts. The best exposures are typically in road cuts near Utah Highway 18 and in Black Gulch. Deposits in the bottom of Black Gulch are cemented with calcium carbonate. Thickness varies from 0 to 40 feet (0-12 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): Several small, isolated remnants of moderately sorted, clay- to boulder-sized, pedogenic-carbonate-cemented gravel are deposited at high levels throughout the southern part of the quadrangle. The deposits are isolated and cannot be clearly related to the current drainage network. Deposits in NE 1/4, section 11, and in SW 1/4, section 12, T. 42 S., R. 16 W. are about 200 feet (61 m) above Halfway Wash, but are not near any well-graded drainages. The deposit in section 12 probably shortly predates or postdates the airport flow.

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 basalt 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 (Higgins and Willis, 1995).

Small deposits cap low hills near Washington on the south border of the quadrangle near the north edge of section 22, T. 42 S., R. 15 W. They are not close to a major drainage, but they are estimated to be about 120 feet (36 m) above major drainages at the level of Qat_4 deposits, and to correlate with remnants of an old erosional surface exposed north of Washington.

Stream-terrace deposits (Qat_3, Qat_4): Gravel- to cobble-size clasts in a sandy matrix form a moderately sorted, partially indurated conglomerate at several levels above the present floodplains of the major tributaries of the Santa Clara and Virgin Rivers. They are much more extensive in the St. George quadrangle (Higgins and

Willis, 1995). They are similar to older terrace deposits (Qato) described above, except that they can be correlated with confidence to river terraces. Most clasts are exotic to the quadrangle, indicating a source several miles upstream. The terraces have a thick pedogenic carbonate (caliche) with up to Stage VI carbonate development (Birkeland and others, 1991). Several levels exist in the area that we combine into three groups for mapping (Higgins and Willis, 1995). Level 3 deposits are 40 to 90 feet (12-27 m) and level 4 deposits are at 90 to 140 feet (27-42 m) above present channels. No level 5 deposits, which are at 140 to 190 feet (42-57 m), were mapped, but some of the Qato deposits may correlate with this level. Thickness varies from 0 to about 20 feet (0-6 m). Using a downcutting rate of 300 feet (90 m) per million years (figure 4) (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. However, the ages are only approximate since downcutting rates probably varied and there is some uncertainty about the age of the basaltic rocks used to establish the downcutting rate (see discussion of the airport flow).

Alluvial boulder-terrace deposits (Qatb): Boulder-terrace deposits are common along many of the small streams and ephemeral washes in the quadrangle. They are composed of poorly sorted, subangular to subrounded boulders with minor clay to cobble-sized matrix. The boulders are primarily basalt, but locally they are derived from the Navajo Sandstone, Carmel Formation, Iron Springs Formation, Grapevine Wash Formation, and the Pine Valley intrusive complex. The Grapevine Wash and

Pine Valley boulders are particularly noticeable. Boulders are typically 1 to 3 feet (20-90 cm) in diameter, but a few exceed 6 feet (2 m) in diameter where near local sources. The deposits are generally 5 to 20 feet (1.5-6 m) thick and armor benches along the washes. These deposits form a series of terraces at several levels from a few feet to about 200 feet (61 m) above the washes. They probably correlate with the better-defined terraces near the larger streams and rivers (Qat_3, Qat_4, and Qato), but correlations are uncertain because the local washes are not well graded to the major drainages. They are 0 to 30 feet (0-9 m) thick and are middle Pleistocene to early Holocene in age.

Alluvial-boulder deposits (Qab, Qabo): Thick remnants of older alluvial gravel and debris-flows rest on sedimentary strata and basalt flows in the northeast corner of the quadrangle near Cottonwood Creek and Spring Hollow. The deposits consist of very poorly sorted boulder gravel with clasts up to 10 feet (3 m) in diameter. Most clasts are sedimentary and igneous rocks derived from the Pine Valley Mountains, but a few basalt clasts are in the deposits in Spring Hollow near the Cedar Bench flow. Older deposits are 250 to 300 feet (76-91 m) above Cottonwood Creek and younger deposits range from about 50 to 150 feet (15-45 m) above nearby drainages. The drainages are not graded to major rivers in the area so the age is poorly constrained, but we estimate the younger deposits are middle to middle-late Pleistocene and the older deposits are early Pleistocene. However, the older deposits may be of Late Tertiary age. The deposits are 30 to 100 feet (9-30 m) thick.

Older alluvial deposit near Washington (Qaow): Poorly to moderately well-sorted alluvial-fan deposits of clay- to small boulder-sized materials cover part of an inclined surface in the southeast part of the quadrangle (E1/2, section 32, T. 42 S., R. 15 W.). They contain 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 drainage 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-fan deposits (Qafo): Remnants of old, poorly sorted boulder deposits with moderate amounts of finer-grained materials cover sloping surfaces in the Mill Creek area north of Washington. Boulders are mostly locally derived basaltic rocks and are up to about 8 feet (2.4 m) in diameter. They were deposited by debris-flow, sheet flow, and colluvial processes. They grade into older boulder-terrace deposits (Qatb) and talus deposits (Qmt), and locally include small amounts of eolian and younger alluvial materials. Current drainages incise the deposits 10 to 100 feet (3-30 m). The deposits are 0 to 20 feet (0-6 m) thick.

Stream deposits (Qal_1-Qal_2): Moderately to well-sorted clay to small gravel deposits are mapped near Halfway Wash and Mill Creek in the southern part of the quadrangle. They are mostly sand, silt, and clay but include some gravel with small boulders. They are similar in age and setting to Qac deposits but are generally better sorted and can be divided into older and younger levels. Qal_1 deposits are up to 20 feet (6 m) above current channels and are 0 to 20 feet (0-6 m) thick. Qal_2 deposits are adjacent to and are dissected by drainages containing Qal_1 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 and caliche (Qe, Qecl): Well- to very well-sorted, fine- to very fine-grained, well-rounded, quartz sand has accumulated in irregular hummocky mounds on the lee side of ridges and in depressions. Locally, it forms poorly developed dunes. Thick pedogenic carbonate (caliche) up to stage VI (Birkeland and others, 1991) is exposed near the base of the deposits in road and stream cuts, and on a few low mounds. This carbonate and cemented sand cap is mapped as Qecl where exposures are large. Most of the sand was locally derived from the Navajo Sandstone and upper member of the Kayenta Formation and has only been transported short distances. Largest deposits are near Mill Creek, downwind of large Navajo outcrops. Deposits vary from 0 to 50 feet (0-15 m) thick.

Mass-Movement Deposits

Slump and landslide deposits (Qms, Qmsy): Several large landslides and slumps have formed on steep slopes beneath basalt flows and resistant bedrock units. 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 in the Petrified Forest Member of the Chinle Formation in the southeast corner of the quadrangle, and in the Temple Cap Formation, Carmel Formation, and Cretaceous bentonitic clays north of Yellow Knolls and near Diamond Valley. The mass-movements incorporate overlying bedrock formations, talus, and basalt. Most of the landslides and slumps are prehistoric and are probably middle to late Pleistocene in age. Only one landslide with historic movement was recognized. It is in the E1/2, section 18, T. 41 S., R. 15 W. and involved reactivated older landslide materials. It is about 300 feet (91 m) long and 200 feet (61 m) wide and has slid a few feet to a few tens of feet. A small spring issues near the base of the slide.

Talus deposits (Qmt): Talus deposits are very poorly sorted, angular boulders with minor fine-grained interstitial material that have accumulated on and at the base of steep slopes. Extensive talus cones are present beneath the basalt-capped ridges. Small amounts of talus, generally included with colluvial deposits, was also derived from the Carmel and Iron Springs Formations in the northern part of the quadrangle. Most of the talus cones in the quadrangle are active, a few are not. The latter form a protective armor over softer bedrock, and are gradually eroding out in relief. Mapped deposits are generalized and are gradational with colluvium. Only large deposits are mapped, but talus boulders are common on all steep slopes in the quadrangle. Thickness varies from 0 to 20 feet (0-6 m).

Colluvium (Qc)

Colluvium is common on most low to intermediate slopes in the quadrangle. It consists of locally derived, poorly sorted, clay- to boulder-sized materials. Most deposits are actively accumulating materials, but some mapped deposits are older and are being dissected by active washes. Active and inactive deposits are not differentiated on the map. The deposits are gradational with, and include alluvium and talus, and are commonly partially covered by eolian sand. They are 10 to 30 feet (3-9 m) thick.

Mixed-Environment Deposits

Eolian sand and alluvial deposits (Qeca): These deposits are composed of alluvial gravel, silt, sand, and clay, and eolian silt and sand that has accumulated on top of the basaltic flows in the central and southern parts of the quadrangle. A pedogenic carbonate soil has developed on most of the deposits. Mappable deposits accumulated only where the flows were in canyons where streams flowed on the flows, planing off their tops and depositing alluvial boulder gravels, sand, and silt. As regional downcutting continued, the streams worked to the sides of the basalts into the softer sedimentary rock. Once isolated from stream deposition, the upper surfaces of the flows continued to accumulate eolian silt and sand. The thickest deposits are on the oldest flows, where a pedogenic carbonate soil horizon has developed up to Stage VI (Birkeland and others, 1991). In areas where streams did not flow across the top of the basalt, the upper surface remained rough such that mostly basalt is still exposed. The thickness varies from 0 to 15 feet (0-18 m).

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) cap. They are mapped on an inclined surface near Washington City, (also partially covered with Qaow deposits), and in St. George. They form broad, sloping benches dissected by current drainages, and have a thick pedogenic carbonate layer. They are from 0 to 30 feet (0-9 m) thick.

Eolian and alluvial deposits (Qea): These deposits are composed mostly of well-sorted eolian sand with a thick pedogenic carbonate, but locally they have been reworked by water and include minor alluvial deposits. They are preserved on surfaces that have been protected from erosion for long periods of time, and are mapped mostly in the Mill Creek area north of Washington. They are 0 to 20 feet (0-6 m) thick.

Alluvial and eolian deposits (Qae, Qaes): 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 that are still undergoing active deposition, and have minor or no pedogenic carbonate (caliche) development (figure 7). In the Washington area they consist primarily of silt- and clay-sized particles (Christensen and Deen, 1983). Deposits that are primarily reworked eolian sand are mapped as Qaes. The deposits are typically 0 to 30 feet (0-9 m) thick, but locally may be thicker.

[figure 7 near here]

Alluvial and colluvial deposits (Qac) and alluvial, colluvial, and eolian deposits (Qaec): Poorly to moderately sorted clay- to boulder-sized material is mapped in minor drainages throughout the quadrangle. It has a component of both alluvial and colluvial deposits. The alluvial deposits are transported along the washes by heavy rainstorms while the colluvial material is derived from side slopes along the washes. These deposits are gradational with colluvial deposits and correlate with level 1 and 2 alluvial deposits (Qal_1, Qal_2). Deposits that are mostly reworked eolian sand are mapped as Qaec. They vary in thickness from 0 to 20 feet (0-6 m).

Artificial Fill (Qf)

These deposits include fill emplaced in the construction of dams across two washes and various materials deposited in a now-abandoned sanitary landfill. Fill emplaced during road and building construction is not shown.

STRUCTURE

Regional Setting

The Washington quadrangle is in the transition zone between the Colorado Plateau and the Basin and Range Provinces (Hamblin, 1970b; Hintze, 1986). The transition zone roughly coincides with the leading edge of the Late Cretaceous Sevier orogenic thrust belt, and rocks in the quadrangle are involved in minor detachments in front of the main thrust belt, and a basal detachment is postulated in underlying Cambrian strata. The transition zone is also part of the active southern segment of the Intermountain Seismic Belt, which coincides with the boundary between relatively thin crust and lithosphere of the Basin and Range Province and thicker more stable crust of the Colorado Plateau Province (Arabasz and Julander, 1986). It consists of a series of down-to-the-west normal faults that step down from the Colorado Plateau into the Basin and Range. The intermediate-level fault block that includes the quadrangle is offset on its eastern edge 6,000 to 8,000 feet (1,830-2,440 m) by the Hurricane fault (figure 1) (Hamblin, 1970b), and it is bounded on the west by the Grand Wash and Gunlock faults. The Gunlock fault attains a maximum stratigraphic displacement of about 3,000 feet (917 m) near Gunlock and the Grand Wash fault has a displacement of about 1,500 feet (457 m) near the Utah-Arizona border (Hintze, 1986).

The regional dip of the rocks in the Washington area is to the northeast at 5 to 10 degrees. Locally, rocks have been compressed into the broad north-east-trending St. George syncline and the much tighter Virgin anticline, the west flank of which affects rocks in the southeast part of the quadrangle.

Faults

Washington Fault Zone

The Washington fault zone is a major down-to-the-west, high-angle normal fault that bifurcates into several splays and trends generally north in northern Arizona and southern Utah (Cook, 1960; Peterson, 1983, Billingsley, 1993). Cook (1960), W.K. Hamblin (unpublished 1:62,500-scale mapping), and Christenson and Deen (1983) mapped the northern terminus in the southern part of the Washington quadrangle where the fault bifurcates into a series of smaller northwest- to northeast-trending faults. Cordova (1978) extended the fault into the northern part of the quadrangle and connected it with the Washington Hollow fault (our plate 1). In the southeastern part of the quadrangle, near Washington City, the Washington fault zone consists of three distinct north-northeast-trending erosional escarpments with bedrock exposed east of the faults. North of Washington the faults are difficult to map. In that area they are mostly obscured by extensive eolian and alluvial deposits, and cut homogenous upper Kayenta and Navajo Formations, placing similar lithologies on both sides of the fault. Several faults with northwest to northeast trends are exposed in limited outcrops in that area, but their relation to the main Washington fault is unclear. It is possible that the Washington fault does continue northward through Washington Hollow as Cordova (1978) mapped but the Navajo in that area is cut by many fractures and shear zones of probable Cretaceous age, making relationships unclear. One or more of these fractures may form a direct link between the Washington and Washington Hollow faults.

The Washington fault zone has about 700 feet (213 m) of offset in the Washington area based on tenuous projections of the Springdale Sandstone from outcrops about 2 miles (3.2 km) east of the fault and by projecting the m_2 marker bed in the Kayenta Formation. A splay of the fault zone cuts the Washington basalt flow in the southeast corner of the quadrangle and late Pleistocene sediments are offset south of the quadrangle (Christenson and Deen, 1983; Hecker, 1993) indicating that the fault should be considered active with late Quaternary offset.

Washington Hollow Fault and Related Faults

The Washington Hollow fault trends north-northwest near the northern border of the quadrangle (figure 8). It is down-to-the-west and has about 500 feet (152 m) of offset. In one exposure it dips 80 degrees southwest and has striations with a rake of 82 degrees south (plate 1). North of the quadrangle, the fault cuts the Tertiary Claron Formation and Pine Valley intrusive rocks (Cook, 1960), indicating late Tertiary movement. Cordova (1978) projected this fault southward to connect with the Washington fault; which we agree is possible. The Navajo is severely brecciated throughout Washington Hollow but we were unable to identify a distinct fault.

[figure 8 near here]

Several smaller faults with offsets up to about 100 feet (30 m) are mapped in the northeast part of the quadrangle near the Washington Hollow fault. Most trend northwest but both down-to-the-west and down-to-the-east offsets were recognized. The faults are high-angle and mostly dip slip. One well-exposed bedrock fault surface dips about 80 degrees west and has striations with a rake of 60 degrees south. Most of these faults project south into large fractures in the Navajo Sandstone, indicating that the Navajo is also offset, but the distinct fault traces rapidly become lost among the many fractures. However, the faults in the layered strata are indicative of the amount of faulting that likely exists in the Navajo in the Washington Hollow area.

St. George fault

The St. George fault is a north-trending, high-angle, down-to-the-west normal fault exposed near the center of the southern border of the quadrangle where it offsets the upper Kayenta and Navajo Formations. It extends south into the St. George quadrangle where it is exposed in a rock quarry (Higgins and Willis, 1995). Cordova (1978) extended the fault northward through the Washington quadrangle along a large fracture zone that is prominently exposed in the Navajo Sandstone in section 17, T. 41 S., R. 15 W. A basalt flow flowed down a narrow, straight, stream channel differentially eroded along the fracture from section 5 to section 17, T. 42 S., R. 15 W., but the basalt is not faulted (plate 1). We have chosen not to map the fault along the fracture zone since Middleton flow obscures the connection between the St.

George fault and the fracture, but we recognize that this fracture is the most likely location of the fault if it does extend north through the quadrangle.

Christenson and Deen (1983) mapped a series of small faults with several orientations in the Navajo Sandstone just north of the Middleton basalt flow near the St. George fault, and they showed a sharp bend in the St. George fault near its northern end. We were unable to recognize these faults or the bend in our mapping.

The St. George fault projects beneath two well-exposed basalt flows that are not offset, indicating that latest movement was at least 1 million years ago. The 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

A high-angle normal fault is mapped in section 18, T. 42 S., R. 15 W., near the southern quadrangle boundary. 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) mapped a small graben with a few tens of feet of displacement in this location. This fault cuts only Jurassic rocks and thus there are no constraints on timing of movement.

Two faults cut the Cedar Bench basalt flow near the northern edge of the quadrangle. Both form prominent scarps in the basalt north of the quadrangle that become less distinct southward. One is queried on the map because the scarp is indistinct within the quadrangle (plate 1). The faults cut the middle Quaternary basalts and have offsets of less than 100 feet (30 m) in the quadrangle.

St. George Syncline

Strata in the quadrangle are folded into a very broad, poorly defined syncline, that Cordova (1978) called the St. George syncline. The fold is too broad to be recognized in the field or shown on the map but it is indicated by a change from northeast dips in the southwest part of the quadrangle to north and north-northwest dips in the southeastern part. The axis is poorly defined due to the lack of bedding planes on which to make measurements in the Navajo Sandstone but it must trend north-northeast approximately through the middle of the south part of the quadrangle. It may die out near the middle of the quadrangle. A dip of 7 degrees northwest was measured on an unusual thin-bedded layer in the middle of the Navajo (section 32, T. 41 S., R. 15 W.) but it is difficult to correlate this measurement with the broad syncline.

Fractures and Brecciation

All competent bedrock units in the quadrangle are cut by fractures, but by far the most prominent fractures are in the massive sandstone beds of the upper Kayenta and Navajo Formations. We recognize three main fracture types in these rocks and brecciation is also locally intense.

The first type are generally evenly spaced, parallel, high-angle, open joints (figure 2). The joints trend generally north but they swing slightly northeast or northwest in broad swatches. In a few areas, such as near Yellow Knolls, the uniform pattern is interrupted by high-angle conjugate joints with a sharply different orientation. Joints in this category are generally not healed or recemented and in many areas they weather to form a pattern of straight, narrow cracks in the rock a few inches to several feet wide and locally more than 50 feet (15 m) deep. Locally, they have iron-manganese oxide and calcite fillings. The joints are sharp and there is no evidence of brecciation or offset along the fractures. These joints are represented on the map by generally north-trending, mostly vertical joint symbols.

The second type of fractures are less prominent, though they are also common in the quadrangle. They are best exposed in and near sections 6 and 7, T. 42 S., R. 15 E, and in Washington Hollow. 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 in relief. There is generally some brecciation near the fracture and in some cases cross-beds in the sandstone are offset a few feet. However, many do not show evidence of structural deformation or offset. These are shown on the map by high-angle to vertical joint symbols and locally as mapped fractures.

The third type of fractures are similar to the second type except that they are larger and longer. They form large, straight gashes in the rock, and several are more than a mile (1.6 km) long (figure 9). Brecciation and siliceous and calcareous recementation is generally intense along these fractures. Several have crushed zones 5 to 10 feet (1.5-3 m) wide that are generally non-resistant and form large gashes that develop into washes. A linear basalt flow east of Yellow Knolls flowed down a canyon weathered along one of these fractures. In the Washington Hollow area, the fractures form a conjugate set that weather to form canyons. Generally, Middle Jurassic stratified rock is faulted where the fractures can be traced into them, indicating that many of these fractures are faults. The largest and most prominent of these fractures are mapped individually.

[figure 9 near here]

The Navajo Sandstone is strongly brecciated near the large fractures and is pervasively brecciated throughout the Washington Hollow area. The brecciated rock weathers into rough knobby knolls and slopes rather than vertical cliffs and canyons typical of the Navajo in non-brecciated areas.

ECONOMIC GEOLOGY

Volcanic Cinders and Rocks

Volcanic cinders are mined from the Big Sand cinder cone in section 25, T. 41 S., R. 16 W., in the west-central part of the quadrangle (figure 10). The cinders are used primarily for making cinder block, but some are used as road metal in residential driveways and as decorative stone in landscaping. The material is quarried with front-end loaders and is sorted through screens to remove fines and to create a uniform size. Color is critical in assessing value. Shades of dark red and reddish brown are more popular than grays or black. The cone has a thick surficial layer of white pedogenic carbonate that must be scraped back before the usable material can be excavated. Presently, quarrying has opened a large pit on the northeast flank of the cone that extends several tens of feet below the surrounding ground surface.

[figure 10 near here]

Two other cones in the quadrangle have not been quarried, one on Lava Ridge and one at Twin Peaks. Both are older than the Big Sand cone and the cinders are extensively eroded. They also have thick pedogenic carbonate rinds and introduced wind-blown sand that are costly to remove. A small sliver of the young Snow Canyon cinder cone is within the quadrangle in sections 3 and 10, T. 41 S. R. 16 W. This cone is within Snow Canyon State Park and is currently protected from exploitation.

Basalt boulders are popular for local landscaping because of their interesting shapes and dark colors. Such rocks have been removed from several of the lava flows in various parts of the quadrangle, but no specific localities or quarries are known.

Gypsum

The Temple Cap Formation in the northern part of the quadrangle contains three main beds and several minor beds of gypsum. The gypsum is bedded to nodular and is up to ten feet (3 m) thick in outcrops (figure 11). It is mostly pale gray, pale pinkish gray, or pale orangish gray and has colored streaks and mottling that impart patterns popular with artists. The gypsum nodules are currently quarried and are sold to art supply companies for sculpturing. The most desirable blocks are rounded nodules from 2 to 4 feet (61-122 cm) in diameter that have stronger colors. Blocks are quarried with back-hoes and front-end loaders and are hand-sorted for color, hardness, and flaws that might make them break during sculpturing. A few truck loads are removed annually.

[figure 11 near here]

Ornamental Stone

Blocks of sandstone from several of the local formations are commonly used in landscaping. Rocks that are darker shades of red and orange and that have mottled, banded, or flow patterns caused by leaching are generally considered the most desirable. Rocks from the Kayenta Formation are most commonly used because they are better cemented than the Navajo Sandstone. The Moenave Formation, well-cemented pedogenic carbonate, and basalt boulders are also used.

The Iron Springs Formation has some beds of "picture rock" or "landscape stone", which 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. No quarries or prospects are known in the quadrangle.

Building Stone

Dense sandstone beds in the Kayenta Formation and lower part of the Navajo Sandstone and basalt blocks were used as building stone in many older historic buildings in the area. Early pioneers built the most prominent historic landmark in the St. George basin, the St. George LDS (Mormon) Temple, from sandstone blocks quarried from the Kayenta Formation in the southern part of section 13, T. 42 S., R. 16 W., in the southwest part of the quadrangle, and from basalt quarried in the St. George quadrangle. An abandoned quarry in NW1/4, section 12, T. 41 S., R. 15 W., just east of the quadrangle boundary, produced large slabs of flat, well-cemented sandstone from just below the top of the Navajo. The slabs parted along near-planar cross-beds, and are unusually well cemented, making them useful in construction and landscaping. Similar beds are present in the quadrangle.

The Washington basalt flow in the southeast corner of the quadrangle is strongly jointed, forming blocks with flat surfaces about the right size for buildings and walls. Several workings are present along the edge of the flow just east of the quadrangle, where blocks separate along joints. Some blocks were also collected from the talus slopes below the ledge in the quadrangle.

Metals

In several areas near Utah Highway 18 in the western part of the quadrangle, the Navajo Sandstone is crossed by fractures and joints filled with manganese and iron oxide veins. The veins range up to about 4 feet (1.2 m) thick, but most are only a few inches thick. The total amount present is not large and there has been no known use of the materials. A prospect was dug along a fracture near the middle of section 2, T. 42 S., R. 16 W.

No other metallic mineralization is known in the Washington 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 10 miles (16 km) northeast of the quadrangle (James and Newman, 1986; Proctor and Brimhall, 1986). Anomalous concentrations of silver are present in the Springdale Sandstone in areas surrounding the mining district and some gold has been reported, but none of ore grade (Proctor and Brimhall, 1986).

Gravel, Roadfill, Riprap, and Sand

Gravel, essential for construction, is in limited supply in the quadrangle. Scattered, small, moderately-sorted terrace deposits in the southern part of the quadrangle contain small amounts of gravel and thin, poorly sorted gravel lenses are locally present beneath and between basalt flows. Construction projects have removed most terrace deposits in the southwestern part of the quadrangle. Boulder- (Qab, Qabo), boulder-terrace- (Qabt), and old alluvial-deposits (Qafo and Qaeo) have been used locally for road fill. Talus from the basalt flows has also been utilized locally for fill and riprap.

Large deposits of windblown sand (Qe) are scattered throughout the quadrangle. However, its fine-grain size and iron-oxide staining have limited commercial use.

Clay

The Chinle, Temple Cap, Carmel, and Iron Springs Formations, and the mapped bentonitic beds, contain various types of clays. No testing was done for this study, and no prospects or quarries are known in the quadrangle.

Oil and Natural Gas

No oil or gas exploration wells have been drilled in the Washington quadrangle. The nearest production was from the Virgin oil field, 20 miles (32 km) northeast of Washington, which was developed in 1907. Production through 1963 was 195,000 barrels of oil from 30 wells, although over 200 wells were drilled (Eppinger and others, 1990). Oil was produced 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 Callville 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). The Timpoweap probably also underlies the quadrangle, but has not been tested.

Geothermal Resources

The quadrangle is in an area with geothermal potential (Mabey and Budding, 1985; Budding and Sommer, 1986). Quaternary basaltic volcanoes, some as young as 10,000 years old, are in the quadrangle; however, basalts are believed to ascend through relatively small pipes from depths of several miles (Best and Brimhall, 1974). 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 (274 m) (Pete Tolman, personal communication, 1995), but no testing has been reported.

WATER RESOURCES

Water is the most valuable resource of the Washington quadrangle since wells and springs in the quadrangle are a major domestic water source for the rapidly growing St. George area (table 2). Cordova and others (1972), Cordova (1978), Clyde (1987), Horrocks-Carollo Engineers (1993), and a report by Utah Division of Water Resources (1993) studied water in considerable detail. 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

No rivers cross the quadrangle, but the Virgin River is just a few hundred feet south of the southeast quadrangle corner, and the Santa Clara River is just south of the southwest corner. A few washes and canyons carry perennial streams that are sourced from springs within or just north of the quadrangle. Cottonwood Creek crosses the northeast corner of the quadrangle and the upper part of Washington Hollow has a perennial stream that dries up as it seeps into the porous Navajo Sandstone; the middle interval of the wash is generally dry. The upper part of Mill Creek is generally dry, but the lower part has a perennial spring-fed flow. Halfway Wash and City Creek also have small spring-fed perennial flows.

Ground Water

The Virgin River forms the major base.level in the area and the unconfined potentiometric surface slopes toward the river from the north (Cordova and others, 1972; Cordova, 1978; Clyde, 1987). Within the Washington quadrangle, strata dip generally northward toward the Pine Valley Mountains, opposite the direction of water flow. Important aquifers in the quadrangle are in the Moenkopi, Chinle, Moenave, Kayenta, Navajo, and Iron Springs Formations, and in unconsolidated sediments (Cordova, 1972; Clyde, 1987). Of these, the Navajo aquifer, which consists of more than 2,000 feet (610 m) of porous, well-sorted, fine- to medium-grained sandstone (it includes the upper part of the Kayenta Formation), is the most important. Wells in the Navajo in Washington Hollow provide much of the St. George area drinking water (Horrocks-Carollo Engineers, 1993), and several large wells extract Navajo ground water in the Big Sand area (table 2). The primary recharge area for the Navajo aquifer is limited to the Navajo outcrop belt (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. (Horrocks-Carollo Engineers, 1993). Increased development on the Navajo aquifer recharge area is cause for concern since the aquifer is unconfined and may be contaminated with pollution from septic systems and other sources.

[table 2 near here]

Several small springs used primarily for irrigation issue near the contact between the middle and upper members of the Kayenta Formation in the southern part of the quadrangle (Jensen and Lowe, 1992). 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. 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. Small springs also emerge along fractures and faults in the Carmel and Iron Springs Formations in the northern part of the quadrangle. The water from these springs generally flows short distances down washes until it crosses the Navajo Sandstone, where it sinks into the subsurface.

The water quality in many springs and wells in the quadrangle is reported in Cordova and others (1972), Cordova (1978), Clyde (1987), and Freethey (1993). In general, water is fresh and of high quality in the Navajo aquifer, and 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 (Christenson, 1992). It 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.

Earthquakes

The Washington quadrangle is within the Intermountain Seismic Belt and the area has experienced several historic earthquakes of magnitude 4 or greater (Anderson and Christenson, 1989; Christenson and Nava, 1992; Christenson and Deen, 1983; 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 of 0.21 g for St. George (Black and others, 1992). Ground shaking 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 triggered many rock falls, at least two of which caused property damage, and caused a change in flow of hot springs near Hurricane (figure 1). 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 peak horizontal ground acceleration 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 (Anderson and Christenson, 1989; Christenson and Deen, 1983; Hecker, 1993). The Washington fault crosses the northeastern part of the quadrangle. 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) (Hamblin, 1970b; 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) in areas south of the quadrangle (Earth Science Associates reported in Christenson and Deen, 1983; and Hecker, 1993). Basalt in the southeast 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 areas near Washington City, amplifies waves that cause ground shaking, increasing damage. Flooding may result from failure of dams, canals, 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 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.

Slumps and Landslides

Basal detachments of slumps and landslides within the quadrangle develop primarily in clay-rich strata, which absorbs moisture, forming a weak, pasty substance (Harty, 1992). Landslides in the southeast corner of the quadrangle are in the Petrified Forest Member of the Chinle Formation. Slides in the north-central and northwestern parts are in the Temple Cap Formation, Carmel Formation, and in Cretaceous bentonitic beds (Kb). Most landslides last moved during the Pleistocene epoch when conditions were wetter than they are today (Christenson, 1992). Although slopes are now mostly 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. We recognized one historical landslide (map unit Qmsy) near the east edge of section 18, T. 41 S., R. 15 W., north of Yellow Knolls. It is about 300 feet by 200 feet (91 by 61 m) and has open fractures and rotated trees and shrubs. A small spring issues from near the base of the slide.

Developments on prehistoric landslides suffered some damage in the St. George area as a result of the 1992 magnitude 5.8 earthquake (Black and Christenson, 1993; Higgins and Willis, 1995).

Rock Falls

Significant rock falls are common in the quadrangle, as evidenced by abundant rock debris on and at the base of steep slopes. Rocks fall naturally when less resistant rock layers are eroded from beneath more resistant, fractured caprock, or during 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 of steep slopes are in the most danger.

Major rock-fall hazards primarily involve the basalt-capped ridges and the upper member of the Kayenta Formation. 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. Although a rock-fall hazard exists near the base of all slopes, the degree of hazard varies locally 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 that 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 the problem (Daily Spectrum newspaper, various issues from 1990 to 1995). Local 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 and 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 the area. In swell tests using a 60-pounds-per-square-foot (293 kg/m^2) 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 lower and middle members of the Kayenta Formation and the Whitmore Point Member of the Moenave Formation, the Temple Cap Formation, the Carmel Formation, and Cretaceous beds may 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, heaved and cracked floor slabs and walls, and failed wastewater disposal systems (Mulvey, 1992). Even if engineering precautions are taken to protect buildings, expansive soils can damage sidewalks, roads, porches, garages, driveway and patio slabs, and underground utilities. Damage can occur quickly. Thompson (1992) found an average time lapse of two years and seven months from construction to repairs in similar settings in the Denver, Colorado area.

Soluble Soil and Rock

Soluble soil and rock, deposits that contain minerals that dissolve when exposed to water, are common in the quadrangle. These include gypsiferous deposits, weathered limestone, and pedogenic and ground-water calcium carbonate. The lower member of the Kayenta Formation has gypsiferous beds that are subject to settlement, collapse, piping, and local heaving problems due to dissolution of gypsum (Christenson and Deen, 1983).

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 just south of the quadrangle (Higgins and Willis, 1995).

Collapsible and Compressible Soil

Geologically young materials are susceptible to hydrocompaction (Mulvey, 1992). Subsidence develops 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 (4,883 kg/m^2) 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 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 and debris flows are probably the most frequent natural hazard in the Washington quadrangle. Streams and washes in the quadrangle typically have small flows or are dry, but several have large catchment basins and unusually high spring snow melt at higher elevations and summer cloudbursts can turn them into raging torrents. Halfway Wash, Black Gulch, Twist Hollow, City Creek, Middleton Wash, Mill Creek, and Cottonwood Creek are particularly vulnerable. Large amounts of unconsolidated sediment and weathered bedrock in these drainages increases the danger of debris flows.

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. However, if radon gas is inhaled, 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 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 has 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 areas containing sediments derived from Miocene intrusive igneous rocks in the Pine Valley Mountains to the north. 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 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. 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 quadrangle area are of two main types, ash and lava flows from local sources, and wind-blown ash and dust from local and distant sources (Mabey, 1985; Bugden, 1992). Only hazards from local sources are discussed here. Volcanic activity in southwest Utah during mid-Cenozoic time was characterized by violent felsic-eruptions of large volumes of pyroclastic material but late Cenozoic eruptions resulted in smaller, less violent mafic cinder cones and flood basalts. The most recent basalt flow in the area is the Santa Clara flow, part of which is in the northwest corner 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 the amount of downcutting next to the flow and the amount of weathering of the basalt. It is likely that flows from future eruptions would follow drainages into populated areas. Hazards include damage and injuries from molten lava, explosively ejected cinders and volcanic gas, blockage of transportation corridors and rivers, disruption of utilities, and fires (Mabey, 1985).

SCENIC AND RECREATIONAL RESOURCES

The Washington quadrangle is in the "red rock" country of southwestern Utah and includes many 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 Zion National Park and Snow Canyon State Park. Several roads within the quadrangle are popular for their vistas of the St. George basin, Snow Canyon, and the towering cliffs of Zion National Park.

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Lehi F. Hintze shared his expertise during many hours in the field. This study benefited from numerous discussions and field trips with Spencer J. Reber and Ward O. Abbott of St. George. Mark Jensen of the Utah Department of Environmental Health provided information on domestic water supplies. Robert Nusbaum of the College of Charleston, South Carolina, and Douglas Sprinkel and Miriam Bugden of the Utah Geological Survey collected and analyzed several basalt samples. Larry Bulloch, Director of Public Works; Kent Provstgsard, engineering; and Wayne McArthur, Director of the Water and Power Department of St. George City willingly provided information. Dave Black of Black, Miller and Associates, Joel Myers of Kleinfelder, Wayne Rodgers of Southwest Testing, and Roy Rushing of Delta Geotechnical Consulting all contributed their knowledge of the geologic hazards in the area.

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Captions

Figure 1. Geographic and geologic features and 7 1/2' quadrangles near the Washington quadrangle. Basalt flows are shaded.

Figure 2. Strong north-trending, near-vertical joint set in the Navajo Sandstone near Yellow Knolls. The amount of jointing and brecciation in the Navajo varies greatly across the quadrangle. Light-color bands are due to leaching of iron-oxides.

Figure 3. North view across head of Washington Hollow toward Pine Valley Mountains. The Navajo Sandstone forms the blocky cliffs and bare steep slopes in the lower part of the photograph. The Temple Cap Formation forms darkest and lightest bands above the Navajo. The white band is the gypsiferous interval in the Temple Cap. The Co-op Member of the Carmel Formation forms the light-colored, well-bedded interval. Cretaceous strata cap the low hills. The Tertiary Claron Formation is exposed near the base of the mountains beneath the Pine Valley intrusive rocks.

Figure 4. 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 calculations use 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. 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 are 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 5. Geochemical classification of basaltic rocks in the Washington quadrangle. The West Black Ridge (Tbwb) flow is only present in the St. George quadrangle but we consider it correlative with the older flows (Tbo) mapped in the Washington quadrangle. The Washington flow data (*) are an average of five analyses on ankaramite flows reported in Best and Brimhall (1974). See table 1 for other sources of data. Classification from Le Bas and others (1986).

Figure 6. Ratios of major oxides of basaltic rocks in the St. George and Washington quadrangles. See figure 5 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 (*) are an average of five analyses on ankaramite flows reported in Best and Brimhall (1974). See table 1 for other sources of data.

Figure 7. A wash is eroded down to bedrock through about 12 feet (4 m) of Qae deposits in Washington Flat in the northern part of the quadrangle. The large boulders are from the Iron Springs Formation. The erosion was probably caused by a break in a waterline.

Figure 8. View northeastward across the Wahington Hollow fault. The Carmel and Iron Springs Formations on the left side of the fault are offset down against the Temple Cap Formation (white and dark beds) on the right side.

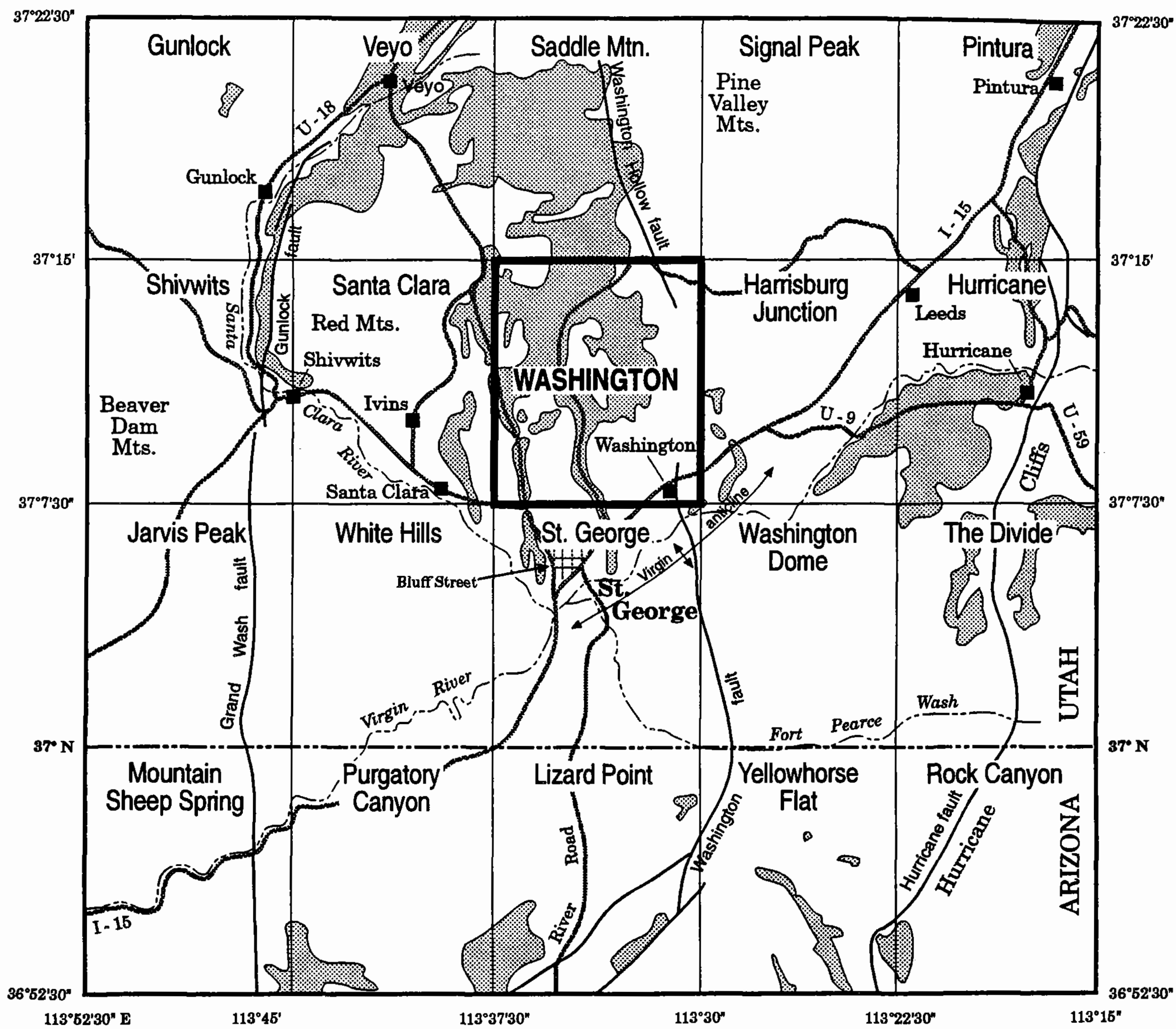
Figure 9. View northwestward along a large brecciated fracture in the Navajo Sandstone in section 7, T. 42 S., R. 15 W. The crushed rock has eroded out in relief, leaving a linear depression. The brecciated rock is partially recemented with calcite and quartz. In highly fractured areas the Navajo erodes to form sloping hills instead of the more typical cliffs. Compare with figure 2.

Figure 10. View southward toward the Big Sand cinder cone. Cinders are excavated from a large pit for making bricks. A thick pedogenic carbonate soil is visible near the rim of the hill.

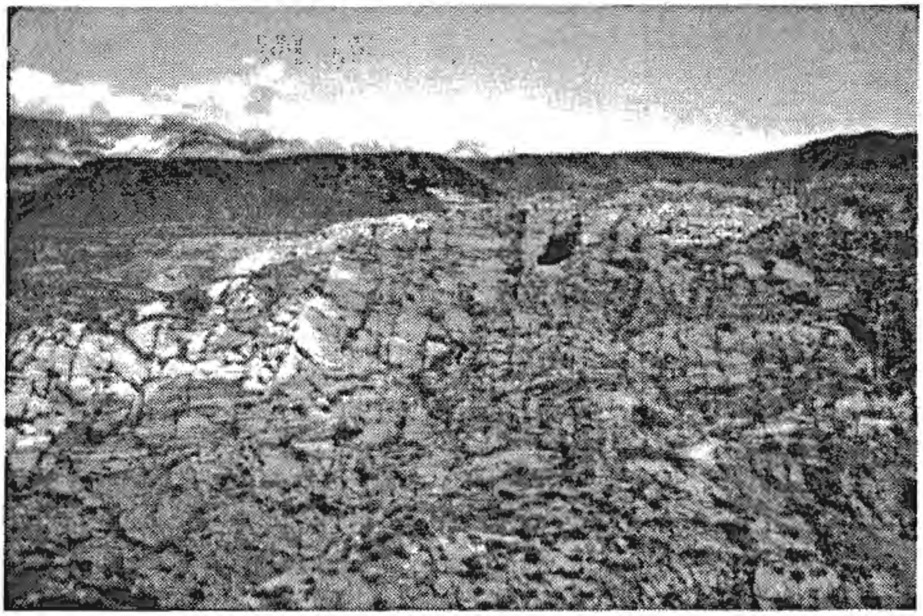
Figure 11. Gypsum nodules in a quarry in the NE1/4, section 11, T. 41 S., R. 15 W. The nodules are sold to art-supply retailers for sculpturing.

Table 1. Chemical analyses and normative calculations of basaltic rocks in and near the Washington quadrangle. Iron oxide data listed under Fe_2O_3 are recalculated to 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 the 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.

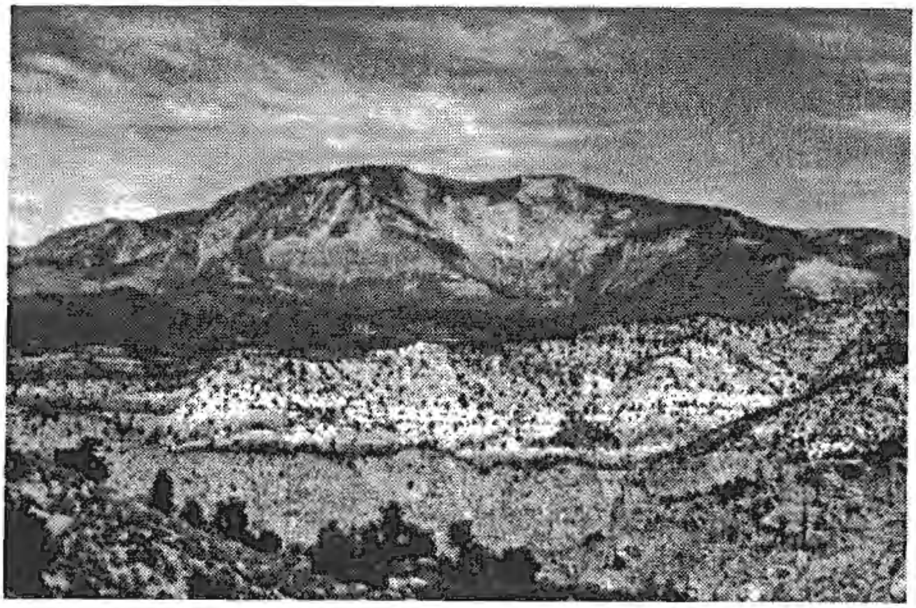
Table 2. Major drinking water sources in the Washington quadrangle.
Data from files of Utah Department of Environmental Quality, Division of Drinking Water. Flow is in gallons per minute. Navajo aquifer includes the upper part of the Kayenta Formation.



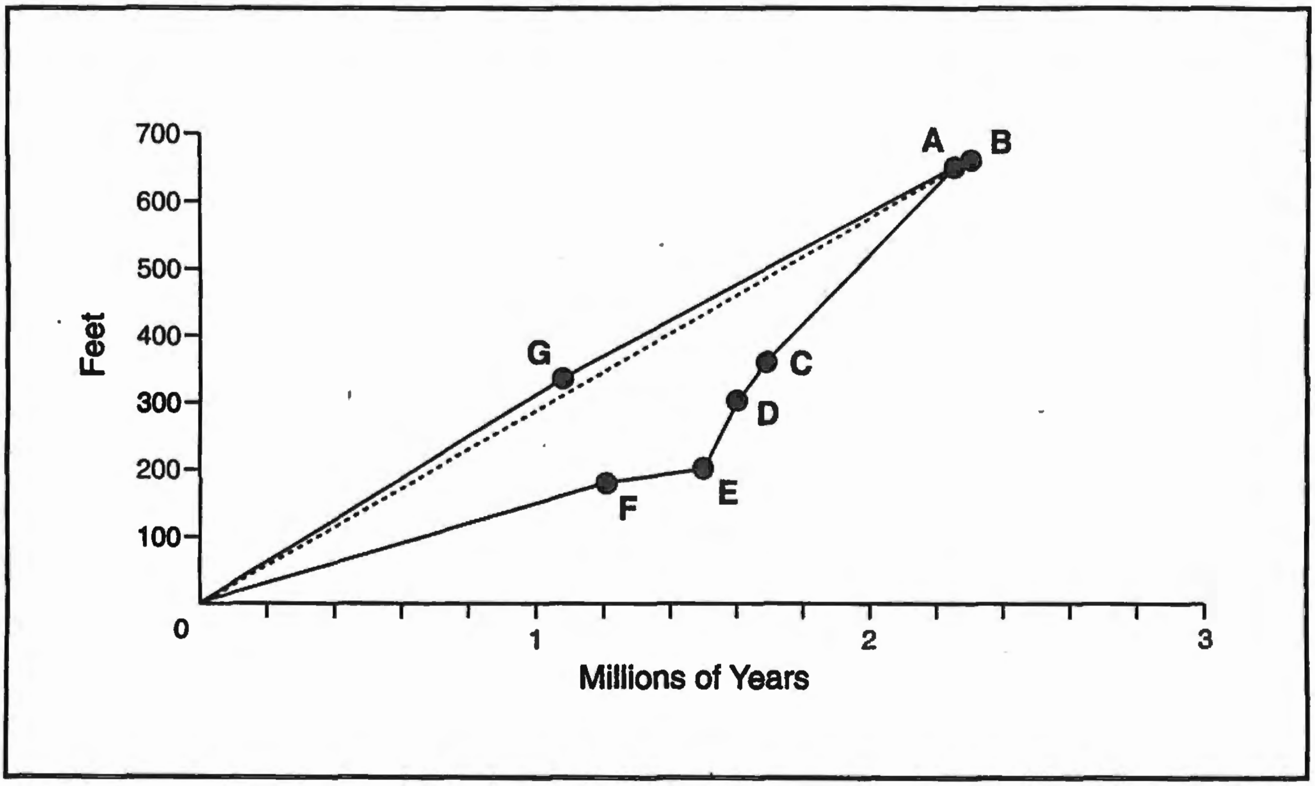
Washington Figure 1



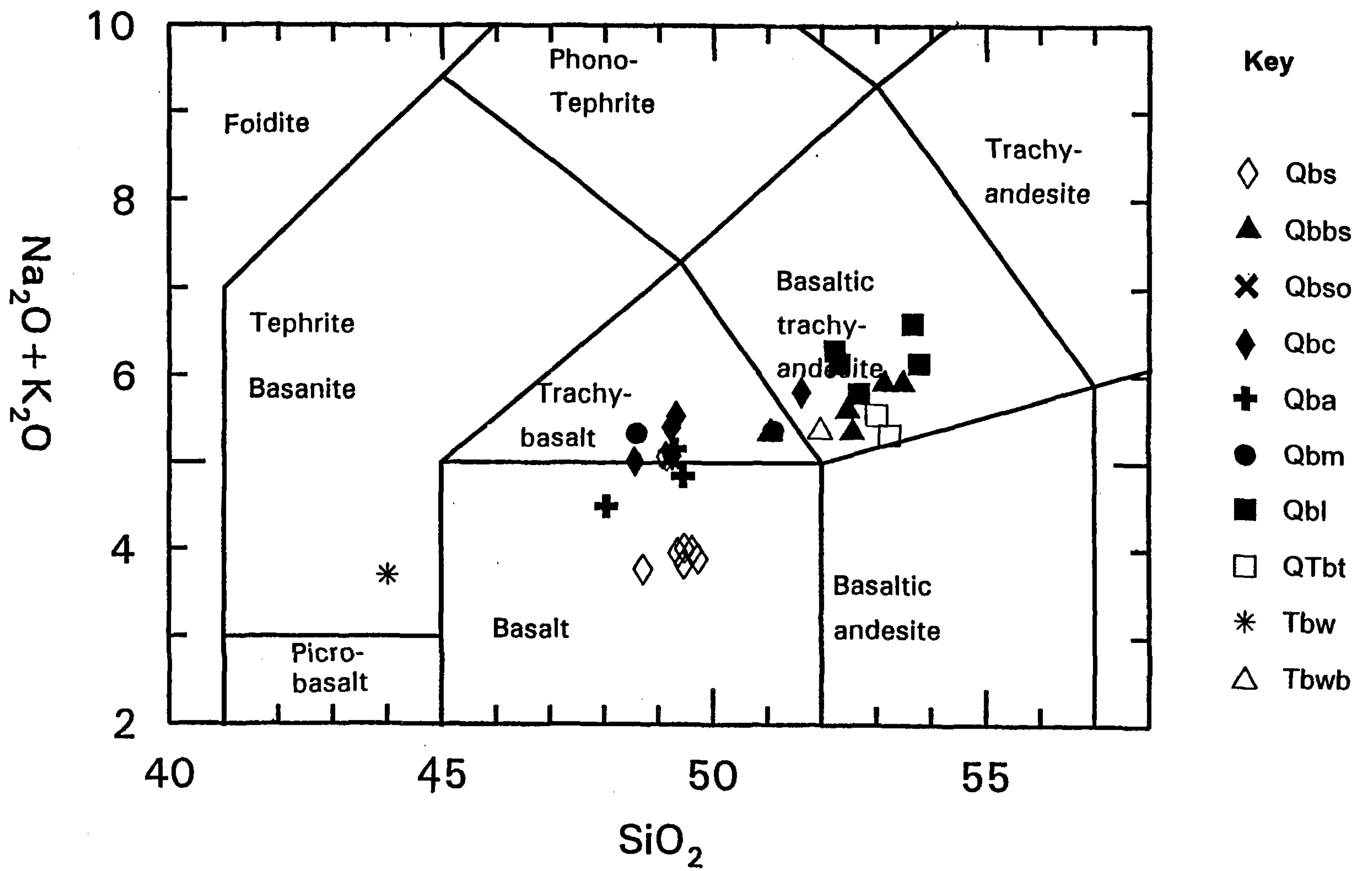
Washington Figure



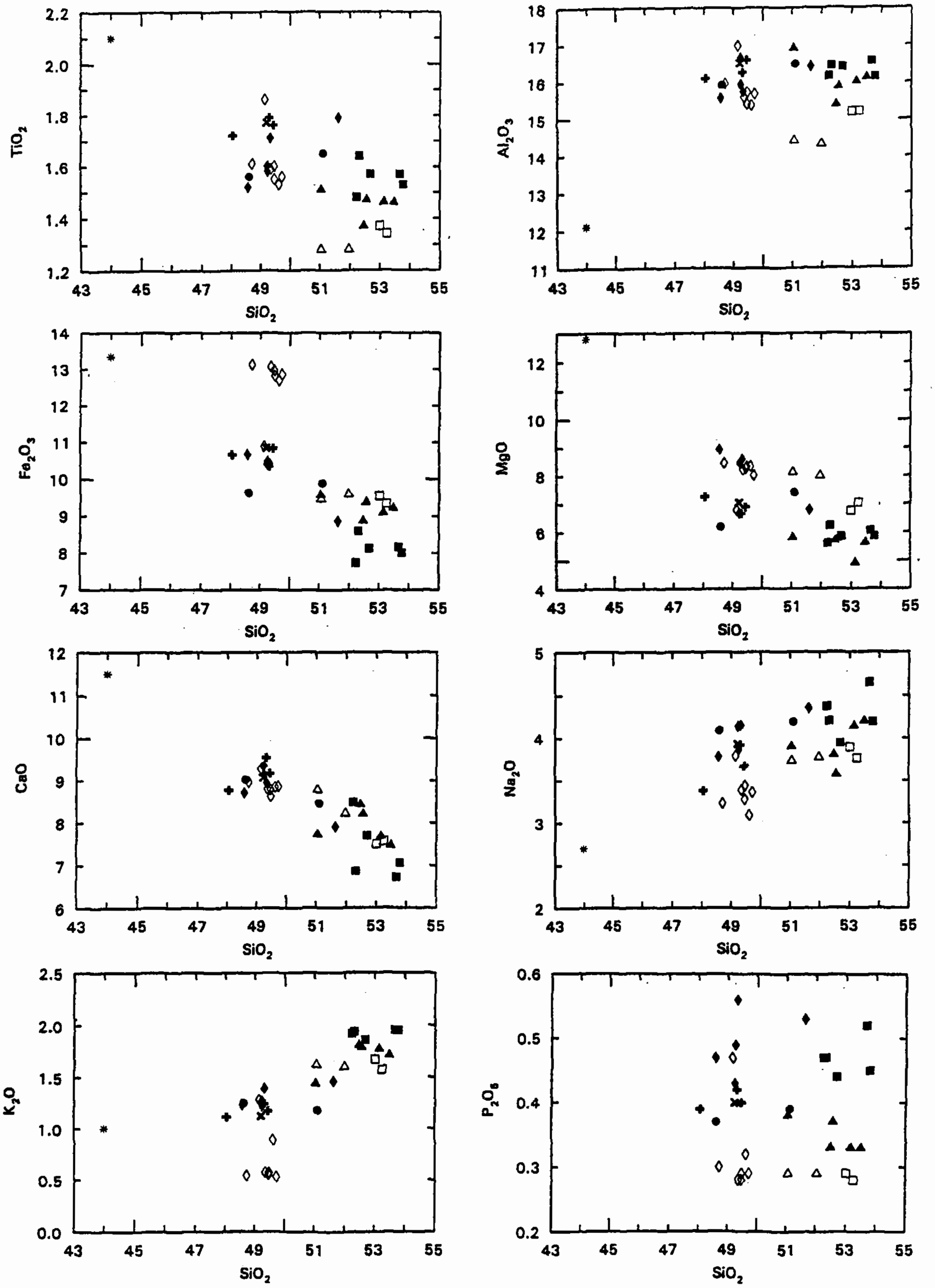
Washington Figure 3



Washington Figure 4

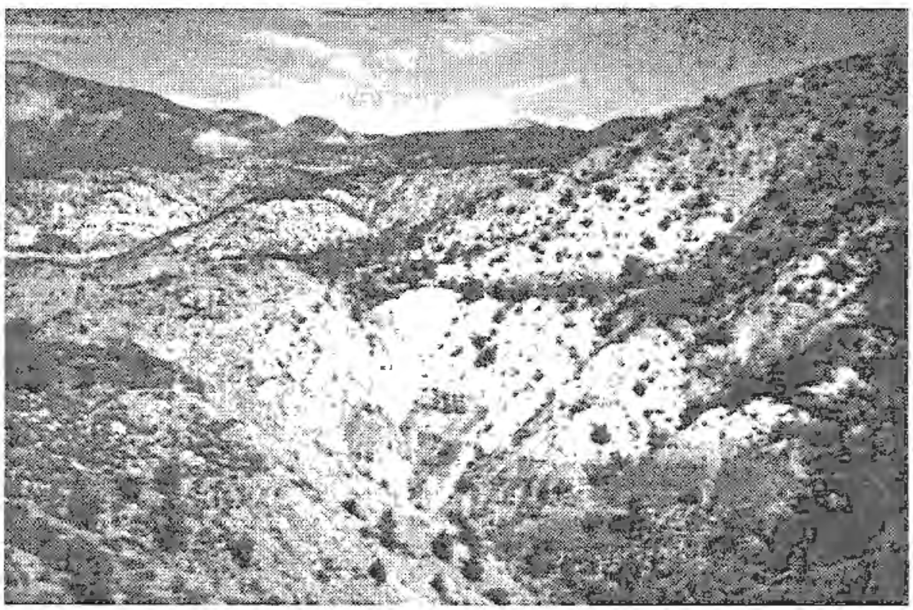


Washington Figure 5



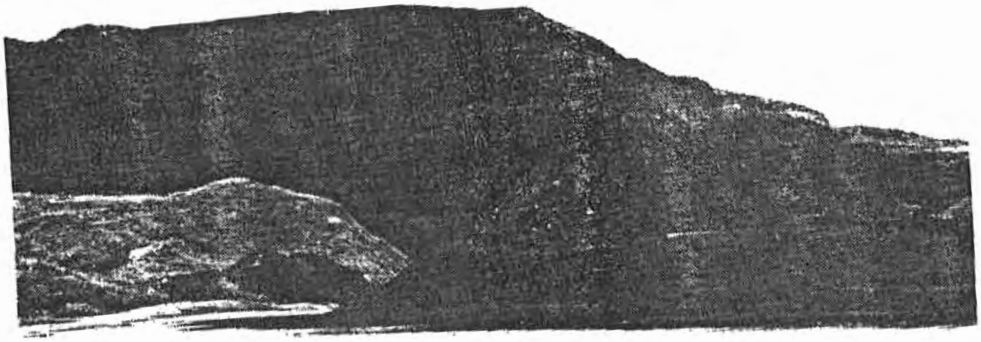
Washington Figure 6

Washington Figure 7

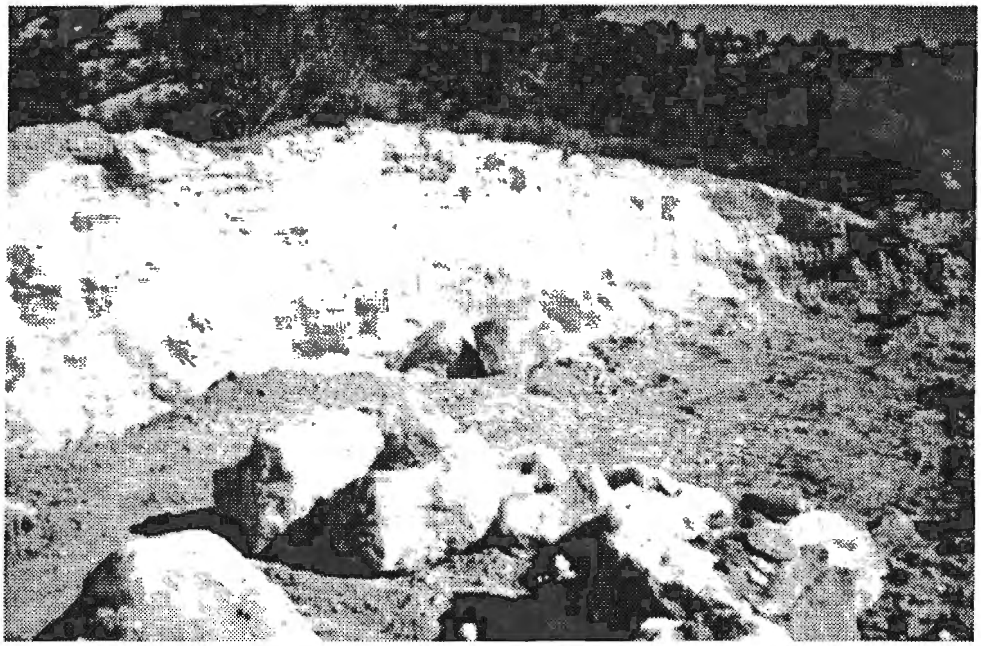


Washington Figure 8

Washington Figure 9



Washington Figure



Washington Figure 11

Sample	94N1	94N2	Ank-av	WA1001	WA0406	WA0201
Map Unit	Tbwb	Tbwb	Tbw	QTbt	QTbt	Qbl
Latitude	37°06'24"	37°06'24"	---	37°09'53"	37°12'37"	37°13'23"
Longitude	113°35'47"	113°35'47"	---	113°31'37"	113°34'56"	113°36'17"
SiO_2	51.06	51.98	44.00	53.25	53.01	52.24
TiO_2	1.28	1.28	2.10	1.34	1.37	1.48
Al_2O_3	14.42	14.33	12.10	15.22	15.20	16.17
Fe_2O_3	9.47	9.59	13.34	9.34	9.55	7.74
MnO	0.13	0.12	0.00	0.13	0.12	0.11
MgO	8.11	7.99	12.80	7.04	6.75	5.60
CaO	8.78	8.22	11.50	7.57	7.50	8.49
Na_2O	3.73	3.77	2.70	3.76	3.89	4.37
K_2O	1.62	1.60	1.00	1.57	1.67	1.92
P_2O_5	0.29	0.29	0.00	0.28	0.29	0.47
LOI	0.59	0.39	0.00	0.01	0.01	1.66
Total	99.51	99.39	98.20	99.55	99.40	100.28
Nb	20	17	0	20	20	20
Zr	158	154	0	138	138	219
Y	15	17	0	18	18	24
Sr	499	495	0	484	474	654
Rb	29	30	0	30	32	24
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	595	590	800
Sc	0	0	0	0	0	0
V	0	0	0	0	0	0
%An	36.09	35.36	74.73	38.62	36.70	33.89
Q	0.00	0.00	0.00	0.00	0.00	0.00
or	9.75	9.60	6.00	9.39	10.00	11.56
ab	32.13	32.39	6.15	32.19	33.36	37.45
an	18.14	17.72	18.21	20.25	19.34	19.20
ne	0.00	0.00	9.22	0.00	0.00	0.13
di	19.46	17.46	31.73	12.76	13.23	16.38
hy	0.47	6.81	0.00	17.79	14.35	0.00
ol	12.78	8.77	19.35	0.23	2.19	6.90
mt	4.10	4.09	5.30	4.17	4.22	4.40
il	2.48	2.47	4.05	2.57	2.64	2.86
ap	0.68	0.68	0.00	0.66	0.68	1.11

Sample	WA1101	SC-4	SC-4a	SC-5	SC-6	SG0801
Map Unit	Qbl	Qbl	Qbl	Qbl	Qbl	Qbm
Latitude	37°11'40"	37°13'57"	37°13'57"	37°13'35"	37°13'39"	37°06'48"
Longitude	113°36'07"	113°37'21"	113°37'21"	113°36'47"	113°37'42"	113°33'03"
SiO_2	53.67	52.69	52.69	52.32	53.78	48.61
TiO_2	1.57	1.57	1.57	1.64	1.53	1.56
Al_2O_3	16.57	16.42	16.42	16.45	16.15	15.93
Fe_2O_3	8.17	8.13	8.13	8.60	8.01	9.63
MnO	0.12	0.12	0.12	0.13	0.12	0.13
MgO	6.05	5.84	5.84	6.23	5.85	6.18
CaO	6.72	7.70	7.70	6.86	7.06	9.02
Na_2O	4.65	3.94	3.94	4.20	4.19	4.09
K_2O	1.95	1.86	1.86	1.94	1.95	1.25
P_2O_5	0.52	0.44	0.44	0.47	0.45	0.37
LOI	0.01	0.00	0.00	0.00	0.00	2.58
Total	100.03	97.89	97.89	97.97	98.28	99.39
Nb	20	19	20	20	18	14
Zr	228	253	257	260	253	168
Y	24	27	27	27	27	20
Sr	696	690	691	700	699	642
Rb	26	21	22	24	27	18
Th	0	7	10	11	5	0
Pb	0	21	20	21	32	0
Ga	0	18	18	18	18	0
Zn	0	66	67	65	64	0
Cu	0	35	32	31	31	0
Ni	0	95	97	108	94	0
Co	0	55	55	51	48	0
Cr	0	118	123	147	129	0
La	0	32	30	36	27	0
Ba	790	683	693	606	792	445
Sc	0	20	19	18	16	0
V	0	146	136	133	128	0
%An	32.08	39.35	39.35	36.36	35.49	41.39
Q	0.00	0.08	0.08	0.00	0.53	0.00
or	11.58	11.19	11.19	11.66	11.69	7.69
ab	39.55	33.95	33.95	36.16	35.96	31.55
an	18.68	22.02	22.02	20.66	19.78	22.28
ne	0.00	0.00	0.00	0.00	0.00	2.41
di	9.08	11.10	11.10	8.64	10.16	17.50
hy	7.53	13.05	13.05	9.63	13.42	0.00
ol	4.88	0.00	0.00	4.34	0.00	9.97
mt	4.47	4.53	4.53	4.63	4.46	4.62
il	3.00	3.04	3.04	3.17	2.95	3.08
ap	1.21	1.04	1.04	1.11	1.06	0.89

Sample	94N12	WA1104	WA0803	94N3	SC1107	WA0404
Map Unit	Qbm	Qba	Qba	Qba	Qbso	Qbc
Latitude	37°06'46"	37°07'58"	37°08'32"	37°05'06"	37°12'59"	37°12'25"
Longitude	113°32'55"	113°36'15"	113°36'22"	113°35'25"	113°37'56"	113°35'05"
SiO_2	51.11	48.05	49.45	49.31	49.22	48.57
TiO_2	1.65	1.72	1.76	1.79	1.77	1.52
Al_2O_3	16.50	16.10	16.60	16.27	16.52	15.57
Fe_2O_3	9.89	10.66	10.84	10.35	10.85	10.67
MnO	0.13	0.14	0.14	0.14	0.14	0.14
MgO	7.40	7.25	6.88	6.65	7.04	8.93
CaO	8.46	8.77	9.16	9.53	9.07	8.71
Na_2O	4.19	3.38	3.67	3.92	3.93	3.78
K_2O	1.18	1.11	1.17	1.24	1.12	1.23
P_2O_5	0.39	0.39	0.40	0.42	0.40	0.47
LOI	0.26	2.29	0.02	0.01	0.01	0.15
Total	101.19	99.90	100.12	99.65	100.11	99.70
Nb	16	24	22	26	22	26
Zr	215	156	153	183	150	162
Y	22	22	20	30	20	18
Sr	655	614	600	623	592	638
Rb	19	12	14	12	14	16
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	440	510	680	540	580	745
Sc	0	0	0	0	0	0
V	0	0	0	0	0	0
%An	39.07	47.12	44.96	43.71	43.96	44.10
Q	0.00	0.00	0.00	0.00	0.00	0.00
or	6.96	6.77	6.96	7.41	6.67	7.36
ab	35.38	29.54	31.27	30.13	30.98	28.07
an	22.68	26.32	25.54	23.39	24.30	22.15
ne	0.00	0.00	0.00	1.85	1.36	2.33
di	13.34	12.86	14.17	17.39	14.80	14.82
hy	0.36	4.11	0.89	0.00	0.00	0.00
ol	12.70	11.27	12.11	10.60	12.80	16.82
mt	4.56	4.82	4.76	4.82	4.77	4.43
il	3.13	3.37	3.37	3.44	3.39	2.92
ap	0.9	0.93	0.93	0.98	0.93	1.10

Sample	94N10	94N11	94N4	94N5	WA1105	WA1106
Map Unit	Qbc	Qbc	Qbc	Qbc	Qbbs	Qbbs
Latitude	37°14'09"	37°14'43"	37°14'20"	37°14'38"	37°08'47"	37°09'47"
Longitude	113°33'03"	113°33'08"	113°35'14"	113°35'14"	113°36'23"	113°36'38"
SiO_2	49.24	49.33	49.25	51.63	53.15	53.49
TiO_2	1.58	1.71	1.60	1.79	1.46	1.46
Al_2O_3	16.66	15.76	15.95	16.44	16.02	16.13
Fe_2O_3	10.41	10.41	10.48	8.87	9.09	9.22
MnO	0.14	0.14	0.14	0.13	0.12	0.12
MgO	6.66	8.59	8.46	6.79	4.91	5.63
CaO	9.33	8.94	9.12	7.91	7.68	7.47
Na_2O	4.14	4.15	3.86	4.35	4.14	4.20
K_2O	1.27	1.39	1.22	1.46	1.77	1.71
P_2O_5	0.43	0.56	0.49	0.53	0.33	0.33
LOI	0.20	0.01	0.01	0.67	0.98	0.01
Total	100.08	101.02	100.61	100.59	99.70	99.81
Nb	25	34	25	19	22	22
Zr	189	227	206	274	168	165
Y	20	19	20	25	20	20
Sr	677	781	704	704	544	552
Rb	18	19	19	21	24	22
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	589	661	771	563	795	775
Sc	0	0	0	0	0	0
V	0	0	0	0	0	0
%An	44.60	42.31	44.18	36.35	36.23	36.14
Q	0.00	0.00	0.00	0.00	0.42	0.00
or	7.57	8.19	7.22	8.69	10.67	10.19
ab	28.97	27.57	28.59	37.05	35.73	35.85
an	23.33	20.22	22.63	21.16	20.30	20.29
ne	3.45	4.04	2.24	0.00	0.00	0.00
di	16.56	16.30	15.63	11.81	13.21	12.02
hy	3.00	1.00	0.00	3.36	11.70	12.82
ol	11.58	14.50	15.01	8.47	0.00	0.94
mt	4.51	4.64	4.50	4.80	4.38	4.33
il	3.03	3.24	3.04	3.42	2.83	2.80
ap	1.01	1.29	1.14	1.24	0.78	0.77

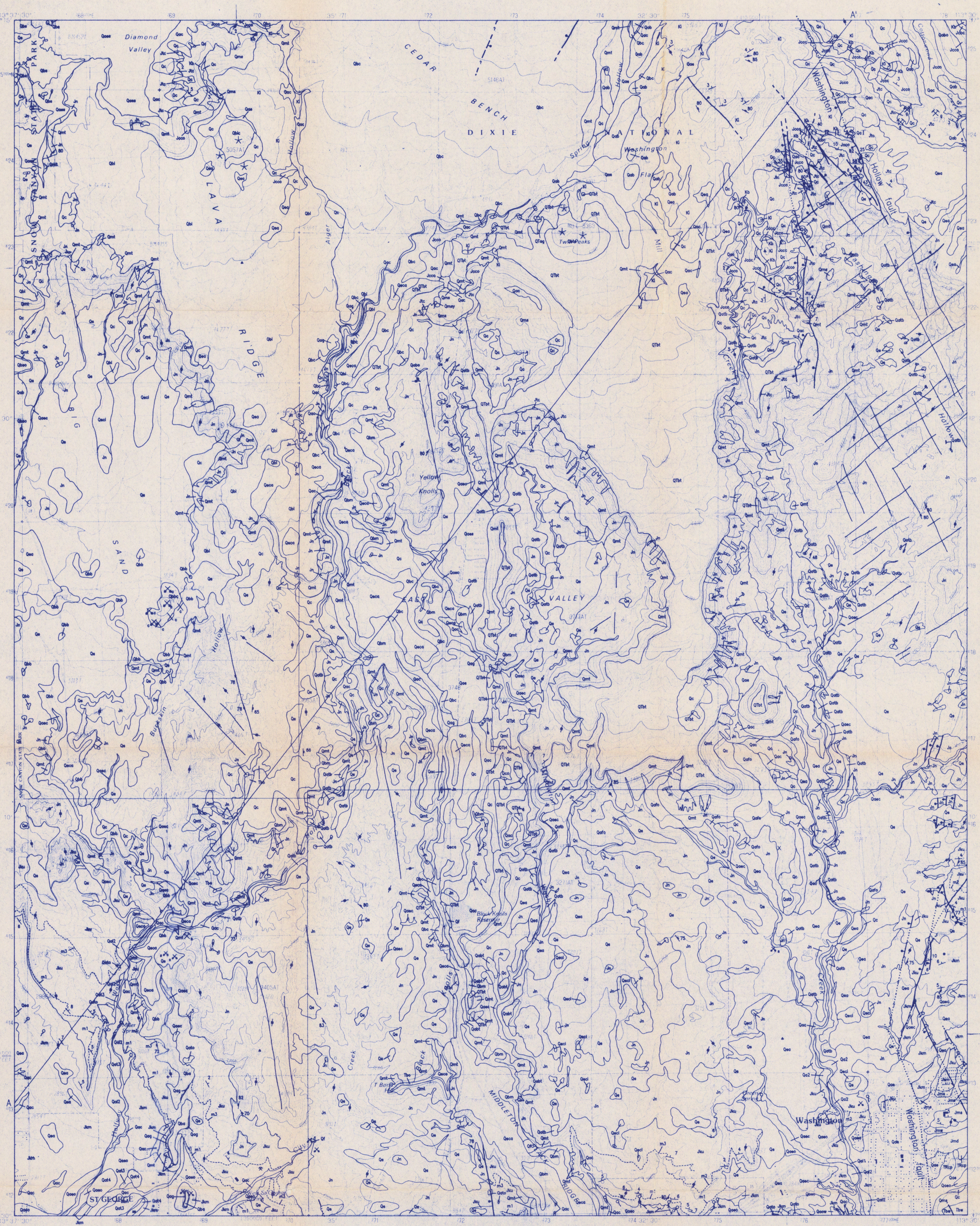
Sample	WA1102	WA1103	SC-2	SC-2a	92N1	92N3
Map Unit	Qbbs	Qbbs	Qbbs	Qbbs	Qbs	Qbs
Latitude	37°11'28"	37°11'25"	37°10'29"	37°10'29"	37°12'24"	37°12'25"
Longitude	113°36'13"	113°36'19"	113°37'14"	113°37'14"	113°39'09"	113°38'48"
SiO_2	51.05	52.48	52.57	52.57	49.73	49.36
TiO_2	1.51	1.37	1.47	1.47	1.56	1.59
Al_2O_3	16.92	15.39	15.88	15.88	15.69	15.61
Fe_2O_3	9.58	8.88	9.38	9.38	12.87	13.07
MnO	0.13	0.12	0.13	0.13	0.18	0.18
MgO	5.80	5.69	5.76	5.76	8.00	8.21
CaO	7.73	8.43	8.21	8.21	8.86	8.80
Na_2O	3.90	3.80	3.57	3.57	3.36	3.39
K_2O	1.44	1.81	1.79	1.79	0.53	0.57
P_2O_5	0.38	0.33	0.37	0.37	0.29	0.28
LOI	1.00	1.38	0.00	0.00	0.01	0.01
Total	99.47	99.71	98.18	98.18	96.99	97.04
Nb	22	20	20	20	10	15
Zr	177	162	193	191	1020	90
Y	20	18	22	22	1030	10
Sr	584	526	582	582	310	320
Rb	12	26	23	24	6	5
Th	0	0	6	8	0	0
Pb	0	0	24	24	0	0
Ga	0	0	20	22	0	0
Zn	0	0	80	79	0	0
Cu	0	0	54	53	0	0
Ni	0	0	83	84	0	0
Co	0	0	52	56	0	0
Cr	0	0	104	98	0	0
La	0	0	30	31	0	0
Ba	980	730	741	746	240	260
Sc	0	0	21	15	0	0
V	0	0	151	141	0	0
%An	42.52	37.86	42.16	42.16	47.93	47.25
Q	0.00	0.00	0.64	0.64	0.00	0.00
or	8.70	10.95	10.74	10.74	3.13	3.37
ab	33.75	32.91	30.67	30.67	28.41	28.67
an	24.96	20.05	22.36	22.36	26.14	25.68
ne	0.00	0.00	0.00	0.00	0.00	0.00
di	9.44	16.53	13.33	13.33	12.91	13.10
hy	10.60	10.94	14.19	14.19	11.48	8.64
ol	4.24	0.91	0.00	0.00	9.87	12.40
mt	4.46	4.26	4.37	4.37	4.43	4.48
il	2.93	2.66	2.83	2.83	2.96	3.02
ap	0.90	0.78	0.87	0.87	0.67	0.65

Sample	92N6	92N9	92N2	92N4	92N7
Map Unit	Qbs	Qbs	Qbs	Qbs	Qbs
Latitude	37°15'07"	37°08'11"	37°11'51"	37°14'47"	37°15'03"
Longitude	113°37'51"	113°38'21"	113°38'53"	113°37'22"	113°37'04"
SiO_2	49.48	49.15	49.62	49.47	48.72
TiO_2	1.60	1.86	1.53	1.55	1.61
Al_2O_3	15.73	16.99	15.38	14.51	15.96
Fe_2O_3	12.82	10.89	12.70	12.97	13.13
MnO	0.17	0.15	0.18	0.17	0.17
MgO	8.32	6.78	8.33	8.26	8.44
CaO	8.62	9.28	8.84	8.78	8.96
Na_2O	3.44	3.79	3.09	3.28	3.23
K_2O	0.57	1.28	0.89	0.55	0.54
P_2O_5	0.29	0.47	0.32	0.28	0.30
LOI	0.01	0.01	0.10	0.01	0.01
Total	99.34	98.92	96.87	97.42	98.19
Nb	20	30	15	15	10
Zr	100	160	280	90	100
Y	30	30	740	10	20
Sr	280	540	310	320	290
Rb	5	5	5	5	5
Th	0	0	0	0	0
Pb	0	0	0	0	0
Ga	0	0	0	0	0
Zn	0	0	0	0	0
Cu	0	0	0	0	0
Ni	0	0	0	0	0
Co	0	0	0	0	0
Cr	0	0	0	0	0
La	0	0	0	0	0
Ba	200	400	250	240	250
Sc	0	0	0	0	0
V	0	0	0	0	0
%An	46.99	46.28	49.34	48.08	50.11
Q	0.00	0.00	0.00	0.00	0.00
or	3.37	7.57	5.26	3.26	3.19
ab	29.09	29.72	26.17	27.83	27.32
an	25.78	25.60	25.49	25.77	27.44
ne	0.00	1.29	0.00	0.00	0.00
di	12.22	14.03	13.24	13.06	12.20
hy	9.18	0.00	11.62	11.69	8.01
ol	12.17	12.29	10.17	10.35	13.59
mt	4.49	4.88	4.40	4.43	4.51
il	3.04	3.54	2.91	2.95	3.06
ap	0.67	1.09	0.74	0.65	0.69

NO.	SOURCE NAME	TYPE	FLOW	LATITUDE	LONGITUDE	AQUIFER
1.	Gray Spring 2	Spring		37° 08' 44.0"	113° 37' 24.0"	Navajo
2.	Gray Spring 1	Spring		37° 08' 44.0"	113° 37' 24.0"	Navajo
3.	Gray Spring 3	Spring		37° 08' 40.0"	113° 37' 25.0"	Navajo
4.	Miller no. 2	Spring		37° 08' 33.0"	113° 36' 36.0"	Navajo
5.	Miller no. 1	Spring		37° 08' 32.0"	113° 36' 38.0"	Navajo
6.	Sheep Spring	Spring		37° 08' 16.0"	113° 37' 06.0"	Navajo
7.	Millcreek #3-Abnd	Well	1,200	37° 11' 31.0"	113° 30' 46.0"	Navajo
8.	Millcreek no. 2	Well	700	37° 11' 12.0"	113° 30' 58.0"	Navajo
9.	Millcreek no. 1	Well	450	37° 10' 52.0"	113° 31' 07.0"	Navajo
10.	City Creek Well	Well	1,500	37° 09' 17.0"	113° 34' 20.0"	Navajo
11.	Well No. 3	Well	180	37° 10' 16.0"	113° 20' 48.0"	Navajo
12.	Well No. 5	Well	749	37° 09' 57.5"	113° 31' 08.0"	Navajo
13.	Well No. 2	Well	651	37° 09' 50.0"	113° 30' 56.0"	Navajo
14.	Well No. 4	Well	651	37° 09' 44.0"	113° 30' 58.0"	Navajo
15.	Well No. 6	Well	600	37° 09' 23.5"	113° 30' 48.0"	Navajo
16.	Well No. 1	Well	350	37° 08' 34.0"	113° 30' 20.0"	Navajo
17.	#7 Spring	Spring		37° 08' 21.0"	113° 30' 21.0"	Navajo
18.	#6 Spring	Spring		37° 08' 21.0"	113° 30' 21.0"	Navajo
19.	Prisbrey Spring #1	Spring	50	37° 08' 21.0"	113° 30' 21.0"	Navajo
20.	Westover Spring #2	Spring	100	37° 08' 21.0"	113° 30' 21.0"	Navajo
21.	Sproul Springs	Spring	150	37° 08' 21.0"	113° 30' 21.0"	Navajo
22.	Well No. 3	Well		37° 12' 39.0"	113° 37' 14.0"	Navajo
23.	Well No. 2	Well		37° 12' 39.0"	113° 36' 28.0"	Navajo
24.	Well No. 1	Well	400	37° 11' 46.0"	113° 36' 10.0"	Navajo

Utah Geological Survey
Department of Natural Resources
in cooperation with the
U.S. Geologcial Survey

Plate 1
Utah Geological Survey Open-File Map 324
Geologic Map of the Washington Quadrangle



Base from U.S. Geologcial Survey,
Washington 7.5-minute provisional quadrangle, 1986

Field work by authors, 1994-1995

Improved Road
Unimproved Road
Trail

Interstate Route U.S. Route State Route

UTAH
QUADRANGLE LOCATION

1	2	3	1 Veyo 2 Saddle Mountain 3 Signal Peak 4 Santa Clara 5 Harrisburg Junction 6 White Hills 7 St George 8 Washington Dome
4		5	
6	7	8	

ADJOINING 7.5' QUADRANGLE NAMES

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

Interim Geologic Map of the Washington Quadrangle, Washington County, Utah

by

Grant C. Willis and Janice M. Higgins

1995

WASHINGTON, UTAH
PROVISIONAL EDITION 1986
37113-B5-TF-024

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

Plate 2
Utah Geological Survey Open-File Map 324
Geologic Map of the Washington Quadrangle

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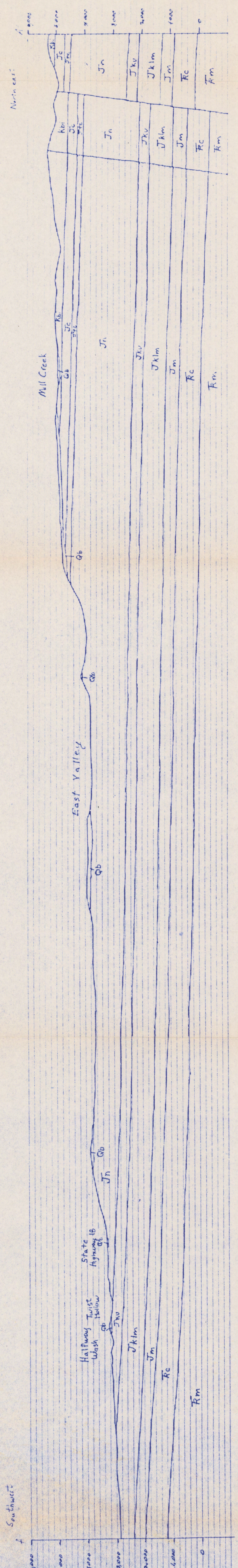
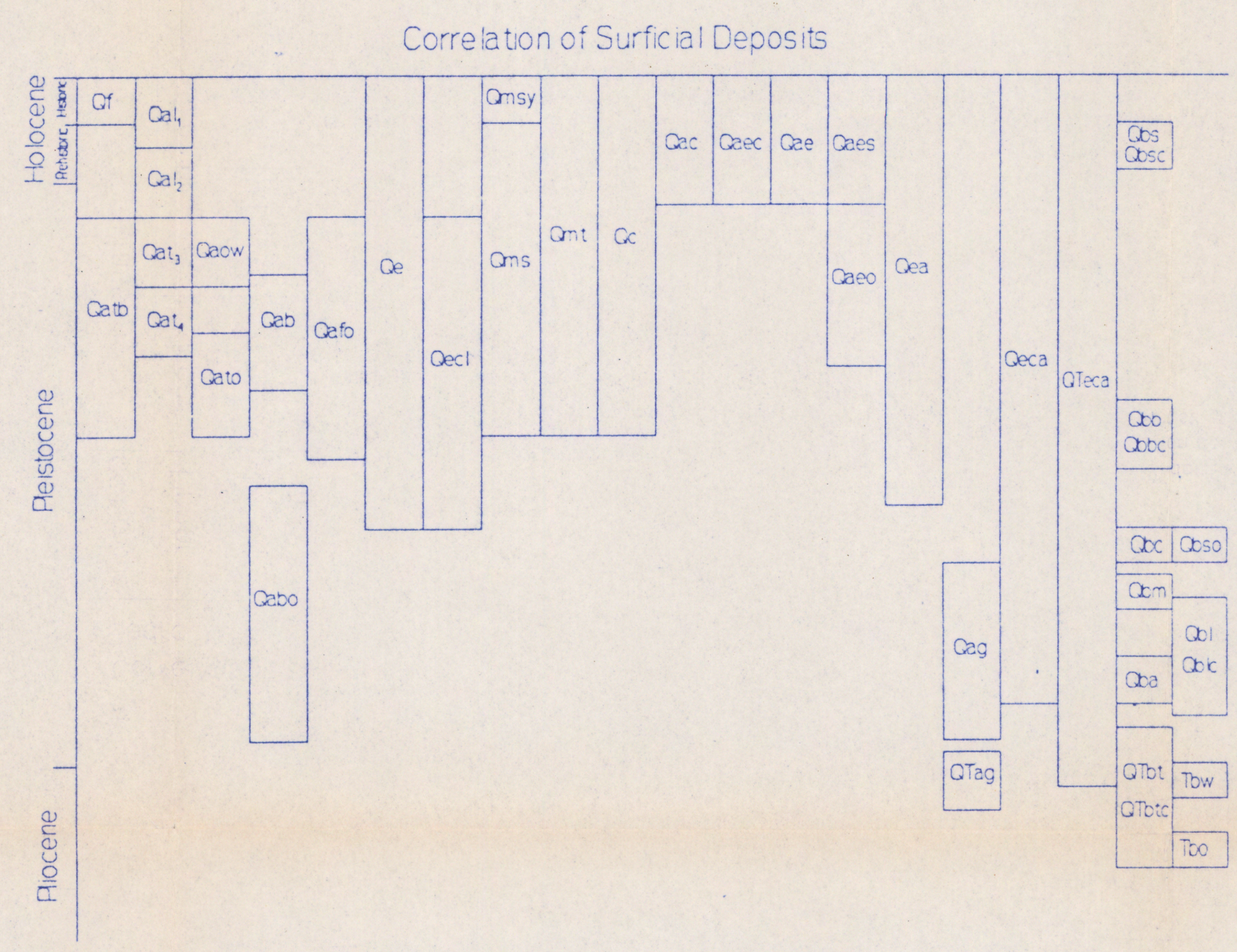
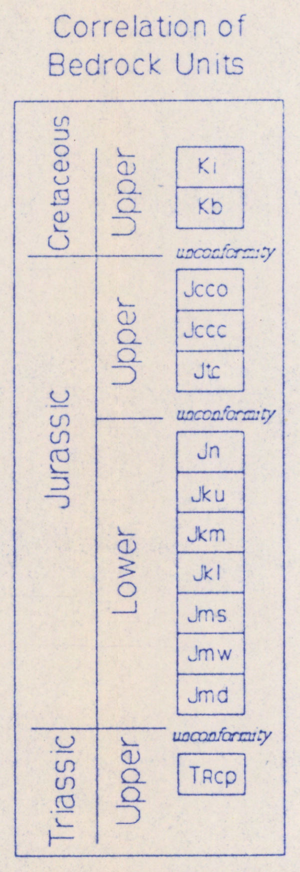




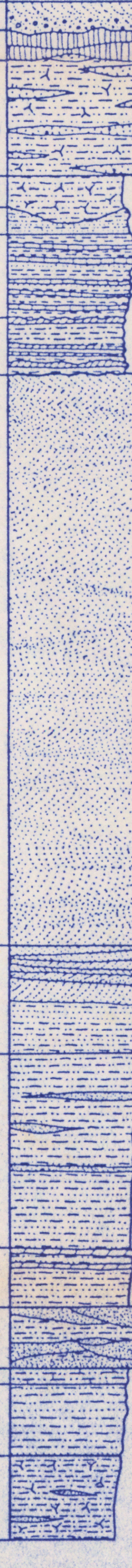


Key to Map Symbols

- Contact
- Marker bed
- High-angle fault – dashed where approximately located, dotted where concealed, queried where hypothetical; bar and ball on down-thrown side; dip of fault plane shown by thick arrow; rake of striations shown by thin arrow
- Prominent fracture
- Strike and dip of inclined bedding
- Strike and dip of joints
  - Inclined
  - Near-vertical
- Pit – gravel or road fill (no letter), sand (s), cinders (c)
- Quarry – gypsum (g), building stone (s)
- Prospect – gypsum (g), cinders (c)
- Spring
- Volcanic vent

System	Series	Formation	Member	Symbol	Thickness feet(meters)
Tert.-Quat.		Unconsolidated Deposits		-	0-100 (0-30)
		Basalt Flows		-	0-150 (0-45)
Cretaceous	Upper	Iron Springs Formation		Ki	400+ (122+)
		bentonitic beds		Kb	59-95 (18-23)
Jurassic	Middle	Carmel Formation	Crystal Cr. Mbr.	Jccc	0-50 (0-15)
			Co-op Creek Member	Jcco	285 (87)
		Temple Cap Formation		Jtc	200 (61)
	Lower	Navajo Sandstone		Jn	2000 (610)
		Kayenta Formation	Upper Member	Jku	380 (116)
			Middle Member	Jkm	680 (207)
			Lower Member	Jkl	110 (34)
		Moenave Formation	Springdale Sandstone Mbr.	Jms	115 (35)
			Whitmore Point Mbr.	Jmw	55(17)
			Dinosaur Canyon Member	Jmd	250 (76)
Triassic	Upper	Chinle Formation	Petrified Forest Mbr.	TRcp	300 (91)

Lithology



Description of Map Units

QUATERNARY

Qf **Artificial fill** -- Material emplaced for the contruction of dams and in landfills.

Alluvial Deposits

Qal_1 **Younger alluvial-stream deposits** -- Moderately to well-sorted silt, sand, and minor pebble-gravel in large active drainages; includes benches up to 20 feet (6 m) above current channels; 0-20 feet (0-6 m) thick.

Qal_2 **Older alluvial-stream deposits** -- Moderately to well-sorted silt, sand, and pebble-gravel deposits; dissected by channels incised up to 40 feet (12 m); mapped only in major drainages; 0-20 feet (0-6 m) thick.

Qatb **Boulder-terrace deposits** -- Poorly to moderately sorted mud- to large boulder-sized materials deposited in poorly developed terraces; clasts are mostly basalt; terraces are in several levels from 20 feet to 200 feet (6-60 m) above current drainages; mapped primarily near Mill Creek and Twist Hollow; 0-20 feet (0-6 m) thick.

Qat_{3-4} **Stream-terrace deposits** -- Moderately sorted pebble to cobble gravel with some clay and sand deposits; partially cemented by pedogenic carbonate; well-rounded clasts; many clasts are exotic; subscripts denote relative ages and heights above the current drainage: level 3 are 40 to 90 feet (12-27 m) and level 4 are 90 to 140 feet (27-42 m); 0-20 feet (0-6 m) thick.

Qato **Older stream-terrace deposits** -- Moderately sorted pebble to cobble gravel with some clay and sand deposits; partially cemented by pedogenic carbonate; well-rounded clasts; many clasts are exotic; they are 120 to 200 (36-61 m) above major drainages; not correlative with the current drainages; 0-20 feet (0-6 m) thick.

Qafo **Older alluvial-fan deposits** -- Poorly sorted, basalt-boulder deposits with moderate amounts of fine-grained matrix; form alluvial fans and debris flows in Mill Hollow area; deposited at several levels up to 150 feet (46 m) above current drainages; higher levels have a thick pedogenic carbonate (caliche); 0-20 feet (0-6 m) thick.

Qaow **Older alluvial deposits** -- Moderately sorted, rounded, cobble- to small boulder-gravel that partially covers a broad sloping surface near Washington City; clasts are mostly basalt but a few percent are sedimentary and intrusive igneous clasts derived from near the Pine Valley Mountains; about 60 feet (18 m) above current drainages; 0-10 feet (0-3 m) thick.

Qab, Qabo
Boulder deposits -- Very poorly sorted, angular to sub-angular, boulder deposits with clasts up to 10 feet (3 m) in diameter; clasts are mostly from Upper Cretaceous and Tertiary formations and intrusive igneous rocks from the Pine Valley Mountains; deposits are eroded remnants of an apron of old alluvial-fan deposits on the flank of the Pine Valley Mountains; Qab deposits are 50 to 150 feet (15-45 m) above nearby drainages; older boulder deposits (Qabo) are 250 to 300 feet (76-91 m) above nearby drainages; but these drainages are not adjusted to regional base level; probably early to middle-late Pleistocene, but may be as old as Late Tertiary; up to 100 feet (30 m) thick.

Eolian Deposits

Qe **Eolian sand** -- Well- to very well-sorted, fine- to very fine-grained, well-rounded, frosted quartz sand; deposited in irregular hummocky mounds in depressions and on the lee side of ridges; locally forms poorly developed dunes; has thick pedogenic carbonate in most areas; 0-50 feet (0-15 m) thick.

Qecl **Eolian caliche and sand** -- Thick pedogenic carbonate (caliche) mixed with minor to moderate amounts of eolian sand (Qe); mapped in areas where most eolian sands have been stripped off, leaving the carbonate cap covering bedrock exposures; 0-20 feet (0-6 m) thick.

Mass-Movement Deposits

Qms, Qmsy
Landslide and slump deposits -- Very poorly sorted clay- to boulder-sized debris in chaotic, hummocky mounds; includes slump blocks in excess of 100 feet (30 m) across; basal detachments are developed on Petrified Forest Member in southern part of quadrangle and on Temple Cap Formation, Carmel Formation, and bentonitic beds in northern part; displace overlying bedrock formations, talus, and basalt flows; probably late Pleistocene to early Holocene; a small landslide in E 1/2, section 18, T. 41 S., R. 15 W. has historic movement (Qmsy); thickness highly variable.

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

Colluvial Deposits

Qc **Colluvial deposits** -- Poorly sorted, angular to rounded, fine-grained to boulder-sized material deposited on moderate slopes; lacks well-defined drainage pattern; deposited by sheetwash, debris flow, and slope-creep processes; locally includes talus, eolian, or alluvial deposits; includes both active and dissected deposits; 0-30 feet (0-18 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 other deposits 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 deposited in broad, nearly flat areas; locally includes abundant eolian sand and minor gravel; minor to no pedogenic carbonate development; up to 50 feet (15 m) thick.

Qaes **Alluvial and eolian deposits of mostly sand** -- Similar to Qae deposits but consists mostly of sand; deposited in areas near thick eolian deposits; up to 50 feet (15 m) thick.

Qaeo **Older alluvial and eolian deposits** -- Similar to Qae but is deposited on older surfaces dissected by current drainages and has thick pedogenic carbonate; mapped in Washington and St. George areas; 0-30 feet (0-9 m) thick.

Qea **Eolian and alluvial deposits** -- Well-sorted eolian sand; locally reworked by alluvial processes and includes alluvial mud, sand, and gravel; has very thick pedogenic carbonate; deposited on old surfaces that have been protected from erosion for long periods and where eolian deposits can accumulate; 0-20 feet (0-6 m) thick.

Qeca **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 flows; 0-20 feet (0-6 m) thick.

Basalt Flows and Related Deposits

Qbs, Qbsc
Santa Clara flow and cinder cone -- Dark-brownish-gray to black, subalkaline basalt flows (Qbs) and cinder cone (Qbsc); has small, abundant olivine phenocrysts in an aphanitic groundmass; flows have very jagged aa surface; cinder cones have youthful appearance; estimated 10,000-20,000 years old.

Qbb, Qbbc
Big Sand flow and cinder cone -- Dark-reddish-gray to dark-brownish-gray, quartz-bearing, basaltic trachyandesite; has large plagioclase and quartz, and small olivine phenocrysts; flow (Qbb) has abundant "rafts" of scoria; cinder cone (Qbbc) is well-formed and has thick pedogenic carbonate rind; age poorly constrained but estimated at 0.75 million years.

Qbc **Cedar Bench flow** -- Dark-greenish-gray trachybasalt; has small olivine phenocrysts in an aphanitic groundmass; is very brittle and breaks with a conchoidal fracture; moderately jointed; four cooling units with combined thickness over 100 feet (30 m) in upper Black Gulch; south of Black Gulch is one thin unit 5 to 10 feet (1.5-3 m) thick on top of Middleton flow, locally with thin intervening gravel; K-Ar dated at 1.2±0.1 Ma (Best and others, 1980).

Qbm **Middleton flow** -- Moderate- to dark-gray to moderate-brownish-gray, quartz-bearing, basaltic trachyandesite; has large plagioclase (up to 0.4 inches, 1 cm) and quartz, and small olivine phenocrysts; consists of multiple flows of differing mineralogy separated by gravels in road cut near southern edge of quadrangle; 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), which conflicts with calculated ages on other flows in area (see discussion in text).

Qba **Airport flow** -- Dark-greenish-gray to dark-brownish-gray trachybasalt; small olivine phenocrysts; as mapped may include parts of a quartz-bearing, basaltic trachyandesite flow; strongly jointed; weathering along fractures imparts a "patch-work" 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 date conflicts with calculated ages on other basalts (see discussion in text).

Qbso **Snow Canyon Overlook flow** -- Very dark-brown to brownish-black, trachybasalt with small phenocrysts of clinopyroxene and olivine; dense, brittle, and strongly jointed; age not determined but overlies Lava Ridge flow and is probably less than 1.5 million years old.

Qbl, Qblc
Lava Ridge flows and cinder cones -- Moderate- to dark-gray to moderate-brownish-gray, quartz-bearing, basaltic trachyandesite; has large plagioclase and quartz, and small olivine phenocrysts; consists of partially eroded cone (Qblc) and multiple flows and flow lobes (Qbl); several stacked flows are exposed in Black Gulch; age is poorly known, but is younger than Twin Peaks flows; the Middleton flow (dated at 1.5±0.1 Ma) may be from this source.

Qag **Alluvial gravel beneath basalt flows** -- Small isolated remnants of poorly to moderately sorted silt, sand, and gravel exposed beneath basalt flows; 0-50 feet (0-15 m) thick.

QUATERNARY-TERTIARY

QTbt, QTbtc
Twin Peaks flows and cinder cones -- Dark-gray to dark-brownish-gray, quartz-bearing, basaltic trachyandesite; has large plagioclase and quartz, and small olivine phenocrysts; moderately jointed; consists of extensively eroded cinder cones (QTbtc) and multiple flows (QTbt) at slightly different erosional levels; is older than Lava Ridge and Cedar Bench flows; cinder cones may be source of older remnants (Tbo) mapped in southern part of quadrangle and of West Airport Ridge flow (dated at 2.3±0.1 Ma and 2.24±0.11 Ma by Best and others, 1980; and Hamblin and others, 1981) in St. George quadrangle.

QTag **Alluvial gravel beneath basalt flows** -- Isolated boulder gravel beneath Twin Peaks flow; consists of boulders of Cretaceous and Tertiary sedimentary and igneous rocks derived from Pine Valley Mountains; 0-30 feet (0-9 m) thick.

TERTIARY

Tbw **Washington flow** -- Dark-greenish-gray tephrite basanite; has abundant small clinopyroxene and olivine phenocrysts in a seriate groundmass; dense; strongly jointed; caps ridge 360 feet (110 m) above the adjacent Virgin River; K-Ar dated at 1.7±0.1 Ma (Best and others, 1980).

Tbo **Older flows** -- Dark-gray to dark-brownish-gray, quartz-bearing, basaltic trachyandesite; large plagioclase and quartz, and small olivine phenocrysts; strongly jointed; consists of two main flow remnants 400 (120 m) and 660 feet (200 m) above current drainages; higher remnant is probably correlative with the West Black Ridge flow that was 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.

unconformity

CRETACEOUS

Ki **Iron Springs Formation** -- Yellowish-gray, brownish-gray, and yellowish-orange, fine- to coarse-grained sandstone and conglomeratic sandstone, interbedded with pale-reddish-gray, gray, and greenish-gray siltstone, mudstone, and fine-grained sandstone; mostly densely cemented but is locally friable; locally silicified; ledge and slope former; about 400 feet (120 m) preserved in quadrangle; complete thickness is 3,500 to 4,000 feet (1,070-1,220 m).

Kb **Bentonitic bed** -- Pale-gray to pinkish-gray, bentonitic clay and minor siltstone and fine-grained sandstone; nonresistant and poorly exposed; weathers to form soft "popcorn" soil; tentatively correlated with beds fission-track dated at 80.0±5 Ma (Hintze and others, 1994); 60 to 95 feet (18-23 m) thick.

unconformity

Jccc **Crystal Creek Member of the Carmel Formation** -- Reddish-brown, thin-bedded, poorly exposed sandstone and mudstone; exposed in only a few small outcrops beneath unconformity; 0 to 50 feet (0-15 m) thick.

Jcco **Co-op Creek Member of the Carmel Formation** -- Pale-gray, pale-greenish-gray, or pale-yellowish-gray, interbedded limestone, sandstone, and mudstone; fossiliferous; thin uniform bedding; 285 feet (87 m) thick.

unconformity

Jtc **Temple Cap Formation (Sinawava Member)** -- Dark-reddish-brown to pale-gray, slope-forming mudstone, claystone, and gypsum; contains three main beds of nodular gypsum 5 to 15 feet (1.5-4.5 m) thick; has thin volcanic ash beds with common biotite; 200 feet (61 m) thick.

unconformity

Jn **Navajo Sandstone** -- Pale-yellowish-gray to moderate-grayish-red, well-sorted, fine- to medium-grained quartz sandstone; grains are well-rounded and frosted; prominent eolian cross-beds; strongly jointed; about 2,000 feet (610 m) thick.

unconformity

JURASSIC

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 to 5 feet (0.3-1.5 m) apart in upper part; upper part is entirely fine- to medium-grained, well-rounded, frosted quartz sand that resembles Navajo Sandstone except it has fluvial sedimentary structures; has three prominent marker beds labeled m_{1-3}; forms prominent ledges and cliffs; 380 feet (115 m) thick.

Jklm **Lower and middle members of the Kayenta Formation** -- shown on cross section only.

Jkm **Middle member of the Kayenta Formation** -- Interbedded reddish-brown siltstone, purplish-red to reddish-brown mudstone, and reddish-brown, fine-grained, calcareous, slightly mottled sandstone; punky gypsum in some intervals near the base; cross-cutting gypsum stringers are common; generally coarsens upward; forms slopes and small ledges; 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-purplish-red mudstone; three interbeds of light-pinkish-gray to light-olive-gray dolomite, each about 6 inches (15 cm) thick, are present near the top; 110 feet (33 m) thick.

Jm **Moenave Formation, unidvided** -- shown on cross section only.

Jms **Springdale Sandstone Member of the Moenave Formation** -- Pale-reddish-brown to grayish-yellow, fine- to medium-grained, cross-bedded sandstone with interbedded light-purplish-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 to 6 inch (5-15 cm) thick beds of light-greenish-gray dolomitic limestone that contain algal structures and fossil fish scales; nonresistant and poorly exposed; about 55 feet (17 m) thick.

Jmd **Dinosaur Canyon Member of the Moenave Formation** -- Interbedded moderate-reddish-brown siltstone and pale-reddish-brown to grayish-red, fine-grained, thin-bedded sandstone with laminated cross-beds; poorly exposed; 250 feet (76 m) thick.

unconformity

TRIASSIC

TRc **Chinle Formation, undivided** -- shown on cross section only.

TRcp **Petrified Forest Member of the Chinle Formation** -- Light-brownish-gray to grayish-purple bentonitic shale and siltstone with several interbeds of pale-yellowish-brown, cross-bedded sandstone up to 10 feet (3 m) thick; petrified wood is common; clays weather to a "popcorn" surface; poorly exposed; 300 feet (215 m) exposed but is about 700 feet (91 m) thick.

TRm **Moenkopi Formation** -- shown on cross section only.