ENGINEERING GEOLOGY OF THE ST. GEORGE AREA

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WASHINGTON COUNTY, UTAH

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ABSTRACT

The St. George area of southwestern Utah has grown dramatically in population during the past decade and will continue to grow in years to come. Increased construction activities accompanying this growth require careful planning with input from many disciplines, including geology. Geologic constraints on construction are best applied in early planning stages, and this report provides the basis to evaluate geologic conditions and make general planning decisions.

The study area lies in the St. George Basin, a topographic depression along the border between the Basin and Range and the Colorado Plateau physiographic provinces at the confluence of the Virgin and Santa Clara rivers. Bedrock in the area consists of Upper Permian to Lower Jurassic sandstone, shale, siltstone, limestone, gypsum, and conglomerate. These beds are folded in the southeast into the northeast trending Virgin anticline, but elsewhere dip gently to the north and northeast. Upper Tertiary and Quaternary basalt flows and alluvial gravel, sand, silt, and clay overlie these rocks in over 50 percent of the area. Several north-trending normal faults are present, the most prominent of which is the Washington fault.

Engineering geologic conditions vary widely. Soils range from indurated gravels to highly expansive clays, and rock materials range from resistant basalt, conglomerate, and sandstone to weak shale and gypsum beds. Flood-plain areas in valley bottoms present potential problems for construction due to high percentages of expansive clays, high flood hazard, and shallow ground water. Low benches and alluvial fans, having sandy and gravelly soils and low flood hazard, generally present the fewest foundation problems although shallow ground water occurs locally. Most rock materials are suitable for foundations, except for bentonitic and gypsiferous units such as the Petrified Forest Member of the Chinle Formation, the Shnabkaib Member of the Moenkopi Formation, and the Dinosaur Canyon Member of the Moenave Formation. These units are locally subject to slope instability as well. Earthquake hazard is moderate throughout the area due to the proximity of the potentially active Grand Wash, Hurricane, and Washington faults. The largest earthquake in the area occurred in 1902 (est. Richter magnitude 6.3), located 20.5 miles (33 km) north of St. George in Pine Valley.

INTRODUCTION

Background and purpose

The St. George area of southwestern Utah is becoming increasingly popular as both a winter resort and a permanent residence for many people due in part to its mild winter climate and proximity to the many spectacular scenic areas of southern Utah. Results of the 1980 U.S. census show that the population of St. George has grown from 7,097 in 1970 to 11,350 in 1980. However, most of the population growth is occurring in surrounding communities. Washington City has grown from 750 in 1970 to 3,092 in 1980, and Santa Clara from 271 to 1,091 during the same period. As the area continues to be populated, land well-suited for development becomes scarce and urbanization expands into less favorable areas, such as hillsides and flood plains. In order to provide planners with information necessary to make decisions regarding geologic constraints on development, the Utah Geological and Mineral Survey (UGMS) undertook this engineering geology study. The area covered by this report includes the cities/towns of St. George, Santa Clara, Ivins, Middleton, Washington, Bloomington, and the surrounding parts of the Santa Clara and Virgin river valleys (Figure 1). The report identifies geologic, hydrologic, and soil conditions of importance to development. Some of the factors considered include shallow ground water, foundation conditions, slope stability, flood hazard, and earthquake hazard. The report and accompanying maps are for regional planning purposes, and do not preclude the necessity of site investigations. A glossary of terms is included in the Appendix.

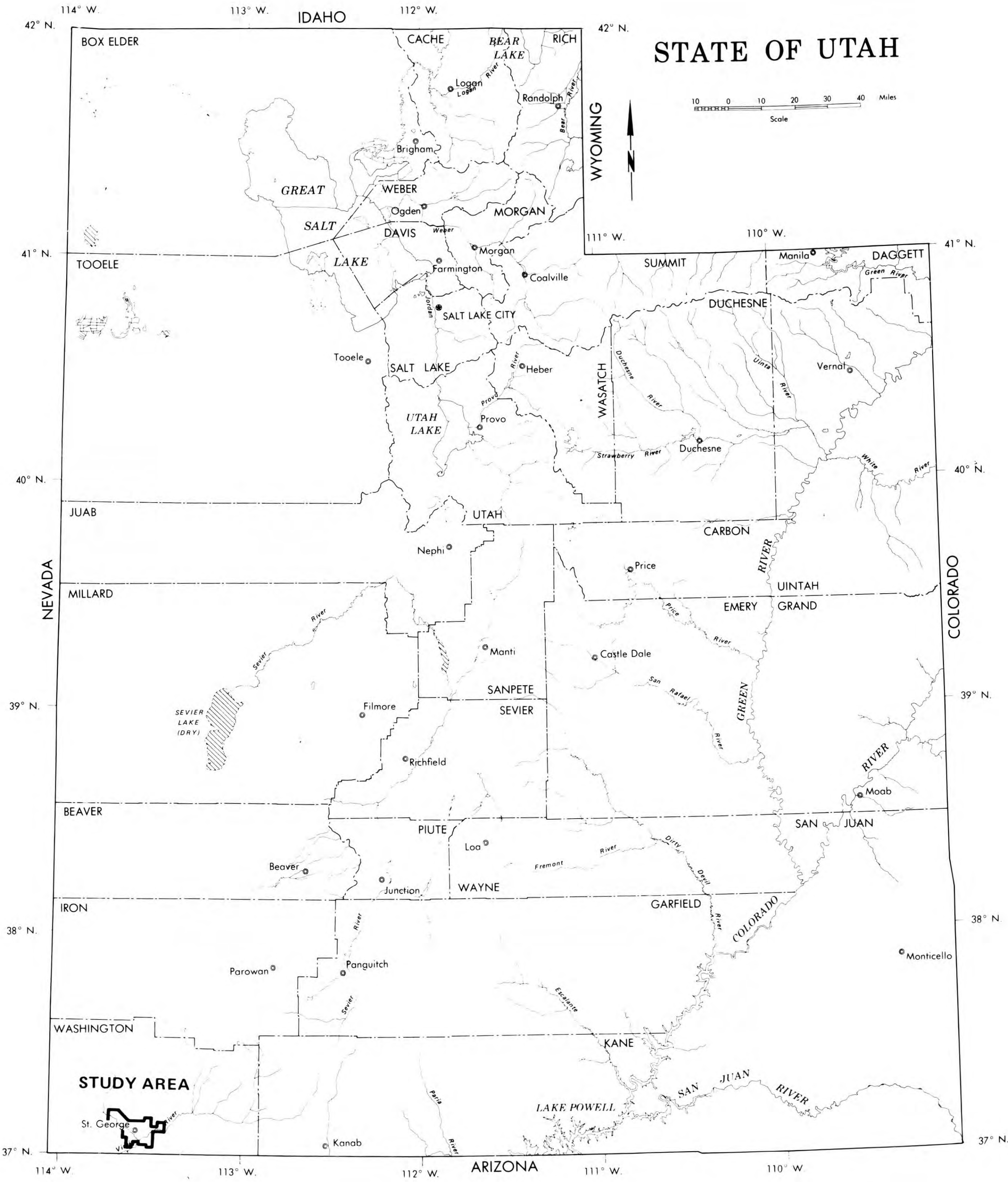

Figure 1. Location of study area.

Scope of work

The scope of work for this report consisted of:

1) Review of all geologic, hydrologic, and soils literature available for the area.

2) Detailed field mapping using 1:24,000 and 1:80,000 scale black and white stereo aerial photographs.

3) Discussions with local planners, building inspectors, homeowners, geologists, and others familiar with geologic conditions and problems in the area.

4) Collection of water-well drillers logs from the Utah Division of Water Rights.

5) Inspection of existing excavations from June 1978 to March 1979.

6) Drilling of over 100 4-inch (10 cm) diameter auger holes to depths of up to 40 feet (12 m) in St. George and Bloomington to determine depth to water and bedrock.

Soil classifications and map unit boundaries for most soil units (Qf, Qs, Qog; Plate 1) are modified from the USDA Soil Conservation Service Soil Survey of Washington County (Mortensen and others, 1977). Geologic mapping was done at a scale of 1:24,000 and subsequently reduced to 1:31,250 (Plate 1). Field work was begun in 1977 by Bruce N. Kaliser. Detailed field mapping was completed during 1978-79 by Roy D. Deen with field checking and revision by Gary Christenson in 1981.

GENERAL GEOLOGY

Physiography

The study area lies at the border between the Basin and Range and the Colorado Plateau physiographic provinces in the St. George Basin section of the Colorado Plateau (Stokes, 1977). The St. George Basin is bounded on the east by the Hurricane Cliffs, on the west by the Beaver Dam Range, and on the north by the Pine Valley Mountains. The southern edge extends into Arizona.

The physiography of the St. George Basin is characterized by cuestas, buttes, and benches formed as streams cut into the gently dipping and folded rocks along the western edge of the Colorado Plateau. Where capped by sandstone and basalt layers, cuestas and buttes have steep cliff faces with prominent talus accumulations at the bases of slopes. Several of the buttes and mesas, particularly Washington, Middleton, and West Black ridges, are basalt capped. These ridges were formerly stream channels along which lava flowed from sources to the north. Deposition of these lavas armored channel bottoms, and erosion of the surrounding softer sedimentary rocks has resulted in an inversion of topography in which old stream channels are now resistant basalt ridges (Cook, 1960). Hills in areas of shale, less resistant siltstone, and thin, friable sandstone are rounded with gentle slopes and low relief.

The principal drainage course in the St. George Basin is the Virgin River which flows from east to west along the southern edge of the study area. The major tributaries of the Virgin River in this area are Mill Creek, Middleton Wash, and the Santa Clara River which flow from the north, and Fort Pierce Wash which flows from the south. These streams and associated smaller drainages have cut valleys and constructed flat to gently sloping flood plains and alluvial fans in lowlands. Stream terraces are most prevalent along the Santa Clara River, where gravels are found at several different levels above the modern channel. Terraces along both the Santa Clara and Virgin rivers are best developed where the rivers traverse exposures of the Petrified Forest Member of the Chinle Formation. The relatively soft, easily eroded rock of this unit is conducive to rapid planation by streams forming broad flood plains. As the streams cut down, the edges of the flood plains are abandoned and remain as elevated stream terraces.

Stratigraphy

Deposits ranging in age from Permian to latest Holocene are found in the study area. Bedrock consists chiefly of Permian, Triassic, and Jurassic sedimentary rocks, including limestone, sandstone, siltstone, shale, and gypsum with minor conglomerate units. Upper Jurassic, Cretaceous, and lower Tertiary rocks found to the north in the Pine Valley Mountains have been removed by erosion in the St. George area, but upper Tertiary and Quaternary basalts and Quaternary clay, silt, sand and gravel are present. The geologic map of the area is shown in Plate 1.

Permian - The oldest rock unit exposed in the area is the Kaibab Limestone (Pk, Plate 1). The Kaibab is principally a marine deposit which is exposed only in the core of the Virgin anticline along the southern edge of the study area. The unit is chiefly a cliff-forming limestone, but includes an underlying thin, non-resistant shale and an overlying thicker shale with red sandstone, gypsum, and thin limestone interbeds. Deposition of the Kaibab Limestone was followed by a period of erosion during which gravel-filled channels were cut into the Kaibab strata (Cook, 1960). The Kaibab is unconformably overlain by the Triassic Moenkopi Formation.

Triassic and Jurassic - The majority of rocks exposed in the area are of Triassic age. These rocks include, from oldest to youngest, the Moenkopi, Chinle, Moenave, and Kayenta formations and the lower Navajo Sandstone. The Moenkopi Formation crops out principally in the southern and eastern parts of the area south of the Virgin River. The Chinle and Moenave formations underlie the lowlands of the Virgin and Santa Clara river valleys, with the Kayenta Formation and Navajo Sandstone forming cliffs and capping mesas along the northern edge of the area (Plate 1). The upper parts of the Navajo Sandstone are of Jurassic age.

Five members of the Moenkopi Formation are exposed in the St. George area. From oldest to youngest, these are: Lower Red Member (TRmkl, Plate 1), Virgin Limestone Member (TRmkv), Middle Red Member (TRmkm), Shnabkaib Member (TRmks) and the Upper Red Member (TRmku) (Gregory, 1950; McKee, 1954). The lowermost Moenkopi Formation (Timpoweap Member) of Gregory (1950) is not found in the area (McKee, 1954). The Lower, Middle, and Upper Red members are similar and consist of gypsiferous, brown to red shale and sandstone deposited in a mudflat environment (McKee, 1954). Gypsum beds are found in the Lower Red Member. The gray, resistant limestone beds of the Virgin Limestone Member were deposited in a marine environment. The Shnabkaib Member is a red, green, and white gypsum and gypsiferous shale deposited in shallow marine restricted bay and lagoon environments (Gregory, 1950; McKee, 1954). Contacts between members of the Moenkopi Formation are generally gradational but recognizable. The upper contact with the overlying Shinarump Member of the Chinle Formation is unconformable.

The Chinle Formation in the St. George area consists of two members, the lower Shinarump Member (TRcs, Plate 1) and the overlying Petrified Forest (Painted Desert) Member (TRcp) (Gregory, 1950; Stewart, 1957; Cook, 1960). The Shinarump Member is a cliff-forming fluvial sandstone and conglomerate which commonly occurs as a caprock overlying the less-resistant Moenkopi Formation. The Petrified Forest Member consists of thick, terrestrial (chiefly lacustrine) variegated red-brown, purple, green, and blue shales with local sandstone, gypsum, and bentonite interbeds. The unit is a slope former and is discomformably overlain by the Moenave Formation.

The Moenave Formation (TRmn, Plate 1) includes the lower Dinosaur Canyon Sandstone Member and the upper Springdale Sandstone Member (Harshbarger and others, 1957; Cook, 1960). Rocks of the Dinosaur Canyon Sandstone Member consist of fluvial and eolian, red to green, thin-bedded shale, siltstone, and sandstone. The lowermost beds of the unit contain bentonite. The Springdale Sandstone Member is a ledge-forming white to red sandstone with thin shale lenses deposited in a fluvial environment. It is found locally in the study area, but is not differentiated on Plate 1 due to its restricted areal extent and lack of distinctive character. The Moenave Formation is conformably overlain by the Kayenta Formation.

The Kayenta Formation (TRk, Plate 1) consists of fluvial red sandstone, siltstone, and shale which intertongue in the upper part with the overlying Navajo Sandstone (JTRn, Plate 1) (Harshbarger and others, 1957; Cook, 1960). The Kayenta Formation is exposed in the south face of the Red Hills, the prominent cliffs north of St. George.

The Navajo Sandstone is a sandstone of eolian origin characterized by large-scale crossbedding which conformably overlies the Kayenta Formation. It caps the Red Hills and is exposed extensively north of St. George. The Navajo Sandstone is cut by an extensive set of widely spaced joints and commonly weathers to form barren, rounded knobs, cliffs, and ridges.

Tertiary and Quaternary - Rocks representing the period following deposition of the Navajo Sandstone and preceding deposition of upper Tertiary basalts are absent in the St. George area. However, rocks present in the Pine Valley Mountains to the north indicate that deposition continued into Cretaceous and early Tertiary time (Cook, 1960). Rocks representing this time period have been removed from the St. George area by erosion during late Tertiary and Quaternary time. Active erosion during this time was accompanied by intermittant basaltic volcanism. Volcanic centers were chiefly north of the study area near the Pine Valley Mountains, but lava flowed southward as far as the present Virgin River. Basalt flows reached the study area as they flowed down tributary stream valleys to the ancestral Virgin River. Once the basalt solidified, the stream channels shifted to the margins of the flows and downcut new channels into the surrounding less-resistant sedimentary rocks. The erosion-resistant basalt flows now occur as long, narrow, south and west-trending sinuous ridges which represent old stream channels. Successively younger flows occur on successively lower ridges, and the different periods of basalt volcanism and ages of flows can be differentiated on the basis of height above modern stream grade (Hamblin, 1963). Four different ages of basalt flows are found in the area (Plate 1). The oldest is late Tertiary and the remaining three flows are Quaternary. The highest and oldest flow (Tb, Plate 1) has been potassium-argon dated at 2.24 $\pm$ 0.11 million years before present (m.y.B.P.). The most extensive flows which form Middleton and Washington Black ridges, and the lower level of West Black Ridge (Qb_1, Plate 1) are 1.07 $\pm$ 0.04 m.y. old (Hamblin and others, 1981). The flow exposed in the walls of the Virgin River Valley in the extreme eastern part of the area (Qb_2, Plate 1) has not been dated but is younger than flows forming the black ridges. The youngest basalt flows (Qb_3) are the North and South Black rocks near Santa Clara which were probably extruded during the last several thousand years (Hamblin, 1963).

Quaternary sediments cover approximately one-half of the map area. These deposits consist chiefly of alluvial fines (clay and silt), sand, and gravel, and have been differentiated accordingly. The geologic nature of these deposits is described below and a detailed engineering geologic description is included in subsequent sections addressing engineering geology (Soils, page 6).

Fine-grained deposits of silt and clay (Qf, Plate 1) are found chiefly on the Virgin and Santa Clara river flood plains and were deposited during periods of over-bank flooding along these streams. Areas of fine-grained deposits also underlie the cities of St. George and Washington and represent alluvial, eolian, and local residual deposits of silt and clay derived from shale and siltstone bedrock. These deposits are chiefly Holocene age, but may locally include upper Pleistocene deposits. Sandy deposits (Qs, Plate 1) are of alluvial and eolian origin. Channel and flood-plain deposits of the Santa Clara and Virgin rivers and deposits in tributary washes are principally sand with varying percentages of gravel, silt, and clay. Sandy deposits in areas adjacent to but higher than these channel deposits consist of mixtures of eolian and alluvial fan sands, derived chiefly from the Navajo, Kayenta, and Moenave formations. A large area of eolian sand is found on the Santa Clara Bench. Sands of various ages from late Pleistocene to Holocene are included in this unit. The oldest sandy deposits are found in the area of the landing field in the southeast part of the map area (hereafter informally named the landing field bench). The upper part of this deposit contains a thick, strongly developed caliche horizon indicative of Pleistocene age deposits. Erosion of the upper part of the caliche horizon on the bench has resulted in a concentration of gravel-size caliche rubble at the surface.

Older Quaternary gravels (Qog, Plate 1) include deposits of various origins, chiefly old stream gravels of the Virgin and Santa Clara rivers and Fort Pierce Wash. These gravels presently are found in terraces at several levels above the modern stream channels. The deposits consist of sandy gravel with cobbles, locally interbedded with sand and gravelly sand. In most cases, the gravel deposits are capped by variable thicknesses of sand, silt, and clay. Mappable deposits of modern gravels are not present. All gravels mapped are probably of early Holocene and Pleistocene age. In general, the gravels are found at elevations between the intermediate and youngest basalt flows (Qb_1 and Qb_3), indicating a range in age from more than several thousand years to less than about 1 m.y.

Landslide deposits of Quaternary age (Qls, Plate 1) are found on steep hillsides underlain by the Chinle Formation (Petrified Forest Member). They consist chiefly of broken rock materials found along the slopes of West, Middleton and Washington Black ridges. Here basalt-capped, steep slopes underlain by shale have failed in a series of rotational slump blocks. Part of the slumping post-dates deposition of older gravels, and some small slump blocks occur on lower slopes near the upper levels of the flood plains of the Santa Clara and Virgin rivers. This indicates that, although not presently active, failures on these slopes may have occurred during late Pleistocene and possibly during Holocene time.

Structure

The St. George Basin is a fault block within the fault system which forms the western edge of the Colorado Plateau. It has been downdropped 6000-8000 feet (1830-2440 m) along the Hurricane fault on the east (Hamblin, 1970). The area to the west has in turn been downdropped along the Grand Wash fault which forms the eastern boundary of the Basin and Range province in this area (Figure 8, page 21). In Utah, displacement on the Grand Wash fault is not precisely known, but ranges from somewhat less than the cliff height of 1500 feet (457 m) at the Arizona border to only a few hundred feet west of the St. George Basin (Hamblin, 1970).

The regional dip of bedding in the Triassic and Jurassic rocks of the St. George Basin is to the northeast at 5 to 10 degrees. However, the geologic structure of the basin is dominated by the Virgin anticline which trends northeast along the southern edge of the study area. The Virgin anticline is a broad, generally symmetrical fold with maximum flank dips of 25 to 30 degrees to the northwest and southeast (Cook, 1960). Three structural and/or topographic domes are found along its axis. From west to east they are the Bloomington, Washington, and Harrisburg domes. Folding of the anticline occurred during Late Cretaceous - early Tertiary time in either the Sevier Orogeny (Rowley and others, 1979) or Laramide Orogeny (Hamblin, 1970).

Several north-trending normal faults are found north of St. George and in the Washington area (Plate 1). Sense of displacement is down to the west on most faults. The most prominent of these faults is the Washington fault which trends north-south through Washington along 200 East Street. The time of last movement is unknown, but the well-preserved geomorphic expression of the fault and offset of 1 m.y. old basalt along associated secondary faults indicates a Quaternary age. The fault becomes less distinct north of Washington, and is expressed as a fault zone up to 0.7 mile (1.1 km) wide. It is very distinct to the south and continues beyond the study area into northern Arizona. Apparent displacement increases from 100 feet (30 m) north of Washington to about 2500 feet (760 m) at the Arizona state line (Dobbin, 1939; Hamblin, 1970). The Washington fault post-dates folding of the Virgin anticline and is probably a Basin and Range structure with inception of movement during the late Tertiary.

ENGINEERING GEOLOGY

Interpretations regarding the effects of geologic conditions on engineered structures can be made from a study of rock and soil types, terrain, and ground and surface water conditions. The following sections discuss various engineering geologic considerations of importance in the St. George area. These include foundation conditions, slope stability, flood hazard, and earthquake hazard. This information is summarized in Table 1 which provides a description of the engineering geologic characteristics of each geologic unit shown on Plate 1. Thus, Plate 1 and Table 1 may be used together to quickly assess conditions at any particular location by first determining the geologic unit exposed at the location from Plate 1 and then finding the description of that unit in Table 1.

Soils

A wide variety of soil types are present in the study area. The thickest soils are generally restricted to areas underlain by Quaternary sediments. As discussed previously, soil types in these sediments consist predominantly of: 1) silt and clay (Qf), 2) sand (Qs), or 3) gravel (Qog). Grain size classes and soil classifications used in this report conform to the Unified Soil Classification System (USCS, Appendix). Map unit boundaries (Qf, Qs, Qog; Plate 1) have been taken in part from the Soil Survey of Washington County (Mortensen and others, 1977). Soil associations mapped in that report were combined into the three units listed above based on the Unified Soil classifications provided in Mortenson and others (1977).

Fine-grained soils consist predominantly of silt and clay, and are generally classified under the USCS Group Symbols CL, CH, ML, or ML-CL. In terms of engineering characteristics, the soils vary but generally exhibit low to medium shear strength, medium compressibility, poor to good compaction characteristics, and moderate shrink-swell potential. They have low permeabilities, generally not in excess of 2 inches/hour (1.4×10^{-3} cm/sec) (Mortensen and others, 1977).

Sandy soils consist of clayey, silty, and poorly-graded clean sands classified under USCS Group Symbols SC, SM, SC-SM, SP, and SP-SM. These soils generally possess medium shear strengths, low to medium compressibility, and fair to good compaction characteristics. They exhibit low shrink-swell potential. Permeabilities are quite variable, but are as high as 20 inches/hour (0.014 cm/sec) (Mortensen and others, 1977) and in general are higher than permeabilities in fine-grained soils. Sandy soils are locally indurated by caliche, a secondary calcium carbonate accumulation commonly termed "hardpan." Caliche is found in older deposits exposed to near-surface weathering. The thickest and most strongly indurated caliche in sandy soils is found on the landing field bench in the southeast corner of the study area. Caliche begins at depths of 1 to 2 feet (0.3 - 0.6 m) in these soils and extends to 5 feet (1.5 m) or more (Figure 2). This caliche layer is similar to concrete in its engineering properties. In the upper 1 to 2 feet (0.3 - 0.6 m) loose caliche rubble with some clasts up to several inches in diameter are common. Elsewhere in the study area, less strongly indurated caliche horizons are found in sandy soils but in general this caliche does not significantly affect the engineering properties of the soil.

Gravelly soils consist principally of clayey, silty, and sandy gravels (USCS Group symbols GC, GM, GP). These soils exhibit medium to high shear strength, low to medium compressibility, and fair to good compaction characteristics. They have a low shrink-swell potential and highly variable permeabilities. Clayey and silty gravels have permeabilities in the range of 0.6 to 6.0 inches/hour (4.2×10^{-4} to 4.2×10^{-3} cm/sec) (Mortensen and others, 1977). However, sandy gravels may have permeabilities much higher than this. Gravelly deposits in the area are found on benches and terraces along rivers, and represent older deposits presently undergoing erosion. Thus, many of the gravelly soils exhibit strongly developed caliche horizons and other secondary cementation and are strongly indurated below depths of 1 to 2 feet (0.3 - 0.6 m). This is particularly true of the older terraces at higher elevations south of the Santa Clara River and along the Virgin River. The younger terraces

Figure 2. Indurated caliche horizon in sandy soils (Qs) exposed at the edge of the landing field bench in the southeast corner of the area.

found nearer the modern stream levels are only weakly indurated.

The thickest soils are the sandy and fine-grained soils along the Virgin and Santa Clara rivers including the areas known as St. George and Washington fields. Based on widely-spaced drill-hole data, maximum soil thicknesses in these areas range from about 40 to 70 feet (12 to 21 m) at which depth bedrock is encountered. Soil thickness decreases away from the channel and flood-plain areas of the major river valleys. For example, in the alluvial deposits beneath St. George at distances of a mile or less from the Virgin River, bedrock is at depths generally less than 30 feet (9 m). Depths to bedrock of less than 5 feet (1.5 m) can be found in both St. George and Washington. Sandy and gravelly deposits occur on benches and in stream terraces throughout the area. These deposits range in thickness from about 5 to 30 feet (1.5 - 9 m), and are locally thicker in the Santa Clara Bench area.

In addition to the soils discussed above which are shown on Plate 1, there is a class of soils which has not been shown. These are the residual soils which have developed on bedrock. They consist of weathered, disintegrated rock which has not been transported by wind or water, and are generally thin, particularly in upland areas. Many of the more resistant rock types have essentially no soil cover. This includes some basalt flows, the Navajo Sandstone, Kayenta Formation, the Shinarump Member of the Chinle Formation and the Kaibab

Table 1. Construction conditions, St. George area, Washington County, Utah.

		Geologic Unit(s) (Plate 1)	Description	Topography/Distribution
UNCONSOLIDATED MATERIALS		Qf (fine-grained)	Silt and clay (ML, CL, ML-CL), locally sandy; non-plastic to high plasticity, non-indurated	Flat to very gentle slopes on flood plains, alluvial lowlands, and benches (Cottam Bench)
		Qs (sand)	Sand (SP), silty sand (SM), and clayey sand (SC); non-plastic to medium plasiticity, non-indurated to strongly indurated	Flat to gentle slopes on flood plains, alluvial lowlands, and benches
		Qog (older gravel)	Sandy, silty, and clayey gravel (GP, GM, GC) and gravelly sand (SP, SM); non-plastic to medium plasticity, weakly to strongly indurated	Flat-topped, steep-sided benches (terraces) along major drainages (Virgin and Santa Clara rivers, Mill Creek, Sand Hollow, Fort Pierce Wash)
		Qls (landslide debris)	Broken rock debris in slump blocks, chiefly Chinle Formation (Petrified Forest Member-TRcp) and basalt (Qb, Tb)	Moderately steep slopes with irregular, stepped topography along southern tips of West, Middleton, and Washington Black ridges
ROCK MATERIALS		Qb_3, Qb_2, Qb_1, Tb (basalt flows)	Dense, fractured basalt flows; Qb_3, Qb_2 - locally covered by eolian sand, no residual soil cover; Qb_1, Tb - capped by gravelly residual soils with strongly indurated caliche horizons at 2 feet (0.6 m) or less	Flat-topped, steep sided flows in lowland areas (Qb_3, Qb_2) and capping ridges such as West, Middleton, and Washington Black ridges (Qb_1, Tb)
		Jn (Navajo Fm.)	Fractured, fine- to medium-grained cross-bedded sandstone	Gentle to steep slopes, caps cliffs along northern edge of area
		Jk (Kayenta Fm.)	Fractured, thin-bedded shale, siltstone, and sandstone	Gentle to steep slopes, cliff faces, and hilltops along northern edge of area
		TRmn (Moenave Fm.)	Non-resistant shale, siltstone, and friable sandstone with resistant sandstone locally at top; generally finely fractured with evaporite layers, weathers rapidly	Gentle slopes, underlies much of St. George, Middleton, and Washington. Locally steep slopes underlying basalt (Qb_1, Tb) in West and Middleton Black ridges
	CHINLE FM	TRcp (Petrified Forest Mbr.)	Variegated claystone and shale, with minor sandstone interbeds, bentonitic, finely fractured, weathers rapidly	Flat to moderately sloping lowland and bench areas along the Santa Clara and Virgin rivers
		TRcs (Shinarump Mbr.)	Resistant, dense, fractured sandstone and conglomerate	Gentle dip slopes and ridge crests forming hogbacks of Bloomington Hill, Webb Hill, Nichols Peak, and Shinob Kibe
	MOENKOPI FM	TRmku, TRmkm TRmkl, (Upper, Middle, Lower Red mbrs.)	Fractured shale and sandstone, gypsiferous	Steep cliff faces (TRmku) in hills capped by TRcs (see above), slope former in flanks of Virgin anticline (TRmkm, TRmkl) in southwest part of area
		TRmks (Shnabkaib Mbr.)	Fractured gypsiferous shale and gypsum, thin-bedded, weathers rapidly	Flat to gentle slopes in southern part of area, commonly at base of cliffs, forms barren, badland topography
		TRmkv (Virgin Limestone Mbr.)	Dense, fractured limestone with thin interbeds of shale and sandstone, gypsum beds near top of Pk	Steep slope and cliff-former in Virgin anticline in southern part of area
		Pk (Kaibab Fm.)		

*Compressiblity, shrink-swell potential, shear strength, and compaction characteristics of Qf, Qs, and Qog taken from Mortensen and others (19

Foundation Stability*	Slope Stability	Other (flood hazard, liquefaction potential, suitability for soil absorption fields)
Fair to poor; subject to settlement and heave due to moderate shrink-swell potential, low to medium shear strength, medium compressibility with local soluble soil constituents (gypsum), poor to good compaction characteristics, easily excavated, generally shallow ground water	Moderately stable in cut slopes, unstable if wet, natural slopes gentle to flat, easily eroded	Flood hazard high in flood-plain areas, low on benches; liquefaction potential moderate if underlain by clean sandy (SP) soils in areas of shallow ground water; unsuitable to suitable for soil absorption fields
Fair to good; locally subject to settlement and heave where clayey or gypsiferous, low shrink-swell potential, medium shear strength, low to medium compressibility, fair to good compaction characteristics, easily excavated except where indurated (e.g. landing field bench in southeast map area), locally shallow ground water, local shallow rock	Unstable to moderately stable in cut slopes, unstable if wet, natural slopes gentle to flat except where indurated, easily eroded except where indurated	Flood hazard high in flood-plain and channel areas, low on benches; liquefaction potential high in areas of clean sand (SP) with shallow groundwater, generally suitable for soil absorption fields except where sands lack fine-grained material (silt and clay) or contain excessive amounts of clay
Fair to good; low shrink-swell potential, medium to high shear strength, low compressibility, fair to good compaction characteristics, easy to difficult to excavate depending on induration, local shallow rock	Stable in gentle slopes, low to high stability in cut slopes depending on induration, easily eroded and unstable where only slightly indurated	Flood hazard low, liquefaction potential low, generally unsuitable for soil absorption fields
Poor; majority of broken rock debris consists of thin armor of basalt blocks overlying brecciated bentonitic shales with low shear strength, high compressibility, and high shrink-swell potential	Slump blocks not presently active but could be reactivated by loading, wetting, or undercutting; slopes potentially unstable, failures are generally rotational slumps	Flood hazard low, liquefaction potential low, unsuitable for soil absorption fields, introduction of water into the subsurface should be avoided
Good; high shear strength, incompressible, extremely difficult to excavate	Stable except around edge of flow where rock fall and rock topple failures occur; potentially unstable if heavily loaded or deeply wetted around edges of flows if underlain by Ŧcp (see below)	All rock materials: Flood hazard generally low, liquefaction potential nil, unsuitable for soil absorption fields; all mapped rock units include local areas of residual soils, alluvial deposits, and/or eolian sand in which construction conditions may deviate from those listed
Good; high shear strength, incompressible, extremely difficult to excavate	Stable, local rock fall hazard in cliff areas	
Fair to good; variable depending on rock type and degree of weathering, moderate to difficult to excavate	Stable, local rock fall hazard in cliff areas	
Poor to good; possible settlement problems where gypsum is abundant (in St. George and west of West Black Ridge), easy to extremely difficult (upper sandstone) to excavate depending on degree of weathering and rock type	Stable except where underlain by Chinle Formation (Ŧcp) in slopes	
Poor; weathers to clays with high shrink-swell potential causing both settlement and heave, easy to excavate except for thin sandstone layers	Unstable to stable in natural slopes, readily destabilized by grading, loading, or wetting; abundant evidence for past instability in steep slopes (Qls), locally unstable in cut slopes	
Good; high shear strength, incompressible, extremely difficult to excavate	Stable, local rock fall hazard in steep cliff areas	
Fair; local settlement problems where gypsiferous, local heaving problems due to expansive clays, difficult to excavate	Stable, local rock fall hazard in cliff areas (chiefly Ŧmku)	
Poor; subject to settlement, collapse, piping, and heave due to gypsum and expansive clays, easily excavated	Moderately stable in natural slopes, readily destabilized in artificial cuts particularly if bedding dips toward cut, failures are generally translational block slides, easily eroded	
Fair to good; high shear strength, incompressible, extremely difficult to excavate in limestone; conditions in shale and gypsum layers (particularly top of Pk) similar to those for Ŧcp and Ŧmks above	Stable, local rock fall hazard in cliff areas; conditions in shale and gypsum layers similar to Ŧmks above	

Limestone. Other rock units have variable thicknesses of residual soils depending on the rock type and slope on which they occur. Shales and siltstones on gentle slopes generally have the thickest residual soils. These soils commonly grade downward into soft, highly weathered bedrock and the combined thickness of weathered material may be 10 feet (3 m) or more. Residual soils are localized and erratic in occurrence, but in general can be assumed present in thicknesses from a few inches up to several feet in areas mapped as bedrock. The soil texture and composition varies with rock type, i.e. residual soils in areas of sandstone will be sandy, those in areas of shale and siltstone will be fine-grained. Therefore, an area mapped as Chinle Formation (Petrified Forest Member) can be assumed to consist of variable amounts of barren shale-siltstone outcrops in high areas with shallow, fine-grained (clayey) residual soils on lower slopes.

Ground water

Ground water is found in both rock and unconsolidated basin-fill aquifers. Nearly all rock units, or layers within units, in the area have yielded some water to wells or springs. The major exceptions are the Tertiary and Quaternary basalts which in general cap ridges and are well-drained and dry. Many springs are found in the St. George area, and most discharge from rock aquifers with yields generally less than 50 gallons per minute (3 liters/sec) (Cordova and others, 1972). Yields from springs and wells in these rock aquifers are dependent principally on the nature of fracturing of the rock. Rocks such as the Navajo Sandstone which can be highly fractured produce the greatest yields, and most springs in the area discharge from the Navajo-Kayenta sequence in the Red Hills north of St. George. A warm-water spring and warm-water well are found north of Washington. The discharge point of the spring may be controlled by the Washington fault, but its heat source is not known.

Although springs in basin-fill aquifers are rare, the majority of water discharged from wells comes from unconsolidated basin-fill deposits in lowland areas. Those wells generally yield less than 250 gallons per minute (16 liters/sec), and discharge increases as gravel content of the aquifer increases (Cordova and others, 1972). Long term water level data current to 1972 indicate that withdrawals due to pumping have not significantly affected the amount of ground water in storage (Cordova and others, 1972).

The chemical quality of ground water varies in both rock and basin-fill aquifers with grain size and evaporite content . In rock aquifers, the dissolved solids concentration is lowest in water from the Navajo Sandstone (less than 1,000 mg/l) and highest in the Chinle and Moenkopi formations (greater than 3,000 mg/l). Chemical quality of water in unconsolidated basin-fill aquifers is highly variable (144-6860 mg/l) but averages around 1,400 mg/l (Cordova and others, 1972).

In addition to providing irrigation and culinary water, ground water is also very important in terms of building foundations and buried utilities. Shallow ground water (depth to water generally less than 10 feet [3 m]) may flood basements or any below-ground facilities and may adversely affect foundation stability, particularly in sloping ground or in sandy soils when subjected to earthquake ground shaking (see Foundation Conditions, p. 13). Of principal importance is the depth to the water table in the unconsolidated basin-fill deposits which underlie large sections of most cities and towns in the area. The water table in these areas which include the flood plains of the Virgin and Santa Clara rivers and adjacent alluvial lowlands is locally very shallow. The depth to water varies seasonally with changes in river level, precipitation, and irrigation, but may be within 10 feet (3 m) of the surface during spring and summer.

In lowland areas adjacent to flood plains, the depth to water is variable. In 1978, a drilling program was undertaken in St. George to define shallow ground-water conditions. It was found that the depth to water in alluvium was generally between 10 and 20 feet (3 to 6 m) below ground surface throughout the city with local and seasonal variations to depths less than 10 feet (3 m). The water table slopes to the south roughly parallel to the surface. In order to maintain this southerly gradient, recharge to alluvium must be occurring in the northern and central parts of the city. This recharge is principally in the form of seepage from buried rock aquifers into the overlying unconsolidated alluvium, as shown by the numerous springs encountered in excavations in St. George, particularly in the vicinity of the Mormon Temple. Water is probably flowing chiefly from sandy layers in the Moenave and Chinle formations which underlie the city. Ground water then flows south along permeable zones in the alluvium, generally over an irregular, buried bedrock surface, toward the Virgin River. This recharge, in combination with perched water tables which may exist above subsurface clay layers, accounts for the irregularities in the shallow water table.

Local shallow ground water may occur in alluvium at the mouths of dry washes where they empty into the Virgin and Santa Clara rivers. However, in most areas outside the flood plains of the Virgin and Santa Clara rivers and adjacent lowlands, the main body of ground water is generally below the construction zone (upper 10 feet [3 m]). Local perched conditions may be present, and an investigation of ground-water levels, including consideration of seasonal variations, should be performed prior to construction.

Slope stability

The stability of natural slopes is dependent on lithology, ground-water conditions, and attitude of bedding or jointing. In the St. George area, most natural slopes are stable under present conditions. The most common causes of slope destabilization include: 1) loss of support due to removal of material from the slope, particularly from the base, caused by natural processes (lateral stream cutting) or activities of man (road cuts, foundation excavation, mining or other materials extraction), 2) introduction of water, causing a build-up of pore pressure, or simple increase in load from the added weight, and 3) ground shaking, either accompanying earthquakes or human activities (blasting, heavy equipment operation). Existing slope failures in the area are principally related to item 1, loss of support due to removal of material by man.

The types of failure most likely to affect slopes in the study area are rock falls and topples, rock slides, and debris flows. An assessment of general slope stability for each geologic unit is included in Table 1.

Rock falls and topples are simply downslope movements of rock masses or single blocks (generally unsaturated) through free-fall, rolling, bouncing, or toppling mechanisms (Varnes, 1978). Caprocks of jointed sandstone, limestone, and basalt are most susceptible to this type of failure. The potential depends on the joint pattern in the cap rock, the competency of the underlying

Figure 3. Fresh rock fall scar (light area in cliff near top) in hillside north of Bloomington. Rockfall is in the Shinarump Member of the Chinle Formation which caps the hill, underlain by the Upper Red Member of the Moenkopi Formation.

material, and the steepness and orientation of the slope. Within the study area, conditions conducive to rock falls and topples exist along West, Middleton, and Washington Black ridges; along the south faces of Bloomington and Webb hills (Figure 3); and along the sandstone bluffs of the Red Hills and other cliffs along the northern edge of the study area from St. George to north of Ivins. The hazard is easily recognized by an accumulation of talus at the base of the slope. The extent of the hazard is difficult to evaluate, but during cloudburst storms or earthquake ground shaking the potential exists for dangerous rock falls and topples to occur.

Rock slides are of two types, 1) rotational (slump) or 2) translational (block slide). Rotational failures or rock slumps occur when an incompetent layer fails and a block of material moves downslope along a bowl-shaped, concave-upward slide plane. Rock slumps are common on steep slopes in incompetent rock where materials are generally wet but unsaturated (Varnes, 1978). Many inactive and several active rock slumps are found in the area. The steep slopes at the southern tips of West, Washington, and Middleton Black ridges are characterized by large numbers of rock slumps (Qls, Plate 1). Here, basalts capping the ridges are underlain by weak bentonitic beds of the Chinle Formation (Petrified Forest Member). The slopes are characterized by a series of slumps from top to bottom, resulting in stepped topography with each basalt-capped slump block forming a step (Figure 4). Where exposed in slump blocks, Chinle beds are

Figure 4. View south along the east side of West Black Ridge, showing stepped topography resulting from rock slumps along the hillside. Note cut on far left which has removed part of the toe of the lowermost slump block.

highly deformed. The age of these slump features is not known, but west of West Black Ridge along the Santa Clara River, slumps extend to near the upper flood-plain level, indicating that they have possibly been active since the river reached this level. This level was present during Holocene time because the South Black Rocks lava flow (estimated age 1000-2000 years) rests upon it. The length of time it existed prior to this is not known. The majority of landslide activity was probably during wet intervals of Pleistocene time. No evidence of modern slump activity on these slopes was found.

Although apparently stable at present, these slopes may be destabilized by removal of material from the base. Some material has already been removed in road cuts and other excavations along West Black Ridge (Figure 4). No evidence of renewed slumping in these areas has been observed to date.

Two recently active slumps are shown in Plate 1. One occurs north of Santa Clara at the edge of the Santa Clara Bench (T. 42 S., R. 16 W., sec. 16). Here the Chinle Formation is overlain by Quaternary gravels, and both have been involved in slumping. Slide planes have developed in the Chinle Formation and slumping has disrupted Truman Drive and a canal at the base of the slope (Lund, 1981). Another slump occurred in a road cut near Green Valley subdivision 3 miles (4.8 km) southeast of Santa Clara (T. 42 S., R. 16 W., sec. 26) (Figure 5). This slump has been removed, but was also in the Chinle Formation (Petrified Forest

Figure 5. Shallow slump in a road cut in the Chinle Formation (Petrified Forest Member).

Member) and demonstrates the potential instability of slopes in this formation throughout the area.

The other type of rock slide is the translational failure or block slide which commonly occurs on steep dip slopes in well-jointed rock. These slides are not a serious hazard on natural slopes in the area, but can become hazardous when artificial cuts are made at the base of or into a dip slope. Two such slides or potential slides are shown in Plate 1. In a cut for the St. George and Washington Canal between Nichols Peak and Shinob Kibe (T. 42 S., R. 15 W., sec. 25), bedding dips to the northwest at 38 degrees. The cut has removed support from rocks updip to the east, and joints are presently widening as blocks of rock slide down-dip, threatening to drop into and possibly damage the canal (Figure 6). This failure is in the Shnabkaib Member of the Moenkopi Formation. Another similar slope failure has occurred in a road cut south of the Virgin River in the eastern part of the area (T. 42 S., R. 14 W., sec. 20). The road cut intersects the generally east-dipping rocks of the Moenkopi Formation (Shnabkaib Member), overlain by a thick sequence of Quaternary stream gravels. Failure has occurred along bedding planes in the underlying rock, resulting in collapse of gravels onto the road shoulder.

Debris flows and mudflows are the other major types of slope movement which may occur in the area. Debris flows are essentially floods of debris-laden water resulting from cloudbursts which wash loose slope debris (mud, rock fragments) into canyons and ultimately onto lowland areas (Varnes, 1978). Mudflows are similar but lack the coarse rock fragments (boulders,

Figure 6. Widened joints due to block slide in the Moenkopi Formation (Shnabkaib Member) along the St. George and Washington Canal.

cobbles) common in debris flows. Debris flows and mudflows can be much more damaging than floods because of the coarse material entrained by the water and the thick deposits left after the waters subside. Areas susceptible to debris flows and mudflows are those along washes and on alluvial fans at the mouths of canyons where steep, entrenched stream channels emerge from confining channel walls and open onto flat lowland areas. Debris flows and mudflows generally do not extend far beyond the cliff front. Areas particularly susceptible would be along washes draining cliffs north of Ivins. The limit of debris flow and mudflow hazard areas would not extend beyond the flood-prone area boundary shown on Plate 2, and would only include those flood-prone areas along the bases of high cliffs.

Flooding

The study area is traversed by two major perennial streams, the Virgin and Santa Clara rivers, and by numerous intermittent drainages. All are subject to periodic flooding, and may pose a threat due to overbank flooding. The historic record of major floods compiled for the period 1850 to 1981 (Wooley, 1946; Butler and Marsell, 1972; Utah Division of Comprehensive Emergency Management, 1981) indicates the erratic and unpredictable nature of flooding in the St. George area (Table 2). Periods of more than 10 years may elapse between major floods, or they may be separated by periods of several days or less. This is because nearly all flooding in the St. George area is in response to cloudburst storms during the summer months, although the largest flood on record occurred in late fall (December 6, 1966; Butler and Mundorff, 1970). Both the Santa Clara and the Virgin rivers have well-developed flood plains which are flooded periodically, in many cases washing out or damaging bridges, dams, and canals and inundating fields which are on the flood plains. Historically, floods have inundated much of both the Washington Fields and the St. George Fields, at one time forming a lake along the Virgin River (Table 2, August 10, 1955). In addition, flooding along tributary washes such as Mill Creek through Washington and Warner Creek south of the Virgin River below Washington have done considerable damage and inundated surrounding lowland areas, including Washington Fields (Butler and Marsell, 1972).

Maps showing flood-prone areas have been prepared by the U.S. Geological Survey (1970a; 1970b) and by the U.S. Department of Housing and Urban Development (HUD) Federal Insurance Administration (1974; 1975; 1976; 1978; 1980). These maps outline the extent of the 100-year flood (flood with a one percent chance of occurring annually) on major streams, and were used to compile Plate 2. As such, Plate 2 does not reflect flood-control improvements made since the date of publication of the source map. Various techniques exist for delineation of the 100-year flood, and some differences in extent of flooding are found between maps by the two agencies. Maps by the U.S. Geological Survey (1970a; 1970b) were used to delineate flood-prone areas along the Virgin and Santa Clara rivers. The HUD maps were used in the remainder of the area. Detailed flood-plain information for the Virgin River and Fort Pierce Wash is provided by the U.S. Army Corps of Engineers (1973).

Plate 2 shows the areas affected by channel and overbank flooding during large storms in their respective drainage basins. Plate 2 does not depict flooding due to breaching or overflow of canals or sheet-flooding from localized cloudbursts. The potential for flooding from canals is present in any area downslope from a canal. Sheet flooding is possible nearly everywhere, but is most probable in low, poorly-drained areas underlain by impermeable materials (rock, clayey soils) or at the base of steep, barren hillsides. Flooding due to such cloudbursts has occurred periodically in downtown St. George, such as in September 1949 (Table 2).

Foundation conditions

The suitability of soil and rock materials for foundations is a function of bearing capacity, ease of excavation, ground-water conditions, and slope

Table 2. Major cloudburst floods in the St. George area, 1850-1981

Date	Locality	Stream	Remarks
7/8/1870	St. George	--	Flood damage to cotton factory, gristmill, and farms.
7/10/1870	St. George	--	Flood from mountain gap NW of city damaged land and crops in west part of town.
6/4/1872	St. George	--	A few cellars filled.
9/2/1872 (prior to)	St. George	Santa Clara River	Water 30 feet (9 m) deep in Santa Clara River flooding adjacent lowlands. Orchards, fields, and ditches damaged.
8/12/1882	St. George	--	Violent rain, sidewalks and roads damaged.
7/4-5/1883	Washington, St. George	Streams draining south from Pine Valley Mountains	Cotton factory millrace and dam washed out at Washington; damage to farms, dams, ditches, and roads.
7/21/1883	St. George	Virgin River	Flood tears out all dams between Washington and Mesquite, Nevada.
7/16/1896	St. George	--	Water 3.5 feet (1.1 m) deep on west side of town.
7/20/1896	Santa Clara	--	Roads washed out, cellars filled, fields flooded and covered with sand.
8/18/1900	Washington	--	Portions of town under water, gristmill dam torn out and ditches badly damaged.
9/1-2/1900	Washington	--	Flooded town, filled ditches, and diversion dams swept away.
10/14/1900	Washington	Mill Creek	Dams washed out.
8/2/1901	St. George	--	Ditches washed out or filled with debris, basements flooded, Virgin River greatly swollen.
8/3/1901	Santa Clara	--	Ditches damaged, roads washed out.
7/25/1902	Bloomington	Virgin River	Diversion dam partially destroyed.
8/13/1902	Bloomington	Virgin River	--
8/15/1902	Bloomington	Fort Pierce Wash	Caused flood in Virgin River.
7/23/1903	Bloomington	--	Destroyed field, damaged canal.
7/21/1904	St. George, Bloomington	Virgin and Santa Clara rivers, Mill Creek(?)	St. George-Cottonwood canal filled up with boulders and sand; flood down Virgin and Santa Clara rivers washed out Bloomington Dam; floods down wash west of Washington tore away telephone pole.
8/24/1905	St. George	Virgin River	Largest flood known to date, Price Dam carried away, damage to Jarvis Field Dam and Washington Field Dam, animals and debris swept away, cropland flooded.
8/20/1906	Bloomington	Virgin and Santa Clara rivers	Damage to Price and Jarvis dams.
9/1/1909	St. George	Virgin and Santa Clara rivers	Dams washed away, bottom land and farming land washed away, canal damaged.
9/4/1909	Bloomington	Virgin River	Canal damaged, bottom land destroyed.
7/20/1911	St. George	--	Roads, canals, and crops damaged.
8/16/1916	St. George	--	Irrigation canals damaged.
8/13/1930	St. George	--	Flood on Shivwits Indian Reservation; highway culvert washed out.
10/31/1946 (prior to)	St. George	--	Flash floods in regular streams and dry washes.
9/1/1949	St. George	--	Cloudburst on Red Hill flooded business district; basements filled, goods damaged, irrigation ditches taken out.
9/8/1949	St. George	--	Main Street flooded; homes, businesses, streets, and sidewalks damaged.
6/26/1954	St. George	--	Flood in Warner Valley, film set destroyed.

(Table 2 cont.)

Date	Locality	Stream	Remarks
8/3-4/1955	Washington	--	Floods from Warner Valley flooded Washington Fields. Highway 91 blocked by flood debris, damage to farmland and equipment.
8/10/1955	St. George	--	Lake formed over entire valley of St. George and Washington fields, major flood waters from Warner Valley. Crops, roads, canals, and farm bridges washed out.
8/22/1955	St. George	Santa Clara River	Farms along river suffered loss to field crops.
8/24/1955	Santa Clara	Santa Clara River	City water line damaged, roads washed out in many places.
8/25/1955	St. George, Ivins	Santa Clara River	Three feet of water swept over U.S. Highway 91, Ivins water supply pipeline washed out, crops and land along Santa Clara River damaged.
9/28/1962	Santa Clara	--	Roads washed out, creeks over their banks.
8/12/1964	St. George	Twist Hollow	Highway 18 flooded, discharge twice that of 50-year flood.
8/12/1964	St. George	The Gap	--
12/6/1966	St. George	Santa Clara, Virgin Rivers	Virgin River overtopped irrigation dam spillway south of St. George flooding low-lying farms, gutting fields, and washing away haystacks and harvested sugar beets. Peak discharge highest on record for Virgin River, recurrance interval of this flood may be 100 years.
1969	Santa Clara	--	Two floods during 1969.
1970	St. George	--	Two floods during 1970.
1971	--	Ft. Pierce Wash	--
1975	St. George	--	--
1976	Washington	Mill Creek	--
1977	Washington St. George Ivins	--	Two floods in St. George during 1977.
1978	--	Ft. Pierce Wash	--
1979	Santa Clara	--	--
1980	St. George Santa Clara Bloomington	Ft. Pierce Wash, Virgin and Santa Clara rivers (?)	Two floods in St. George during 1980.
1981	St. George	--	--

Sources: Wooley (1946); Butler and Marsell (1972); Utah Division of Comprehensive Emergency Management (1981).

stability. Bearing capacity is assessed in terms of shear strength and compressibility (volume change due to loading), and can be increased through mechanical compaction of soils. Ease of excavation is dependent on hardness, extent of weathering, and joint spacing in rock and on induration and grain size in soil materials. Ground-water conditions and slope stability are significant factors in evaluating foundations and have been considered in previous sections. Foundation conditions have been assessed according to geologic unit and are shown in Table 1. No laboratory soil testing was performed for this study. The following general evaluations are based on data in Mortensen and others (1977) and U.S. Department of Interior Bureau of Reclamation (1974).

In general, unweathered rock formations form incompressible foundations with high shear strengths. Mechanical compaction of these materials is generally ineffective and unnecessary. The principal foundation problem related to these materials is the difficulty of excavation, particularly in highly resistant rock units. Areas where difficult excavation may be encountered include basalts of West, Middleton, and Washington Black ridges and South and North Black rocks, and areas of exposed conglomerate, sandstone, or limestone in the

Navajo, Kayenta, Chinle (Shinarump Member), Moenkopi, and Kaibab formations. Rocks in these areas are very hard and residual soils generally thin. Blasting may be required in some places but once excavated, these units make excellent foundations, provided slopes are stable.

In contrast to the resistant, unweathered rock units, most soils and non-resistant or weathered rock materials (chiefly the Moenave, Chinle, and Moenkopi formations) are easily excavated but may have undesirable foundation conditions. Potential problems with foundations that are attributable to soil conditions include: 1) settlement or heave due to expansive clays, 2) settlement caused by leaching of gypsum by ground water, and 3) piping caused by removal of soil materials by moving ground water. Expansive clays which shrink and swell with changes in moisture content present the most widespread foundation problems in the St. George area. Expansive clays are found chiefly in the Petrified Forest Member of the Chinle Formation but also in the Shnabkaib Member and to a lesser extent in the Upper, Middle, and Lower Red members of the Moenkopi Formation. Problems with expansive clays in the Chinle Formation have arisen in Washington, east of 400 East Street and north of Center Street. In this area, a trailer court has been placed on the Chinle Formation. Cracking in sidewalks, curbs, trailer skirts, and trailer windows has occurred due to shrinking and swelling of clays in this foundation material. Similar problems may arise in any areas underlain by the Chinle Formation. Expansive clays in the Shnabkaib Member of the Moenkopi Formation are probably responsible for buckling and cracking in the St. George and Washington Canal west of the Shinob Kibe near Washington.

The extent of foundation problems caused by dissolution of gypsum is not known, but may be locally significant. Gypsum is most abundant in the Shnabkaib Member of the Moenkopi Formation, the upper part of the Petrified Forest Member of the Chinle Formation, and in the lower Moenave Formation (Plate 1). Kaliser (1971, 1972) has noted gypsum in these materials, particularly in the area between St. George and Santa Clara, and states that they present a possible foundation problem. Expansive clays are also found in these formations, and it is difficult to determine which is most responsible for observed foundation problems. In general, settlement due to dissolution of gypsum is probably most important in areas of heavy irrigation (cropland, lawns) and in septic tank absorption fields, where supplies of relatively clean water are constantly moving through soils. In view of the low precipitation amounts received in the area, 4 to 10 inches/year (20 to 25 cm/year), near surface dissolution of gypsum by rainfall is not considered significant.

Evidence for piping (removal of soil materials by subsurface flow of water) and/or dissolution of soluble materials (gypsum) in soils forming open voids and subsurface cavities, is present in the study area. Sinkholes appear periodically in St. George, notably in the Dixie High School area. Open cavities nearly 1 foot (0.3 m) in diameter have been encountered in excavations on the Dixie Senior High School grounds. Fine-grained alluvium and fine-grained sedimentary rocks (claystone, siltstone) susceptible to piping, and gypsiferous soils susceptible to dissolution are found beneath St. George and elsewhere in the area (Costa and Baker, 1981; Mortensen and others, 1977). An additional prerequisite for both piping and dissolution is subsurface flow of ground water, which is known to occur in St. George. Piping requires a free face for exit of seepage water. Incipient cavities formed by the dissolution of gypsum may be important in initiating piping and subsequent soil collapse. If gypsum is present in sufficient quantity, dissolution alone may account for some sinkholes. Shallow piping and erosion is evident in retention dikes and embankments south of Washington. The access road and embankment for the St. George and Washington Canal (Figure 7) and the upper parts of retention dams east of Washington Fields have locally undergone shallow piping resulting from infiltration of rain water. Soil materials in these structures are chiefly derived from the Shnabkaib and Middle Red members of the Moenkopi Formation.

Foundation conditions discussed to this point have involved specific problems, chiefly related to areas underlain by weathered rock and residual soils. Approximately half of the study area is underlain by alluvial and eolian materials on which most construction has taken place. Of these, the fine-grained soils (Qf, Plate 1) are least suitable for foundations because of their moderate shrink-swell potential, low to medium shear strength, and medium compressibility (Mortensen and others, 1977). The poor to good compaction characteristics of these soils indicate that in some cases even

Figure 7. Piping and settlement along canal embankment.

mechanical compaction will not greatly increase shear strength or reduce compressibility. Also, strict moisture control is necessary to minimize shrinking and swelling of soils which may damage foundations. Sandy soils generally provide adequate foundations. They exhibit low shrink-swell potential, have medium shear strength, and medium to low compressibilities (Mortensen and others, 1977) depending on the percentage of fines. As the percentage of fines increases, shrink-swell potential and compressibility generally increase. Most sandy soils possess fair to good compaction characteristics, and thus form stable foundations when properly compacted. Gravelly soils share these characteristics, but have an even higher inherent shear strength and lower compressibility. Both sandy and gravelly soils are locally indurated, which further increases their foundation stability, but also increases excavation difficulties.

A foundation problem unique to transported soils may result from subsidence due to hydrocompaction. Certain low-density soils, ranging in texture from silty sand to clay, are subject to settlement when saturated for the first time since deposition (Curtin, 1973). One environment in which these soils are found is the alluvial fan environment in hot, dry areas. Sediment in alluvial fans is in part deposited from relatively viscous mudflows or debris flows, particularly in areas of clay-rich source rocks. Upon deposition, these flows dry and harden, and if not reworked by later streamflow, form a deposit of low-density, loose-framework material susceptible to collapse upon re-wetting. Subsidence due to hydrocompaction in soils has been identified in the Cedar City and Hurricane areas along the Hurricane Cliffs (Kaliser, 1977). Similar conditions may exist in the St. George area in alluvial fan deposits at the base of cliffs such as east of Washington Fields and north of Ivins. Although no reported incidences of settlement due to hydrocompaction have been documented, such conditions should be considered in soil/foundation studies prior to construction. To date, no single field soil characteristic has been found reliable in identifying hydrocompactible (collapsible) soils, and lab consolidation tests are generally required.

An additional potentially adverse foundation condition involves soil response to ground shaking. Ground shaking may result from an earthquake or activities of man (blasting, movement of heavy machinery). Sandy, poorly graded soils with few fines in high water-table areas may lose all shear strength during shaking. This phenomenon is known as liquefaction, and may occur where the above conditions exist. They may exist locally in sandy soils (Qs, Plate 1) along the Virgin and Santa Clara rivers and in adjacent lowland areas which may include portions of St. George, Santa Clara, and Bloomington. Most sands in the area contain appreciable fines which reduce the risk, but any construction projects proposed in these areas should include an evaluation of liquefaction potential in their soil/foundation investigation.

Construction materials

Naturally-occurring construction materials in the St. George area consist chiefly of sand and gravel for aggregate and rock for riprap. Materials from gravel pits along the Virgin and Santa Clara rivers have been utilized by the Utah Department of Transportation (UDOT) in construction of Interstate 15 as well as by local government agencies and private contractors in road and building construction. Considerable quantities of aggregate suitable for use in roadbeds and asphalt pavement occur in the study area, but sources of concrete aggregate are much less common.

Major sand and gravel deposits are found in stream terraces along the Virgin and Santa Clara rivers and along Fort Pierce Wash (Qog, Plate 1). The quality of aggregate in these deposits is variable. Most are suitable for use in roadbeds and asphalt, and sand in all deposits is generally suitable for use in concrete aggregate. However, gravels may be coated with calcium carbonate or contain large percentages of gypsum or soft materials making them unacceptable for use in concrete aggregate. In general, stream terrace deposits at higher elevations above the modern stream are older and contain more calcium carbonate and more weathered clasts than those closer to stream level. Therefore, better quality aggregate is found in the lower terraces. Gravel in deposits along the Santa Clara River and Fort Pierce Wash are suitable for aggregate in roadbeds and asphalt surfacing, but contain unacceptable quantities of softer sandstone and calcium carbonate-coated clasts for use in concrete (personal communication, Clark Maxwell, UDOT materials engineer, 1982). Because of the addition of material from the Santa Clara River and Fort Pierce Wash, gravels along the Virgin River south of St. George are also of poor quality (Utah State Department of Highways, 1966?).

Gravels of highest quality are found in lower terraces along the Virgin River east of St. George. Gravels in higher terraces, particularly those near Washington south of the Virgin River (Qog, Plate 1), are strongly indurated and are generally poor sources of aggregate. The best sources are north of the Virgin River in the lower terraces in sections 19 and 20, T. 42 S., R. 14 W. These gravels are presently the only local source of concrete aggregate from terrace deposits in the area. Both sand and gravel can be extracted in sufficient quantities, and mixing with other sources is not required.

Although not presently utilized, several potential bedrock sources of aggregate are found in the area. These include outcrops of the Kaibab Limestone (Pk, Plate 1), Shinarump Member (conglomerate) of the Chinle Formation (TRcs), and Tertiary/Quaternary basalt (Tb, Qb_1, Qb_2, Qb_3) (Utah State Department of Highways, 1966?). Such sources involve increased excavation costs and require separate sources of sand, but provide a uniform grade of coarse aggregate for use in roadbeds or asphalt surfacing. However, some of these bedrock sources may contain materials deleterious to concrete such as gypsum, volcanic glass, or chert, and may not be suitable for use as concrete aggregate. Limestone is presently being quarried from sources west of the study area and mixed with sand from stream terraces along the Santa Clara River for use as concrete aggregate.

Potential sources of riprap are found in outcrops and talus accumulations throughout the area. Probably the best sources are the basalt in West, Middleton, and Washington Black ridges and North and South Black rocks. Basalt is very dense and highly erosion resistant. The spacing of fractures in these rocks causes them to naturally break into blocks of suitable size for riprap. Basalt from West and Middleton Black ridges has been utilized by the Utah State Department of Highways (1966?) for riprap. In comparison to basalt, most sedimentary rock in the area is less resistant to erosion and is too highly fractured to break into large blocks suitable for riprap. The sedimentary units which are potential sources of riprap are the Shinarump Conglomerate (TRcs, Plate 1) and the Navajo Sandstone (JTRn). Sandstone or conglomerate beds in other units may be locally suitable, but they do not represent major sources of riprap.

Suitability for soil absorption systems

The suitability of an area for wastewater disposal in soil absorption systems is dependent on soil types, slope, flood hazard, depth to ground water, and depth to bedrock. Soil type, specifically grain size characteristics and clay content, determines the permeability and filtering capacity of soils in an absorption system. Fine-grained soils with high clay content, particularly if clays are expansive, lack sufficient permeability to perform satisfactorily. Wastewater moves very slowly from drain lines into these soils, and the system can easily become overloaded. Surface seepage of unrenovated water may result. Expansive clays are particulary unsuitable because initial percolation tests may indicate sufficient permeability, but once the clays are saturated for a period of time, they swell and permeability is reduced. However, a certain percentage of fine-grained material is necessary for proper filtering or renovation of wastewater. If soils lack fines, permeability may be too high and filtering capacity too low to properly renovate wastewater. Silty and clayey sands containing clay but in quantities less than 25-30 percent are best suited for soil absoption systems.

Steep slopes are generally unsuitable for soil absorption systems. Wastewater does not have a sufficiently long travel-path before it intersects the surface as it moves laterally away from drain lines and surface seepage of unrenovated or partially renovated wastewater results. The U.S. Environmental Protection Agency (1980) recommends that slopes be less than 25 percent to avoid surface seepage. The Utah Department of Health Wastewater Disposal Regulations (Parts IV and V) do not stipulate a maximum slope, but state that "liquid moving horizontally through the soil in any direction from the maximum effluent level will have to pass through at least 6 feet (2 m) of undisturbed soil before surfacing". Areas of high flood hazard must also be avoided since contamination of both surface and ground water may occur if absorption fields are submerged beneath flood waters. Areas of high ground water or shallow bedrock are also unsuitable. If an insufficient thickness of soil is present above the water table to renovate wastewater, contamination of ground water may occur. Likewise, if shallow bedrock is present, unrenovated wastewater may get into fractures and contaminate bedrock aquifers. Fractured bedrock has very little filtering capacity. If bedrock is unfractured, ground water contamination may not be a problem but low permeabilities in unfractured rock can cause system failure. The U.S. Environmental Protection Agency (1980) recommends a minimum of 2 to 4 feet (0.6 to 1.2 m) of undisturbed, unsaturated soil between the bottom of the absorption field and the seasonal high water table or bedrock. Part IV of the Utah Wastewater Disposal Regulations (presently under revision) requires at least 4 feet (1.2 m) of soil between bedrock or any impervious formation and the bottom of absorption systems, and that high ground-water elevation be at least one foot (0.3 m) below the bottom of absorption systems and at least 4 feet (1.2 m) below finished grade.

Much of the study area is poorly suited for soil absorption systems due to the presence of exposed or shallow bedrock. All areas shown on Plate 1 as Permian, Triassic, and Jurassic rock are generally unsuitable, as are areas of Tertiary or Quaternary basalt or landslide deposits (Table 1). Isolated thick residual soils suitable for soil absorption systems, may exist within these areas of rock. The remainder of the study area is underlain by Quaternary age deposits of fines, sand, and gravel which are locally suitable but exhibit considerable variation. Deposits of fines (Qf, Plate 1) are less suitable due to excessively low permeabilities. Deposits of gravel (Qog) are likewise less suitable because of excessively high or low (where indurated) permeabilities and shallow bedrock (Mortensen and others, 1977). Shallow ground water and high flood hazard (Plate 2) are a problem locally in areas of fine-grained soils. Excessively high permeability, strongly indurated layers, and steep slopes may be found in gravelly deposits which further reduce their suitability for soil absorption systems. Sandy soils (Qs, Plate 1) are best suited except for clean eolian sands lacking fines, sands with excessive clay content, or strongly indurated sand such as at the landing field bench. Areas of shallow ground water and high flood hazard (Plate 2) occur in sandy soils as well. Soil absorption system failures caused by shallow ground water have recently occurred in southeast St. George, Middleton, and Ivins (Fisk and Clyde, 1981).

Seismicity and Quaternary faults

The St. George area lies at the southern end of the Intermountain seismic belt - a zone of pronounced earthquake activity extending from northwestern Montana to southwestern Utah. The Intermountain seismic belt has one of the highest levels of earthquake risk in the contiguous United States, outside of California and western Nevada (Arabasz and others, 1979). In Utah, the zone of seismicity generally follows the north-south trending Hurricane and Wasatch fault zones. An easterly trending zone of relatively high seismicity, the southern Nevada seismic zone, intersects the Intermountain seismic belt in the vicinity of St. George (Anderson, 1978).

The complete record of historical earthquakes of Richter magnitude 2.0 and greater within a 22-mile (35 km) radius around St. George compiled from Arabasz and others (1979), DuBois and others (1982), and University of Utah Seismograph Stations (1982) is shown in Table 3. This record covers the period 1850 to December 1981, and records 23 events, some of which consisted of more than one shock within a relatively short time period. Locations of these events are shown in Figure 8. Locations and magnitudes of earthquakes before about 1938 are very approximate and are based principally on non-instrumental intensity data from felt reports. Routine epicenter determinations from widely-spaced regional seismograph data began in 1950, but locations are not sufficiently accurate to correlate earthquakes with known faults (Arabasz and others, 1979; Anderson, 1978). Installation of a state-wide instrumental network of seismograph stations began in 1962 (Arabasz and others, 1979), and more recent events are much more accurately recorded.

The greatest magnitude events to affect the area

Table 3. Earthquakes of Richter magnitude 2.0 or greater in the St. George area, 1850 to December 1981.

Index to Numbers in Fig. 8	Date	Magnitude	Maximum Intensity	Epicenter Location Latitude(N)	Longitude(W)
1	4/20/1891	5.0*	VI	37°06.38′	113°34.41′
2	11/17/1902	6.3*	VIII	37°23.58′	113°31.20′
3	12/05/1902	5.0*	VI	37°23.68′	113°31.20′
4	11/04/1903	3.0*	III	37°06.38′	113°34.41′
5	11/23/1903	4.3*	V	37°06.38′	113°34.41′
6	11/26/1920	4.3*	V-VI	37°06.38′	113°34.41′
7	5/03/1944	3.7*	IV	37°06.38′	113°34.41′
8	11/02/1949	4.7	VI	37°06.38′	113°34.41′
9	5/02/1952 (10:15)	3.7*	IV	37°14.47′	113°16.90′
10	5/02/1952 (16:15)	2.3	II	37°14.47′	113°16.90′
11	11/20/1955	3.7*	IV	37°06.00′	113°54.00′
12	3/02/1962	2.6	—	36°57.60′	113°28.80′
13	6/08/1966	3.2	—	37°00.00′	113°48.00′
14	12/16/1970	2.6	—	36°50.40′	113°43.20′
15	7/01/1972	2.3	—	37°05.29′	113°29.51′
16	7/02/1972	2.5	—	37°18.47′	113°49.85′
17	9/02/1972	3.2	—	37°14.01′	113°21.78′
18	8/05/1979	3.6	—	36°58.89′	113°40.08′
19	9/04/1979	2.3	—	36°55.18′	113°33.58′
20	11/18/1979	2.0	—	37°07.21′	113°24.70′
21	1/14/1980	2.1	—	37°18.68′	113°33.33′
22	4/29/1980	2.7	—	36°55.60′	113°29.43′
23	12/02/1981	2.1	—	37°10.67′	113°34.29′

Sources: Arabasz and others (1979); DuBois and others (1982); University of Utah Seismograph Stations (1982).
*Magnitude not instrumentally measured, but estimated from maximum Modified Mercalli intensity assuming Gutenberg-Richter relation (Gutenberg and Richter, 1956).

occurred near the turn of the century with one estimated Richter magnitude 6.3 and two estimated magnitude 5.0 events. The maximum recorded Modified Mercalli intensity (Appendix) was VIII for the magnitude 6.3 earthquake in 1902 which was located approximately 20.5 miles (33 km) north of St. George (Figure 8). Since 1950, no earthquakes of magnitude greater than 4.0 have occurred and the maximum intensity has been IV (Appendix).

Surface fault rupture has not been associated with any of the earthquakes recorded in the St. George

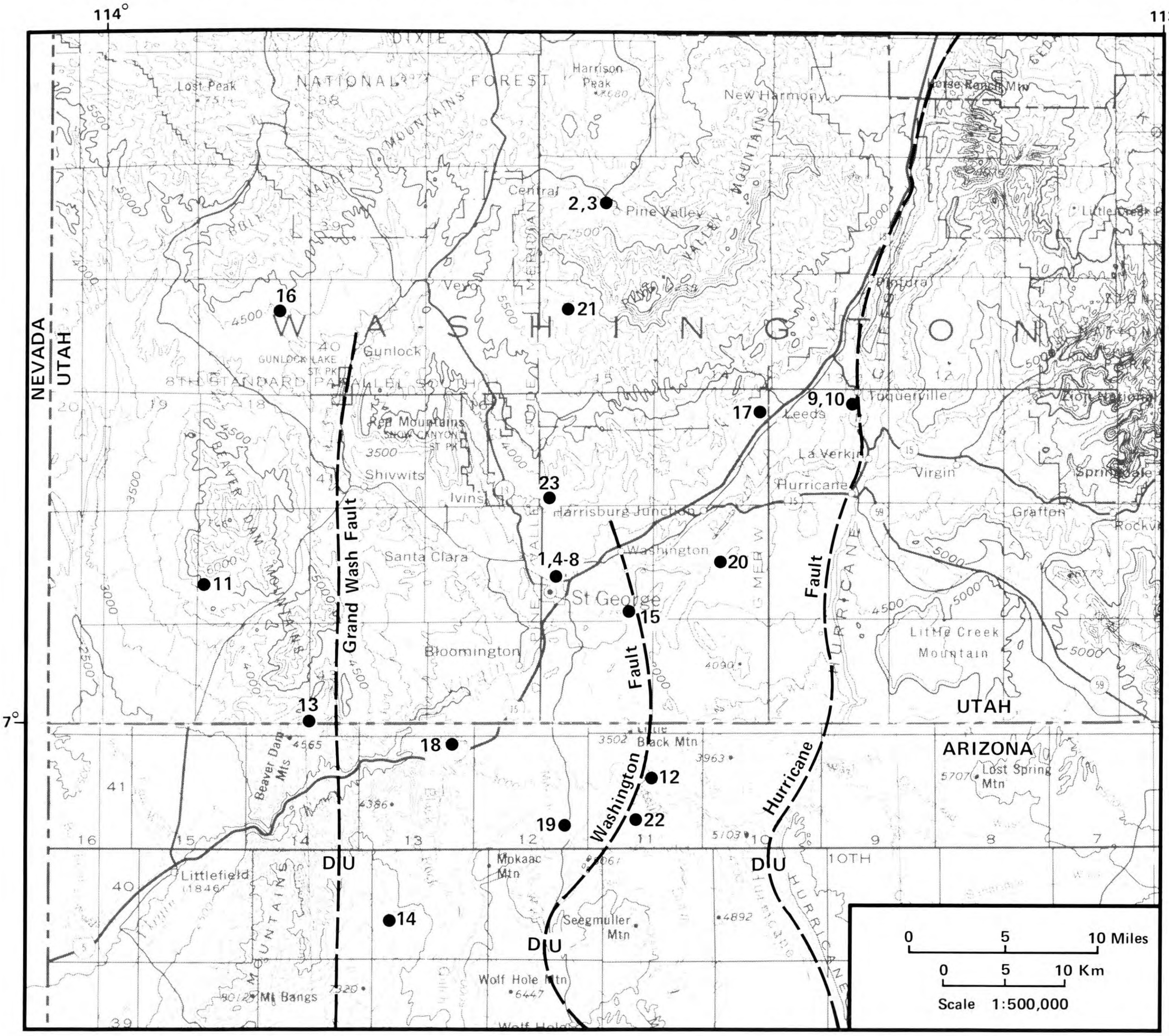

Figure 8. Location of earthquake epicenters listed in Table 3 (1850 to December 1981) and approximate locations of main traces of major faults (D, downthrown side; U, upthrown side) in the St. George area.

area. However, several major faults are present in southwestern Utah and northwestern Arizona on which surface rupture is suspected to have occurred during Quaternary time (Figure 8). Fault traces shown on Figure 8 are modified from Hintze (1980) and Wilson and others (1969). One fault with indications of recent activity is the Hurricane fault which forms the east side of the St. George Basin, 14 miles (23 km) east of St. George. This fault is a normal fault (down on the west) which follows the base of the Hurricane Cliffs with total displacement increasing from south to north (Hamblin, 1970). It shows evidence of late Pleistocene movement (10,000 to about 500,000 years B.P.; Anderson and Miller, 1979). The Hurricane fault is flanked by numerous short fault segments which also displace deposits of probable late Pleistocene age and, in Arizona, Holocene age (Hamblin, 1970; Huntoon,

Figure 9. View to the north of the scarp of the Washington fault in the SW ¼ sec. 13, T. 43 S., R. 15 W. Displacement is up on the right (east) exposing light-colored Moenkopi Formation (Shnabkaib Member). Quaternary alluvium buries downthrown block (left).

1977). Estimates of the time of inception of movement on the Hurricane fault range from Miocene (Hamblin, 1970) to Quaternary (Anderson and Mehnert, 1979). In either case, total displacement of 2000 feet (600 m) during Quaternary time is postulated with an uplift rate east of the fault of about 1000 ft/million years (300 m/m.y.) calculated from offsets in basaltic flows cut by the fault (Hamblin and others, 1981).

Another major structure suspected but not proven active during Quaternary time is the northern extension of the Grand Wash fault, 11 miles (18 km) west of St. George (Anderson and Miller, 1979). This fault forms the west edge of the St. George Basin trending northward from the Grand Wash Cliffs in Arizona to Gunlock, Utah (Figure 8). Total displacement increases from north to south along the fault (Hamblin, 1970). Along the Arizona segment of the fault, Moore (1972) considers movement to have occurred in late Pliocene (?) to Holocene time. Hamblin (1970) finds evidence for main fault movement 10 to 20 m.y. ago (early Miocene-late Pliocene) but with several hundred feet of movement during the last 6 million years. Cook (1960) identified three distinct fault segments in the section of the fault in Utah based on changes in sense of displacement, although predominant displacement is down to the west. The three segments of the Grand Wash fault in southern Utah are the Cedar Pocket Canyon, Shebit, and Gunlock faults. Lovejoy (1976) considers movement on this part of the fault to be primarily Laramide (Late Cretaceous-early Tertiary).

Many lesser, short fault segments of suspected Quaternary age are present just north of the study area (Anderson and Miller, 1979). The only suspected Quaternary fault in the study area is the Washington fault (Figure 8, Plate 1). This fault zone extends from north of Washington to south of the Utah-Arizona border, although only the northern segments are suspected of Quaternary activity by Anderson and Miller (1979). Scarps are higher on these northern segments, but this is probably due to the greater competency of the displaced rocks of the Moenave and Kayenta formations in this area. To the south, the fault generally offsets rock of the less resistant Moenkopi Formation (Middle Red and Shnabkaib members; Figure 9). Total displacement decreases from 2500 feet near the Arizona-Utah border to approximately 100 feet near Washington (Hamblin, 1970). Hamblin (1970) cites evidence in Arizona for movement during the last 6 million years, and one-million-year-old basalts (Qb_1, Plate 1) between Washington and the Virgin River are offset within the fault zone in the study area. No surface evidence of offset of Holocene deposits was found along any segment of the Washington fault in the study area. However, recent trenching by Earth Science Associates (personal communication, Dwight Hunt, 1982) has indicated definite late Pleistocene and possible Holocene movement on the segment of the fault along the east side of Washington Fields (Plate 1).

Due to the level of seismicity and presence of these Quaternary and suspected Quaternary faults, the St. George area is in seismic zone 2 of the Uniform Building Code (UBC) and the Utah Seismic Safety Advisory Council (USSAC) statewide seismic zonation. Utah is divided into three (UBC) or four (USSAC) seismic zones, with zone 1 being least hazardous (lowest projected earthquake probability and magnitude) and zones 3 and 4 being most hazardous (highest projected earthquake probability and magnitude). Earthquake hazard near St. George is thus considered moderate, with a maximum expected Modified Mercalli intensity of VII (Appendix) in UBC seismic zone 2. All construction should conform to specifications listed in the Uniform Building Code for structures in seismic zone 2.

CONCLUSIONS AND RECOMMENDATIONS

The St. George area will probably continue to grow rapidly, with the majority of construction taking place in the Ivins-Santa Clara Bench, Washington-Middleton, and Bloomington areas. This development can occur in an efficient and safe manner through proper planning based on a knowledge of natural conditions. The information provided in this report is directed toward those involved in planning and development. Geologic factors are most important in early feasibility studies and initial site planning, when potential hazardous conditions must be identified and mitigating measures planned. The geologic conditions that exist in the St. George area which are of greatest importance to planning include:

1) Expansive soils derived from bentonitic shales of the Chinle Formation (Petrified Forest Member) and Moenkopi Formation (principally Shnabkaib Member) which adversely affect foundations and soil absorption systems.

2) Potential settlement or subsidence due to piping or dissolution of gypsum in soils derived principally from the Moenkopi, Chinle and Moenave formations which may cause foundation settlement or soil collapse.

3) High ground-water conditions in lowland areas, chiefly in St. George and the flood plains of the Virgin and Santa Clara rivers. These conditions may result in basement flooding, soil absorption system failure, and soil instability during ground shaking.

4) Potentially unstable slopes, particularly those slopes underlain by the Moenkopi Formation (Shnabkaib Member) and Chinle Formation (Petrified Forest Member).

5) Debris flow and mudflow hazards at canyon mouths, along streams, and on alluvial fans.

6) Flood hazard in stream-channel and flood-plain areas of all major drainages.

7) Moderate earthquake hazard due to events on the Hurricane and Grand Wash fault systems, local events on the Washington fault, or random events unassociated with known surface faulting.

The data presented in this report are for general planning purposes only and do not preclude the necessity for site investigations. It is recommended that all proposed subdivisions and major construction projects include a geologic/soils report addressing site conditions. In all cases, site specific investigations are required by the Utah Division of Environmental Health in order to determine suitability for soil absorption systems wherever they are planned. Initial planning and engineering to avoid or mitigate adverse geologic conditions can greatly reduce the need for costly repair, maintenance, and/or replacement of poorly placed or inadequately engineered structures.

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APPENDIX

GLOSSARY

Alluvial fan: A cone-shaped deposit of alluvium made by a stream where it runs out onto a level plain or meets a slower stream.

Alluvium: Sedimentary deposits resulting from the operations of streams.

Anticline: A fold in rock strata that is convex upward.

Aquifer: Stratum or zone below the surface of the earth capable of producing water as from a well.

Bentonite: Clay formed by the decomposition of volcanic ash, generally highly expansive.

Caliche: Secondary accumulation of calcium carbonate developed in soils at or near the ground surface.

Compressibility: Time-dependent reduction in pore space as a result of loading.

Compaction: Instantaneous reduction in pore space by mechanical means.

Cuesta: Sloping surface terminated on one side by a steep slope, formed on gently dipping resistant rock layers.

Eolian: Resulting from the action of wind.

Ephemeral stream: Stream which flows only in response to precipitation, otherwise dry.

Induration: Secondary hardening and cementation of a soil material.

Normal fault: A fault at which the hanging wall (upper block) has moved downward relative to the footwall (lower block).

Permeability: Capacity of a rock or soil material to transmit a fluid, generally water.

Shear strength: The internal resistance of a material to shear stress (movement of one part of the body relative to another part).

Sheet flooding: Overland flow of water not concentrated in channels, generally in response to periods of heavy rainfall.

Shrink-swell: The capacity of a soil material to increase or decrease in volume with changes in moisture content, generally a function of type and percentage of clay.

Talus: Accumulation of rock debris at the base of a slope.

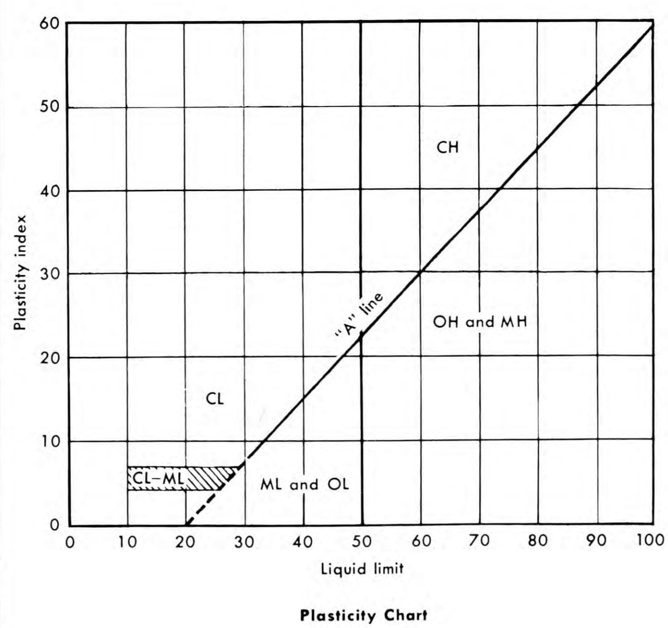
Unconformity: Surface of erosion or nondeposition that separates younger from older rocks.

GEOLOGIC TIME SCALE

ERA	PERIOD	EPOCH	Age estimate of beginning (millions of years ago)
Cenozoic	Quaternary	Holocene	0.01
		Pleistocene	1.6
	Tertiary	Pliocene	5.0
		Miocene	22.5
		Oligocene	37.5
		Eocene	53.5
		Paleocene	65
Mesozoic	Cretaceous		135
	Jurassic		190-195
	Triassic		225
Paleozoic	Permian		280
	Pennsylvanian		320
	Mississippian		345
	Devonian		395
	Silurian		430-440
	Ordovician		500
	Cambrian		570
Precambrian			4500

UNIFIED SOIL CLASSIFICATION SYSTEM

Major divisions			Group symbols		Typical names	Laboratory classification criteria		
Coarse-grained soils (More than half of material is larger than No. 200 sieve size)	Gravels (More than half of coarse fraction is larger than No. 4 sieve size)	Clean gravels (Little or no fines)	GW		Well-graded gravels, gravel-sand mixtures, little or no fines	Determine percentages of sand and gravel from grain-size curve. Depending on percentage of fines (fraction smaller than No. 200 sieve size), coarse-grained soils are classified as follows: Less than 5 per cent. . . . . GW, GP, SW, SP; More than 12 per cent. . . . . GM, GC, SM, SC; 5 to 12 per cent. . . . . *Borderline* cases requiring dual symbols**	$C_u = \frac{D_{60}}{D_{10}}$ greater than 4; $C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ between 1 and 3	
			GP		Poorly graded gravels, gravel-sand mixtures, little or no fines		Not meeting all gradation requirements for GW	
		Gravels with fines (Appreciable amount of fines)	GM*	d	Silty gravels, gravel-sand-silt mixtures		Atterburg limits below "A" line or P.I. less than 4	Above "A" line with P.I. between 4 and 7 are *borderline* cases requiring use of dual symbols
				u				
			GC		Clayey gravels, gravel-sand-clay mixtures		Atterburg limits above "A" line with P.I. greater than 7	
	Sands (More than half of coarse fraction is smaller than No. 4 sieve size)	Clean sands (Little or no fines)	SW		Well-graded sands, gravelly sands, little or no fines		$C_u = \frac{D_{60}}{D_{10}}$ greater than 6; $C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ between 1 and 3	
			SP		Poorly graded sands, gravelly sands, little or no fines		Not meeting all gradation requirements for SW	
		Sands with fines (Appreciable amount of fines)	SM*	d	Silty sands, sand-silt mixtures		Atterburg limits below "A" line or P.I. less than 4	Limits plotting in hatched zone with P.I. between 4 and 7 are *borderline* cases requiring use of dual symbols.
				u				
			SC		Clayey sands, sand-clay mixtures		Atterburg limits above "A" line with P.I. greater than 7	
Fine-grained soils (More than half of material is smaller than No. 200 sieve)	Silts and clays (Liquid limit less than 50)		ML		Inorganic silts and very fine sands, rock flour, silty or clayey fine sands, or clayey silts with slight plasticity			
			CL		Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays			
			OL		Organic silts and organic silty clays of low plasticity			
	Silts and clays (Liquid limit greater than 50)		MH		Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts			
			CH		Inorganic clays of high plasticity, fat clays			
			OH		Organic clays of medium to high plasticity, organic silts			
	Highly organic soils		Pt		Peat and other highly organic soils			



Plasticity Chart

*Division of GM and SM groups into subdivisions of d and u are for roads and airfields only. Subdivision is based on Atterburg limits; suffix d used when L.L. is 28 or less and the P.I. is 6 or less; the suffix u used when L.L. is greater than 28.

**Borderline classifications, used for soils possessing characteristics of two groups, are designated by combinations of group symbols. For example: GW-GC, well-graded gravel-sand mixture with clay binder.

MODIFIED MERCALLI INTENSITY SCALE OF 1931
(Abridged)

I. Not felt except by a very few under especially favorable circumstances.

II. Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.

III. Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration like passing of truck. Duration estimated.

IV. During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls made cracking sound. Sensation like heavy truck striking building; standing motor cars rocked noticeably.

V. Felt by nearly everyone; many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles and other tall objects sometimes noticed. Pendulum clocks may stop.

VI. Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.

VII. Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars.

VIII. Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Disturbed persons driving motor cars.

IX. Damage considerable in specially designed structures; well designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.

X. Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks.

XI. Few, if any (masonry), structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipe lines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.

XII. Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into the air.

Source: Earthquake Information Bulletin; 6 (5), 1974, p. 28.

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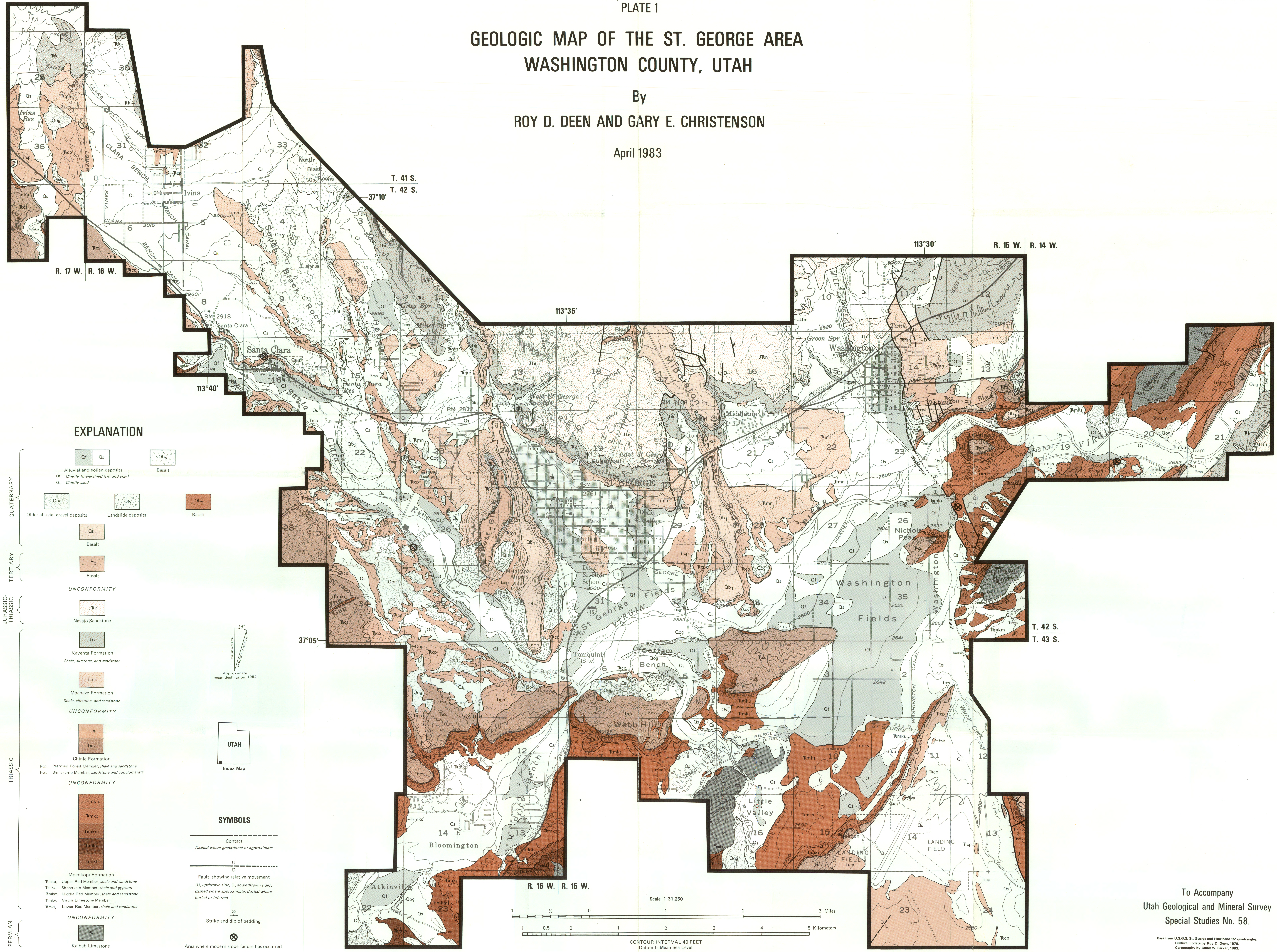
PLATE 1

GEOLOGIC MAP OF THE ST. GEORGE AREA WASHINGTON COUNTY, UTAH

By

ROY D. DEEN AND GARY E. CHRISTENSON

April 1983



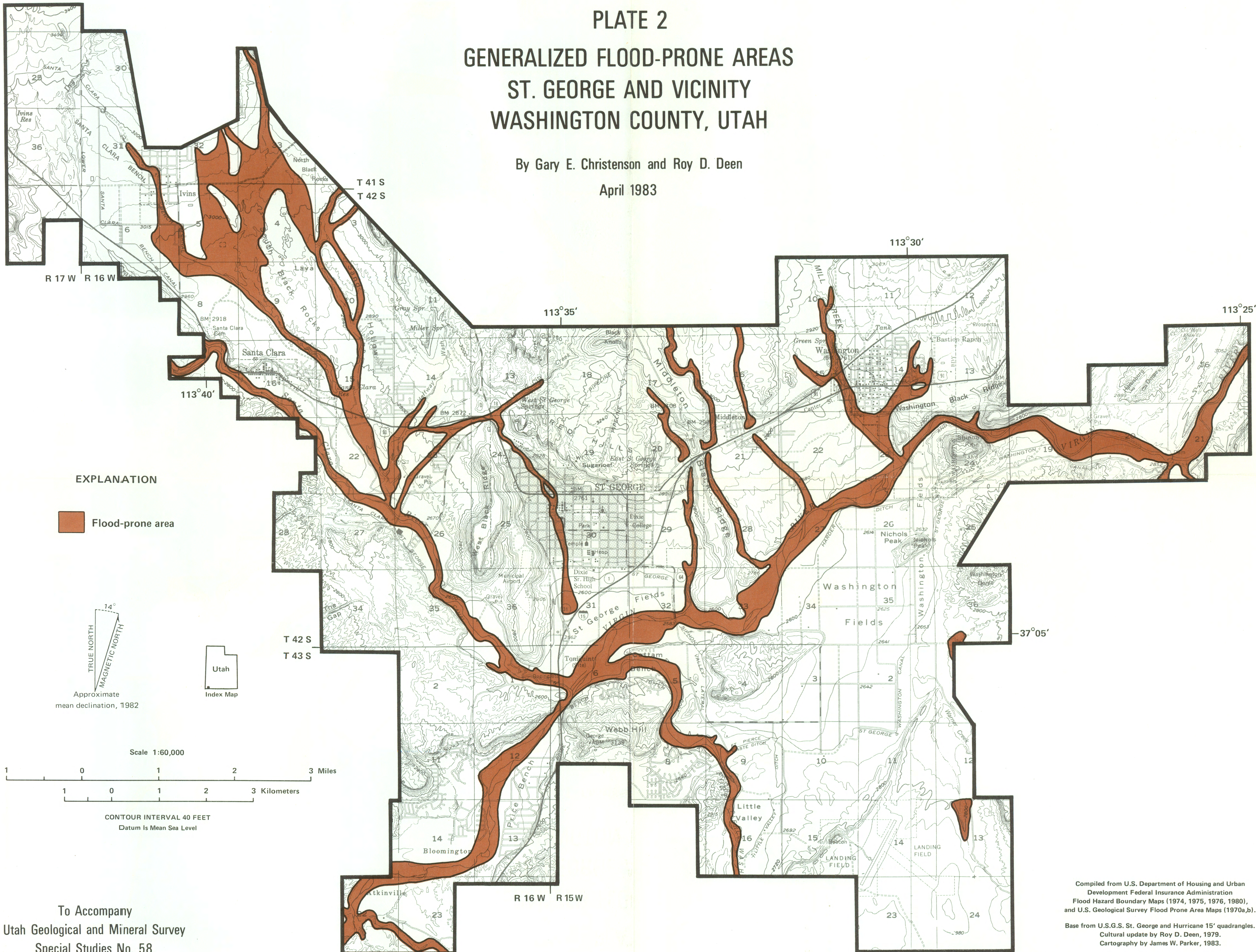
To Accompany
Utah Geological and Mineral Survey
Special Studies No. 58.

Base from U.S.G.S. St. George and Hurricane 15' quadrangles.
Cultural update by Roy D. Deen, 1979.
Cartography by James W. Parker, 1983.

PLATE 2
GENERALIZED FLOOD-PRONE AREAS
ST. GEORGE AND VICINITY
WASHINGTON COUNTY, UTAH

By Gary E. Christenson and Roy D. Deen

April 1983



EXPLANATION

Flood-prone area

Approximate mean declination, 1982

TRUE NORTH

MAGNETIC NORTH

14°

Utah

Index Map

Scale 1:60,000

1 0 1 2 3 Miles

1 0 1 2 3 Kilometers

CONTOUR INTERVAL 40 FEET
Datum Is Mean Sea Level

To Accompany
Utah Geological and Mineral Survey
Special Studies No. 58.

Compiled from U.S. Department of Housing and Urban Development Federal Insurance Administration Flood Hazard Boundary Maps (1974, 1975, 1976, 1980), and U.S. Geological Survey Flood Prone Area Maps (1970a,b).

Base from U.S.G.S. St. George and Hurricane 15′ quadrangles.
Cultural update by Roy D. Deen, 1979.
Cartography by James W. Parker, 1983.