GEOLOGIC HAZARDS AND ADVERSE CONSTRUCTION CONDITIONS

ST. GEORGE–HURRICANE METROPOLITAN AREA, WASHINGTON COUNTY, UTAH

by William R. Lund, Tyler R. Knudsen, Garrett S. Vice, and Lucas M. Shaw

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Cover Image: *A historical slope failure in the Petrified Forest Member of the Chinle Formation and overlying unconsolidated deposits, St. George–Hurricane metropolitan area.*

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SECTION 1: INTRODUCTION TO GEOLOGIC HAZARDS AND ADVERSE CONSTRUCTION CONDITIONS

INTRODUCTION

Purpose

The purpose of this study is to provide planners and other city and county officials with information on the kind and location of geologic hazards and adverse construction conditions that may impact existing and future development in the St. George-Hurricane metropolitan area (figure 1; see study-area definition below). We compiled the data for this study at a scale of 1:24,000 (1 inch = 2000 feet). The maps accompanying this report (plates 1-14) are also at 1:24,000-scale. The maps are designed as an aid for general planning to indicate where more detailed, site-specific special studies are required. The maps are not intended to be enlarged (blown up) for use at scales larger than the scale at which they were compiled, and are not a substitute for site-specific geotechnical investigations. Typically, the maps are based on limited geologic and geotechnical data, the quality of which varies throughout the study area. Consequently, special-study-area boundaries shown on the maps are approximate and subject to change with additional information. Furthermore, small, localized areas of hazard or adverse construction conditions may exist in the study area, but their identification was precluded because of limitations of either data availability or map scale.

Regarding special studies, we recommend a site-specific geotechnical foundation study for all development at all locations in the study area, and a geologic assessment to identify potential geologic hazards and/or adverse construction conditions at sites located within special-study areas shown on the maps accompanying this report. Site-specific studies can resolve uncertainties inherent in these small-scale maps, and help ensure safety by identifying the need for special construction designs or hazard mitigation.

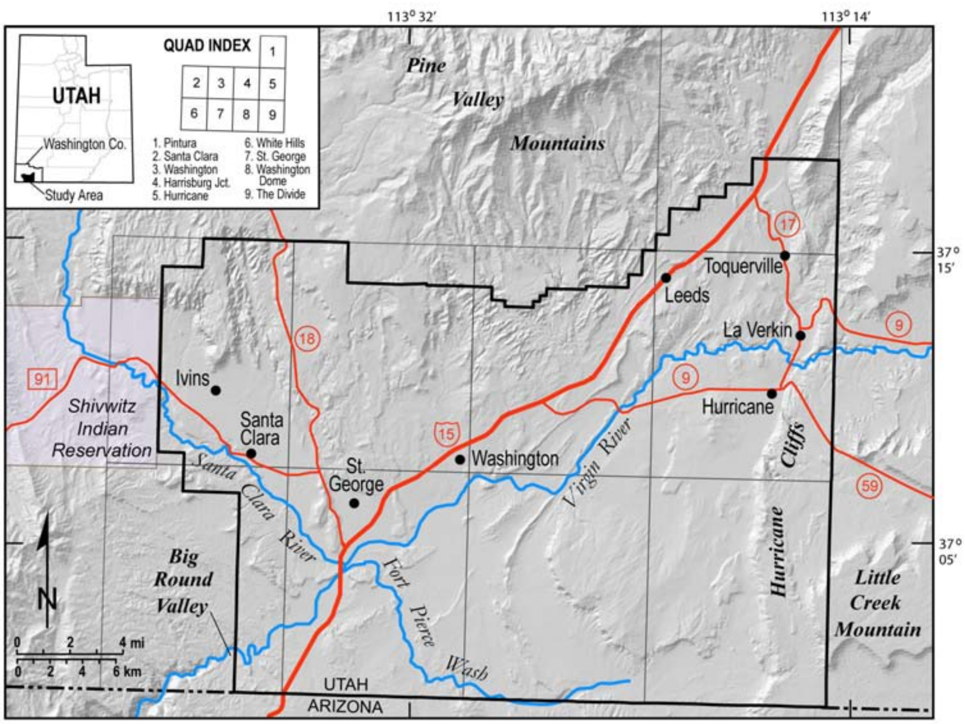

Figure 1. *Map showing the boundaries, principal cities and towns, major transportation routes, and drainages of the St. George–Hurricane metropolitan area.*

Background

Southwestern Utah's mild climate and beautiful scenery have combined to make the St. George–Hurricane metropolitan area one of Utah's fastest growing regions for more than two decades. As land well suited for development becomes increasingly scarce, urbanization has moved into less favorable areas where geologic hazards and adverse construction conditions become concerns to development. Where development takes place in less geologically suitable areas, timely geologic information early in the planning and design process is critical to avoiding or mitigating geologic hazards and adverse construction conditions. Recognizing that fact, the Utah Geological Survey (UGS; then the Utah Geological and Mineral Survey) published *Engineering Geology of the St. George Area, Washington County,* *Utah* (Christenson and Deen, 1983) twenty-five years ago, as a guide to future development in the St. George area. Since that time, growth in the St. George–Hurricane metropolitan area has continued at an ever increasing pace, and has expanded into areas not envisioned in 1983. The population of Washington County has increased by more than 40 percent since 2000, and its current population of 126,000 is projected to reach 400,000 by 2035 (Five County Association of Governments, 2006). Simultaneously, geologic and geotechnical studies conducted in the St. George area, in particular new UGS 1:24,000-scale geologic mapping, have greatly increased our understanding of the region's geologic setting and hazards. These phenomenal levels of past and projected growth combined with newly available geologic and geotechnical information highlight the need for accurate, up to date information about geologic hazards and adverse construction conditions in the St. George–Hurricane metropolitan area.

This study updates and expands upon the Christenson and Deen (1983) report both in terms of the number and kinds of hazards and adverse construction conditions considered and geographic coverage. Additionally, this study uses a Geographic Information System (GIS) format, which permits the powerful organizational and analytical features of computer-based databases and maps to be brought to bear on the identification, characterization, and mitigation of geologic hazards and adverse construction conditions.

Scope of Work

The scope of work performed for this study consisted of:

(1) Identifying and reviewing new geologic, hydrologic, and soils information available for the study area since publication of the Christenson and Deen (1983) report, particularly new information in digital format.

(2) Digitizing essential geologic, hydrologic, and soils information not already available in digital format.

(3) Compiling a new digital geotechnical database incorporating test data and other information from 275 geotechnical reports on file with municipalities in the study area, and from the Utah Department of Transportation.

(4) Compiling a new digital ground-water database incorporating information from well-driller's logs throughout the study area on file with the Utah Division of Water Rights.

(5) Incorporating digital road and land parcel information into the GIS database.

(6) Field checking and mapping as necessary to produce derivative geologic-hazard and adverse-construction-condition maps from the basic geologic, hydrologic, soils, and geotechnical information in the GIS database.

(7) Preparing text documents that describe each geologic hazard or construction condition in detail.

(8) Developing a GIS search application that permits the maps to be queried by geologic-hazard or adverse-construction-condition type and location (township, range, and section; latitude and longitude; UTM; rectangular area; or tax identification number) and produces a map and report on the hazards/adverse construction conditions present.

The principal products of this study are 14 1:24,000-scale geologic-hazard and adverse-construction-condition-susceptibility maps for the St. George–Hurricane metropolitan area (plates 1-14) with accompanying text documents, and a search application which allows the maps to be quickly scanned, geologic hazards/adverse construction conditions identified, and a custom map and explanatory text prepared for a particular land parcel. Each map covers a different geologic hazard or adverse construction condition, and the accompanying text document provides background information on the data sources used to create the map, the nature and distribution of the hazard or adverse construction condition, and possible mitigation measures. An additional text document discusses earthquake-induced ground-shaking; however, there were insufficient data available at the time of this study to prepare a Ground-Shaking-Hazard Map. The geologic hazards and adverse construction conditions included in this study are listed in table 1.

Although we compiled the data used in this study from a wide variety of sources (see reference list in each text document), the principal sources of information used to create the maps, in addition to the new databases specifically created for this project, included (1) nine digital UGS 1:24,000-scale geologic quadrangle maps in the St. George–Hurricane metropolitan area (Harrisburg Junction [Biek, 2003a], Hurricane [Biek, 2003b], Pintura [Hurlow and Biek, 2003], Santa Clara [Willis and Higgins, 1996], St. George [Higgins and Willis, 1995], The Divide [Hayden, 2004], Washington [Willis and Higgins, 1995], Washington Dome [Hayden, 2005], and White Hills [Higgins, 1997]); (2) Natural Resource Conservation Service (NRCS) (formerly the U.S. Soil Conservation Service) *Soil Survey of Washington County Area, Utah* (Mortensen and others, 1977), which had been digitized and made available by the Utah Automated Geographic Reference Center; and (3) Utah Geological and Mineral Survey Special Studies 58, *Engineering Geology of the St. George Area, Washington County, Utah* (Christenson and Deen, 1983).

SETTING

For purposes of this study, we defined the St. George–Hurricane metropolitan area as consisting of approximately 366 square miles in and around the communities of St. George and Hurri-

Table 1. *Geologic hazards and adverse construction conditions considered in this report.*

Geologic Hazards	
Text Document	**Map**
Earthquake Hazard	Surface-Fault-Rupture Hazard
Earthquake-Ground-Shaking Hazard*	None
Liquefaction Hazard	Liquefaction Hazard
Flood Hazard	Flood Hazard
Landslide Hazards	Landslide Hazards
Rock-Fall Hazard	Rock-Fall Hazard
**Text document only, insufficient data were available to prepare a Ground-Shaking-Hazard Map.*	
Adverse Construction Conditions	
Text Document	**Map**
Problem Soil and Rock	(see below)
Expansive Soil and Rock	Expansive Soil and Rock
Collapsible Soil	Collapsible Soil
Gypsiferous Soil and Rock	Gypsiferous Soil and Rock
Shallow Bedrock	Shallow Bedrock
Caliche	Caliche
Wind-Blown Sand	Wind-Blown Sand
Breccia Pipes and Paleokarst	Breccia Pipes and Paleokarst
Soil Piping and Erosion	Soil Piping and Erosion
Shallow Ground Water	Shallow Ground Water

cane in Washington County, Utah (figure 1). We established the study-area boundaries in consultation with officials from Washington County, the Five-County Association of Governments, and the cities and towns within the study area. The study area includes both incorporated cities and towns and parts of unincorporated Washington County (figure 2). As presently defined, the St. George–Hurricane metropolitan area includes large tracts of undeveloped land, but we anticipate that as growth continues in southwestern Utah, those areas will be developed. Principal communities in the study area are Hurricane, Ivins, La Verkin, Leeds, Santa Clara, St. George, Toquerville, and Washington. Table 2 ranks these communities in order of estimated 2006 population, and also shows their population as reported in the 2000 Census.

Principal transportation routes crossing the study area include Interstate 15 (I-15) from north to south, State Route (SR) 9 from I-15 near Washington to the east through Hurricane and La Verkin, SR-17 north from La Verkin through Toquerville before connecting with I-15, SR-18 north from St. George toward the northern study area boundary, and old US-91 west through Santa Clara (figure 2).

Table 2. *Principal communities ranked in order of estimated 2006 population (Five County Association of Governments, 2006).*

Community	2000 Census Population	Estimated 2006 Population
St. George	49,663	69,831
Washington	8186	16,280
Hurricane	8250	11,740
Ivins	4450	7491
Santa Clara	4630	6644
La Verkin	3392	4619
Toquerville	910	1231
Leeds	547	860
Totals	80,028	118,696

Elevations in the study area range from 5912 feet at Little Creek Mountain on top of the Hurricane Cliffs, to 2440 feet in Big Round Valley near where the Virgin River flows into Arizona (figure 1). The study area generally has an arid climate; average annual precipitation at St. George is 8.25 inches for the period 10/1/1892 to 12/31/2005 (Western Regional Climate Center, 2006). Most precipitation comes in the form of intense, short-duration summer cloudburst storms, and occasional longer duration, regional rainstorms that receive moisture from the Gulf of California in the summer and from the Pacific Ocean in the winter. Summer temperatures at lower elevations in the study area commonly exceed 100° Fahrenheit (°F); the long-term average (10/1/1892 to 12/31/2005) maximum temperature for July in St. George is 101.7 °F (Western Regional Climate Center, 2006). Vegetation is typically sparse to moderate, ranging from pinyon/juniper forests at higher elevations to desert grass, shrubs, and cactus at lower elevations. Agriculture has been important along the flood plains and low terraces of the Virgin and Santa Clara Rivers, the study area's two perennial streams (figure 1), but is rapidly being supplanted by new housing and other development.

GEOLOGY

The St. George–Hurricane metropolitan area lies within the St. George basin in southwestern Utah. The St. George basin is in the Transition Zone between the Colorado Plateau (CP) to the east and the Basin and Range Province (BRP) to the west

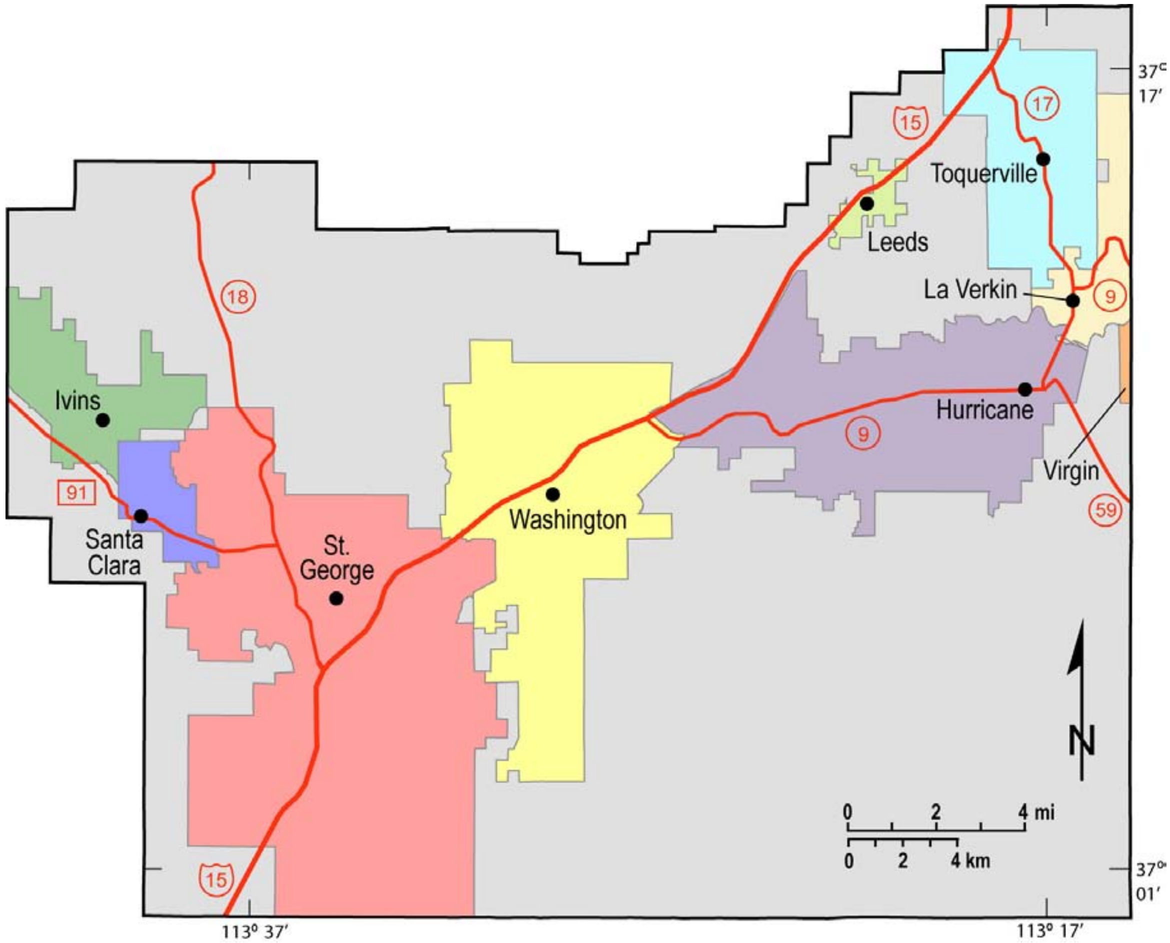

Figure 2. *Boundaries of principal cities and towns; gray-shaded areas are unincorporated Washington County.*

(Stokes, 1977; figure 3). The basin is bounded by the Hurricane fault on the east and the Grand Wash/Gunlock fault on the west, and has been displaced down to the west, chiefly on the Hurricane fault, from the CP, but not down to the level of the BRP. The internal structure and stratigraphy of the basin more closely resemble those of the CP than the BRP. The stratigraphic column of the basin consists of a thick sequence of sedimentary rock formations and thinner unconsolidated deposits that range in age from Paleozoic to latest Holocene (figure 4). Locally the sedimentary rocks are intruded by a quartz monzonite laccolith, which forms the core of the Pine Valley Mountains (figure 1). The sedimentary bedrock units mostly dip gently to the east, but are folded into a series of anticlines and synclines east and north of St. George by eastward directed thrusting associated with the Sevier orogeny. More recently, geologic units in the area, including Holocene surficial deposits, have been displaced down-to-the-west across north-trending, normal faults.

The St. George basin lies within the larger Colorado River drainage basin, and is drained chiefly by the perennial Virgin and Santa Clara Rivers and ephemeral Fort Pearce Wash (figure 1). Because of its high structural and topographic position compared to the Colorado River, erosion is the chief geomorphic process at work in the basin. Sediment-laden flash floods commonly occur in response to intense summer cloudburst

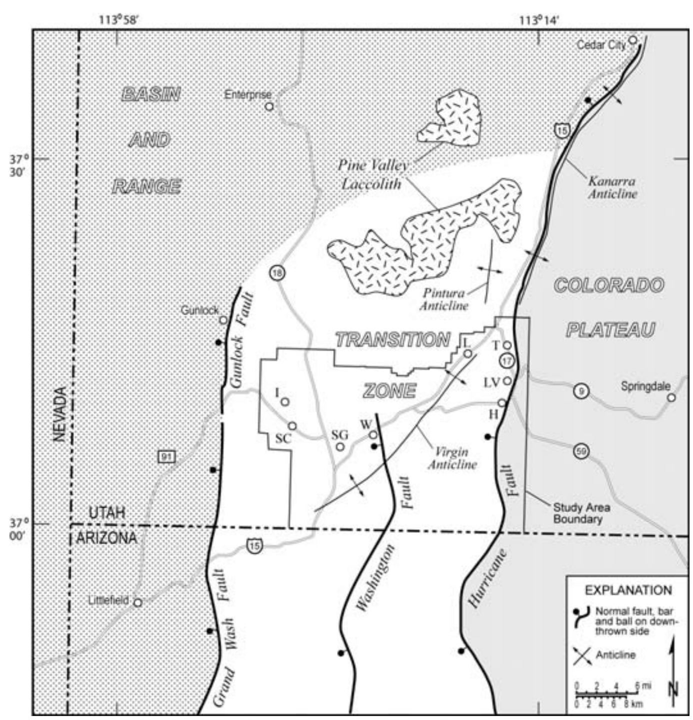

Figure 3*. Location of the study area in the Transition Zone between the Colorado Plateau and the Basin and Range Province; major faults, folds, and the Pine Valley laccolith are shown. I = Ivins, SC = Santa Clara, SG = St. George, W = Washington, H = Hurricane, LV = LaVerkin, T = Toquerville, L = Leeds.*

storms in smaller drainages throughout the basin. Floods in larger drainages may also occur in response to thunderstorms, but are at their largest and most destructive during rapid snowmelt events and when longer duration regional rainstorms linger over their headwaters. Erosion of the comparatively soft sedimentary bedrock formations in the St. George basin has left several generations of Quaternary basalt flows that formerly occupied stream channels isolated on ridge tops of different

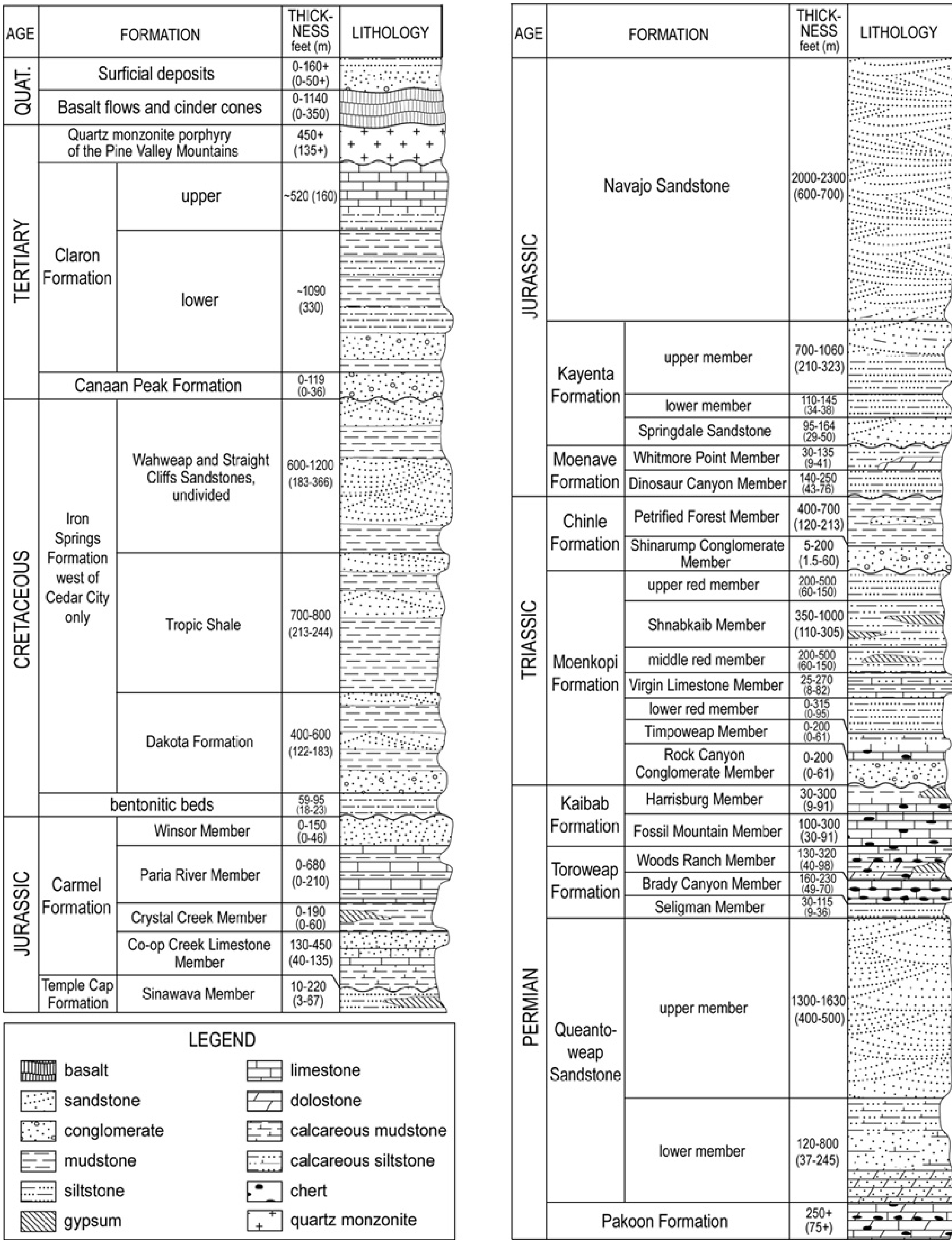

Figure 4*. Stratigraphic section showing the name, age, thickness, and rock type of the geologic units that crop out in the study area (modified from Hintze, 1988).*

heights, creating classic examples of inverted topography (figure 5).

More details on the stratigraphy, structure, and geologic resources of the study area are included on the nine UGS 1:24,000-scale geologic maps and their accompanying text booklets that cover the St. George basin (see Scope of Work above).

RELATIVE IMPORTANCE OF GEOLOGIC HAZARDS AND ADVERSE CONSTRUCTION CONDITIONS

This report provides information on six geologic hazards and nine geology-related adverse construction conditions in the St. George–Hurricane metropolitan area; however, not all of the hazards or adverse construction conditions are of equal concern. On an annual basis, the most widespread and damaging geologic hazard is flooding, and the most troublesome adverse construction condition is expansive (shrink/swell) soil and rock. The flood of 2005 on the Santa Clara and Virgin Rivers provides ample evidence of the destructive power and life-threatening nature of flooding in the study area, and numerous buildings and other structures throughout the area have experienced cracked foundations and walls, as well as other kinds of structural, architectural, and landscape damage from expansive soil and rock. Because of their wide distribution, frequent occurrence, and destructive potential, floods and expansive soil and rock will undoubtedly remain the principal geology-related issues with which planners and developers will contend in the future.

Landslides and rock falls are of increasing concern as land suited for building in lowland areas becomes increasingly scarce and development moves near or onto hillsides. Existing landslides, especially older ones, can be difficult to recognize, but their stability remains suspect and their identification and proper accommodation in project planning and design is critical if slope-stability problems are to be avoided. Some bedrock units contain a high percentage of clay and are correspondingly weak and susceptible to landslides, especially when wet (Christenson, 1986). The close correlation of existing landslides with weak bedrock units provides ample warning that development on slopes underlain by landslide-susceptible bedrock must proceed with caution. Southwestern Utah has a history of damage to buildings and other facilities from rock falls (Lund, 2002, 2005). Favorable conditions for rock fall are widespread in the study area, and damaging events are likely to increase as development moves into those areas unless effective mitigation measures are implemented.

Large, damaging earthquakes are rare events in southwestern Utah, but active faults in the St. George–Hurricane metropolitan area are capable of producing earthquakes as large as M 6.5-7 (Stenner and others, 1999; Lund and others, 2001, 2002). Hazards associated with such large earthquakes (ground shaking, surface fault rupture, landslides, rock falls, and liquefaction) have the greatest potential for catastrophic property damage, economic disruption, and loss of life of any hazard in the study area. Because of their great destructive potential, the effects of large earthquakes must be reduced through land-use planning, adoption and enforcement of modern seismic building codes, and disaster preparedness planning and drills. Moderate earthquakes similar to the magnitude 5.8 M_L St. George earthquake in 1992 are more common than large earthquakes in southwestern Utah, are capable of doing significant property damage, and may be life threatening.

The remaining geologic hazards and adverse construction conditions considered in this report are typically localized in nature, and while potentially costly when not recognized and properly accommodated in project planning and design, the problems associated with them are rarely life threatening.

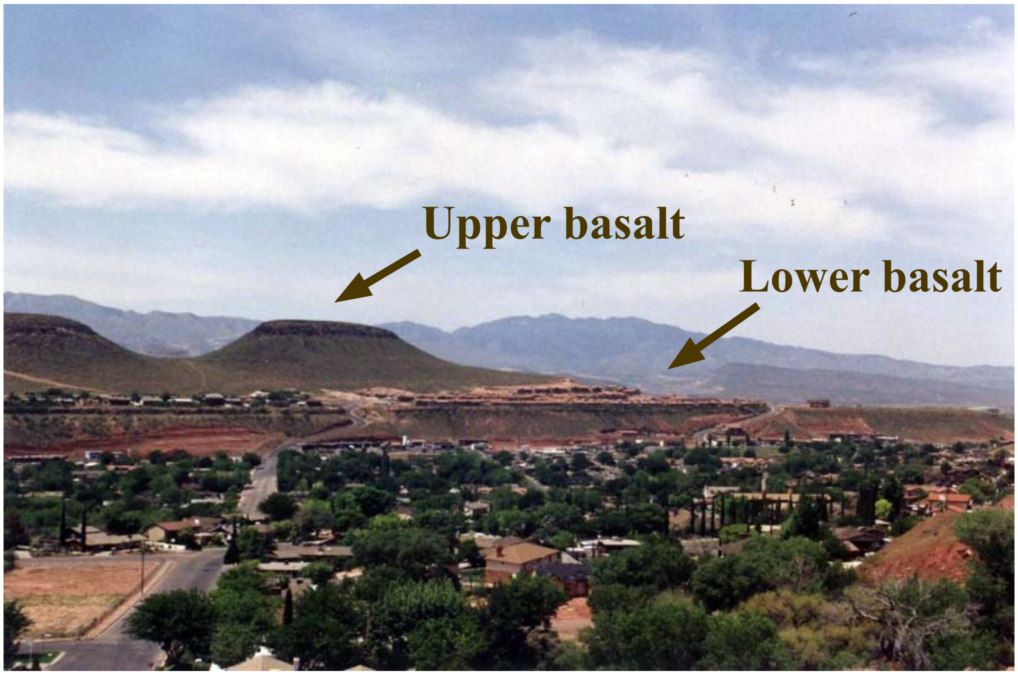

***Figure 5**. Basalt flows occupying former stream channels now cap ridges. Erosion following emplacement of the upper basalt about 2.3 million years ago and lower basalt about 1.1 million years ago has removed the surrounding softer sedimentary bedrock except where protected by the basalt.*

SUMMARY

The St. George–Hurricane metropolitan area continues more than two decades of rapid growth. As urbanization expands into areas less suited for development, geologic hazards and adverse construction conditions become increasing concerns in the planning, design, and construction of new facilities. Recognizing the need of planners and others for timely information on geologic hazards, the UGS published its first report on the engineering geology of the St. George area twenty-five years ago (Christenson and Deen, 1983). Since that time, continued rapid growth in and around St. George has greatly exceeded the area covered by that original study. The advent of computer-based GIS databases, analysis, and mapping techniques, along with twenty-five years of new geologic, hydrologic, soil, and geotechnical information, make publication of this new study of geologic hazards and adverse construction conditions in an expanded St. George–Hurricane metropolitan area timely. The area considered by this study encompasses about 366 square miles, and includes most remaining developable land in the St. George basin. This study is intended to assist planners and other county and municipal officials charged with managing growth in the study area with determining where geologic hazards and/or adverse construction conditions may exist, and where detailed, site-specific, geotechnical studies are necessary. However, we believe that geotechnical engineers, engineering geologists, building officials, developers, and the general public will find this study useful as well.

New 1:24,000-scale geologic mapping by the UGS provided the basic geologic data for this study. The NRCS *Soil Survey of the Washington County Area* (Mortensen and others, 1977) was available at the time of the Christenson and Deen (1983) report, and remains the principal source of soils information in Washington County. However, the soil survey is now available in digital format, which greatly facilitated its use in preparing the maps for this study. We also compiled extensive new digital geotechnical and ground-water databases for this study, which allowed incorporation of much new information not available to Christenson and Deen (1983).

Although this report provides information on 15 individual geologic hazards and geology-related adverse construction conditions, they are not all of equal importance in the study area. Historically, the most widespread and potentially damaging geologic hazard is flooding, and expansive soil and rock represent the most troublesome adverse construction conditions. Flooding is of special concern because it can quickly become life threatening. Landslides and rock falls are of increasing concern in the study area as more development takes place on or at the base of hillslopes. Large earthquakes are rare events in southwestern Utah, but the hazards associated with earthquakes (ground shaking, surface fault rupture, landslides, rock falls, and liquefaction) have the greatest potential for producing catastrophic property damage, economic disruption, and loss of life of any hazard in the study area. The remaining hazards and construction conditions considered in this report are typically localized in nature, and while potentially costly when not recognized and properly accommodated in project planning and design, the problems associated with them are rarely life threatening.

ACKNOWLEDGMENTS

We wish to thank John Williams, now retired executive director of the Five County Association of Governments, for encouragement and assistance in getting this project underway. Dave Maxwell of Southern Utah University helped with early GIS database design and application development. The cities and towns within the St. George–Hurricane metropolitan area (table 2) provided access to geotechnical reports on file with their building or engineering departments and provided funds for air-photo acquisition. Likewise, the Utah Department of Transportation made geotechnical reports associated with transportation corridors in the study area available to us. Several geotechnical consultants provided information and insight on geologic and engineering conditions in the study area. Bill Black, Western Geologic, LLC, and David Simon, Simon Bymaster Inc., provided valuable comments on the Earthquake Hazards section of this report. Finally we extend our gratitude to a special combined committee of the American Public Works Association and the American Society of Civil Engineers consisting of David Black, Walt Jones, Russell Owens, Wayne Rogers and Rick Rosenberg who reviewed and provided comments on the maps and text documents.

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SECTION 2:
EARTHQUAKE HAZARDS

This section is part of Utah Geological Survey Special Study 127, *Geologic Hazards and Adverse Construction conditions—St. George–Hurricane Metropolitan Area, Washington County, Utah.*

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SECTION 2:
EARTHQUAKE HAZARDS

INTRODUCTION

Earthquakes occur without warning and can cause injury and death, major economic loss, and social disruption (Utah Seismic Safety Commission, 1995). An earthquake is the abrupt rapid shaking of the ground caused by sudden slippage of rocks deep beneath the Earth's surface. The rocks break and slip when the accumulated stress exceeds the rock's strength. The surface along which the rocks slip is called a fault. Seismic waves are then transmitted outward from the earthquake source producing ground shaking. The consequences of an earthquake depend upon several factors including its magnitude, depth, and distance from population centers, and geologic and soil conditions at a particular site (Keller and Blodgett, 2006).

Earthquakes cause a wide variety of geologic hazards including ground shaking, surface faulting, liquefaction and related ground failure, slope failure, regional subsidence, and various types of flooding (table 1).

Ground shaking is the most widespread and typically most damaging earthquake hazard (Yeats and others, 1997). Strong ground shaking can last from several seconds to minutes, and can be amplified or reduced depending on local soil and rock conditions (Reiter, 1990). Ground shaking is usually strongest near the earthquake epicenter and decreases away from that point. The type and quality of construction play a large role in determining the extent of damage caused by ground shaking. Large earthquakes (>M 6.5) are commonly accompanied by surface faulting. The rupture may affect a zone tens to hundreds of feet wide and tens of miles long. Little can be done from a design perspective to protect structures or other facilities from the direct effects of surface faulting. Liquefaction (the temporary transformation of a saturated cohesionless soil into a fluid accompanying earthquake ground shaking) may occur in areas of shallow ground water and sandy soils (Reiter, 1990). Liquefaction can cause a variety of kinds of ground failure. Slope failures, including rock falls and landslides, are common in steep terrain during moderate and large earthquakes. Subsidence due to tilting of the downdropped block during a large

Table 1. *Principal earthquake hazards, expected effects, and hazard-reduction techniques (modified from Utah Seismic Safety Commission, 1995).*

HAZARD	EFFECTS	MITIGATION
Ground Shaking	Damage or collapse of structures	Make structures seismically resistant, secure heavy objects
Surface Faulting	Ground displacement, tilting or offset structures	Set structures back from fault traces
Liquefaction	Differential settlement, ground cracking, subsidence, sand blows, lateral spreads	Treat or drain soil, deep pier foundations, other structural design solutions
Rock Fall	Impact damage	Avoid hazard, remove unstable rocks, protect structures
Landslides	Damage to structures, loss of foundation support	Avoid hazard, stabilize slopes, manage water use
Subsidence	Ground tilting, subsidence, flooding, loss of head in gravity-flow facilities	Create buffer zones, build dikes, restrict basements, design tolerance for tilting
Flooding	Earthquake-induced failure of dams, canals, pipelines, etc. with associated flooding; seiches, increased spring flow, stream diversion, ground subsidence in high ground-water areas	Flood-proof or strengthen structures, elevate building, avoid construction in potential flood areas

normal-faulting earthquake can affect large areas extending miles from the surface trace of the fault. Tilting of the ground surface may allow lakes or other water impoundments to inundate formerly dry areas, or lower the ground surface below the local water table causing waterlogged soils and areas of ponded water. Flooding may also result from an earthquake due to damage to water storage or conveyance structures such as dams, pipelines, and canals.

A variety of magnitude scales are used to measure earthquake size (Bolt, 1988; dePolo and Slemmons, 1990). The magnitude scale most commonly used today is the Richter scale (Richter, 1938, 1958; Bolt, 1988), which measures earthquake magnitude based on the amount of earthquake-induced ground shaking recorded on a seismograph. The Richter scale has no upper or lower bounds and is logarithmic such that each one-unit increase in the scale represents a ten-fold increase in the amplitude of ground displacement at a given location. Each one-unit increase in magnitude on the Richter scale represents a 32-fold increase in energy release. Therefore, a Richter magnitude 6 earthquake is 32 times more powerful than a magnitude 5 earthquake, and a magnitude 7 earthquake is 1000 times more powerful than a magnitude 5 earthquake. Unless stated otherwise, all magnitudes reported here are Richter magnitudes. The human detection threshold for earthquakes is about magnitude 2 and significant damage begins to occur at about magnitude 5.5. In the Intermountain West, surface faulting begins at about magnitude 6.5.

SOURCES OF INFORMATION

Sources of data used to evaluate earthquake hazards include: (1) nine digital Utah Geological Survey (UGS) 1:24,000-scale (1 inch = 2000 feet) geologic quadrangle maps covering the study area (Harrisburg Junction [Biek, 2003a], Hurricane [Biek, 2003b], Pintura [Hurlow and Biek, 2003], Santa Clara [Willis and Higgins, 1996], St. George [Higgins and Willis, 1995], The Divide [Hayden, 2004], Washington [Willis and Higgins, 1995], Washington Dome [Hayden, 2005], and White Hills [Higgins, 1997]), (2) information on historical earthquakes in southwestern Utah and northwestern Arizona chiefly from the University of Utah Seismograph Stations earthquake catalog (University of Utah Seismograph Stations, 2006) and the Arizona Earthquake Information Center earthquake catalog at Northern Arizona University (Arizona Earthquake Information Center, 2006), (3) Black and others' (2003; updated from Hecker, 1993) database of Utah's Quaternary faults and folds, which includes estimates of their most recent surface faulting, and (4) Earth Sciences Associates' (1982) paleoseismic study of part of the Washington fault. Additionally, Anderson and Christenson (1989) reviewed Quaternary faulting and folding in the St. George–Hurricane metropolitan area and adjacent areas of southwestern Utah, and Christenson (1995) edited a volume of papers dealing with the 1992 St. George earthquake. Studies by Pearthree and others (1998), Stenner and others (1999), Lund and others (2001, 2002, 2007a), and Amoroso and others (2002) present the first detailed paleoseismic information for the Hurricane fault.

EARTHQUAKES IN SOUTHWESTERN UTAH

In Utah, most earthquakes are associated with the Intermountain seismic belt (ISB) (Smith and Sbar, 1974; Smith and Arabasz, 1991), an approximately 100-mile-wide, north-south trending zone of earthquake activity that extends from northern Montana to northwestern Arizona (figure 1). Since 1850, there have been at least 16 earthquakes of magnitude 6.0 or greater within the ISB (Eldredge and Christenson, 1992; University of Utah Seismograph Stations, 2006). Included among those 16 events are Utah's two largest historical earthquakes, the 1901 Richfield earthquake with an estimated magnitude of 6.5, and the 1934 Hansel Valley magnitude 6.6 earthquake, which produced Utah's only historical surface faulting. In an average year, Utah experiences more than 700 earthquakes, but most are too small to be felt. Moderate magnitude (5.5–6.5) earthquakes happen every several years on average, the most recent being the magnitude 5.8 St. George earthquake on September 2, 1992. Large magnitude (6.5–7.5) earthquakes occur much less frequently in Utah, but geologic evidence shows that most areas of the state within the ISB, including the St. George metropolitan area, have experienced large surface-faulting earthquakes in the Holocene.

Fault-related surface rupture has not occurred in southwestern Utah historically, but the area does have a pronounced record of seismicity. At least 21 earthquakes greater than magnitude 4 have occurred in southwestern Utah in historical time (Christenson and Nava, 1992; University of Utah Seismograph Stations, 2006; figure 2); the largest events were the estimated magnitude 6 Pine Valley earthquake in 1902 (Williams and Tapper, 1953) and the magnitude 5.8 St. George earthquake in 1992 (Christenson, 1995). The Pine Valley earthquake is pre-instrumental and poorly located, and therefore, is not associated with a recognized fault. However, the epicenter is west of the surface trace of the west-dipping Hurricane fault, so the earthquake may have occurred on that structure. Pechmann and others (1995) have tentatively assigned the St. George earthquake to the Hurricane fault.

The largest historical earthquake nearby in northwestern Arizona is the 1959 Fredonia, Arizona, earthquake (approximate magnitude 5.7; DuBois and others, 1982). Since 1987 the northwest part of Arizona has been quite seismically active (Pearthree and others, 1998), experiencing more than 40 earthquakes with magnitudes >2.5, including the 1993 magnitude 5.4 Cataract Canyon earthquake between Flagstaff and the

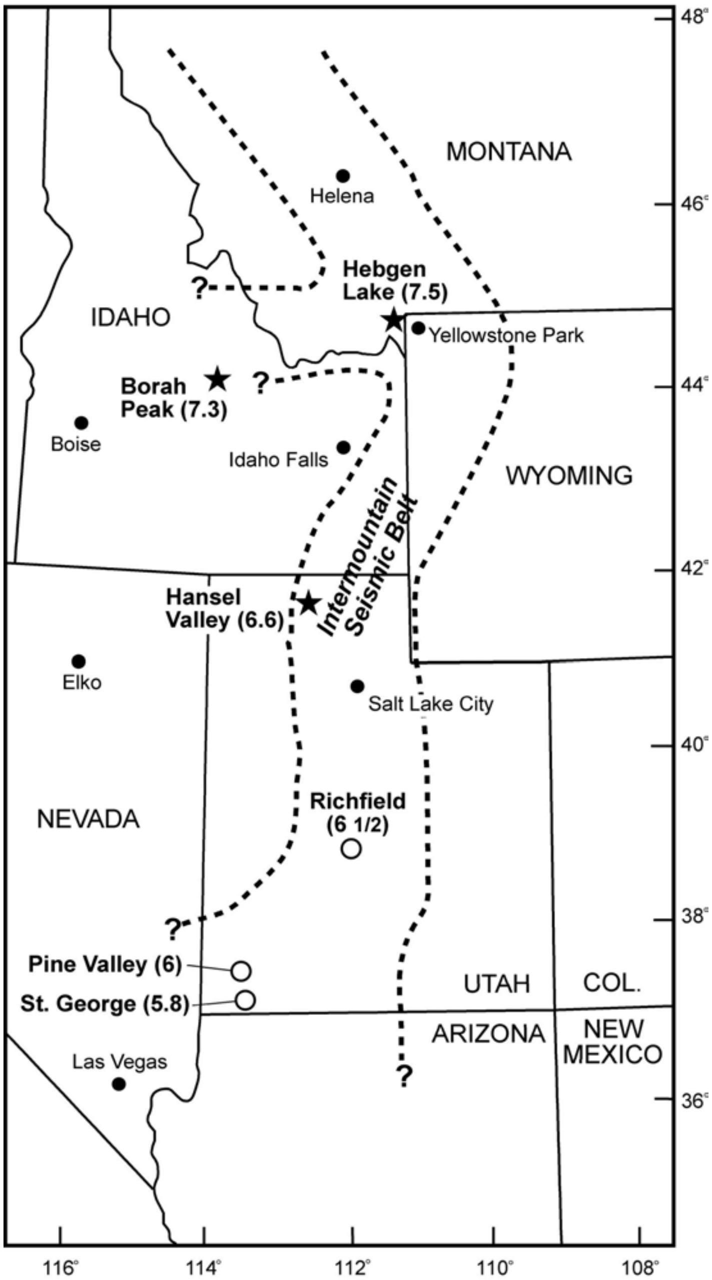

Figure 1. *The Intermountain seismic belt and major historical ISB earthquakes (stars denote earthquakes that produced surface faulting, open circles indicate significant non-surface faulting earthquakes).*

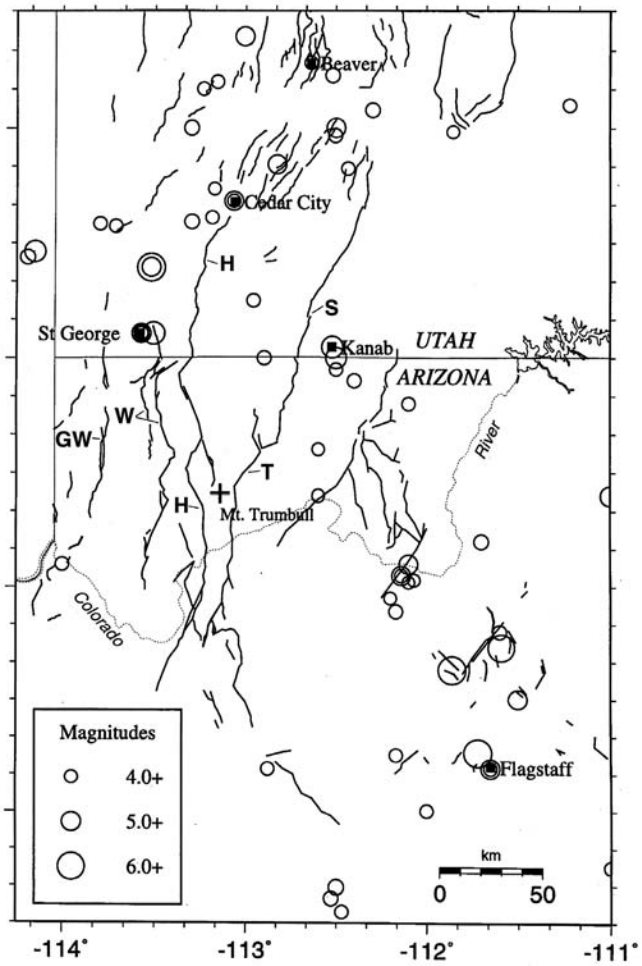

Figure 2. *Earthquake epicenter map of southwestern Utah and northwestern Arizona and major Quaternary faults in the region: H = Hurricane fault; W = Washington fault; GW = Grand Wash fault; S = Sevier fault; T = Toroweap fault. Figure courtesy of the Arizona Geological Survey; epicenter locations from the Arizona Earthquake Information Center earthquake catalog (Arizona Earthquake Information Center, 2006) and University of Utah Seismograph Stations earthquake catalog (University of Utah Seismograph Stations, 2006).*

Grand Canyon. Three poorly documented earthquakes near and north of Flagstaff that occurred in 1906, 1910, and 1912, respectively, are thought on the basis of limited instrumental data and more extensive felt reports to have been in the M 6–6.2 range (figure 2) (Phil Pearthree, Arizona Geological Survey, verbal communication, 2007)

Despite the lack of an historical surface-faulting earthquake in southwestern Utah, available geologic data for faults in the region indicate a moderate rate of long-term Quaternary activity. Mid-Quaternary basalt flows are displaced more than a thousand feet at several locations and alluvial and colluvial deposits were displaced feet to tens of feet in late Quaternary time.

ACTIVE FAULTS

Because earthquakes result from slippage on faults, from an earthquake-hazard perspective, faults are commonly classified as active, capable of generating damaging earthquakes, or inactive, not capable of generating earthquakes. The term “active fault” is frequently incorporated into regulations pertaining to earthquake hazards, and over time the term has been defined differently for different regulatory and legal purposes. In nature, faults possess a wide range of activity levels. Some, such as the San Andreas fault in California, produce repeated large earthquakes and associated surface faulting every few hundred years, while others, like Utah's Wasatch fault and many of the faults in the Basin and Range Province (BRP), generate large earthquakes and surface faulting every few thousand to tens of thousands of years. Therefore, depending on the area of interest or the intended purpose, the definition of "active fault" may vary. The time period over which faulting activity is assessed is critical because it determines which faults are ultimately classified as hazardous and therefore subject to regulatory mitigation (Allen, 1986).

Activity Classes

In California, the Alquist-Priolo Earthquake Fault Zoning Act (Hart and Bryant, 1997), which regulates development along known active faults, defines an "active fault" as one that has had "surface displacement within Holocene time (about the past 11,000 years)." Because California has a well-recognized earthquake hazard and was the first state to implement regulations designed to mitigate those hazards, the California "Holocene" standard has found its way into many regulations in other parts of the country, even in areas where the Holocene is not the best time frame against which to measure surface-faulting recurrence. dePolo and Slemmons (1998) argued that in the BRP, the physiographic region in which the St. George–Hurricane metropolitan area is located, a time period longer than the Holocene is more appropriate for defining active faults because most faults in the province have surface-faulting recurrence intervals (average repeat times) that approach or exceed 10,000 years. They advocate a late Pleistocene age criteria, specifically 130,000 years, to define active faults in the BRP. They base their recommendation on the observation that 6 to 8 (>50%) of the 11 historical surface-faulting earthquakes in the BRP were on faults that lacked evidence of Holocene activity, but which did have evidence of late Pleistocene activity.

Because of the difficulties in using a single "active" fault definition, the Western States Seismic Safety Policy Council (WSSPC) has defined the following fault activity classes for the BRP (WSSPC Policy Recommendation 08-2, 2008; first adopted in 1997 as WSSPC Policy Recommendation 97-1, and revised and readopted in 2002, 2005, and 2008 [WSSPC, 2007]):

Holocene fault—a fault that has moved within the past 10,000 years.

Late Quaternary fault—a fault that has moved within the past 130,000 years.

Quaternary fault—a fault that has moved within the past 1,800,000 years.

WSSPC Policy Recommendation 05-2 states "Earthquakes on faults within the Basin and Range Province have a wide range of recurrence intervals, from hundreds of years to hundreds of thousands of years. Recurrence intervals of a few thousand to tens of thousands of years are typical." Christenson and Bryant (1998) and Christenson and others (2003) recommended adopting the WSSPC fault activity-class definitions in Utah, and we follow that recommendation in this study.

Evaluating Fault Activity

Because both the instrumental and historical records of seismicity in Utah are short (less than 200 years), geologists must use other means to evaluate the record of past surface faulting to assess fault activity levels. The study of prehistorical surface-faulting earthquakes is termed "paleoseismology" (Solonenko, 1973; Wallace, 1981). Paleoseismic studies can provide information on the timing of the most recent surface-faulting earthquake (MRE) and earlier events, the average recurrence interval between surface-faulting earthquakes, net displacement per event, slip rate (net displacement averaged over time), and other faulting-related parameters (Allen, 1986; McCalpin, 1996). Determining the timing of the MRE establishes the fault's activity class (see above). Paleoseismic data from multiple sites can show if a fault ruptures as a single entity, or if it is subdivided into a series of smaller independently seismogenic segments each capable of generating its own earthquakes. Importantly, paleoseismic studies can establish the relation between the elapsed time since the MRE and the average recurrence interval between surface-faulting earthquakes. Once that relation is known, the likelihood of surface faulting in a time frame of significance to most engineered structures can be estimated.

SURFACE-FAULTING HAZARD

Among the potential effects of large normal-slip earthquakes (magnitude ≥6.5) is surface faulting, which occurs when movement at depth on a fault during an earthquake propagates to the surface. The resulting displacement at the ground surface produces ground cracking and typically one or more "fault scarps" (figure 3). When originally formed, fault scarps have near-vertical slopes, and, depending on the size of the earthquake, can range from a few inches to many feet high. Local ground tilting and graben formation by secondary (antithetic) faulting may accompany surface faulting, resulting in a zone of deformation along the fault trace tens to hundreds of feet wide (figure 3). Surface faulting, while of limited aerial extent when compared to other earthquake-related hazards such as ground shaking and liquefaction, can have serious consequences for structures or other facilities that lie along or cross the rupture path (Bonilla, 1970). Buildings, bridges, dams, tunnels, canals, and pipelines have all been severely damaged by surface

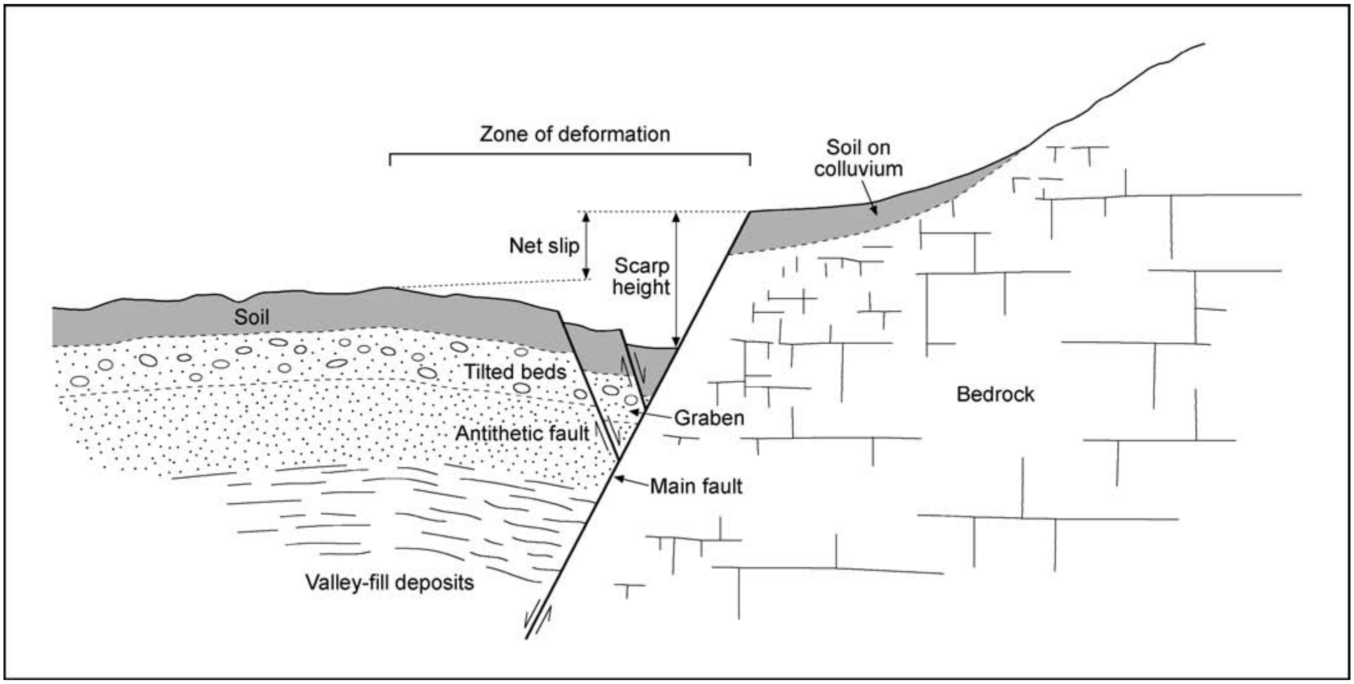

Figure 3. *Cross section of a typical normal fault showing scarp formation and tilted beds and graben formation in the deformation zone associated with the fault (modified from Robison, 1993).*

faulting (Lawson, 1908; Ambraseys, 1960, 1963; Duke, 1960; California Department of Water Resources, 1967; Christenson and Bryant, 1998; U.S. Geological Survey, 2000).

The hazard due to surface faulting is directly related to the activity of the fault: that is, how often the fault ruptures the ground surface and how likely it is to rupture in the future (Christenson and Bryant, 1998). Because designing a structure to withstand surface faulting is generally considered impractical from an economic, engineering, and architectural standpoint for most structures (Hart and Bryant, 1997; Christenson and others, 2003), avoiding active fault traces is the recommended approach for mitigating surface-faulting hazards. Effectively avoiding surface faulting requires conducting a site-specific investigation to (1) identify all potentially active faults at a site, (2) assess the level of activity of the faults, and (3) establish appropriate setback distances based on fault activity level(s).

Faults in the St. George–Hurricane Metropolitan Area

Fault Types

Utah Geological Survey 1:24,000-scale geologic mapping shows that two principal types of faults exist in the St. George–Hurricane metropolitan area: thrust/reverse faults and normal faults (figure 4). Thrust/reverse faulting occurs when the fault hanging wall (the block of rock above the fault plane) moves upward relative to the fault footwall (the block of rock below the fault plane). The distinction between a thrust and a reverse fault depends on the angle (termed the dip angle; figure 4a) that the fault plane makes with a horizontal datum. Reverse faults dip 45 degrees or more (figure 4b), while thrust faults have dips less than 45 degrees (figure 4c). Thrust and reverse faults form in response to compressional (pushing together) forces and typically place older rock on top of younger rock.

Normal faulting occurs when rock in the hanging wall moves downward relative to rock in the footwall (figure 4d). Normal faults form in response to tensional (pulling apart) forces, typically dip between 45 and 90 degrees, and place younger rocks on older rocks. Tensional forces have characterized the regional stress regime in the St. George–Hurricane metropolitan area for the past several million years. Consequently, normal faults in the basin are typically geologically young and many, if not most, are capable of producing earthquakes. Conversely, the thrust and reverse faults in the study area are related to an older, no longer active compressional stress regime, and do not pose a serious earthquake threat.

Normal Faults

The UGS has identified more than 50 normal faults in the St. George–Hurricane metropolitan area (plate 1). Chief among them is the Hurricane fault, a long, complex fault that forms a wide zone of braided and branching faults trending north-south along the eastern edge of the study area (figure 2). Other large faults in the study area include the Washington fault, Warner

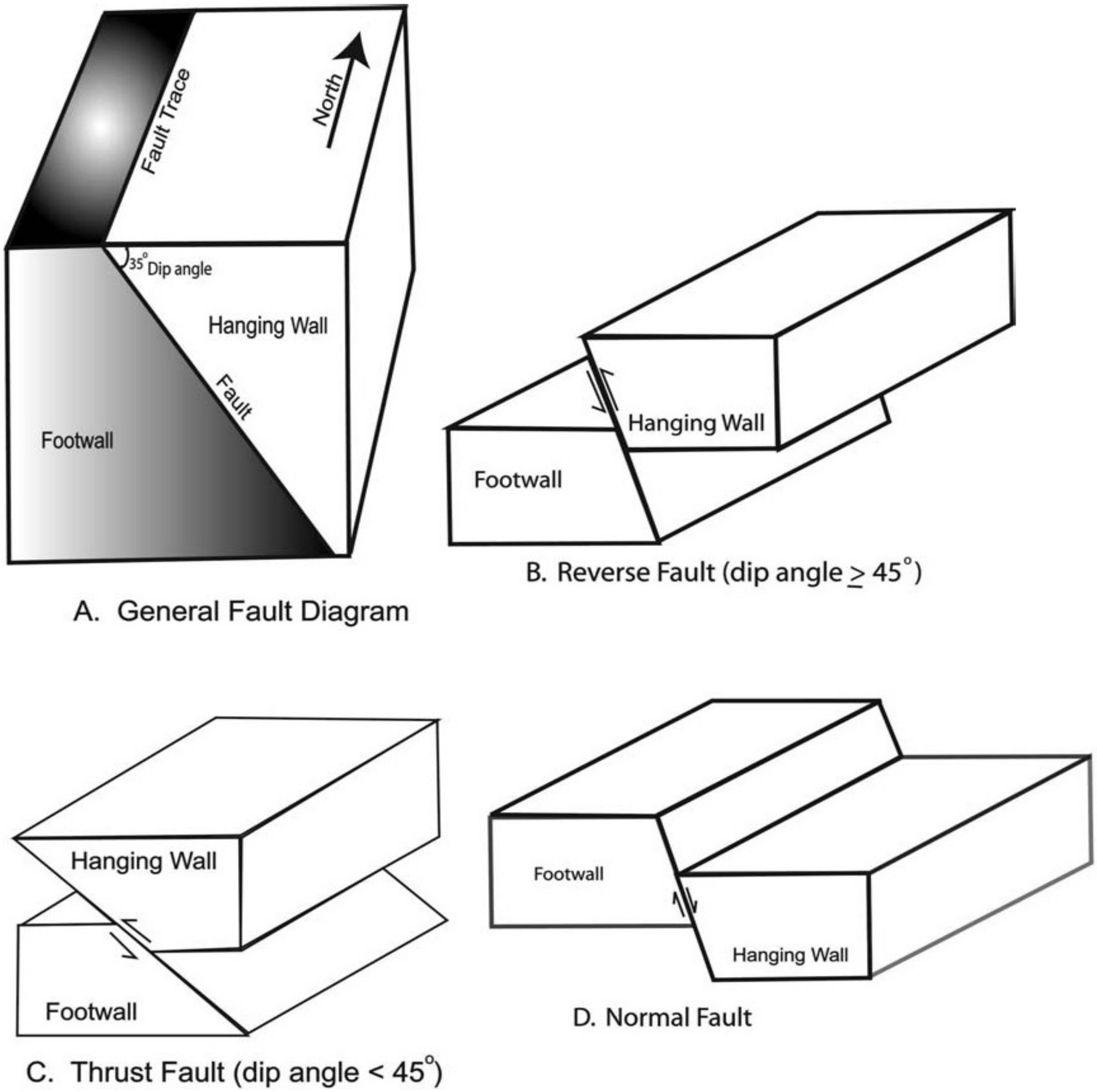

***Figure 4**. Fault types.*

Valley fault, Washington Hollow fault, and St. George fault (plate 1). The maximum displacement across the Hurricane fault is thousands of feet and is hundreds of feet for the other large faults. The remaining normal faults in the basin are typically short, a few miles long or less, and exhibit a few feet to tens of feet of displacement. Many of these shorter, simpler structures may be genetically and mechanically related to the larger, more complex faults in the basin. Several pairs of closely parallel short faults with opposite dips form narrow grabens (blocks of fault-bounded down-dropped rock; figure 3) by normal-fault movement on each of the fault pairs.

Hurricane fault: The 155-mile-long Hurricane fault trends generally north-south where it passes through the St. George–Hurricane metropolitan area (plate 1). It is the longest normal fault in the study area and shows abundant geologic evidence for down-to-the-west, Quaternary surface faulting. Displacement across the fault increases to the north. The displacement is greatest in the oldest deposits; nearly flat-lying Mesozoic and Cenozoic bedrock is displaced thousands of feet, early and middle Quaternary basalt flows hundreds of feet, and late Quaternary alluvial and colluvial deposits up to tens of feet (Pearthree and others, 1998; Stenner and others, 1999; Lund and others, 2001, 2002, 2007a).

Considering its long length, the Hurricane fault almost certainly is divided into individual seismogenic segments, each capable of generating their own earthquakes (e.g., Black and others, 2003). Previous workers (Stewart and Taylor, 1996; Stewart and others, 1997; Pearthree and others, 1998; Reber and others, 2001) have suggested that major convex fault bends and zones of structural complexity are likely candidates for boundaries between seismogenic fault segments. Stewart and Taylor (1996) identified a possible segment boundary at the south end of Black Ridge near Toquerville between the proposed Ash Creek segment in Utah and the Anderson Junction segment to the south in Utah and Arizona (figure 5). Stewart and others (1997) and Reber and others (2001) identified another potential boundary between the Anderson Junction segment and the proposed Shivwitz segment (Pearthree, 1998) to the south, about 6 miles south of the Utah-Arizona border.

Parts of both the Ash Creek and Anderson Junction segments trend through the St. George–Hurricane metropolitan area. There has been no historical surface faulting on either segment, but based on available paleoseismic information, the most recent surface faulting on both segments likely occurred during the Holocene. Stenner and others (1999) trenched the Anderson Junction segment at Cottonwood Canyon in Arizona (figure 5) and found evidence for an early to middle Holocene surface-faulting earthquake. Lund and others (2007a) radiocarbon dated a displaced young alluvial fan at Coyote Gulch (figure 5) on the Ash Creek segment in Utah and obtained a late Holocene age for the time of the most recent surface faulting. Amoroso and others (2002) trenched a multiple-event fault scarp at the Boulder Fan site on the Shivwitz segment (figure 5) and obtained an early Holocene/latest Pleistocene age for the most recent surface faulting there.

Washington fault: The Washington fault is a 42-mile-long down-to-the-west, high-angle normal fault that trends northward from northern Arizona into the St. George–Hurricane metropolitan area (Hayden, 2005). The Washington fault lies west of the larger Hurricane fault (plate 1), and after cutting across most of the study area, it splits into several smaller, generally north-trending faults north of the City of Washington before dying out. Displacement on the Washington fault decreases northward, in a sense opposite to that of the Hurricane fault. According to Peterson (1983), the fault reaches its maximum displacement of 2200 feet about six miles south of the Utah-Arizona state line. Billingsley (1993) reported 1650 feet of displacement at the state line, and Hayden (2005) estimated 700 feet south of Washington. Pearthree (1998) divided the Washington fault into three sections based on structural and geomorphic evidence. The three sections are the Northern, Mokaac, and Sullivan Draw sections, of which only the Northern Section is in Utah. There has been no historical surface faulting on any sections of the Washington fault.

A splay of the Washington fault displaces the 900,000-year-old Washington lava flow (Biek, 2003a; Biek and Hayden, 2007) more than 15 feet (Anderson and Christenson, 1989), and an 11.5-foot-high fault scarp is preserved on mixed older colluvial and alluvial deposits (Anderson and Christenson, 1989; Hayden, 2005) near the Utah-Arizona border. Anderson and Christenson (1989) profiled this scarp and estimated a late Quaternary age

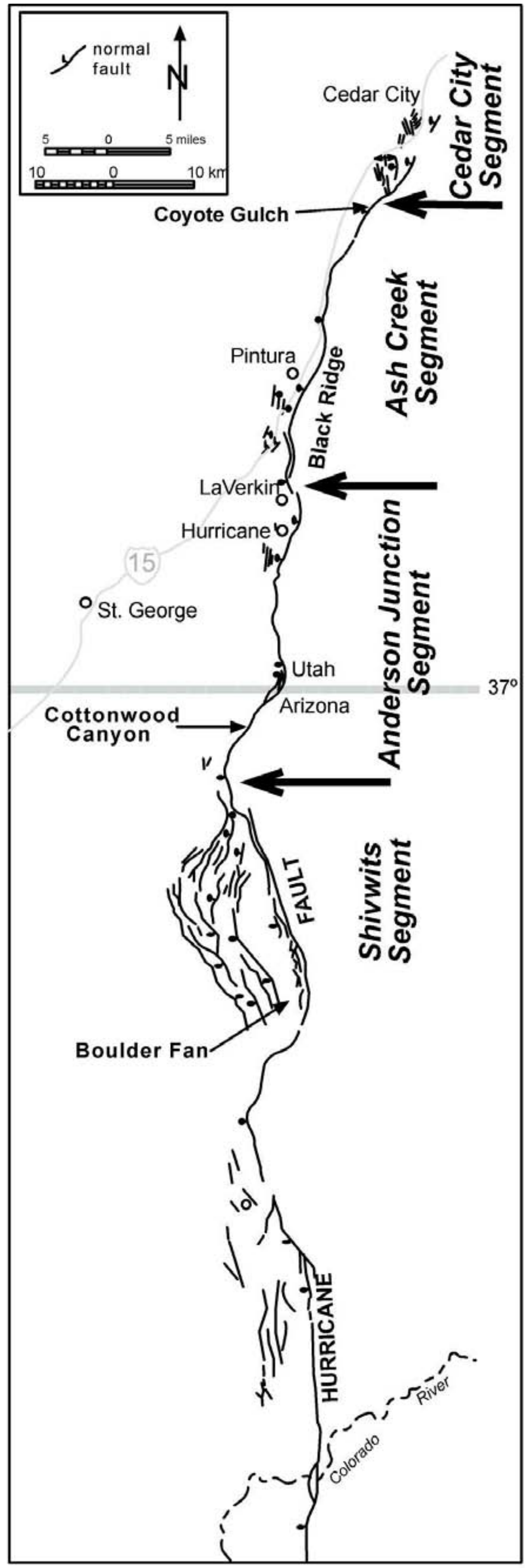

Figure 5. Proposed Hurricane fault segments and paleoseismic investigation sites (after Lund and others, 2002). Large black arrows indicate segment boundaries.

of about 15,000 years. Pearthree (1998), working only on the Arizona portion of the fault, assigned a broader time frame to constrain the time of most recent movement on the Washington fault of <130,000 years. Earth Sciences Associates (ESA, 1982) trenched the Washington fault as part of a U.S. Soil Conservation Service (now Natural Resources Conservation Service) seismic-safety study of flood-retention structures in southwestern Utah. They reported a few inches of displacement in "younger" deposits, but were unsure if this small displacement was fault-related or the result of differential compaction. However, "older" deposits identified by ESA are displaced almost 3.5 feet and represent at least one and possibly more surface-faulting earthquakes. The absence of carbon or other datable material in their trenches limited ESA's definitions of younger and older deposits to 5 to10 ka and 10 to 25 ka, respectively.

Trenching in 2007 by Applied Geotechnical Engineering Consultants, Inc. (AGEC) in Washington Fields prior to residential development exposed the main trace of the Washington fault. With limited time available before the trenches were closed, the UGS conducted a reconnaissance investigation of the exposed fault. The northernmost trench revealed a 13-foot-wide fault zone consisting of at least three splays that dip steeply to the west. Colluvial-wedge deposits provided evidence for three surface-faulting earthquakes that displaced mixed alluvial-colluvial-eolian deposits from about 1 foot to just less than 3.2 feet (Lund and others, 2007b). The most recent earthquake displaced the modern soil Bk horizon and an overlying weakly indurated sand deposit. The fault rupture extended to within 10 inches of the ground surface where it was buried by modern, actively accumulating eolian sand.

The UGS collected five samples of colluvial/eolian sand from within and below the colluvial wedges and submitted them to the Optically Stimulated Luminescence (OSL) Geochronology Laboratory at Utah State University for analysis to constrain the ages of the surface-faulting earthquakes. The OSL age results are shown in table 2. Based on these data, we conclude that the Washington fault has experienced three surface-faulting earthquakes in the past approximately 75.6 ± 5.1 thousand years (kyr), with paleoearthquake 1 (PE-1) occurring shortly before 67.8 ± 4.6 kyr, PE-2 occurring shortly before 30.7 ± 2.1 kyr, and PE-3 occurring shortly before 18.6 ± 1.2 kyr.

Table 2. *Optically stimulated luminescence age estimates for the Washington fault.*

OSL AGE ESTIMATES		
Sample No.	Age Estimate kyr	Remarks
WD-1	67.75 ± 4.56	PE-1 colluvial wedge
WD-2	75.57 ± 5.13	Pre-PE-1 basin-fill deposits
WD-3	18.59 ± 1.16	PE-3 colluvial wedge
WD-4	30.59 ± 2.10	PE-2 colluvial wedge
WD-5	30.81 ± 2.11	PE-2 colluvial wedge

Warner Valley fault: Hayden (2004) defined the Warner Valley fault (plate 1) as a down-to-the-west normal fault bounding the west side of the Warner Valley Dome, a small horst which lies between Sand Mountain and the Hurricane fault south of the town of Hurricane. In Utah, Hayden (2004) mapped the Warner Valley fault for 5.3 miles to the Utah-Arizona border, and indicated that the fault continues into Arizona where it soon dies out. Geologic maps of this area in Arizona (Billingsley, 1992; Billingsley and Workman, 2000) show no southern continuation of the Warner Valley fault, indicating that the fault likely does die out abruptly near the border. However, these same Arizona geologic maps show another west-dipping north-trending fault, called the Dutchman Draw fault, about 1.5 miles west of where the Warner Valley fault enters Arizona. The Dutchman Draw fault branches from the Washington fault about 5.5 miles south of the state line and can be traced to the northeast for approximately 9 miles to within ½ mile of the border before being concealed beneath alluvium along Fort Pearce Wash (Billingsley, 1992; Billingsley and Workman, 2000). Hayden (2004) does not show the Dutchman Draw fault continuing into Utah, indicating that this fault also likely dies out near the state line. This apparent en-echelon right step between the Warner Valley and Dutchman Draw faults may indicate that these faults are part of the same fault system. This is supported by Hamblin (1970) who mapped the two faults in an en-echelon relationship just south of the state line. Hayden (2004) stated that the Warner Valley fault, although buried by alluvial-fan deposits at its north end, probably connects with or is en echelon with the Hurricane fault.

To date, no paleoseismic studies have been conducted on the Warner Valley fault in either Utah or Arizona to determine the timing of most recent surface faulting. However, the likely multiple-event Quaternary scarp that displaces possible Holocene-age deposits along part of the fault's length in Utah argues for a geologically young MRE, and therefore we classify the Warner Valley fault as a Holocene fault until it is demonstrated to be otherwise.

A down-to-the-east normal fault bounds the east side of the Warner Valley Dome (plate 1). Hayden (2004) considered this fault antithetic to the Hurricane fault and not part of the Warner Valley fault system.

Washington Hollow fault: The Washington Hollow fault (plate 1) is a three-mile-long, high-angle normal fault with about 500 feet of down-to-the-west displacement (Willis and Higgins, 1995). As mapped by Willis and Higgins (1995), only the southern half of the fault lies within the study area. The fault consists of several strands and trends in a north-northwest direction north of the City of Washington. Cordova (1978) projected this fault southward to connect with the Washington fault, and Willis and Higgins (1995) agreed that such a connection is possible, thus implying that the Washington Hollow fault has possible Quaternary/Holocene movement. However, Willis and Higgins (1995) did not show the connection on their map. No paleoseismic studies have been conducted on this fault; therefore, despite limited evidence for recent surface-faulting activity, the timing of the MRE on this fault remains unknown until better constrained by a detailed paleoseismic study.

St. George fault: The St. George fault (plate 1) is a north-trending, high-angle, down-to-the-west normal fault exposed in bedrock north of St. George. Higgins and Willis (1995) mapped this fault as trending through the City of St. George, and estimate that it has about 400 feet of displacement. The St. George fault is overlain by the 1.4-million-year-old Middleton lava flow (Biek and Hayden, 2007) which is not displaced by the fault (Higgins and Willis, 1995). Therefore, while Quaternary movement is unlikely on this fault, in the absence of any paleoseismic evidence, movement during the early Quaternary cannot be precluded, and we consider the St. George fault a Quaternary fault until demonstrated to be otherwise.

Other Normal faults: The remaining normal faults in the study area (plate 1) are typically short, a mile or two in length, and likely exhibit only feet to a few tens of feet of displacement. Exceptions to this are several down-to-the-east antithetic faults associated with the Hurricane fault northwest of Anderson Junction in the northeast corner of the study area. The displacement across some of these faults in older Quaternary alluvial-fan deposits (Hurlow and Biek, 2003) is several tens of feet. We assume that their activity is closely related to that of the much larger, adjacent Hurricane fault, but no paleoseismic studies have been conducted on these faults.

Only a few of the remaining normal faults in the study area have received even cursory study. Applied Geotechnical Engineering Consultants, Inc. investigated two closely spaced subarallel faults that create an approximately 165-foot-wide graben (Higgins and Willis, 1995) near the site of the proposed new St. George airport (plate 1). The displacement recorded in bedrock on each fault is about 35 feet or less, but trenching by AGEC showed that both faults displace unconsolidated late Quaternary deposits, indicating that the faults have experienced at least late Quaternary and possibly Holocene surface faulting. A pedogenic B_k soil horizon within two feet of the ground surface is displaced by the western fault and unconsolidated eolian deposits of unknown age are displaced by the eastern fault (Wayne Rogers, AGEC, verbal communication, 2002). The fact that two short, comparatively minor faults show evidence of geologically young displacement implies that they, and by inference other similar and as yet unstudied normal faults in the study area, may rupture to the surface, either independently or coseismically with one of the larger faults in the basin.

Table 3 summarizes what is currently known about the activity level of the normal faults in the St. George–Hurricane metropolitan area.

Classifying Surface-Fault-Rupture Hazard

The Surface-Fault-Rupture-Hazard Map (plate 1) shows the normal faults in the St. George–Hurricane metropolitan area mapped by the UGS (see SOURCES OF DATA). Because of the prevailing tensional tectonic regime in the BRP, we consider all normal faults in the study area to be potentially active until proven otherwise.

Special-Study Areas

Based upon the UGS mapping, we categorized the normal faults in the St. George–Hurricane metropolitan area as either "Well Defined" or as "Buried" or "Approximately Located," and established surface-fault-rupture-hazard special-study areas (Robison, 1993; Christenson and others, 2003) for each fault category.

Well-defined fault: We considered a fault well defined if its trace is clearly detectable by a trained geologist as a physical feature at or just below the ground surface (Hart and Bryant, 1997). We classified normal faults as "well defined" if the UGS 1:24,000-scale mapping shows them as solid lines, indicating that they are recognizable as faults at the ground surface. The surface-fault-rupture-hazard special-study areas established for well-defined faults extend for 500 feet on the downthrown side and 250 feet on the upthrown side of each fault, and are shown on the Surface-Fault-Rupture-Hazard Map (plate 1).

Buried or approximately located faults: The UGS mapped a number of potentially active normal faults or portions of larger normal faults in the study area as buried (dotted lines) or approximately located (dashed lines) because the traces of those faults are not evident at or just below the ground surface. The reasons for the lack of clear surface evidence for these faults are varied, but are chiefly related to one of the following causes: (1) long earthquake recurrence intervals combined with a long elapsed time since the most recent surface-faulting earthquake allow evidence for the faults to be obscured by subsequent erosion and deposition, (2) rapid deposition in some areas that quickly obscures faults, even those with comparatively short recurrence intervals, (3) the faults generate earthquakes that produce

Table 3. St. George metropolitan area normal faults and activity levels.

Fault	MRE St. George basin	Information Source	Comments
Hurricane	Early Holocene ~ 5–10 ka[1] (Anderson Junction segment)	Stenner and others (1999), Lund and others (2007a)	Large multi-segment fault; active in the Holocene
Washington	Late Pleistocene ~ 18 ka	ESA (1982), Anderson and Christenson (1989), Lund and others (2007b)	Possibly segmented; single scarp profile; trenched by ESA and AGEC
Warner Valley	Likely Holocene <10 ka	Hayden (2004)	Age estimate based on stratigraphic and structural relations, no paleoseismic data available
Washington Hollow	Possible late Quaternary	Cordova (1978), Willis and Higgins (1995)	May connect to Washington fault, no paleoseismic data available
St. George	Early Quaternary or older >1.4 Ma[2]	Higgins and Willis (1995), Biek and Hayden (2007)	Possibly not active during the Quaternary
Other normal faults	Generally unknown, some may be late Quaternary	AGEC, verbal communica-tion, 2002	Nearly all lack paleoseismic data

[1] ka = thousand years ago; [2] Ma = million years ago

relatively small scarps (<3 feet) that are quickly obscured, and (4) faulting occurs at or above the bedrock/alluvium contact in relatively steep terrain and is difficult to identify.

Although not evident at the surface, these faults still may represent a significant surface-fault-rupture hazard and should be evaluated prior to development in areas where they may rupture to the ground surface. Because their location is uncertain, the surface-fault-rupture-hazard special-study areas around these faults are broader, extending 1000 feet on each side of the suspected trace of the faults. Special-study-area boundaries around buried or approximately located faults are shown on the accompanying Surface-Fault-Rupture-Hazard Map (plate 1).

Fault Activity Levels

The faults on the Surface-Fault-Rupture-Hazard Map (plate 1) are color-coded to indicate what is presently known about their activity level. Each color-code category includes recommendations for surface-fault-rupture special studies based on the fault activity class and the type of structure proposed. These recommendations are in accordance with UGS Guidelines for Evaluating Surface-Fault-Rupture Hazards in Utah (Christenson and others, 2003).

Red Holocene or suspected Holocene fault: surface-fault-rupture-hazard studies recommended for all structures designed for human occupancy[1], essential facilities[2], and all critical facilities[3].

Orange Late Quaternary fault: surface-fault-rupture-hazard studies recommended for all essential and critical facilities. Studies for other structures designed for human occupancy remain prudent, but should be based on an assessment of whether risk-reduction measures are justified by weighing the probability of occurrence against the risk to lives and potential economic loss (dePolo and Slemmons, 1998). Earthquake risk-assessment techniques are summarized in Reiter (1990) and Yeats and others (1997).

Green Quaternary fault: surface-fault-rupture-hazard studies recommended for all essential and critical facilities. Studies for other structures intended for human occupancy are optional because of the low likelihood of surface faulting, although surface rupture along the fault is still possible.

Purple Activity class unknown: paleoseismic data are lacking, recommend treating as a Holocene fault until proven otherwise.

[1] ***Structure designed for human occupancy*** *means any residential dwelling or any other structure used or intended for supporting or sheltering any use or occupancy, which is expected to have an occupancy rate of at least 2000 person-hours per year, but does not include an accessory building.*

[2] ***Essential facility*** *means buildings and other structures intended to remain operational in the event of an adverse geologic event, including but not limited to public utility facilities; dams, reservoirs, and other water storage facilities; jails and other detention facilities; emergency vehicle fueling and storage facilities; designated emergency shelters; emergency preparedness, response, and communication facilities; aviation control towers, air traffic centers, and emergency aircraft hangers.*

[3] ***Critical facility*** *means Occupancy Category III and IV structures as defined in the International Building Code (IBC, table 1604.5, p. 281; International Code Council, 2006a), and include school; hospitals and other health-care facilities; fire, rescue, and police stations; high occupancy buildings; water storage and treatment facilities, and facilities containing hazardous materials.*

USING THIS MAP

The Surface-Fault-Rupture-Hazard Map (plate 1) shows potentially active faults along which surface faulting may occur. A special-study area is shown around each fault, within which the UGS recommends that a site-specific, surface-fault-rupture-hazard study be performed prior to construction. These studies can resolve uncertainties inherent in generalized hazard mapping and help ensure safety by identifying the need for fault setbacks.

Utah Geological Survey Guidelines for *Evaluating Surface-Fault-Rupture Hazards in Utah* (Christenson and others, 2003) include a detailed rationale for performing surface-fault-rupture-hazard studies, minimum technical requirements for conducting and reporting those studies, recommendations regarding when surface-fault-rupture-hazard studies should be conducted based on fault activity class and the type of facility proposed, and procedures for establishing safe setback distances from active faults. City and county officials, planners, and consultants should refer to the UGS guidelines regarding the details of conducting and reviewing surface-fault-rupture-hazard investigations.

For well-defined faults color-coded red, orange, and green (Holocene, late Quaternary, and Quaternary, respectively), we recommend that surface-fault-rupture-hazard studies be performed in accordance with the UGS guidelines. Because paleoseismic data are lacking for the purple-coded faults (fault activity class unknown), we recommend that those faults be considered Holocene faults until paleoseismic studies demonstrate otherwise.

Because buried and approximately located faults lack a clearly identifiable surface trace, they are not amenable to trenching, which is the standard surface-fault-rupture-hazard evaluation technique used to study well-defined faults (McCalpin, 1996). Where development is proposed in a special-study area for a buried or approximately located fault, we recommend that at a minimum the following tasks be performed to better define the surface-fault-rupture hazard in those areas.

1. Review of published and unpublished maps, literature, and records concerning geologic units, faults, surface and ground water, previous subsurface investigations, previous geophysical investigations, and other relevant factors.
2. Stereoscopic interpretation of aerial photographs to detect any subtle fault-related features expressed in the site topography, vegetation or soil contrasts, and any lineaments of possible fault origin.
3. Field evaluation of the proposed site and surrounding area to observe pertinent surface evidence for faulting; map geologic units as necessary to define critical geologic relations; evaluate geomorphic features such as springs or seeps (aligned or not), sand blows or lateral spreads, or other evidence of earthquake-induced features; and excavation of test pits to evaluate the age of the deposits onsite to constrain the time of most recent surface faulting.

If the results of these studies reveal evidence of possible surface-faulting-related features, those features should be trenched in accordance with the UGS guidelines. Following the above-recommended studies, if no evidence of surface faulting is found, development at the site can proceed as planned. However, we recommend that construction excavations and cuts be carefully examined for evidence of faulting as development proceeds.

MAP LIMITATIONS

The Surface-Fault-Rupture-Hazard Map (plate 1) is based on 1:24,000-scale geologic mapping. We believe that the inventory of potentially active faults obtained from that mapping and shown on the map is complete or nearly so at that scale. However, some smaller faults may not have been detected during the mapping or are concealed beneath young geologic deposits. Additionally, buried and approximately located faults by definition lack a clearly identifiable surface trace, and therefore their location is imperfectly known. Site-specific fault-trenching studies should be preceded by a careful field evaluation of the site to identify the surface trace of the fault, other faults not evident at 1:24,000-scale, or other fault-related features at a site-specific scale prior to trenching.

HAZARD REDUCTION

Because surface faulting is typically confined to relatively narrow zones along the surface trace of a fault, early recognition and avoidance is the most effective strategy for mitigating this hazard. Once the activity class of the fault is determined (see Fault Activity Classes above), we recommend that facilities be set back from the fault trace and any associated zone of deformation in accordance with the UGS guidelines (Christenson and others, 2003). Carefully locating all potentially active fault traces on a site, assessing their level of activity and amount of displacement, and establishing an appropriate setback distance from the fault remain the most reliable procedures for mitigating damage and injury due to surface faulting.

In Utah, earthquake-resistant design requirements for construction are specified in the seismic provisions of the International Building Code (International Code Council, 2006a) and

International Residential Code (International Code Council, 2006b), which are adopted statewide. IBC Section 1802.2.7 requires that an investigation be conducted for all structures in Seismic Design Categories C, D, E, or F (see Earthquake Ground Shaking section) to evaluate the potential for surface rupture due to faulting.

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SECTION 3:
LIQUEFACTION HAZARD

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Plate 2. Liquefaction-hazard map for the St. George–Hurricane metropolitan area .... on DVD

SECTION 3: LIQUEFACTION HAZARD

INTRODUCTION

Liquefaction and liquefaction-induced ground failures are major causes of earthquake damage (Keller and Blodgett, 2006). Upon liquefaction, a soil loses its strength and ability to support the weight of overlying structures or sediments. Liquefaction chiefly occurs in areas where ground water is ≤50 feet deep, when a water-saturated, cohesionless soil is subjected to strong ground shaking (Seed, 1979; Martin and Lew, 1999). Cohesionless soils have loose grains that do not readily stick together and are typically sandy, with little clay, although some silty and gravelly soils are also susceptible to liquefaction. In general, an earthquake of magnitude 5 or greater is necessary to induce liquefaction. Larger earthquakes are more likely to cause liquefaction, and may result in liquefaction at greater distances from the earthquake epicenter.

Liquefaction and liquefaction-induced ground failure can have four major adverse effects: (1) foundations may crack, (2) buildings may tip, (3) buoyant buried structures, such as septic tanks and storage tanks, may rise, and (4) liquefied soils and overlying materials may move down even gentle slopes. Structures that are particularly sensitive to liquefaction-induced ground failure include buildings with shallow foundations, railway lines, highways and bridges, buried structures, dams, canals, retaining walls, utility poles, and towers.

Four types of ground failure commonly result from liquefaction: (1) loss of bearing capacity, (2) ground oscillation and subsidence, (3) lateral spreading, and (4) flow failures (Youd, 1978; Youd, 1984; Tinsley and others, 1985; figure 1). The expected mode of ground failure at a given site largely depends upon the ground-surface slope. Where slopes are less than 0.5 percent, liquefaction may cause damage in one of two ways. The first occurs with the loss of bearing capacity and resulting deformation of soil beneath a structure, which causes the structure to settle or tilt. Differential settlement is commonly accompanied by cracking of foundations and damage to structures. Buoyant buried structures, such as gasoline-storage or septic tanks, may also float upward under these conditions. The second instance

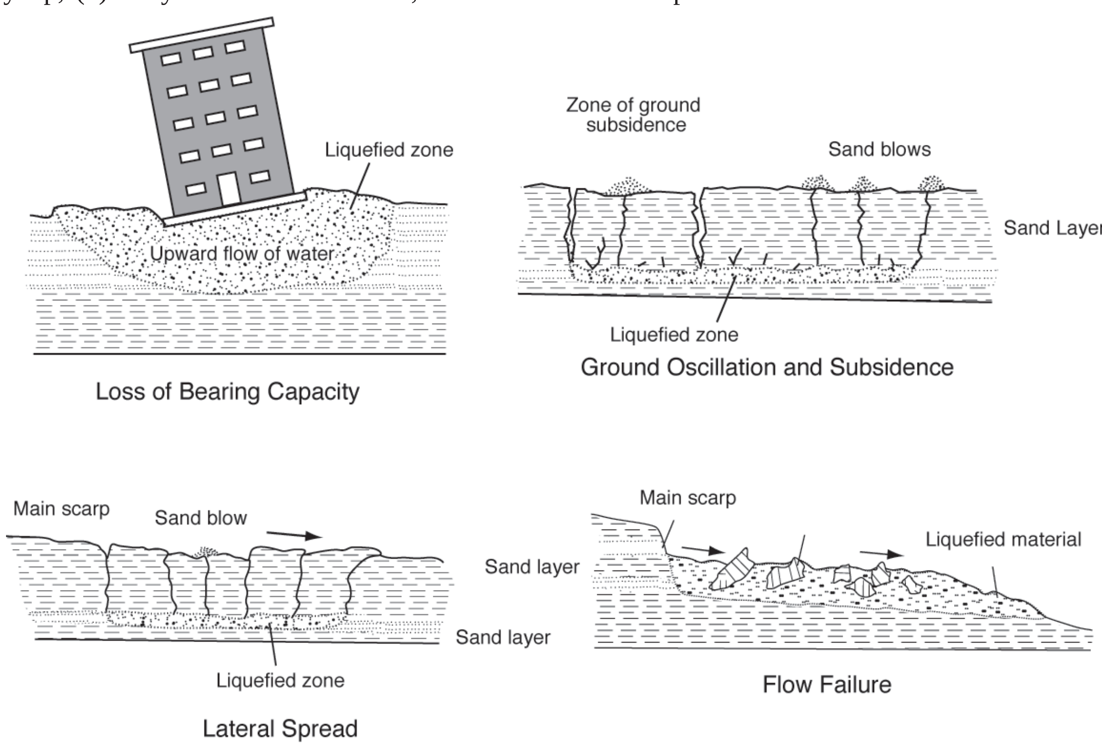

Figure 1. *Four principal types of liquefaction-induced ground failure; arrows indicate direction of movement (modified from Youd, 1984; Harty and Lowe, 2003).*

occurs when ground oscillation causes liquefaction at depth below soil layers that do not liquefy. Under these conditions, liquefaction commonly causes overlying soil blocks to detach and jostle back and forth on the liquefied layer. Damage to structures and buried facilities is caused by subsidence of the blocks, opening and closing of fissures between and within the blocks, and formation of sand blows as liquefied sand is ejected through the fissures from the underlying pressurized liquefied layer.

Ground failure by lateral spreading may occur where the ground surface slopes from 0.5 to 5.0 percent, particularly near a "free face" such as stream banks or cut slopes. Lateral spreads are characterized by surficial soil blocks which are displaced laterally downslope as a result of liquefaction in a subsurface layer. Lateral spreading can cause significant damage to structures and may be particularly destructive to pipelines, utilities, bridge piers, and structures with shallow foundations.

Flow failures may occur where the ground surface slopes more than about 5.0 percent. Flow failures are composed chiefly of liquefied soil or blocks of intact material riding on a liquefied layer. Flow failures can cause soil masses to be displaced several miles and are the most catastrophic mode of liquefaction-induced ground failure.

SOURCES OF DATA

We evaluated liquefaction hazard in the St. George–Hurricane metropolitan area using the following data: (1) 275 geotechnical reports obtained from municipalities in the study area and from the Utah Department of Transportation, (2) water-well drillers logs on file with the Utah Division of Water Rights, (3) the occurrence of wet, or potentially wet soils mapped by the Natural Resources Conservation Service (NRCS; formerly the U.S. Soil Conservation Service) (Mortensen and others, 1977), and (4) the distribution of unconsolidated geological deposits typically associated with liquefaction from nine digital Utah Geological Survey (UGS) 1:24,000-scale (1 inch = 2000 feet) geologic quadrangle maps covering the study area (Harrisburg Junction [Biek, 2003a], Hurricane [Biek 2003b], Pintura [Hurlow and Biek, 2003], Santa Clara [Willis and Higgins, 1996], St. George [Higgins and Willis, 1995], The Divide [Hayden, 2004], Washington [Willis and Higgins, 1995], Washington Dome [Hayden, 2005], and White Hills [Higgins, 1997]). The geotechnical and water-well data are unevenly distributed throughout the study area; geotechnical data are available only where development has already occurred, and water-well data are largely confined to agricultural areas. Consequently, depth to ground water information is not available for much of the St. George–Hurricane metropolitan area, including many areas where development may occur in the future.

HISTORICAL LIQUEFACTION

The September 2, 1992, M_L 5.8 St. George earthquake produced liquefaction in saturated sand deposits along the Virgin River (Black and others, 1995). The earthquake's epicenter was in Washington Fields, and the earthquake likely occurred on the Hurricane fault (Pechmann and others, 1995). Liquefaction occurred along the river from approximately 1 mile south of Bloomington to approximately 4 miles west of Hurricane (Black and others, 1995). The geologic units affected consisted of well-sorted, modern channel sands with thin sheets of silts and clays from overbank flooding covering them. Liquefaction features recognized included lateral spreads (figure 2), caved stream banks, and sand blows (figure 3). Lateral spreads were the most common feature (17 recorded); the largest was 200 feet long and 66 feet wide. Total lateral movement was about 19 inches (Black and others, 1995). No damage due to liquefaction was reported.

Figure 2. *Lateral-spread cracking from liquefaction along the Virgin River resulting from the September 2, 1992,* M_L *5.8 St. George earthquake (photo by W.E. Mulvey).*

Figure 3*. Sand blows from liquefaction along the Virgin River resulting from the September 2, 1992,* M_L *5.8 St. George earthquake (photo by W.E. Mulvey).*

CLASSIFYING LIQUEFACTION HAZARD

We used information about the age, textural characteristics (grain size and sorting), cementation of unconsolidated geologic deposits, the presence of shallow (≤50 ft) ground water in those units, and the liquefaction response of similar units in historical earthquakes to prepare a Liquefaction-Hazard Map (plate 2) for the study area. As a first determining factor, we considered all unconsolidated geologic units of Quaternary age as potentially susceptible to liquefaction. Age is an important consideration for liquefaction hazard because the older the unit, generally the more consolidated or cemented it is and the less susceptible it becomes to liquefaction. We then evaluated the Quaternary units based on their grain size (fine to coarse grained), sorting (poor to well sorted), and cementation (none to strong), and classified them as having high, moderate, low, or very low/no hazard to liquefaction.

We then compared the classified units with available ground-water information (see Shallow-Ground-Water-Susceptibility Map, plate 14). Where depth to ground water was ≤50 feet, we classified the liquefaction hazard of the corresponding geologic unit as Very High, High, Moderate, Low, or none (table 1) based on the textural characteristics, cementation, presence of shallow ground water, and previous liquefaction response of the units in historical earthquakes. Where depth to ground water was not known, we classified liquefaction hazard based on textural and cementation characteristics alone and assigned a subscript 2 to those hazard units. The subscripted units are considered susceptible to liquefaction until depth to ground water is proven to be >50 feet. Descriptions of the liquefaction-hazard categories are presented below, and table 1 shows the liquefaction hazard of unconsolidated Quaternary geologic units in the study area.

VH Very High—Geologic units that liquefied during the 1992 St. George, Utah, M_L 5.8 earthquake, and consist of well-sorted sands, silty sands, and gravels along modern stream drainages and young alluvial terraces where depth to ground water is ≤10 feet.

H High—Geologic units that consist of well-sorted sands, silty sands, and gravels where depth to ground water is ≤50 feet. None of these units are known to have liquefied during the 1992 St. George earthquake.

H_2 $High_2$—Geologic units with textural characteristics of the High category, but ground-water information is lacking.

M Moderate—Geologic units that consist of moderately sorted sands, silty sands, and gravels where depth to ground water is ≤50 feet.

M_2 $Moderate_2$—Geologic units with textural characteristics of the Moderate category, but ground-water information is lacking.

Table 1. *Liquefaction susceptibility of unconsolidated geologic units.*

Type of Deposit[1]	Geologic Unit[2]	Liquefaction Susceptibility	
		Ground Water ≤50 ft	Ground Water Depth Unknown
Stream and Terrace Alluvium	Qal_1	VH	VH
	Qat_2	VH	VH
Alluvial Deposits	Qaes	H	H_2
	Qae	H	H_2
	Qa	M	M_2
	Qac	M	M_2
	Qaec	M	M_2
	Qap_1	L	L_2
	Qaf_1	L	L_2
	Qaf_2	L	L_2
	Qafy	L	L_2
	Qao	L	L_2
	Qaeo	L	L_2
Eolian Deposits	Qes	H	H_2
	Qea	H	H_2
	Qea_1	H	H_2
	Qea_2	H	H_2
	Qed	H	H_2
Colluvial Deposits	Qc	L	L_2
	Qca	L	L_2
Various	All remaining unconsolidated Quaternary and Tertiary units, bedrock, and areas where depth to ground water is >50 feet.	None[3]	None[3]

[1]Some categories include mixed unit deposits
[2]Refer to UGS 1:24,000-scale geologic maps (see SOURCES OF DATA above and REFERENCES below) for a description of map units.
[3]Not shown on Liquefaction Hazard Map, although may contain small areas of liquefaction hazard too small to show at the scale of this study.

L Low—Geologic units that consist of moderately to poorly sorted sands and gravels where depth to ground water is ≤50 feet. Liquefaction hazard is considered low in these units because of their textural characteristics and/or degree of cementation.

L_2 Low_2—Geologic units with textural characteristics of the Low category, but ground-water information is lacking.

Unclassified areas on the Liquefaction-Hazard Map (plate 2) include unconsolidated Quaternary and Tertiary geologic units with textural or cementation characteristics that generally preclude liquefaction, areas where depth to ground water is >50 feet, and areas where bedrock crops out. These geologic units are considered to have no liquefaction hazard; however, small areas of liquefaction hazard too small to show at the scale of this study may exist locally within unclassified areas of the map.

One remaining unconsolidated unit within the study area represents a special case. Artificial fill (Qf) consists of human-made deposits such as road fill, dam embankments, and levees. The textural characteristics of this unit are both highly variable (depending on the material from which they were constructed) and largely unknown. Due to a lack of geotechnical and ground-water information for these deposits, and their limited geographic extent, Qf deposits were not included in the liquefaction-hazard assessment, and should be evaluated individually as the need arises.

USING THIS MAP

The Liquefaction-Hazard Map (plate 2) shows areas of known or suspected liquefaction hazard in the St. George–Hurricane metropolitan area. The map does not integrate earthquake ground motions with soil characteristics and depth to ground water, which is required to determine relative liquefaction potential (potential equals hazard plus opportunity) in susceptible soils. Consequently, this map does not differentiate ground-failure types or amounts, which are needed to fully assess the hazard and evaluate possible mitigation techniques.

This map is intended for general planning purposes to indicate where a liquefaction hazard may be present and to assist in liquefaction-hazard study design. Requirements for liquefaction special studies are given in the International Building Code (IBC) (International Code Council, 2006a) and are implied in the International Residential Code (IRC) (International Code Council, 2006b), which applies to the design and construction of one- and two-family dwellings and townhouses. In Utah, both the IBC and IRC are adopted statewide. IBC Section 1802.2.6 (p. 343) requires a liquefaction evaluation if a structure is in Seismic Design Category C, and IBC Section 1802.2.7 (p. 343-344) requires a liquefaction evaluation and an assessment of potential consequences of any liquefaction if the structure is in Seismic Design Categories D, E, or F (see Earthquake-Ground-Shaking Hazard text document, table 2). In general, seismic design categories in the St. George–Hurricane metropolitan area for structures built on unconsolidated materials fall into Seismic Design Categories C and D (see Earthquake-Ground-Shaking Hazard text document), thus triggering the IBC requirement for a liquefaction evaluation. Although the IRC does not specifically mention liquefaction, IRC Section R401.4 (p. 67) leaves the need for soil tests up to the local building official in areas likely to have expansive, compressive, shifting, or other unknown soil characteristics, such as liquefiable soils.

IBC seismic design categories are determined on a site- or project-specific basis, and vary throughout the St. George–Hurricane metropolitan area depending on IBC site class, maximum considered earthquake ground motions, and the IBC Occupancy Category of the proposed structure (see Earthquake-Ground-Shaking Hazard text document). Occupancy categories are based on the nature of the structure's use and occupancy and are described in IBC Section 1604.5 (p. 280) and table 1604.5 (p. 281). The IBC specifies four occupancy categories (I, II, III, and IV). Occupancy Category I includes buildings and other structures that represent a low hazard to human life in the event of a failure. Occupancy Category II includes buildings and other structures except those listed in Occupancy Categories I, III, and IV. Occupancy Category III includes buildings and other structures that represent a substantial hazard to human life in the event of failure. Occupancy Category IV includes buildings and other structures designated as essential facilities.

Because the risk to human life and the requirement that certain essential structures remain functional during natural or other disasters varies by occupancy category, we recommend different levels of liquefaction evaluation for different occupancy categories based on mapped liquefaction susceptibility (table 2). We recommend detailed subsurface investigations for Occupancy Category II, III, and IV structures in moderate to very high liquefaction hazard areas; detailed subsurface investigations for Occupancy Category III and IV structures in low hazard areas; reconnaissance investigations for Occupancy Category II structures in low or not susceptible liquefaction areas, followed by a detailed investigation if the liquefaction hazard is determined to be moderate or greater; a reconnaissance evaluation only for Occupancy Category I structures in moderate to very high liquefaction hazard areas; and no investigation for Occupancy Category I buildings in low or not susceptible areas. Martin and Lew (1999) provide guidelines for conducting both reconnaissance (screening) and detailed (quantitative) liquefaction evaluations.

MAP LIMITATIONS

The Liquefaction-Hazard Map (plate 1) is based on limited geological, geotechnical, and hydrological data; site-specific studies are required to produce more detailed information. The map also depends on the quality of those data, which varies throughout the study area. The mapped boundaries between liquefaction-hazard categories are approximate and subject to

Table 2. *Recommended requirements for liquefaction-hazard investigations.*

Liquefaction Susceptibility	**IBC Occupancy Category**			
	I	**II**	**III**	**IV**
	Buildings and Other Structures That Represent Low Hazard to Human Life in the Event of Failure (IBC)	All Other Buildings and Structures Except Those Listed in Categories I, III, and IV (Includes One- and Two-Family Dwellings and Townhouses) (IRC) (IBC)	Buildings and Other Structures That Represent a Substantial Hazard to Human Life in the Event of Failure (IBC)	Buildings and Other Structures Designated as Essential Facilities (IBC)
Very High	Reconnaissance[1]	Detailed[2]	Detailed	Detailed
High Moderate	Reconnaissance	Detailed	Detailed	Detailed
Low	No	Reconnaissance	Detailed	Detailed
Not Susceptible	No	Reconnaissance	Reconnaissance	Reconnaissance

[1] Reconnaissance evaluation; if a moderate to very high liquefaction susceptibility is found, at a minimum, disclosure is recommended and detailed evaluations may be performed at the discretion of the owner.

[2] Detailed evaluation necessary; a detailed liquefaction evaluation should be interdisciplinary in nature and performed by qualified experienced geotechnical engineers and engineering geologists working as a team.

change with additional information. The liquefaction hazard at any particular site may be different than shown because of geological and hydrologic variations within a map unit, gradational and approximate map-unit boundaries, and the map scale. Small, localized areas of higher or lower liquefaction hazard may exist anywhere within the study area, but their identification is precluded because of limitations of either data or map scale. Seasonal and long-term fluctuations in ground-water levels can affect liquefaction hazard at any given site. The map is not intended for use at scales other than the published scale, and is designed for use in general planning to indicate the need for site-specific studies.

HAZARD REDUCTION

Although potentially costly when not recognized and properly accommodated in project design, problems associated with liquefaction rarely are life threatening. As with most geologic hazards, early recognition and avoidance is the most effective way to mitigate this hazard. However, avoidance may not always be a viable or cost-effective hazard-reduction option and other techniques are available to reduce liquefaction hazards (National Research Council, 1985).

Liquefaction damage may be reduced either by improving site conditions to lower liquefaction hazard (for example, compacting or replacing soil; installing drains or pumps to lower the water table) or by designing structures to withstand liquefaction effects (using deep foundations or structural reinforcement). Existing structures threatened by liquefaction may be retrofitted to reduce the potential for damage. Because the cost of reducing liquefaction hazards for existing structures may be high relative to their value, and because liquefaction is generally not a life-threatening hazard, the UGS considers it prudent, although not essential, to reduce liquefaction hazards for existing structures, unless significant ground deformation (lateral spreading) is anticipated and the structures fall into IBC Occupancy Categories III or IV, in which case we do recommend retrofitting. At a minimum, we recommend disclosure of study results if studies confirm a moderate to very high liquefaction potential. Disclosure allows prospective home buyers to make an informed decision on the amount of risk they are willing to accept.

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SECTION 4:
FLOOD HAZARD

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SECTION 4: FLOOD HAZARD

INTRODUCTION

Flooding is the overflow of water onto lands that are normally dry, and is the most universally experienced natural hazard (Keller and Blodgett, 2006). Damaging effects from flooding include inundation of land and property, erosion, deposition of sediment and debris, and the force of the water itself, which can damage property and take lives (Stauffer, 1992; CH2MHILL, 1997; JE Fuller Hydrology and Geomorphology, Inc., 2005, 2007). Historically, flooding is the most prevalent and destructive (on an annual basis) geologic hazard affecting the St. George–Hurricane metropolitan area. The high flood hazard results from the complex interaction of the area's rugged topography and seasonal weather patterns that deliver moisture to southwestern Utah. Three types of floods typically occur in the study area: riverine (stream) floods, flash floods/debris flows, and sheetfloods. All three types of floods are associated with natural climatic fluctuations and may, under certain circumstances, occur in combination with each other. The risk from flooding can be significantly increased by wildfires and by human activities such as placing structures and constrictions in flood plains and erosion-hazard zones, developing urban areas without adequate flood and erosion control, and poor watershed management practices, such as overgrazing or allowing indiscriminate off-road vehicle traffic. Additionally, portions of the study area are subject to inundation in the event of an unintentional release of water from an engineered water-retention or conveyance structure.

SOURCES OF DATA

We used the following sources of data to identify areas within the St. George–Hurricane metropolitan area subject to periodic flooding: (1) Federal Emergency Management Agency (FEMA) National Flood Insurance Program flood insurance rate maps (FIRMs), (2) maps prepared by Alpha Engineering (1994) for the Washington County Water Conservancy District (WCWCD) depicting the Virgin River 100-year flood plain boundary from about a half mile upstream to approximately 12 miles downstream from La Verkin, (3) flood-plain information for the Virgin River and Fort Pearce Wash prepared by the U.S. Army Corps of Engineers (1973), and (4) the distribution of young, water-deposited geologic units shown on nine digital Utah Geological Survey (UGS) 1:24,000-scale (1 inch = 2000 feet) geologic quadrangle maps covering the study area (Harrisburg Junction [Biek, 2003a], Hurricane [Biek, 2003b], Pintura [Hurlow and Biek, 2003], Santa Clara [Willis and Higgins, 1996], St. George [Higgins and Willis, 1995], The Divide [Hayden, 2004], Washington [Willis and Higgins, 1995], Washington Dome [Hayden, 2005], and White Hills [Higgins, 1997]).

FLOOD TYPES

Riverine Floods

Riverine flooding along major drainages in southwestern Utah is usually regional in nature, lasts for several hours or days, typically takes place on perennial streams, has recurrence intervals (average time between floods with the same peak discharge) of from 25 to more than 100 years, and usually can be predicted days to weeks in advance. Riverine floods commonly result from the rapid melt of a winter snowpack or from periods of prolonged heavy rainfall associated with major frontal storms, or from both conditions simultaneously. Depending on the season, southwestern Utah receives moisture from Pacific frontal systems (winter and early spring) and from upper-level, low-pressure systems that deliver subtropical moisture from the Gulf of California (late spring and fall) to the state. These two weather systems generate most of the winter snowpack that accumulates in higher elevations surrounding the St. George–Hurricane metropolitan area and they can produce sustained, high-volume rainstorms. Where uncontrolled, riverine floods can inundate large areas along flood plains and cause extensive erosion and flood damage over a wide area, as occurred most recently along the Santa Clara and Virgin Rivers in January 2005 (figure 1).

Measurements or careful estimates of historical peak flows on the Virgin River date to 1909 (U.S. Army Corps of Engineers, 1973) but are not available for every year. Similarly, records of historical peak flows for the Santa Clara River and Fort Pearce Wash contain gaps. The largest recorded natural flood on the Virgin River in the study area occurred in January 2005. The U.S. Geological Survey (USGS, 2006a) reported a peak discharge of

Figure 1. Damage to homes caused by flooding on the Santa Clara River in January 2005.

21,000 cubic feet per second (cfs) on the Virgin River at Hurricane, Utah. The largest recorded flow on the Santa Clara River was 6390 cfs near Santa Clara in 1966 (USGS, 2006a). The USGS (2006a) recorded a peak flow of 6200 cfs on the Santa Clara River at St. George in January 2005. The 2005 flood on the Virgin and Santa Clara Rivers resulted from a prolonged rain event on an above normal snowpack at low elevations, and is the most damaging flood recorded in the study area. Twenty-eight homes were seriously damaged or destroyed (figure 1), in all about $85 million in private property was lost, and an estimated $145 million in damage was done to roads, bridges, parks, and utility lines (FEMA, no date; USGS, 2006b). Washington County received a federal disaster declaration following the flood. Damage from the 1966 flood on the Virgin and Santa Clara Rivers (peak flow on the Virgin River at Hurricane was 20,100 cfs; USGS, 2006a), which held the previous damage record, was $14 million in 1966 dollars (U.S. Army Corps of Engineers, 1973). The largest flood of record on Fort Pearce Wash occurred in August 1994, and had a peak discharge of 8760 cfs (USGS, 2006a).

Flash Floods and Debris Flows

Flash Floods

Flash floods occur in response to intense cloudburst rainfall that often accompanies summer convective thunderstorms. By their nature, flash floods are sudden, intense, and localized. Because cloudburst storms result from strong convective cells produced by differential atmospheric heating, flash floods are largely a summer-time phenomenon in desert regions. Flash floods can affect large drainages; both the Virgin and Santa Clara Rivers have been subject to flash flooding, especially in their upper reaches, but the most intense and unpredictable floods, and therefore often the most damaging, take place on small- to medium-sized watersheds characterized by ephemeral stream flow and normally dry stream channels. Cloudburst storms only rarely are recorded by a rainfall gauging station, so even the most damaging flash floods are seldom well documented.

Flash floods have damaged every major settlement in southwestern Utah at least once (Woolley, 1946; Butler and Marsell, 1972; Utah Division of Comprehensive Emergency Management, 1981; CH2MHILL, 1997), and most cities and towns in the study area, including St. George, Santa Clara, Hurricane, and La Verkin, have been affected numerous times. In recent years, many communities have implemented various flood-control measures (stream channelization, flood- and debris-retention basins, diversion structures, and floodways) to eliminate or reduce the risk from flash floods. However, as communities continue to grow and expand into previously undeveloped areas they may again become at risk from flash floods (Lund, 1992).

Alluvial fans (figure 2) are relatively flat to moderately sloping surfaces comprised of loose to weakly consolidated sediment deposited in the shape of a fan by a stream at a topographic break such as the base of a mountain front, escarpment, or valley side (National Research Council, 1996). Because of their topographic location, alluvial fans are particularly subject to flash floods in response to cloudburst storms centered over their drainage basins. Flash floods on alluvial fans are characterized by great flow path uncertainty and by abrupt sediment deposition often causing channel avulsion as the stream loses its competence to carry material eroded from steeper, upstream source areas (FEMA, 1999b).

Debris Flows

Floodwaters entering an alluvial fan typically contain a large proportion of sediment ranging in size from clay to boulders.

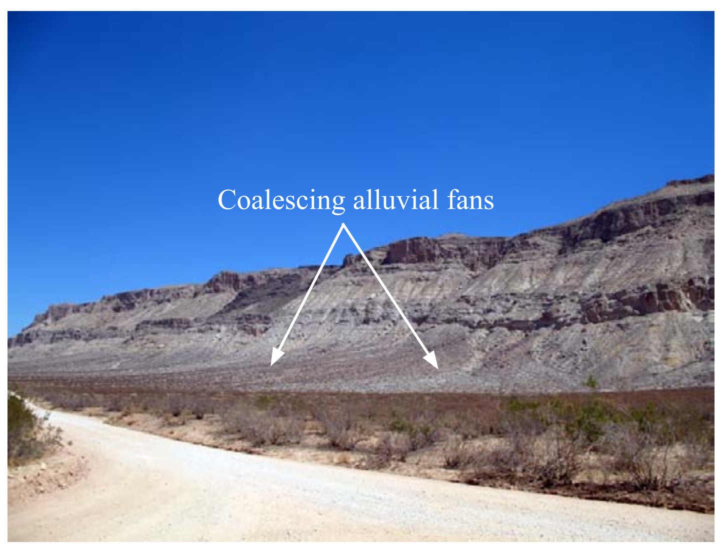

Figure 2. Coalescing alluvial fans at the base of the Hurricane Cliffs are subject to periodic flash floods and debris flows.

As the proportion of sediment increases, flash floods transform into debris floods and finally, when sediment comprises greater than 60 percent by volume of the flowing material, into a debris flow. A debris flow moves as a viscous fluid capable of rafting large boulders, trees, and other heavy debris over long distances. Like flash floods, debris flows are fast moving and under some conditions can exceed 35 miles per hour (U.S. Geological Survey, 1997). Their greater density and high speed make debris flows particularly dangerous to life and destructive to property. Debris flows are capable of destroying buildings, roads, and bridges lying in their path and of depositing thick layers of mud, rock, and other debris.

The volume and frequency of debris flows depends on several factors including the amount of sediment in a drainage that is available for erosion and transport, the magnitude and frequency of storms, the amount of vegetation in the drainage, and soil conditions (Giraud, 2004, 2005). The sediment carried by a debris flow can be deposited anywhere on an active alluvial-fan surface. The active fan surface includes those areas where modern deposition, erosion, and alluvial-fan flooding may occur. In general, those parts of the fan surface where sediment has been deposited during the Holocene (past 10,000 years) are considered active unless proven to be otherwise. Typically, the upper part of an active alluvial fan has a higher debris-flow hazard due to greater velocities, impact pressures, burial depths, and event frequency (Giraud, 2004, 2005).

Weathering of the sedimentary bedrock units in the study area generally produces fine-grained sediment (sand, silt, and clay), which is easily transported by lower velocity runoff. Small to moderate storms periodically remove the sediment from drainage basins during flash floods, thus making debris flows a less common hazard than flash floods. Additionally, except along the Hurricane Cliffs where debris-flow deposits are present on many alluvial-fan surfaces (figure 2), most of the study area lacks the steep, high-relief topography needed to produce large debris flows.

Sheetfloods

Sheetflooding refers to a broad expanse of unconfined moving storm water that spreads as a thin, continuous, relatively uniform sheet over a large area and is not concentrated into well-defined channels. The flow distance is short and duration is measured in minutes to hours. Sheetflooding usually occurs before runoff is sufficient to promote channel flow, or after a period of intense rainfall. In the study area, sheetfloods typically occur in one of two ways, either as the end product of flooding across an alluvial fan after the flood waters have dropped their load of sediment and begin to slow down and spread out across the lower (toe) part of fan surface, or as runoff from moderate to steep slopes during intense cloudburst storms. Although lacking the depth and velocity to cause serious damage to structures, sheetfloods can cause localized inundation, especially where conditions allow for ponding or entrance into a basement or other below-ground facility, and they can deposit considerable fine sediment.

Unintentional Water Release from Water-Retention Structures

An unintentional release of water due to the failure of a water-retention or conveyance structure may occur with little warning. The extent of associated flooding depends on reservoir volume and nature of the failure (Harty and Christenson, 1988; Solomon, 1996). The severity of flooding that may accompany the failure of a water-retention structure was clearly demonstrated on January 1, 1989, when the Quail Creek dike failed (figure 3) and catastrophically released 25,000 acre feet of water into the Virgin River. Downstream evacuation prevented fatalities, but flooding caused millions of dollars in damage to structures, highways, and farmland (Gourley, 1992). Near Bloomington, approximately 12 miles downstream from the failed dike, the peak flow was 60,000 cfs, almost three times greater than the largest natural flood of record on the Virgin River.

Figure 3. *The Quail Creek dike failure, January 1989 (photo courtesy of Benjamin Everitt).*

CLASSIFYING FLOOD-PRONE AREAS

FEMA 100-Year Flood Maps

The Federal Emergency Management Agency through the National Flood Insurance Program (NFIP) is currently (February 2008) updating flood insurance rate maps (FIRMs) that show the boundaries of the expected 100-year and 500-year floods (floods with a 1 percent and 0.2 percent annual chance, respectively, of occurring in any given year) along selected drainages in the St. George–Hurricane metropolitan area. The new maps are digital, and through the use of advanced GIS techniques are substantially more accurate than the currently available paper-based FIRMS dating mostly from the 1980s and 90s. Final adoption of the new digital FIRMS is expected sometime in 2008. The boundaries and explanations for of the new 100-year and 500-year flood zones are shown on the Flood-Hazard Map (appendix) as they were available in February, 2008. The NFIP uses the FIRMs to make federally subsidized flood insurance available to homeowners in flood-prone areas once required flood-proofing design features are incorporated into house construction. Where development is contemplated within or near the boundaries of a NFIP 100-year flood zone, the most recent version of the applicable FIRM should be consulted.

Washington County Water Conservancy District Flood Boundary Maps

The WCWCD prepared 100-year-flood-plain-boundary maps (25,000 cfs maximum flood) for a reach of the Virgin River extending from Dixie (Pah Tempe) Hot Springs in Timpoweap Canyon to about 4 miles south of the SR-9 highway bridge across the Virgin River in Hurricane. The maps are at a scale of 1 inch = 300 feet and are the most detailed flood maps available in the study area (Alpha Engineering, 1994). We do not show the boundaries of the WCWCD-determined flood plain on our Flood-Hazard Map because the difference in scale between the WCWCD maps (1 inch = 300 feet) and our 1:24,000-scale (1 inch = 2000 feet) topographic base maps results in a poor topographic match. The WCWCD maps can be consulted at the WCWCD offices (136 N. 100 East, St. George) if questions arise regarding mapped flood boundaries. However, the WCWCD maps are special-purpose maps, and the NFIP FIRMs remain the maps on which federal flood insurance eligibility is based for this reach of the Virgin River.

Other Flood-Prone Areas

Flood insurance rate map coverage in the St. George–Hurricane metropolitan area is limited to perennial streams (Virgin and Santa Clara Rivers), Fort Pearce Wash, and a few other large ephemeral drainages. Flood hazards remain unidentified over much of the remainder of the FIRMs. Additionally, those portions of the study area not covered by FIRMs contain numerous ephemeral streams, alluvial fans, and other areas subject to periodic flooding, chiefly as a result of cloudburst storms. We used the distribution of geologically young, flood- and debris-flow deposits shown on UGS 1:24,000-scale geologic maps (see Sources of Data) to identify flood-prone areas and their relative susceptibility (Low, Medium, High, and Very High) to flooding in the study area. The probability of flooding in any area over a fixed period of time is uncertain; however, the relative flood hazard can be estimated from the distribution of historical flooding in the study area and southwestern Utah. The four flood-hazard categories are described below. Table 1 shows the geologic units associated with each flood-hazard category and relative hazard based on geologic deposit genesis.

VH Very High: Active flood plains and low terraces along perennial streams (large drainage basins) subject to periodic riverine and flash flooding and accompanying erosion, and active alluvial fans, chiefly at the base of the Hurricane Cliffs, subject to flash floods and debris flows. Many of the geologic deposits in this category coincide with stream segments covered by FIRMs.

H High: Stream channels, flood plains, and low terraces along normally dry ephemeral streams (smaller drainage basins) that are periodically inundated by flash floods and debris flows during infrequent cloudburst storms. Some geologic deposits in this category may coincide with stream segments covered by FIRMs.

M Medium: Active pediments and sloping depositional surfaces flanking ridges and other upland areas that are chiefly inundated by sheetfloods, but possibly by flash floods and debris flows during infrequent cloudburst storms.

L Low: Valley bottoms and minor ephemeral drainages subject to possible sheetfloods and minor flash floods from adjacent upland areas during infrequent cloudburst storms.

River Stability Studies

In 1997, the City of St. George contracted with CH2MHILL consultants in association with JE Fuller Hydrology & Geomorphology, Inc. to conduct a river stability study of the Virgin and Santa Clara Rivers and Fort Pearce Wash in the vicinity of St. George (CH2MHILL, 1997). A principal result of the study was the delineation of erosion-hazard zones along the stretches of the drainages studied. An erosion-hazard zone as defined by CH2MHILL (1997) is a "land area adjoining a body of water or adjacent to or located partially or wholly within a delineated flood plain which due to soil instability, is likely to suffer flood-related erosion damage." Erosion-hazard zones are independent of FIRMs 100-year flood zones, and are intended to prevent damage from erosion during flooding, "whether or not the property is located in a FIRMs 100-year flood zone" (CH2MHILL, 1997). Erosion-hazard zones are based chiefly on a geomorphic analysis of river behavior over time, and are determined through a combination of air photo interpretation, field observations, geology and soils mapping, and consideration of the location and design of structures in active stream channels including bridges, water diversion dams, and channel stabilization structures.

The CH2MHILL (1997) report included several river management recommendations based largely on the erosion-hazard zones. The recommendations called for adoption of erosion

Table 1. *Flood-hazard categories based on the genesis of geologic deposits mapped by the UGS.*

Hazard Category	Geologic Units[1]	Description	Hazard Type	Comments
Very High	Qal_1, Qaf_1, Qafy, Qa, Qa/Qafo,	Active flood plains and low terraces along perennial streams, and active alluvial fans.	Riverine flood, flash flood, debris flow	Chiefly the Virgin and Santa Clara Rivers, Fort Pearce Wash, and active alluvial fans at the base of the Hurricane Cliffs.
High	Qal_1, Qac, Qaec	Stream channels, flood plains, and low terraces along ephemeral streams.	Flash flood, debris flow	Normally dry streams with comparatively small drainage basins subject to flooding during infrequent cloudburst storms.
Moderate	Qap_1, Qc, Qca, Qat_2	Active pediment surfaces, higher stream terrace surfaces, and sloping depositional surfaces flanking upland areas.	Chiefly sheetflood, possible flash flood and debris flow	Active depositional surfaces on the flanks and at the base of upland areas subject to flooding during infrequent cloudburst storms.
Low	Qae, Qaes, Qea	Valley bottoms receiving active deposition and minor ephemeral drainages.	Sheetflood, minor flash flood	Valley bottoms subject to infrequent flooding from adjacent upland areas during cloudburst storms.

[1]Refer to UGS geologic quadrangle maps (see SOURCES OF DATA above and REFERENCES below) for a description of map units.

corridors along the drainages within which future building would be regulated through issuance of special use permits that require enhanced design considerations to reduce the risk from erosion during flooding. The City of St. George incorporated the erosion-hazard zones into their Flood Damage Prevention Ordinance in 1999 along with a requirement that structures built within the zones incorporate erosion-hazard-mitigation measures. During the January 2005 floods, the erosion-hazard zones were credited with saving numerous homes and preventing more than $5 million in property damage (FEMA, no date). The only homes damaged or destroyed within the erosion-hazard zones were those build before the Flood Damage Prevention Ordinance was adopted (FEMA, no date).

Following the 2005 flood, the WCWCD contracted with JE Fuller Hydrology & Geomorphology, Inc. to conduct a river stability study of the Virgin and Santa Clara Rivers from the Santa Clara River confluence downstream to the southern limits of Bloomington, Utah (JE Fuller Hydrology & Geomorphology, Inc., 2005). In 2007, the WCWCD initiated a Virgin River stability study update from the Santa Clara River confluence upstream to the Washington Fields diversion dam (JE Fuller Hydrology & Geomorphology, Inc., 2007a), and a Fort Pearce Wash stability study update and mining plan (JE Fuller Hydrology & Geomorphology, Inc., 2007b). Also in 2007, JE Fuller Hydrology & Geomorphology, Inc. was funded by a FEMA grant to the Washington County Commission to make an erosion-hazard zone delineation study of selected other areas in Washington County not covered by the previous three studies (JE Fuller Hydrology & Geomorphology, Inc., 2007c). Each of these studies included new or updated erosion-hazard zones and river management recommendations for the drainages covered.

The Flood-Hazard Map (plate 3) prepared for this study includes the boundaries of the erosion-hazard zones established for the Virgin and Santa Clara Rivers and Fort Pearce Wash (JE Fuller Hydrology & Geomorphology, Inc., 2005, 2007a, 2007b). The erosion-hazard zone boundaries for selected other areas in Washington County (JE Fuller/Hydrology & Geomorphology, Inc., 2007c) were not available in digital format. Only one small area along Sand Hollow Wash covered in the JE Fuller Hydrology & Geomorphology, Inc. (2007c) study lies within the St. George–Hurricane metropolitan area.

USING THIS MAP

The Flood-Hazard Map (plate 3) shows drainages covered by FIRMs, other flood-prone areas identified using geologic data, and erosion-hazard zones along the Virgin and Santa Clara Rivers and Fort Pearce Wash. The map provides a basis for requiring site-specific studies and identifies areas where FIRMs can be consulted to determine the availability of federally subsidized flood insurance. Site-specific studies can resolve uncertainties inherent in generalized hazard mapping and help ensure safety by identifying the need for flood-resistant design. However, because intense cloudburst storms may create a potential for flash floods and possible debris flows, and sheetfloods anywhere in the study area, even locations outside of identified flood-prone areas could be subject to periodic flooding. This map also shows where existing developments lie in flood-prone areas where flood-resistant-design measures should be considered. An evaluation of flood-mitigation measures already in place and their likely effectiveness is beyond the scope of this study.

Through the NFIP, FEMA makes federally subsidized flood insurance available to qualified individuals residing in participating communities. Many mortgage lenders require NFIP insurance before loaning money for home purchase or construction within a FIRM 100-year flood zone. Flood insurance rate maps are legal documents that govern the administration of the NFIP. Homeowners who suspect that they live within a FIRM 100-year flood zone, or individuals contemplating purchasing a home within a flood-prone area, should consult the corresponding FIRM directly and strongly consider purchasing NFIP insurance. Individuals who own their homes may elect to purchase NFIP insurance on a voluntary basis.

MAP LIMITATIONS

The Flood-Hazard Map (plate 1) is based on limited geological, geotechnical, and hydrological data; site-specific studies are required to produce more detailed flood-hazard information. The map also depends on the quality of those data, which varies throughout the study area. The mapped boundaries of the flood-hazard categories are approximate and subject to change with additional information. The flood hazard at any particular site may be different than shown because of geological and hydrological variations within a map unit, gradational and approximate map-unit boundaries, and the generalized map scale. Small, localized areas of higher or lower flood hazard may exist within any given hazard area, but their identification is precluded because of limitations of map scale. The map is not intended for use at scales other than the published scale, and is designed for use in general planning to indicate the need for site-specific studies.

HAZARD REDUCTION

Early recognition and avoidance of areas subject to flooding are the most effective means of flood-hazard reduction. However, avoidance may not always be a viable or cost-effective hazard-reduction option, especially for existing developments, and other techniques are available to reduce potential flood damage. These may include, but are not limited to, source-area stabilization, engineered protective structures, flood and debris-flow warning systems, and floodproofing. Some of these techniques can be expensive and their cost versus benefit ratio should be carefully evaluated. With regard to sheetflooding, a properly sized and integrated system of street and storm drains is usually adequate to mitigate this hazard. If hazard-reduction techniques are not implemented, risk may be accepted, but an informed decision is only possible if the flood potential and consequences are clearly understood and disclosed. If the risk is significant but acceptable, the individual houses may be insured, either through NFIP, if eligible, or by a private insurance provider so damaged items covered by insurance can be repaired if flood damage occurs.

Flooding studies are recommended in all hazard categories reported in table 1. The first consideration in stream-flow-flooding- and debris-flow-hazard reduction is proper identification of hazard areas through detailed mapping, and qualitative assessment of the hazard (Giraud, 2004, 2005). The stream-flow-flooding-hazard assessment should determine the active flooding area, the frequency of past events, and the potential inundation and flow depths. A debris-flow-hazard assessment should determine active depositional areas, the frequency and volume of past events, and sediment burial depths. The level of detail for a hazard assessment depends on several factors including the type, nature, and location of the proposed development; the geology and physical characteristics of the drainage basin, channel, and alluvial fan; the history of previous flooding and debris-flow events; the level of risk acceptable to property owners and land-use regulators; and proposed risk-reduction measures.

Where development is proposed in areas identified on the Flood-Hazard Map (plate 1) as having a potential flood hazard, a site-specific study should be performed early in the project design phase. A site-specific investigation can establish whether a flood and/or debris flow hazard is present at a site and provide appropriate design recommendations.

Role of Government in Flood Risk Reduction

To adequately reduce risks from flooding, including debris flows, engineered flood- and debris-retention basins or other significant and often costly flood-control structures may be required. Although some cities and counties attempt to address these issues in the subdivision approval process, problems arise because these structures: (1) benefit the community as well as individual subdividers, (2) typically are expensive, (3) require reliable maintenance and periodic sediment removal, (4) may divert flows and increase hazards in adjacent areas, and (5) must often be located in areas not owned or controlled by an individual subdivider (Giraud, 2004, 2005). Because of this, risk reduction from flooding and debris flows may be considered a government public works responsibility. This is particularly true in urban settings where hazard areas encompass more than one subdivision and include pre-existing development already permitted by a city or county.

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SECTION 5: LANDSLIDE HAZARD

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SECTION 5:
LANDSLIDE HAZARD

INTRODUCTION

Landslide is a general term that refers to the gradual to rapid movement of a mass of rocks, debris, or earth down a slope under the force of gravity (Bates and Jackson, 1987). The term covers a wide variety of mass-movement processes, and includes both deep-seated and shallow slope failures (Black and others, 1999). The moisture content of the affected materials when a slope fails may range from dry to saturated.

Landslides can be both damaging and deadly. The U.S. Geological Survey (USGS) (2005) estimates that in the United States, landslides on average cause $1–2 billion in damages and more than 25 deaths annually. Harty (1991) mapped nearly 10,000 landslides statewide in Utah, and Schuster (1996) reported that the multiple landslides that occurred in Utah in 1983–1984 as the result of a combination of heavy precipitation in the fall and rapid melting of a record snow pack in the spring were among the three most economically devastating slope-failure events in the United States in recent decades. The total estimated direct cost for the 1983-1984 Utah slope failures is more than $310 million (Anderson and others, 1984; B.N. Kaliser, personal communication, 1984, in Schuster, 1996). The Thistle landslide in Utah County in April 1983 is recognized, both in terms of direct and indirect costs, as the most expensive individual landslide in North American history (Schuster, 1996; USGS, 2006).

Rock and soil units susceptible to slope failure underlie parts of the St. George–Hurricane metropolitan area, and various types of landslides have disrupted transportation routes, houses and commercial sites (Christenson, 1986), and public utilities (figure 1) in the study area.

SOURCES OF DATA

Sources of data used to evaluate landslide hazards include (1) nine digital Utah Geological Survey (UGS) 1:24,000-scale (1 inch = 2000 feet) geologic quadrangle maps covering the study area (Harrisburg Junction [Biek, 2003a], Hurricane [Biek, 2003b], Pintura [Hurlow and Biek, 2003], Santa Clara [Willis and Higgins, 1996], St. George [Higgins and Willis, 1995], The Divide [Hayden, 2004], Washington [Willis and Higgins, 1995], Washington Dome [Hayden, 2005], and White Hills [Higgins, 1997]); (2) *Engineering Geology of the St. George Area, Washington County, Utah* (Christenson and Deen, 1983); (3) "Geologic Hazards of the St. George Area, Washington County, Utah" (Christenson, 1992); (4) *Landslide Map of Utah* (Harty, 1991); (5) "Landslide Distribution and Hazards in Southwestern Utah" (Harty, 1992); and (6) 275 geotechnical reports collected from municipalities in the study area and from the Utah Department of Transportation. The geotechnical data are unevenly distributed throughout the study area and generally are only available where development has already occurred. We compiled the test data in the geotechnical reports into a single comprehensive geotechnical database for this study. The database contains information from several hundred test pits and borings. Only a limited number of the geotechnical reports dealt directly with landslides; however, we used the test data to characterize the geotechnical properties of materials in which landslides have occurred in the basin.

Figure 1. *A historical slope failure in the Petrified Forest Member of the Chinle Formation and overlying unconsolidated deposits threatens nearby homes in the St. George–Hurricane metropolitan area.*

LANDSLIDE CAUSES

Three broad factors acting either individually or in combination contribute to all landslides (Varnes, 1978; Wieczorek, 1996). The three factors are: (1) increase in shear stress, (2) low material strength, and (3) reduction of shear strength. Common factors that increase shear stress include removing support from the toe of a slope, adding mass to the top of a slope, transitory stresses from earthquakes and explosions, and the long-term effects of tectonic uplift or tilting. Low strength rock or soil typically reflect the inherent characteristics of the material or are influenced by discontinuities (joints, faults, bedding planes, desiccation fissures). Factors that reduce shear strength include both physical and chemical weathering, and the addition of water to a slope, which increases pore-water pressures that reduce the effective intergranular pressure within the slope materials, and tend to lubricate existing slip surfaces.

Although one or a combination of the above causes may make a rock or soil mass susceptible to failure, a trigger is required for failure to occur (Varnes, 1978; Cruden and Varnes, 1996). A trigger is an external stimulus or event that initiates slope failure either by increasing stresses or reducing the strength of slope materials (Wieczorek, 1996). Common landslide triggers in Utah include a transient snowmelt-induced rise in ground-water levels to an instability threshold (Ashland, 2003); prolonged or extreme periods of above normal precipitation; lawn watering above unstable slopes; leakage from canals, pipes, and other water conveyance structures; earthquake shaking; and erosion.

LANDSLIDE TYPES AND PROCESSES

Varnes (1978) grouped all landslides into one of five types based on their mode of movement. The five types are: fall, topple, slide, spread, and flow (figure 2). The characteristics of the material that failed, the rate of failure, the state of activity, and the style of failure allow further subdivision and description of the various failure types. Cruden and Varnes (1996) provide a detailed description of Varnes' updated nomenclature system.

All five of Varnes' (1978) landslide types are not equally prevalent or even present in the St. George–Hurricane metropolitan area; consequently, we have simplified the classification of slope failures in the study area into three general categories that reflect both the principal types of failures present, and the techniques used to reduce the hazards presented by those failure types. The three categories are "Landslides," "Rock Falls," and "Debris Flows." Because of their close association in the study area with flash floods and their relatively infrequent occurrence, debris flows are discussed in the Flood Hazard section of this study. Rock falls are addressed separately in the Rock-Fall Hazard section, so only landslides are discussed further here.

LANDSLIDES

The Landslide Category as defined for this study consists almost exclusively of slides as described by Varnes (1978) and Cruden and Varnes (1996) (figure 2c). Due to the study area's arid climate, spreads and slow- moving flows (figure 2d and 2e), which typically depend on a high water content to mobilize, are comparatively rare, and therefore are not considered further here.

A slide is the downslope movement of a soil or rock mass occurring dominantly on surfaces of rupture or on relatively thin zones of intense shear strain (Cruden and Varnes, 1996). Slides may be either rotational or translational (figure 3). Rotational slides have curved, concave rupture surfaces, which may be either shallow or deep seated, along which the slide mass

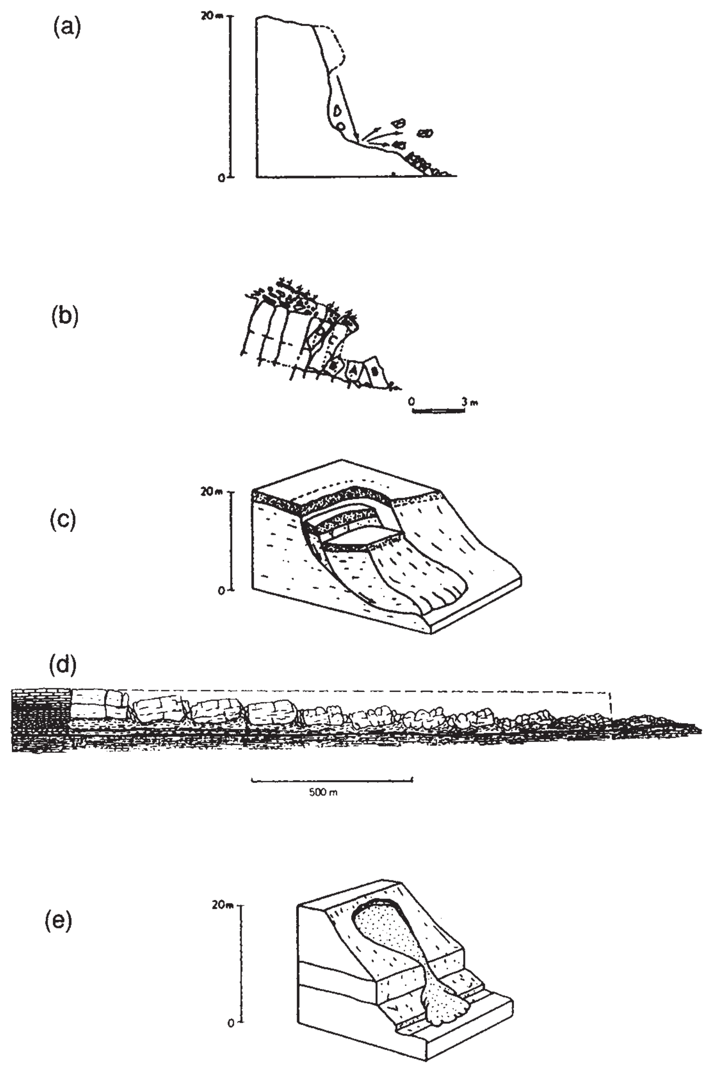

Figure 2. Types of landslides: (a) fall, (b) topple, (c) slide, (d) spread, (e) flow. Broken lines indicate original ground surfaces; arrows show portions of trajectories of individual particles of displaced mass (from Cruden and Varnes [1996]; reprinted with permission of the Transportation Research Council).

may move, sometimes with little internal disruption. Because of the curved rupture surface (figure 4), the head of a rotational slide commonly tilts backward toward the slide's main scarp. Rotational slides may be very slow to rapid and dry to wet, although most occur in the presence of at least some ground water. Translational slides move along planar or gently undulating shear surfaces and typically slide out over the original ground surface (figure 3; Cruden and Varnes, 1996). Translational slides commonly utilize discontinuities such as bedding planes, joints, or faults as a surface of rupture, and if the slide plane is long enough and particularly in the presence of water, may transition into a flow. Translational slides range from very slow to rapid.

Triggering mechanisms for slides are varied and in some cases may not be readily discernable (Giraud, 2002); however, periods of above average precipitation are particularly effective in triggering slope failures in Utah (Fleming and Schuster, 1985; Godfrey, 1985; Hylland and Lowe, 1997; Ashland, 2003). Although plentiful under static (non-earthquake) conditions, both rotational and translational slides may accompany earthquakes with Richter magnitudes greater than 4.5 (Keefer, 1984). For example, the September 2, 1992, M_L 5.8 St. George earthquake, which is thought to have occurred on the Hurricane fault (Pechmann and others, 1995), caused a large, destructive translational landslide near Springdale, Utah, 27 miles from the earthquake epicenter that destroyed three houses and a water tank, threatened several other structures, and closed State Route 9 (Jibson and Harp, 1996).

Landslide Descriptions

The nine UGS 1:24,000-scale geologic quadrangle maps that provide the basic geologic information for this study include 108 landslides. The resulting average landslide density is approximately one slope failure per 5 square miles, low when compared to many other areas of the state (Harty, 1991; Hylland and Lowe,

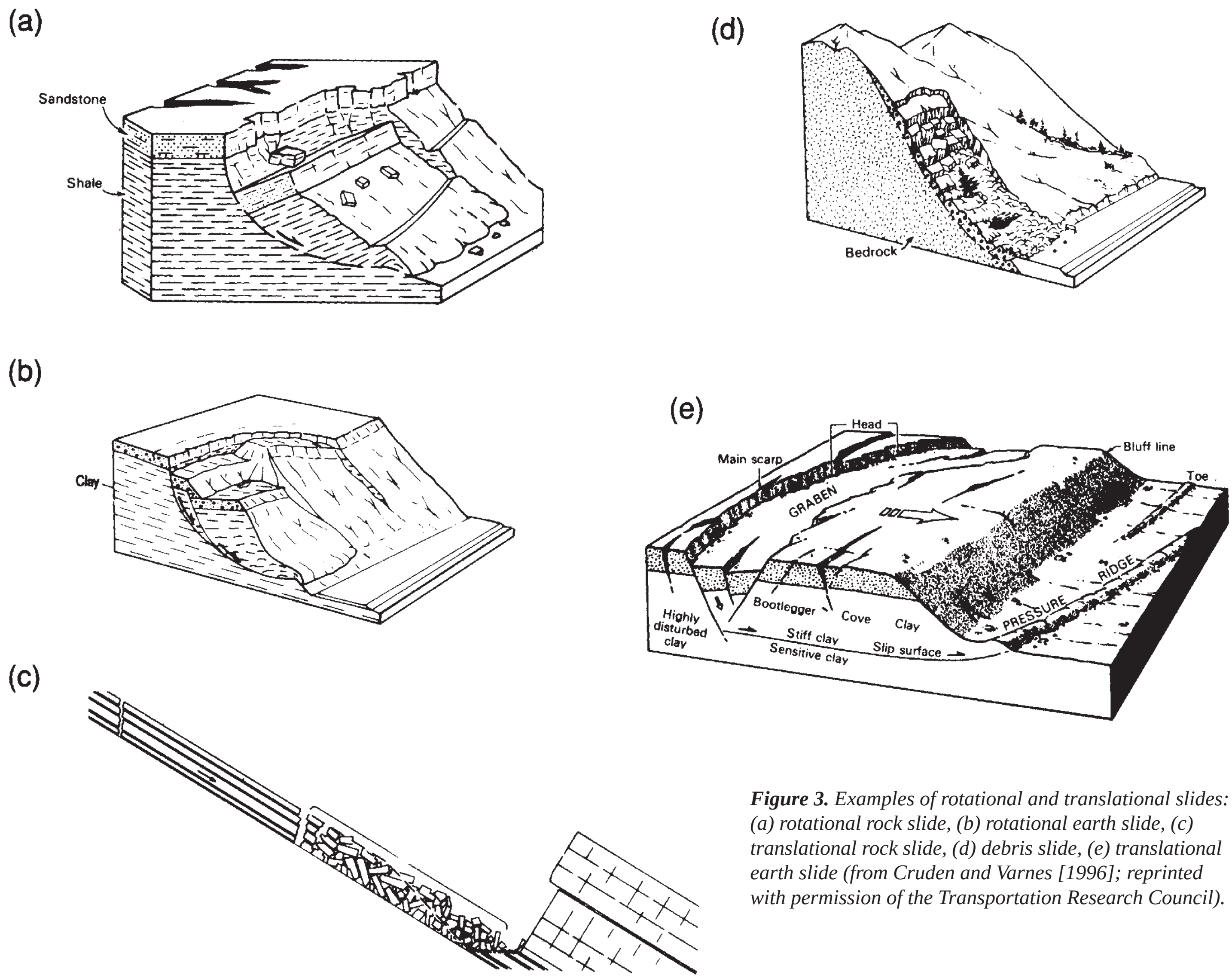

Figure 3. *Examples of rotational and translational slides: (a) rotational rock slide, (b) rotational earth slide, (c) translational rock slide, (d) debris slide, (e) translational earth slide (from Cruden and Varnes [1996]; reprinted with permission of the Transportation Research Council).*

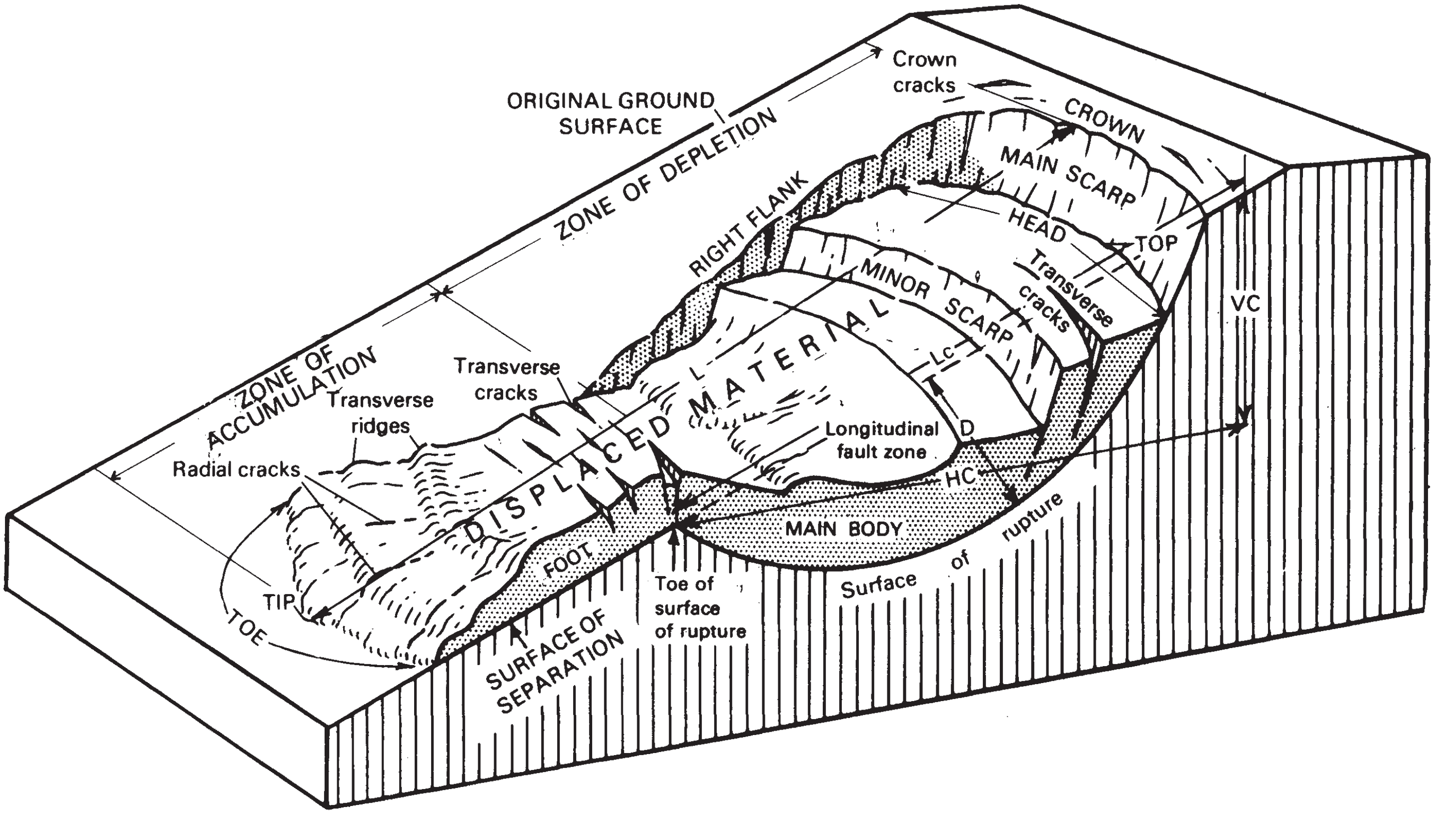

Figure 4. Block diagram of an idealized complex earth slide (from Cruden and Varnes [1996]; reprinted with permission of the Transportation Research Council).

1997). Of the 108 landslides, the majority are rotational failures (Grant Willis, UGS Mapping Program, verbal communication, 2002). Two of the mapped landslides are historical, and both of those are rotational failures. The UGS maps also include a cluster of 15 very old landslides of Quaternary-Tertiary age in the southwestern part of the study area (Willis and Higgins, 1996; Higgins, 1997). According to Higgins (1997), the cluster represents erosional remnants of a single large landslide that originated from the west. The remnants now cap ridge crests and mesa tops more than 400 feet above the nearest stream. We did not include these very old, isolated landslide remnants in our landslide inventory.

The maps used to identify landslides in the study area are all 1:24,000-scale, general-purpose geologic maps prepared by the UGS. A study by Willis and McCrink (2002) compared five maps covering all or part of a single 7.5-minute (1:24,000 scale) quadrangle in the Santa Cruz Mountains, California, to determine which types of maps and mapping methods did the best job of identifying landslides. Four of the maps showed landslides identified using a variety of reconnaissance and detailed mapping techniques. The fifth map was a 1:24,000-scale, general-purpose, geologic map showing both bedrock and unconsolidated deposits, similar to the UGS geologic maps used in this study. Results of the comparison showed that the general-purpose geologic map identified the fewest number of landslides, and not surprisingly, that the larger the map scale and the more detailed the mapping techniques, the greater the number of landslides that were identified. However, the quadrangle studied by Willis and McCrink (2002) is one of steep slopes and dense vegetative cover, factors that make landslide recognition difficult. The lack of dense vegetative cover over most of the St. George–Hurricane metropolitan area makes landslide recognition easier, and the area's arid climate results in fewer landslides overall. The results of our aerial photograph analysis and field checking revealed no significant landslides not previously identified by UGS mappers, so we believe that the landslide inventory provided by the UGS geologic maps, while likely not complete, is nearly so except for landslides too small to be represented at 1:24,000-scale.

Landslide Hazard Classification

The landslides shown on the UGS geologic maps are present in 23 different geologic units, the majority of which (21) are bedrock formations. The preponderance of landslides in bedrock is not unexpected considering that: (1) bedrock crops out at or near the surface over large areas of the study area, (2) many bedrock units stand at steep natural slopes, (3) a few bedrock units consist of weak, failure-prone material (figure 1), and (4) comparatively few unconsolidated geologic units crop out on slopes steep enough to induce landslides large enough to be mapped at 1:24,000-scale.

We classified landslide hazards using the following three-step procedure.

(1) Geologic units on the UGS geologic maps were grouped into four relative susceptibility categories based on their lithologic characteristics as they relate to material strength and stability, and on the number of landslides mapped in each unit.

(2) Post-failure landslide slope inclinations (% slope) of representative landslides in the basin were measured to identify the critical slope inclination above which slope failures may initiate in the various susceptibility categories.

(3) The results of steps (1) and (2) were integrated to create four Landslide Susceptibility Categories.

Landslide Susceptibility Categories

We consider bedrock units consisting chiefly of weak rock types (gypsum, shale, claystone, mudstone, siltstone) to have greater susceptibility to failure than rock units comprised of stronger rock types (sandstone, conglomerate, limestone, monzonite, basalt). We considered the number of landslides mapped in each geologic unit to be an important, but secondary, indicator of overall landslide susceptibility. While the presence of landslides clearly indicates susceptibility to slope failure, the number of landslides in a geologic unit may, at least in part, be a function of the unit's total outcrop area. A geologic unit that contains mostly weak rock types but crops out over a small area may exhibit fewer total landslides than a stronger unit that crops out over a much larger area. Additionally, a number of landslides in the study area mapped in relatively strong geologic units are likely the result of failure in an underlying weaker unit that undermined the more competent overlying rocks.

Utah Geological Survey geologic maps show only two landslides in unconsolidated geologic units in the study area. We believe the lack of landslides in unconsolidated deposits is a function of both map scale and the material characteristics of the units. Landslides in unconsolidated units tend to be small and therefore most cannot be shown on the 1:24,000-scale maps which form the basis for this study. Additionally, most unconsolidated deposits in the study area are thin, non-cohesive, and are rarely present on slopes steep enough to generate landslides.

We ranked geologic units in the study area into four broad susceptibility categories ranging from most susceptible (Very High) to least susceptible (Low), based chiefly on the perceived strength characteristics and relative percentage of strong versus weak lithologies in each unit, and secondarily on the number of landslides present in each unit. Table 1 shows the results of the ranking.

Table 1. *Landslide susceptibility of geologic units.*

Susceptibility Category	Geologic Unit	Comments
A	Existing landslides	Existing slope failures are considered the most likely units in which landsliding may initiate (Ashland, 2003).
B	Petrified Forest Mbr., Chinle Fm.	This rock unit consists chiefly of bentonitic clay, which is highly expansive and has low shear strength especially when wet. This unit includes the greatest number of landslides mapped in the study area.
C	Woods Ranch Mbr., Toroweap Fm.; Harrisburg Mbr., Kaibab Fm.; Shnabkaib Mbr. and red members, Moenkopi Fm.; Whitmore Point Mbr., Moenave Fm.; Temple Cap Fm.; Carmel Fm.; Cretaceous bentonitic beds; Iron Springs Fm.	These bedrock units contain varying amounts of gypsum, shale, claystone, mudstone, siltstone, or a combination of the above that imparts weak shear strength characteristics to the units, at least locally, and makes them susceptible to slope failure. These units contain the second greatest number of landslides in the study area.
D	Remaining bedrock and unconsolidated geologic units in the study area.	These geologic units either contain a higher percentage of stronger rock types, crop out on slopes too low to generate slope failures, or generate failures that are too small to map at 1:24,000-scale. As a result, they exhibit few or no mapped landslides. Some landslides identified within these units are likely the result of failures in underlying, weaker geologic units.

Post-Failure Landslide Slope Inclinations

We measured post-failure slope inclinations for representative landslides in each of the susceptibility categories in table 1. Post-failure slope inclination is the overall slope of the displaced landslide mass, and is calculated by dividing the difference between the landslide head and toe elevations by the horizontal distance from the head to toe (Hylland and Lowe, 1997), which gives the tangent of the overall slope angle. Multiplying that value by 100 gives percent slope. We measured both slope lengths and elevation differences from 1:24,000-scale geologic maps. Hylland and Lowe (1997) consider post- failure slope inclinations (percent slope) to represent the approximate maximum quasi-stable slope for a geologic unit under conditions of material strength, nature and origin of discontinuities, and ground-water conditions at a given site. Table 2 shows representative post-failure slope inclinations measured for geologic units comprising the different susceptibility categories in the study area.

Considering the regional scale of this study and the intended use of the maps as land-use planning tools to indicate where site-specific studies are needed, we selected the lowest post-failure slope inclination measured for each susceptibility category as the critical slope inclination for that category (table 2).
The critical slope inclination is the minimum slope above which landslides typically begin to initiate in a particular susceptibility category, and serves as a trigger value for initiating site-specific, slope-stability evaluations for that susceptibility category.

Landslide-Hazard Categories

We combined the four landslide-susceptibility categories (table 1) with the critical slope inclinations determined for each of those categories (table 2) to determine landslide-hazard in the study area. The four levels of landslide hazard for the St. George–Hurricane metropolitan area are described below. Due to the highly landslide-prone nature of the clay-rich Petrified Forest Member of the Chinle Formation (landslide-susceptibility category B, table 1), we included areas where the Petrified Forest Member crops out on slopes less than 15 percent in the Moderate Hazard category (see hazard category MB below).

Table 2. Representative post-failure and critical slope inclinations for landslide susceptible geologic units.

Susceptibility Category[1]	Representative Post-Failure Slope Inclinations	Critical Slope Inclination
A[1]	Not applicable	Not applicable
B	15-59% (8.5°-30.5°)	15% (8.5°)
C	20-80% (11.3°-38.7°)	20 % (11.3°)
D	30-80% (16.7°-38.7°)	30 % (16.7°)
[1]Category A unit classification (existing landslides) is not slope dependent.		

VH Very High: Existing landslides (Category A).

H High: Areas where Category B geologic units crop out on slopes greater than 15 percent (8.5°).

M_C Moderate C: Areas where Category C geologic units crop out on slopes greater than 20 percent (11.3°).

M_B Moderate B: Areas where Category B geologic units crop out on slopes less than 15 percent (8.5°).

L Low: Areas where Category D geologic units crop out on slopes greater than 30 percent (16.7°).

While it is possible to classify relative landslide hazard in a general way on the basis of material characteristics and critical slope inclinations, landslides ultimately result from the effects of site-specific conditions acting together to drive the slope toward failure. For that reason, all development in areas of sloping terrain where modifications to natural slopes will be extensive or where landscape irrigation or onsite wastewater disposal systems may cause ground-water levels to rise (Ashland, 2003; Ashland and others, 2005, 2006), require a site-specific investigation to evaluate the effect of development on slope stability.

USING THIS MAP

The Landslide-Hazard Map (plate 4) shows areas of relative landslide hazard, and provides a basis for requiring site-specific hazard studies. Site-specific studies can resolve uncertainties inherent in generalized geologic-hazard mapping and help ensure safety by identifying the need for hazard mitigation.

The Landslide-Hazard Map (plate 4) identifies areas based on previous landslide history, material characteristics, and slope where site-specific, slope-stability conditions (material strength, orientation of bedding or fractures, ground-water conditions, erosion or undercutting) should be evaluated prior to development. The level of investigation needed at a given site depends on the relative hazard and the nature of the proposed development (structure size and placement, required cutting and filling, and changes in ground-water conditions). A valid landslide-hazard evaluation must address all pertinent conditions that could affect, or be affected by, the proposed development, including earthquake ground shaking. This can only be accomplished through the proper identification and interpretation of site-specific geologic conditions and processes (Hylland, 1996). Such conditions in areas near to the site that may affect the site must also be considered.

The analysis of natural and modified slopes for static and/or seismic stability is a challenging geotechnical problem. Blake and others (2002) consider the following steps as required for a proper static slope stability analysis.

"Accurate characterization of:

1. Surface topography,
2. Subsurface stratigraphy,
3. Subsurface water levels and possible subsurface flow patterns,
4. Shear strength of materials through which the failure surface may pass,
5. Unit weight of the materials overlying potential failure planes.

The stability calculations are then carried out using an appropriate analysis method for the potential failure surface being analyzed. A seismic slope-stability analysis requires consideration of each of the above factors for static stability, as well as characterization of:

1. Design-basis earthquake ground motions at the site, and
2. Earthquake shaking effects on the strength and stress-deformation behavior of the soil, including pore pressure generation and rate effects."

Blake and others (2002) consider all of the above factors vital for a proper slope stability analysis, but note that some factors are more easily characterized than others. They identify two factors, subsurface stratigraphy/geologic structure and soil shear strength, as particularly challenging to accurately characterize.

Accordingly, landslide-hazard studies must be interdisciplinary in nature and performed by qualified, experienced geotechnical engineers and engineering geologists working as a team. Utah Geological Survey Circular 92 *Guidelines for Evaluating Landslide Hazards in Utah* (Hylland, 1996) presents minimum standards for performing landslide-hazard evaluations in Utah. Circular 92 outlines a phased approach to slope-stability studies beginning with a geologic evaluation and progressing through reconnaissance and detailed geotechnical-engineering evaluations as necessary based on the results of the previous phase. Blake and others (2002) and Black and others (1999) provide additional guidance for evaluating landslide hazards. Local jurisdictions may adopt more stringent requirements for slope-stability evaluations, as they deem necessary, to meet local needs and conditions. For example, the City of St. George requires studies on all slopes greater than 15 percent that lie within designated Hillside Development Overlay Zones, and that requirement takes precedence over the recommendations in this report. The UGS recommends that the following site-specific investigations be conducted for each of the landslide-hazard categories (table 3).

Table 3. *Recommendations for landslide-hazard studies.*

Map Unit	Landslide-Hazard Category	Recommended Site-Specific Study
VH	Very High	Detailed engineering geologic and geotechnical-engineering evaluation necessary. Predevelopment stabilization recommended for historical and geologically young (late Pleistocene) landslides.
H	High	Detailed engineering geologic and geotechnical-engineering evaluation necessary.
M	Moderate	Geologic evaluation and reconnaissance geotechnical-engineering evaluation necessary; detailed engineering geologic and geotechnical-engineering evaluation may be necessary.
L	Low	Geologic evaluation and reconnaissance geotechnical-engineering evaluation necessary, detailed geotechnical-engineering evaluation generally not necessary.

MAP LIMITATIONS

The Landslide-Hazard Map (plate 4) is based on limited geological, geotechnical, and hydrological data; site-specific studies are required to produce more detailed geotechnical information. The map also depends on the quality of those data, which varies throughout the study area. The mapped boundaries of the landslide-hazard categories are approximate and subject to change with additional information. The landslide hazard at any particular site may be different than shown because of geological variations within a map unit, gradational and approximate map-unit boundaries, and the generalized map scale. Small, localized areas of higher or lower landslide hazard may exist within any given map area, but their identification is precluded because of limitations of map scale. This map is not intended for use at scales other than the published scale, and is designed for use in general planning to indicate the need for site-specific studies.

HAZARD REDUCTION

As with most geologic hazards, early recognition and avoidance is the most effective way to mitigate landslide hazards. However, avoidance may not always be a viable or cost-effective hazard-reduction option, especially for existing developments, and other engineering techniques are available to reduce potential landslide hazards. Techniques for mitigating landslide hazard include care in site grading, with proper compaction of fills and engineering of cut-and-fill slopes; paying careful attention to site drainage and dewatering of shallow or perched ground water where landslides may be a hazard; constructing retaining structures at the toe of slopes; and mechanical stabilization using tieback or other means that penetrate the landslide mass, pinning it to underlying stable material. Other techniques used to reduce landslide hazards include bridging, weighting, or buttressing slopes with compacted earth fills and installation of landslide warning systems (Keller and Blodgett, 2006). However, some geologic units, for example the Petrified Forest Member of the Chinle Formation, may be too weak to buttress, and may continue to move upslope of the buttress (Francis Ashland, UGS Geologic Hazards Program, written communication, 2007)

Where development is proposed in areas identified on the Landslide-Hazard Map as having a potential for slope failure, a phased site-specific study should be performed early in the project design phase. A site-specific investigation can establish whether the necessary conditions for failure are present at a site. If the conditions for slope failure do exist, the consultant should provide appropriate design recommendations.

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SECTION 6:
ROCK-FALL HAZARD

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SECTION 6: ROCK-FALL HAZARD

INTRODUCTION

Rock fall is a natural mass-wasting process that involves the dislodging and downslope movement of individual rocks and small rock masses (Varnes, 1978; Cruden and Varnes, 1996). Rock falls pose a hazard because a rolling boulder can cause significant damage to property, roadways, and vehicles and thus pose a serious safety threat (Keller and Blodgett, 2006). Rock-fall hazards are found where a source of rock exists above slopes steep enough to allow rapid downslope movement of dislodged rocks by falling, rolling, and bouncing. The large-scale, less common phenomenon involving failure and subsequent disintegration of large rock masses (generally exceeding 100,000 cubic yards), known as rock avalanches (Wieczorek and others, 1998), is not included in this rock-fall hazard evaluation.

Rock-fall hazard is based on a number of factors including geology, topography, and climate. Rock-fall sources include bedrock outcrops or boulders on steep mountainsides or near the edges of escarpments such as cliffs, bluffs, and terraces. Talus cones and scree-covered slopes are indicators of a high rock-fall hazard, but other less obvious areas may also be vulnerable. Rock falls are initiated by freeze/thaw action, rainfall, weathering and erosion of the rock and/or surrounding material, and root growth. Rock fall is also the most common type of slope failure caused by earthquakes. Keefer (1984) indicates that earthquakes as small as magnitude 4.0 can trigger rock falls. All nine historic Utah earthquakes of magnitude 5 or greater have caused rock falls. Additionally, slope modification such as cuts for roads and building pads or clearing of slope vegetation for development can increase or create a local rock-fall hazard. However, in many cases a specific triggering event is not apparent. Although not well documented, rock falls in Utah appear to occur more frequently during spring and summer months. This is likely due to spring snowmelt, summer cloudburst storms, and/or large daily temperature variations (Case, 2000).

Notable recent Utah rock falls include many triggered by the September 1992 M_L 5.8 earthquake near St. George; a January 1995 event in Big Cottonwood Canyon near Salt Lake City in which a boulder crushed a car causing a fatality (Hylland, 1996); a house severely damaged by a rock fall in October 2001 in the town of Rockville in Washington County (figure 1; Lund, 2002); a guest house destroyed by a rock fall in Provo in April, 2005 (Giraud, 2005); and a rock fall in Parowan Canyon in Iron County, that damaged an above-ground electrical generating plant penstock in June 2005 (figure 2; Lund, 2005).

***Figure 1**. Home damaged by a rock fall in Rockville, Utah, October 2001.*

***Figure 2.** Parowan City electrical generating plant penstock damaged by a rock-fall boulder, June 2005.*

SOURCES OF DATA

Sources of data used to evaluate rock-fall hazards include: (1) nine digital Utah Geological Survey (UGS) 1:24,000-scale (1 inch = 2000 feet) geologic quadrangle maps covering the study area (Harrisburg Junction [Biek, 2003a], Hurricane [Biek, 2003b], Pintura [Hurlow and Biek, 2003], Santa Clara [Willis and Higgins, 1996], St. George [Higgins and Willis, 1995], The Divide [Hayden, 2004], Washington [Willis and Higgins, 1995], Washington Dome [Hayden, 2005], and White Hills [Higgins, 1997]) (2) *Engineering Geology of the St. George Area, Washington County, Utah* (Christenson and Deen, 1983); (3) "Geologic Hazards of the St. George Area, Washington County, Utah" (Christenson, 1992); (4) *Landslide Map of Utah* (Harty, 1991); (5) "Landslide Distribution and Hazards in Southwestern Utah" (Harty, 1992); and (6) 275 geotechnical reports collected from municipalities in the study area and from the Utah Department of Transportation. The geotechnical data are unevenly distributed throughout the study area and generally are only available where development has already occurred. We compiled the test data in the geotechnical reports into a single comprehensive geotechnical database for this study; however, only a limited number of the geotechnical reports dealt directly with rock falls.

ROCK FALL DESCRIPTION

Rock fall is the most common slope-failure type in the study area. The combination of steep slopes capped by well-jointed, resistant bedrock formations such as the Shinarump Member of the Chinle Formation and numerous Quaternary basalt flows, provide ample opportunity to generate rock falls (figure 3). The nine UGS geologic maps that cover the study area include numerous areas mapped as talus. Talus deposits consist of very poorly sorted, angular, cobble- to boulder-size clasts chiefly deposited by rock fall at the base of steep slopes. Additionally, widespread areas mapped as colluvium, which consist chiefly of poorly to moderately sorted clay- to boulder-size sediment deposited by slopewash and soil creep, may include local talus deposits. The widespread distribution of talus in the study area, and the direct relation of talus deposits to the rock-fall process attest to the extent of the rock-fall hazard in the St. George–Hurricane metropolitan area.

Figure 3. *Slope typical of many in the study area that are capped by a resistant bedrock unit and littered with rock-fall boulders. Note heavy equipment grading site for new home construction.*

ROCK- FALL HAZARD CLASSIFICATION

The Rock-Fall Hazard Map (plate 5) shows areas susceptible to rock fall. The map contains three relative hazard categories: High, Moderate, and Low. Elsewhere, rock-fall hazard is absent or, if present, is too localized to show on 1-24,000-scale maps. Each of the three hazard categories consists of three components: (1) a rock source, in general defined by bedrock geologic units that exhibit relatively consistent patterns of rock-fall susceptibility throughout the study area, (2) an acceleration zone, where rock-fall debris detached from the source gain momentum as they travel downslope—this zone often includes a talus slope, which becomes less apparent with decreasing relative hazard and is typically absent where the hazard is low, and finally (3) a runout zone (rock-fall shadow zone), which includes gentler slopes where boulders have rolled or bounced beyond the base of the acceleration zone (figure 4). The boundary of the rock-fall shadow zone is established using a shadow angle (Evans and Hungr, 1993; Wieczorek and others, 1998), which is the angle formed by a horizontal line and a line extending from the base of the rock source and the outer limit of the runout zone (figure 4). Shadow angles vary based on rock type, boulder shape, slope steepness, slope composition, and rock source height. Our field investigation showed that a shadow angle of 22° is generally applicable in the study area, and defines a runout zone sufficiently wide to include the limits of rock-fall

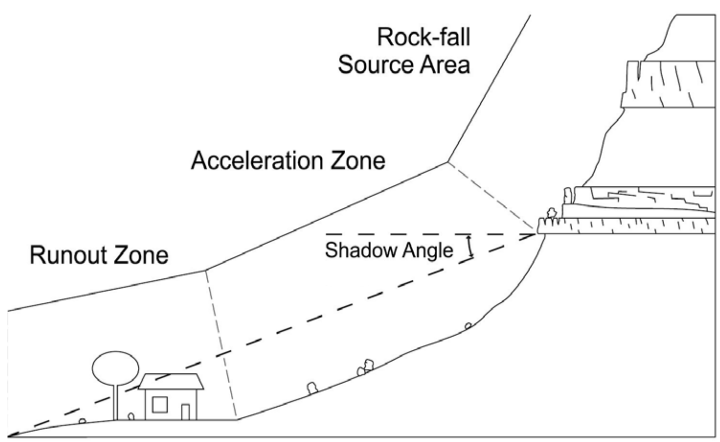

Figure 4. *Components of a characteristic rock-fall path profile.*

debris observed in the study area. The 22° shadow angle was further validated using the Colorado Rock-Fall Simulation Program (CRSP) (Jones and others, 2000).

We define the three rock-fall-hazard categories in the St. George–Hurricane metropolitan area as follows:

H High rock-fall-hazard areas include steep slopes below resistant cliff-forming units where the acceleration and runout zones are littered with abundant rock-fall boulders greater than 1.5 feet in diameter. Such large boulders can do significant damage to property and threaten lives. Rock units in high rock-fall-hazard areas chiefly include the Shinarump Member of the Chinle Formation, upper Kayenta Formation, Springdale Sandstone Member of the Kayenta Formation, Navajo Sandstone, Virgin Limestone Member of the Moenkopi Formation, Kaibab Formation, Toroweap Formation, and Tertiary–Quaternary basalt flows. Where jointed or fractured, outcrops of these rock units can produce large, angular boulders.

M Moderate rock-fall-hazard areas are present where slopes provide sufficient relief to create an acceleration zone, but where only sparse rock-fall debris is present on slopes or in the runout zone at the base of the slope. Typically rock units in moderate-hazard areas crop out in the slope instead of forming a capping unit, or where a capping unit is present, the resulting rock-fall debris is typically less then 1.5 feet in diameter. Rock units in moderate rock-fall-hazard areas include the Kayenta Formation, Moenave Formation, and portions of the Kaibab Formation and Navajo Sandstone.

L Low rock-fall-hazard areas are present where fine-grained, comparatively soft rock units such as mudstone and shale crop out on steep slopes, or where rock units typical of moderate- or high-hazard categories crop out in areas of low to moderate relief. Low rock-fall hazard areas typically contain sparse rock sources of limited extent. Low rock-fall hazard is most common adjacent to low relief outcrops of Navajo Sandstone and basalt.

Rock-fall hazard is considered negligible in the remainder of the study area not included in one of the above hazard categories.

USING THIS MAP

The Rock-Fall-Hazard Map (plate 5) shows areas of relative rock-fall hazard in the St. George–Hurricane metropolitan area where site-specific hazard studies are recommended prior to construction (table 1). These studies can resolve uncertainties inherent in generalized hazard mapping and help ensure safety by identifying the need for rock-fall-resistant design or mitigation. For most areas, site-specific assessment may only require a field geologic evaluation to determine if a rock-fall source is present. However, if a source is identified, additional work to adequately assess the hazard is needed. Rock-fall sources should be evaluated for the following parameters: rock type, joints, fractures, bedding planes, and potential clast size. Slopes below rock sources should be evaluated for slope angle, aspect, substrate, surface roughness, vegetation, and distribution,

Table 1. *Recommended requirements for site-specific investigations related to rock-fall hazards to protect life and safety.*

Hazard Potential	Classification of Buildings and Other Structures for Importance Factors[1]				
	I	II		III	IV
	Buildings and Other Structures That Represent a Low Hazard to Human Life in the Event of Failure	One- and Two-Family Dwellings and Townhouses	All Other Buildings and Structures Except Those Listed in Groups II, III, and IV	Buildings and Other Structures That Represent a Substantial Hazard to Human Life in the Event of Failure	Buildings and Other Structures Designated as Essential Facilities
High, Moderate	No[2]	Yes	Yes	Yes	Yes
Low	No[2]	Yes	Yes	Yes	Yes
None	No	No	No	No	No

[1]Occupancy category from the International Code Council (2006).
[2] Property damage possible, but little threat to life safety.

size range, amount of embedding, and weathering of rock-fall boulders. In addition, evaluation of the runout zone below a source can be estimated using a simple 2-dimensional model such as CRSP. This map does not consider rock-fall hazards caused by cuts, fills, or other alterations to the natural terrain.

MAP LIMITATIONS

The Rock-Fall-Hazard Map (plate 5) is based on limited geologic and geotechnical data; site-specific studies are required to produce more detailed geotechnical information. The map also depends on the quality of those data, which varies throughout the study area. The mapped boundaries between rock-fall-hazard categories are approximate and subject to change with additional information. The rock-fall hazard at any particular site may be different than shown because of geological variations within a map unit, gradational and approximate map-unit boundaries, and the regional map scale. Small, localized areas of higher or lower rock-fall hazard may exist within any given map area, but their identification is precluded because of limitations of map scale. This map is not intended for use at scales larger than the published scale, and is designed for use in general planning to indicate the need for site-specific studies.

HAZARD REDUCTION

Early recognition and avoiding areas subject to rock fall is the most effective means of reducing rock-fall hazards. However, avoidance may not always be a viable or cost-effective hazard-reduction option, especially for existing developments, and other techniques are available to reduce potential rock-fall damage. These may include but are not limited to rock stabilization, engineered structures, or modification of at-risk structures or facilities. Rock-stabilization methods are physical means of reducing the hazard at its source using drilled bolts, steel mesh, or grout on susceptible outcrops. Engineered catchment or deflection structures such as berms or benches can be placed below source areas, or at-risk structures themselves could be designed to stop, deflect, retard, or retain falling rocks.

The UGS recommends retaining a geotechnical firm familiar with rock-fall hazards early in the project design phase to conduct a site-specific investigation of the proposed site. If a rock-fall hazard is present, the geotechnical consultant should provide design or site preparation recommendations as necessary to reduce the hazard. In areas where a site-specific evaluation indicates that rock falls are possible, but the rock-fall hazard is low, disclosure of the hazard to landowners and residents may be an acceptable alternative to avoidance or costly hazard-reduction efforts. Disclosure ensures that buyers are informed of the hazard and are willing to accept the associated risks.

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SECTION 7:
PROBLEM SOIL AND ROCK

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SECTION 7: PROBLEM SOIL AND ROCK

INTRODUCTION

Soil and rock with characteristics that make them susceptible to volumetric change, collapse, subsidence, or other engineering-geologic problems are classified as problem soil and rock (Mulvey, 1992). Geologic parent material, climate, and depositional processes largely determine the type and extent of problem soil and rock. Geologic materials and conditions in the St. George–Hurricane metropolitan area are highly variable; as a result, various categories of problem soil and rock exist both locally and over broad areas of the study area. Problem soil and rock can be costly factors in construction and land development if they are not recognized and taken into consideration in the planning process (Shelton and Prouty, 1979). However, problem soil and rock rarely if ever cause rapid catastrophic property damage or present a threat to life safety; therefore, for purposes of this study, problem soil and rock are considered adverse construction conditions and not geologic hazards. This study addresses eight principal types of problem soil and rock: (1) expansive soil and rock, (2) collapsible (hydrocompactible) soil, (3) gypsiferous soil and rock, (4) breccia pipes and paleokarst, (5) shallow bedrock, (6) caliche, (7) wind-blown sand, and (8) soils susceptible to piping and erosion.

The definitions of soil and rock used in this report generally conform to those in general use by engineers and engineering geologists (Sowers and Sowers, 1970; U. S. Bureau of Reclamation, 1974, no date). For this study we define soil as any generally nonindurated accumulation of solid particles produced by the physical and/or chemical disintegration of bedrock with gases or liquids between the particles and which may or may not contain organic matter. Rock is defined as lithified or indurated crystalline or noncrystalline materials in which primary features of the rock mass, such as bedding, joints, or crystalline structure are still recognizable. By this definition, rock weathered in place, even though it can be excavated without blasting or ripping, would still be considered rock and not a residual soil if primary features of the rock unit are still recognizable and can influence the engineering properties of the material.

SOURCES OF DATA

Sources of data used to evaluate problem soil and rock include: (1) 275 geotechnical reports on file with municipalities in the study area and from the Utah Department of Transportation (UDOT), (2) Natural Resources Conservation Service (NRCS) (formerly the U.S. Soil Conservation Service) *Soil Survey of Washington County Area, Utah* (Mortensen and others, 1977), (3) nine digital Utah Geological Survey (UGS) 1:24,000-scale (1 inch = 2000 feet) geologic quadrangle maps covering the study area (Harrisburg Junction [Biek, 2003a], Hurricane [Biek, 2003b], Pintura [Hurlow and Biek, 2003], Santa Clara [Willis and Higgins, 1996], St. George [Higgins and Willis, 1995], The Divide [Hayden, 2004], Washington [Willis and Higgins, 1995], Washington Dome [Hayden, 2005], and White Hills [Higgins, 1997]), (4) Utah Geological and Mineral Survey Special Studies 58, *Engineering Geology of the St. George Area, Washington County, Utah* (Christenson and Deen, 1983), and (5) "Geologic Hazards of the St. George Area, Washington County, Utah" (Christenson, 1992). Geotechnical data are unevenly distributed throughout the study area and typically are available only where development has already occurred. We compiled the data in the 275 consultant's and UDOT geotechnical reports into a single comprehensive geotechnical database for this study. The database contains information from more than 5000 test pits and exploration borings. Where possible, we used these data to characterize geologic and soils units to estimate their geotechnical properties in parts of the study area with similar geology but lacking geotechnical information.

EXPANSIVE SOIL AND ROCK

Expansive soil and rock increase in volume as they get wet, and shrink as they dry out. Expansive soil and rock contain a significant percentage of clay minerals that can absorb water directly into their crystal structure when wetted. Some sodium-montmorillonite clay can swell as much as 2000 percent upon wetting (Costa and Baker, 1981). The resulting expansion forces can be greater than 20,000 pounds per square foot (Shelton and

Prouty, 1979), and can easily exceed the loads imposed by small structures, resulting in cracked foundations and other structural damage (figure 1).

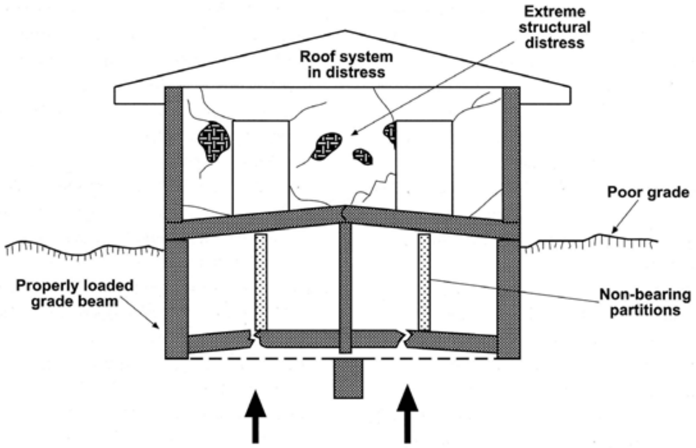

Figure 1. *Typical structural damage to a building from expansive soil (after Black and others, 1999).*

Description

Many bedrock formations in the St. George–Hurricane metropolitan area consist in whole or part of shale, claystone, or mudstone strata, which contain expansive clay minerals. These rock units and the expansive soils derived from them are capable of significant expansion and contraction (shrink/swell) when wetted and dried, causing structural damage to buildings (figure 2); cracked driveways; damage to curbs, gutters, and sidewalks; and heaving of roads and canals. Expansive soils are chiefly derived from weathering of clay-bearing rock formations (figure 3) and may be residual (formed in place) or

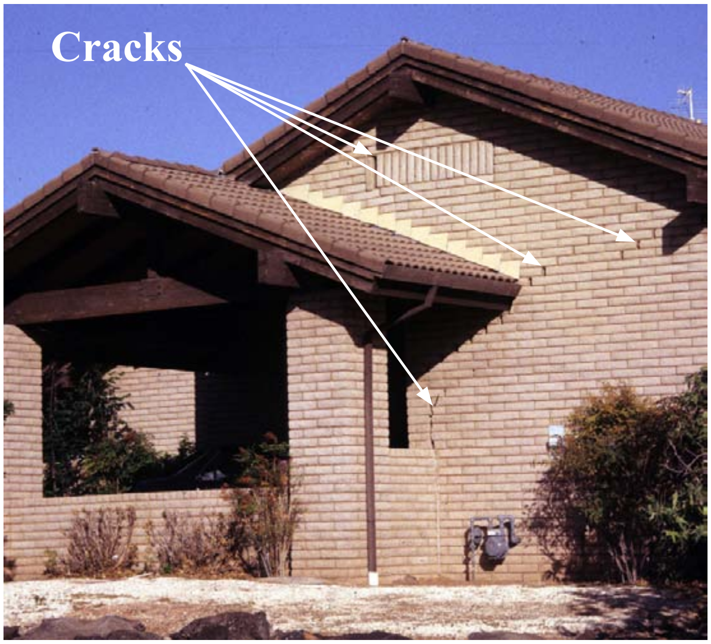

Figure 2. *Home in Santa Clara damaged by expansive soil/rock.*

Figure 3. *Outcrop of the Petrified Forest Member of the Chinle Formation (Blue Clay), which has a high content of expansive clay minerals and a correspondingly high shrink/swell potential. The blue clay crops out over a wide area in the study area and is responsible for many foundation and other structural problems.*

transported (usually a short distance) and deposited in a new location. The principal transporting mechanisms are water or wind, but soil creep and mass-wasting processes may play important roles locally.

Geotechnical Data Evaluation

The geotechnical database compiled for this study includes laboratory test data for soil samples collected from numerous test pits and exploratory borings in the study area. The database includes nearly 700 samples with liquid limit (LL) and plasticity index (PI) data, and more than 800 samples with swell/collapse test (SCT) data. Swell/collapse test results are the most reliable indicator of a soil's capacity to shrink or swell. For purposes of this study, an SCT value of ≥3 percent swell is considered problematic from an engineering standpoint (Russell Owens, Alpha Engineering, verbal communication, 2000). Plasticity index and LL data are commonly used as qualitative indicators of shrink/swell potential (table 1) (Chen, 1988; Russ Owens, Alpha Engineering, verbal communication, 2000; International Building Code [IBC], [International Code Council, 2006a]) either in the absence of SCT data or to assist in selecting samples for swell/collapse testing.

The IBC states that a soil meeting the following four provisions shall be considered expansive: (1) PI ≥15, (2) ≥10 percent of soil

Table 1*. Correlation of soil swelling potential with plasticity index (Chen, 1988).*

Swelling Potential	Plasticity Index
Low	0-15
Medium	10-35
High	20-55
Very High	35 and above

particles pass the No. 200 sieve (0.075 mm), (3) ≥ 10 percent of the soil particles are less than 5 micrometers (0.005 mm) in size, and (4) expansion index ≥20 as determined in accordance with American Association of Testing Materials Standard Test Method D 4829 (IBC Section 1802.3.2, p. 344).

Table 2 shows the relation between Unified Soil Classification System (USCS) soil types and fine-grained bedrock contained in the geotechnical database with SCT results, and the PI and LL data available for those materials.

***Table 2**. Relation of high SCT values (≥3%) to USCS soil types and fine-grained bedrock in the geotechnical database.*

USCS Soil Type[1]	Total	Number Tested	Percent Tested	Swell ≥3%	Percent Swell ≥3 %
GW[2]	4	0	0	-	-
GP	82	0	0	-	-
GM	152	2	1.3	0	0
GC	23	1	4.4	1	100
SW	14	1	7.1	0	0
SP	156	3	1.9	0	0
SM	1653	222	13.4	7	3.2
SC	255	83	32.6	14	16.9
ML	546	61	11.1	5	8.2
CL	1085	234	21.6	100	42.7
OL	6	0	0	-	-
MH	11	1	9.1	0	0
CH	184	69	37.5	54	78.3
OH	9	2	22.2	2	100
Bedrock[3]	552	113	20.5	61	54.0
Fill	45	7	15.6	6	85.7
Other[4]	319	4	1.3	0	0

[1]Soils classified according to the USCS; [2]soil categories include soils classified as borderline, for example CH/SC and SP/SM soils, respectively; [3]fine-grained bedrock, chiefly weathered siltstone, mudstone, claystone, and shale; [4]includes weathered coarse-grained sedimentary bedrock, basalt, bedrock not identified as to type, caliche, and other miscellaneous materials.

Of the 803 SCT values in the database, 250 (31.1%) exhibited ≥3 percent swell and therefore fall into the problematic-swell category. Table 2 shows that most problematic-swell values (215; 86%) are associated with just three kinds of material: CH-type, high plasticity inorganic clays; clay-rich bedrock; and CL-type, low to medium plasticity clays. More than 78 percent of the CH clays tested reported values ≥3 percent swell. Similarly, 54 percent of all fine-grained bedrock samples and 42.7 percent of all CL clays tested had problematic-swell values. Note that for all three material types, a relatively small number of the total available samples were tested for swell/collapse: 37.5 percent of CH clays, 20.5 percent of fine-grained bedrock, and 21.6 percent of CL clays. The relatively low percentage of potentially problematic-swell materials tested for swell/collapse potential in past geotechnical studies likely reflects the application of engineering judgment by geotechnical engineers and engineering geologists familiar with soil conditions in the St. George–Hurricane metropolitan area. When geotechnical firms tested unengineered fill material on sites being considered for development, 85.7 percent of the samples gave problematic-swell values (table 2). This high percentage again likely reflects the judgment of geotechnical engineers and engineering geologists, who recognized that certain fills were clay rich and preferentially selected them for testing.

Table 3 compares the percentage of soil and bedrock samples with PI values ≥10 and ≥20 with the percentage of soil and rock samples with swell values ≥3 percent. The comparison shows that as an estimator of swell potential, PI values ≥10 systematically overestimate the percentage of problematic-swell values recorded for all three material types by an average of 13.6 percent. Conversely, PI values ≥20 for CL clays and bedrock underestimate the percentage of high swell values by an average of 24.1 percent. Plasticity Index values ≥20 continue to overestimate the percentage of problematic-swell values for CH clays. Therefore, in general, PI values ≥10 can serve as a rough indicator of problematic-swell potential in the St.

***Table 3.** Relation of PI values to USCS soil types and clay-rich bedrock in the geotechnical database.*

USCS Soil Type[1]	Total	Total PI Values	Percent Tested	PI ≥10	Percent PI ≥ 10	PI ≥ 20	Percent PI ≥ 20	Percent Swell ≥ 3%[4]
CL[2]	1085	330	30.4	178	53.9	35	10.6	42.7
CH	184	26	14.1	26	100	26	100	78.3
Bedrock[3]	552	108	19.6	67	62.0	41	38	54

[1]Soils classified according to USCS; [2]soil categories includes soils classified as borderline such as CL/ML and CL/SC; [3]fine-grained bedrock, chiefly weathered siltstone, mudstone, claystone, and shale; [4]from table 2.

George–Hurricane metropolitan area, and could, when applied judiciously, be used to select samples for more costly and time consuming SCT testing. However, relying on PI values ≥20 to identify problematic-swell potential materials may result in a systematic underestimation of the swell hazard.

Classification

Soil

Expansive soil is considered an adverse construction condition and not a geologic hazard. We classified soils on the basis of their expansive characteristics and potential for volumetric change into three shrink/swell-susceptibility categories. The principal sources of information regarding expansive soil characteristics in the study area are the "Estimated Soil Properties of Significance to Engineering," and "Interpretation of Engineering Test Data" tables in the NRCS *Soil Survey of Washington County Area, Utah* (Mortensen and others, 1977). We compared the ratings and data presented in those tables with the laboratory test results in our geotechnical database. The correlation between the NRCS information and the geotechnical test data are generally good, with a few local discrepancies. The discrepancies are not unexpected given the generalized nature of the NRCS information, and the susceptibility of soil characteristics to local influences such as adjacent or underlying bedrock, depositional process and history, effects of soil-forming processes, and limited depth of characterization (upper 60 inches of the soil column) of the NRCS data.

Details of our geotechnical data analysis are presented in the Geotechnical Data Evaluation section. Information from UGS geologic maps (see SOURCES OF DATA) was used to estimate shrink/swell susceptibility beyond the boundaries of the NRCS mapping and geotechnical database coverage. We did not classify soils with little or no expansive potential. Because expansive soil is considered an adverse construction condition and not a geologic hazard, the classification system presented below is a relative susceptibility ranking (High, Moderate or Low susceptibility) as opposed to a hazard-severity ranking such as those used on the geologic-hazard maps prepared for this study. The expansive-soil-susceptibility categories are as follows:

ESH Soils with high susceptibility for volumetric change are typically clay rich and have a LL ≥45, a PI ≥20, and/or a SCT value of ≥3 percent swell (Chen, 1988; Nelson and Miller, 1992; Russell Owens, Alpha Engineering, personal communication, 2000). Soils with these characteristics are of limited aerial extent at the surface in the study area, but are frequently found at depth as shown by the geotechnical database (see Geotechnical Data Evaluation section). This phenomenon reflects the fact that most of the geotechnical data available for the study area come from the municipalities of St. George, Santa Clara, Ivins, and Washington, portions of which are underlain at shallow depth (typically <20 feet) by bedrock with high or moderate susceptibility for volumetric change. The influence of this shallow, often clay-rich source rock on overlying soils is apparent in the geotechnical data collected from below a depth of 60 inches.

ESM Soils classified by the NRCS as having moderate susceptibility for volumetric change (LL from 20 to 50, and PI from nonplastic [NP] to 30). These values overlap at their upper ends with soils in the high susceptibility category. Chen (1988) recognized that while PI is an indicator of expansive potential, other factors also exert an influence, and therefore reported a range of PI values when categorizing soil's capacity to shrink or swell.

ESL Soils classified by the NRCS as having low susceptibility for volumetric change (LL from 0–30, and PI from NP–15). These values overlap at their upper ends with soils in the moderate susceptibility category. However, the low category includes soils with highly variable potential for volumetric change that do not fit easily into the moderate or high categories.

Rock

Expansive rock is considered an adverse construction condition and not a geologic hazard. We classified bedrock units in the study area into three shrink/swell-susceptibility categories on the basis of relative abundance of expansive clay minerals, abundance and thickness of fine-grained strata in mixed bedrock units, and past experience with expansive rock in the St. George–Hurricane metropolitan area. We did not classify bedrock formations possessing little or no potential for volumetric change. Because expansive rock is considered an adverse construction condition and not a geologic hazard, the classification system presented below is a relative susceptibility ranking (High, Moderate, or Low susceptibility) as opposed to a hazard-severity ranking such as those employed on the geologic-hazard maps prepared for this study. The expansive-rock-susceptibility categories are as follows:

ERH Bedrock units with high shrink/swell susceptibility include claystone horizons in the Virgin Limestone Member of the Moenkopi Formation; the Petrified Forest Member of the Chinle Formation, known locally as the "Blue Clay;" the lower red beds of the Dinosaur Canyon Member and the Whitmore Point Member of the Moenave Formation; the Iron Springs

Formation, which contains abundant clay-rich strata in its lower part; and a thin interval (maximum thickness 90 feet [Willis and Higgins, 1995]) of montmorillonitic clay that lies between the Carmel Formation and the overlying Iron Springs Formation. Landslides mapped within these rock units were also included in the high-susceptibility category. These bedrock units contain an abundance of expansive clay minerals and are commonly associated with expansive rock problems in the study area.

ERM Bedrock units with moderate shrink/swell susceptibility include the Shnabkaib and lower, middle, and upper red members of the Moenkopi Formation; the Co-op Creek and Crystal Creek Members of the Carmel Formation; and the Temple Cap Formation. These rock units are chiefly fine grained and contain alternating strata of shale, claystone, mudstone, siltstone, sandstone, and limestone. Not all or necessarily the majority of these strata contain expansive clay minerals, but past experience in the study area has shown that a sufficiently high percentage of strata do contain expansive clays that foundation problems are often associated with these rock units. Where mapped as undivided, we assigned a moderate susceptibility to the Moenkopi Formation, Carmel Formation, and grouped Triassic, Triassic/Jurassic, and Jurassic/Cretaceous rocks. Landslides mapped within moderate-susceptibility units are also included in this category.

ERL Bedrock units with low shrink/swell susceptibility include the Timpoweap Member of the Moenkopi Formation and the Kayenta Formation. Although we consider these units to have a low susceptibility relative to the bedrock units identified above, they contain some fine-grained, clay-rich strata that may cause shrink/swell problems locally.

Areas of Concealed Highly Expansive Soil or Rock

The Expansive-soil- and rock-susceptibility map (plate 6) shows several irregularly shaped areas throughout the St. George–Hurricane metropolitan area identified as having highly expansive soil or rock in the shallow subsurface (≤20 feet), but little no evidence of such materials at the ground surface. Past engineering experience has shown that when wetted, highly expansive soil or rock can cause differential displacements at the ground surface even when overlain by as much as 20 feet of nonexpansive material (Wayne Rogers, AGEC Inc., verbal communication, 2007). These areas are considered to have a high potential for expansive soil and rock problems despite the lack of surface evidence of such materials. The hazard represented by highly expansive materials at depth is well demonstrated in the Santa Clara Heights area of Santa Clara, where damage to structures has occurred where highly expansive rock is buried by more than 10 feet of nonexpansive sand and gravel.

CHESR Area of highly expansive soil or rock (≥5 percent swell) in the shallow subsurface (≤20 feet), but with little or no evidence of such material at the ground surface. Based on past engineering experience, such highly expansive soil or rock can cause differential displacements at the ground surface even when overlain by as much as 20 feet of nonexpansive material, and these areas are considered to have a high potential for expansive soil and rock problems.

Using This Map

The Expansive-soil- and rock-susceptibility map (plate 6) shows the location of known or suspected expansive soil and rock in the St. George–Hurricane metropolitan area. The map is intended for general planning purposes to indicate where expansive soil and rock conditions may exist and special studies may be required. The UGS recommends performing a site-specific geotechnical foundation/geologic-hazards study for all development at all locations in the study area. Site-specific studies can resolve uncertainties inherent in generalized mapping and help ensure safety by identifying the need for special foundation designs or mitigation techniques. The presence and severity of expansive soil and rock along with other adverse construction conditions and geologic hazards should be addressed in these investigations. If expansive soil or rock is present at a site, appropriate design recommendations should be provided.

Map Limitations

The Expansive-soil- and rock-susceptibility map (plate 6) is based on limited geologic and geotechnical data; site-specific studies are required to produce more detailed geotechnical information. The map also depends on the quality of those data, which varies throughout the study area. The mapped boundaries between susceptibility categories are approximate and subject to change with additional information. The hazard from expansive soil and rock may be different than shown at any particular site because of geological variations within a map unit, gradational and approximate map-unit boundaries, and the small map scale. This map is not intended for use at scales other than the published scale, and is designed for use in general planning to indicate the need for site-specific studies.

Mitigation

Although potentially costly when not recognized and properly accommodated in project design and construction, problems associated with expansive soil and rock rarely are life threatening. As with most adverse construction conditions, early recognition and avoidance is the most effective way to mitigate potential problems. However, expansive soil and rock are widespread in the St. George–Hurricane metropolitan area and avoidance is generally not a viable or cost-effective mitigation option.

In Utah, soil test requirements are specified in the soil and foundations provisions of IBC Chapter 18 (p. 343) and the foundations provisions of the International Residential Code (IRC) (International Code Council, 2006b) Chapter 4 (p. 42), which are adopted statewide. IBC Section 1802.2.2 (p. 343) and IRC Section R401.4 (p. 67) contain requirements for soil investigations in areas where expansive soil may be present. Where the presence of expansive soil or rock is confirmed, possible mitigation techniques include soil or rock removal and replacement with noncohesive, compacted backfill; use of special foundation designs such as drilled pier and beam foundations or stiffened slab-on-grade construction; moisture barriers; foundation soil prewetting; chemical stabilization of expansive clays (Nelson and Miller, 1992); and careful site landscape and drainage design to keep moisture away from buildings and expansive soils (Keller and Blodgett, 2006).

COLLAPSIBLE SOIL

Collapsible soils have considerable dry strength and stiffness in their dry natural state, but can settle up to 10 percent of the susceptible deposit thickness when they become wet for the first time following deposition (Costa and Baker, 1981; Rollins and Rogers, 1994; Keaton, 2005) causing damage to property and structures. Collapsible soils are common throughout the arid southwestern United States and are typically geologically young materials, chiefly debris-flow deposits in Holocene-age alluvial fans, and some wind-blown, lacustrine, and colluvial deposits (Owens and Rollins, 1990; Mulvey, 1992; Santi, 2005). Collapsible soils typically have a high void ratio and corresponding low unit weight (<80 to 90 lb/ft^3; Costa and Baker, 1981; Walter Jones, consulting engineer, written communication, 2007) and a relatively low moisture content (<15%; Owens and Rollins, 1990), all characteristics that result from the initial rapid deposition and drying of the sediments. Intergranular bonds form between the larger grains (sand and gravel) of a collapsible soil; these bonds develop through capillary tension or a binding agent such as silt, clay, or salt. Later wetting of the soil results in a loss of capillary tension or the softening, weakening, or dissolving of the bonding agent allowing the larger particles to slip past one another into a denser structure (Rollins and Williams, 1991).

In general, collapsible alluvial-fan soils are associated with drainage basins that are dominated by soft, clay-rich sedimentary rocks such as shale, mudstone, claystone, and siltstone (Bull, 1964; Owens and Rollins, 1990). Bull (1964) found that the maximum collapse of alluvial-fan soils in Fresno County, California, coincided with a clay content of approximately 12 percent. Alluvial-fan deposits exhibiting dramatic collapse behavior in Nephi, Utah, typically contained 10 to 15 percent clay-size material (Rollins and Rogers, 1994). At clay contents greater than about 12 to 15 percent, the expansive nature of the clay begins to dominate and the soil is subject to swell rather than collapse. Characteristically, collapsible soils consist of silty sands, sandy silts, and clayey sands (Rollins and Williams, 1991), although Rollins and others (1994) identified collapse-prone gravels containing as little as 5 to 20 percent fines at several locations in the southwestern United States.

Soil composition is the primary indicator of collapse potential in alluvial-fan soils. However, along the southern Wasatch Front, Owens and Rollins (1990) found that the degree of collapse generally increased with an increase in the ratio of fan area to drainage-basin area. In other words, alluvial fans (especially large alluvial fans) associated with small drainage basins had a greater likelihood of producing collapse-prone soils. Bull (1964) found a similar relation between fan and drainage-basin size in Fresno County.

Loess, deposits of wind-blown clay, silt, and fine sand, typically have an extremely loose, open structure that is maintained by water-soluble mineral cements or high-plasticity clay that act as a binder between larger grains (Gibbs and Holland, 1960; Costa and Baker, 1981). Like collapse-prone alluvial-fan soils, undisturbed loess typically has a high void ratio, corresponding low in-place density, and is relatively dry. When wetted, loess will collapse; the extent of the collapse largely depends on the texture (grain-size distribution) of the deposit. Gibbs and Holland (1960) found that clay-rich loess deposits tend to collapse less than those containing a higher percentage of silt and fine sand.

Naturally occurring deep percolation of water into collapsible deposits is uncommon after deposition due to the arid conditions in which the deposits typically form, and the steep gradient of many alluvial-fan surfaces. Therefore, soil collapse is usually triggered by human activity such as irrigation, urbanization, or disposal of waste water. Kaliser (1978) reported serious damage (estimated $3 million) to public and private structures in Cedar City, Utah; Rollins and others (1994) documented more than $20 million in required remedial measures to a cement plant near Leamington, Utah; and Smith and Deal (1988) reported damage to a large flood-control structure near Monroe, Utah, to cite a few Utah examples. Damage due to collapse of wind-blown deposits is less well documented in Utah. This may in part be due to the relatively lesser abundance of such deposits, but also to a lesser amount of development on such deposits because they are typically limited to southern Utah, where until recently, construction lagged behind the Wasatch Front.

Description

Review of the 275 consultant's reports used to create the geotechnical database for this study shows that collapsible soil testing is standard practice by most geotechnical engineering firms in the St. George–Hurricane metropolitan area, indicating that a collapsible soil problem is recognized and widespread in the study area. However, geotechnical data are only available for a limited part of the study area. To evaluate collapse potential where geotechnical data are not available, it was necessary to extrapolate based on the geologic unit characteristics shown on the UGS geologic maps (see Sources of Data). The NRCS *Soil Survey of Washington County Area, Utah* (Mortensen and others, 1977) does not present information on soil-collapse potential.

Despite some limited geotechnical data to the contrary, for purposes of this study, we consider bedrock to have no collapse potential. We believe that in those few instances where bedrock units are identified in geotechnical reports as having a significant collapse potential, the material was likely misidentified.

Utah Geological Survey geologic mapping classifies the unconsolidated geologic deposits in the study area into more than 70 different geologic units. Swell/collapse test data are available for only a limited number of those units. Twelve units have reported collapse values of ≥3 percent, the level at which collapse becomes a significant engineering concern (Jennings and Knight, 1975) given a sufficient thickness of susceptible soil (Walter Jones, consulting engineer, written communication, 2007). As discussed above, soil collapse is closely associated with soil texture. A few percent variation in clay content can be the difference between a deposit that will collapse and one that will swell when wetted. The unconsolidated geologic units on UGS geologic maps are defined on geomorphology (landform), genesis, and to a lesser extent texture. Therefore, some unconsolidated geologic units show considerable textural variation. For example, geologic unit Qat_2, which denotes geologically young stream-terrace deposits, is reported, depending on location, to have SCT values in excess of both 3 percent swell and 3 percent collapse. Therefore, while geology can be used as an indicator of collapse potential, it is not an infallible guide, and site-specific soil testing is required.

Geotechnical Data Evaluation

The geotechnical database compiled for this study contains 803 SCT results for soil samples. The results for 391 samples exhibited collapse. Of the 391 collapsible samples, 110 had SCT values ≥3 percent and therefore are problematic from an engineering standpoint. Table 4 shows the relation between USCS soil types and collapse values that are ≥3 percent.

***Table 4**. Relation of high collapse test values (>3%) to USCS soil types in the geotechnical database.*

USCS Soil Type[1]	Total in Database	Number Tested	Percent Tested	Collapse ≥3%	Percent Tested that Collapsed
SM	1512	205	13.6	52	25.4
SC	231	77	33.3	13	16.9
SM/SP	114	14	12.2	7	50.5
SC/SM	20	6	30.0	3	50.0
SM/SW	3	2	66.6	1	33.3
ML	493	57	11.6	11	19.3
CL	744	207	27.8	23	11.1

[1]Soils classified according to the USCS.

As expected, most collapsible soils consist of silty or clayey sands. The high percentages in column 6 (Percent Tested that Collapsed) reported for dual classified soils SM/SP, SC/SM, and SM/SW probably reflect good engineering judgment during the sample selection process. We do not believe that 33 to 50 percent of all dual classified soils in the study area exhibit a significant collapse potential. The silts (ML) tested showed a higher percentage of collapsible samples than did clayey sands (SC). The silts are likely loess deposits of eolian origin. Clay-rich soils (CL) show the lowest potential for collapse, but nevertheless, more than 10 percent of the clay soils tested showed significant collapse potential.

Classification

Collapsible soil is considered an adverse construction condition and not a geologic hazard. Available data on the collapse potential of soils in the study area are limited. We classified unconsolidated geologic units that may be prone to collapse (table 5) into one of four categories on the Collapsible-Soil-Susceptibility Map (plate 7). The categories are based on the type of geotechnical data available, and if the deposit genesis or texture is permissive of collapse. The soils in all four categories could exhibit ≥3 percent collapse, and therefore be regarded as having significant collapse potential. Because collapsible soil is considered an adverse construction condition and not a geologic hazard, the classification system presented below is a relative susceptibility ranking as opposed to a hazard-severity ranking such as those used on the geologic-hazard maps prepared for this study. The collapsible-soil-susceptibility categories are as follows:

Table 5. Geologic deposits known or likely to have a significant potential for soil collapse.

Type of Deposit	Map Units[1]	Collapsible Soil Category
Stream and Terrace Alluvium	Qal_1, Qat_2	CS_A
	Qa_2, Qat_3, Qat_4, Qat_5	CS_B
	Qat_6, Qat_7, $QTat_7$, Tat_8, QTato, Qato, Qatb, Qsg, Qas	CS_D
Fan Alluvium	Qae, Qac, Qap_1, Qaf_1, Qaf_2, Qaf_5, Qaeo	CS_A
	Qa, Qaes, Qaec, Qafy, Qao, Qap_3, Qaco	CS_C
	Qaeg, Qab, Qabo, Qap, Qap_4, Qap_6, Qaf_6, Qafo, Qmfo, Qaow	CS_D
Eolian Deposits	Qes, Qea, Qea_1, Qes/Qaf_5, Qes/Qafo, Qe/Qmsy	CS_A
	Qea_2, Qed	CS_C
	Qea_3, Qecl, Qeo,	CS_D
Colluvial Deposits	Qca	CS_A
	Qmt	CS_B
	Qc	CS_C
	Qmto, Qcao, Qco	CS_D

[1]Refer to UGS geologic quadrangle maps (see SOURCES OF DATA above and REFERENCES below) for a description of map units.

Soil

CS_A Unconsolidated geologic units with reported collapse values of ≥3 percent.

CS_B Unconsolidated geologic units lacking collapse data, but for which other geotechnical information (chiefly low unit weight and moisture content) are indicative of collapse-susceptible material.

CS_C Geologically young (Holocene) unconsolidated geologic units for which no geotechnical data are available, but whose genesis or texture are permissive of collapse (chiefly geologically young alluvial, colluvial, and eolian deposits).

CS_D Older unconsolidated geologic units (Pleistocene) for which no geotechnical data are available, but like category CS_C have a genesis or texture permissive of collapse. Because of their age, these deposits have had greater exposure to natural wetting and collapse may have occurred, and/or the deposits may have become cemented by secondary calcium carbonate or other soluble minerals.

Areas of Highly Collapsible Soil

The Collapsible-Soil-Susceptibility Map (plate 7) shows several irregularly shaped areas throughout the St. George–Hurricane metropolitan area identified by local geotechnical consultants as containing soils with a high (≥5 percent) collapse potential. Past engineering experience has shown that without careful geotechnical investigation and mitigation measures, collapsible soil problems are highly likely in these areas (David Black, Rosenberg Associates, personal communication, 2007).

HCS Area of known high collapse soils. Areas identified by geotechnical consultants working in the St. George–Hurricane metropolitan area as containing high collapse (≥5 percent) soils. Soils in these areas have a high potential for collapsible soil problems.

We did not classify soils, which on the basis of genesis or texture have little or no collapse potential. They are grouped with bedrock, and comprise the remainder of the map area not labeled with respect to collapse potential.

Soil collapse data for the study area and anecdotal evidence from elsewhere in southwestern Utah and adjacent northwestern Nevada (Wayne Rogers, Applied Geotechnical Engineering Consultants [AGEC], verbal communication, 2001) indicate that deposit age is not always a reliable indicator of collapse potential. Although younger (Holocene) geologic units are generally recognized as having a greater collapse potential, two older units within the study area (Qaf_5 and Qaeo) both have collapse values ≥3 percent. Both deposits are Pleistocene in age, and in the case of Qaf_5, may be several hundred thousand years old. Likewise, AGEC found that some deposits possibly as old as Miocene near Mesquite, Nevada, have high collapse potential. Therefore, although less likely to be susceptible, older unconsolidated geologic units in the study area should also be tested for collapse potential.

Using This Map

The Collapsible-Soil-Susceptibility Map (plate 7) shows the location of known and suspected collapsible-soil conditions in the St. George–Hurricane metropolitan area. The map is intended for general planning purposes to indicate where collapsible-soil conditions may exist and special studies may be required. The UGS recommends performing a site-specific geotechnical foundation/geologic-hazards study for all development at all locations in the study area. Site-specific studies can resolve uncertainties inherent in generalized mapping and help ensure safety by identifying the need for special foundation designs or mitigation techniques. The presence and severity of collapsible soil along with other adverse construction conditions and geologic hazards should be addressed in these investigations. If collapsible soil is present at a site, appropriate design recommendations should be provided.

Map Limitations

The Collapsible-Soil-Susceptibility Map (plate 7) is based on limited geologic and geotechnical data; site-specific studies are required to produce more detailed geotechnical information. The map also depends on the quality of those data, which varies throughout the study area. The mapped boundaries between susceptibility categories are approximate and subject to change with additional information. The susceptibility may be different than shown at any particular site because of geological variations within a map unit, gradational and approximate map-unit boundaries, and the small map scale. This map is not intended for use at scales other than the published scale, and is designed for use in general planning to indicate the need for site-specific studies.

Mitigation

Although potentially costly when not recognized and properly accommodated in project design and construction, problems associated with collapsible soil rarely are life threatening. As with most adverse construction conditions, early recognition and avoidance is the most effective way to mitigate potential problems. However, collapsible soil is widespread in the St. George–Hurricane metropolitan area, and avoidance is generally not a viable or cost-effective mitigation option.

In Utah, soil-test requirements are specified in the soil and foundations provisions of IBC Chapter 18 (p. 343) and the foundations provisions of IRC Chapter 4 (p. 42), which are adopted statewide. IBC Section 1802.2.1 (p. 343) contains requirements for soil investigations in areas where questionable soil (soil classification, strength, or compressibility) is present. IRC Section R401.4 (p. 67) states that the building official shall determine whether to require a soil test to determine the soil's characteristics in areas likely to have expansive, compressible, shifting, or other unknown soil characteristics. Where the presence of collapsible soil is confirmed, possible mitigation techniques include soil removal and replacement with noncohesive, compacted backfill; use of special foundation designs such as drilled pier and beam foundations or stiffened slab-on-grade construction; moisture barriers; foundation soil prewetting (Nelson and Miller, 1992; Pawlak, 1998); and careful site landscape and drainage design to keep moisture away from buildings and collapse-prone soils (Keller and Blodgett, 2006).

Figure 4. *Quail Creek dike failure, January 1, 1989, due in part to gypsum dissolution in the underlying Shnabkaib Member of the Moenkopi Formation (photo credit Ben Everitt).*

GYPSIFEROUS SOIL AND ROCK

Gypsum-bearing soil and rock are subject to dissolution of the gypsum ($CaSO_4{\cdot}2H_2O$), which causes a loss of internal structure and volume. Where the percentage of gypsum is 10 percent or more, dissolution can result in localized land subsidence and sinkhole formation (Mulvey, 1992; Muckel, 2004; Santi, 2005). Dissolution of gypsum may lead to foundation problems and may affect roads, dikes, underground utilities, and other infrastructure. Another common gypsum-related foundation problem is locally termed "water rock," which is a strongly indurated gypsum and calcium carbonate layer in the shallow subsurface in unconsolidated deposits. The layer commonly forms at the top of the water table and creates a local confining layer. Breaching the layer during construction may result in artesian ground-water flow that can flood excavations and require an extensive drainage system. "Water rock" has been encountered

Figure 5. *Gypsum-rich Shnabkaib Member (white unit in middle distance) of the Moenkopi Formation southeast of St. George, Utah.*

in construction areas east of Middleton Black Ridge and in the vicinity of Dixie State College (David Black; Black, Miller, and Associates, personal communication, 1995, as reported in Higgins and Willis, 1995; Gary Christenson, UGS, verbal communication, 2000). Gypsum dissolution can be greatly accelerated by application of water, such as that provided by reservoirs (figure 4); septic-tank drain fields; street, roof, or parking lot runoff; and irrigation (Martinez and others, 1998). Gypsum is also a weak material with low bearing strength and is not well suited as a foundation material for heavy structures. Additionally, when gypsum weathers it forms dilute sulfuric acid and sulfate, which can react with certain types of cement, corroding and weakening unprotected concrete. Type V sulfate-resistant cement is typically required in such areas.

Description

In the St. George–Hurricane metropolitan area, gypsum is an important component of the Shnabkaib Member of the Moenkopi Formation (figure 5), the Harrisburg Member of the Kaibab Formation, and the Woods Ranch Member of the Toroweap Formation. Gypsum is also common in the Timpoweap, Virgin Limestone, lower red, middle red, and upper red members of the Moenkopi Formation; in the Kayenta, Temple Cap, and Carmel Formations; and in many fine-grained alluvial and eolian deposits throughout the study area derived from these units. Residual gypcrete and older gypsum-rich alluvial gravel and mixed alluvial and eolian deposits crop out in some parts of the study area (Mortensen and others, 1977; Higgins, 1997; Biek, 2003a), but because gypsum is often concentrated in subsurface horizons by pedogenic processes or evaporation of shallow ground water, problem soils may be difficult to recognize in the absence of subsurface exploration.

Gypsum Dissolution

Gypsum dissolution in bedrock was an important factor in the January 1, 1989, failure of the Quail Creek dike (figure 4; Gourley, 1992). In other parts of the study area, gypsum solution caverns are up to several feet in diameter. In one instance, a bulldozer broke through the roof of a cavern and was suspended by its front blade and back ripper (J and J Construction Company, personal communication, 1995, as reported in Higgins and Willis, 1995). David Black (Black, Miller, and Associates, personal communication, 1995, as reported in Higgins and Willis, 1995) reported honeycomb gypsum with solution cavities as much as 2 feet wide in an excavation for a swimming pool in central St. George.

Corrosive Soil and Rock

Gypsum is the most common sulfate mineral in soils in the western United States (Muckel, 2004). Gypsum is soluble and along with associated sulfates, such as sodium sulfate and magnesium sulfate, can dissolve in water to form a weak acid solution that is corrosive to concrete in areas where the percentage of soil gypsum is one percent or greater (Muckel, 2004). The ions within the acid react chemically with the cement (a base) in the concrete. Gypsum-induced corrosion of unprotected concrete slabs, walls, and masonry blocks is widespread in the St. George–Hurricane metropolitan area (figure 6), and damage can become severe after just a few years exposure (David Black, Rosenberg Associates, personal communication, 2007). Precipitation of excess sulfate in soils causing foundation slabs to lift and crack is also becoming an increasingly common problem in the study area (David Black, Rosenberg Associates, personal communication, 2007).

***Figure 6**. Corrosion of masonry block walls in the St. George area due to the reaction of the non-Type V cement used in the masonry blocks with high-sulfate soils (photo credit David Black, Rosenberg Associates).*

Classification

Soil

Gypsiferous soil is considered an adverse construction condition and not a geologic hazard. Available data on gypsiferous soil in the study area are limited. We grouped unconsolidated gypsiferous deposits (table 6) into two susceptibility categories on The Gypsiferous-Soil- and Rock-Susceptibility Map (plate 8) based upon the origin and nature of the deposits. Both categories may contain abundant gypsum (>10%), and may have significant potential for dissolution and collapse. Soils containing gypsum in concentrations less than 10 percent are widespread in the study area, and while not presenting a soil collapse problem, they can corrode unprotected concrete and masonry structures. Data on the distribution of such soils are generally lacking. The gypsiferous-soil categories are as follows:

GS_A Includes gypsiferous silt and clay and local gypsum, collectively referred to as gypcrete, that caps sloping irregular surfaces that cut across the Shnabkaib and upper red members of the Moenkopi Formation (Higgins, 1997), and gypsiferous alluvial and eolian deposits that contain clay- to boulder-sized sediments that typically weather to a soft, white, powdery gypsiferous soil (Biek, 2003a). These deposits crop out at the ground surface and typically are easily recognized.

GS_B Includes gypsum-bearing soils mapped by the NRCS (Mortensen and others, 1977). The gypsum in the soils is largely pedogenic (formed by dissolution and re-precipitation at depth during the soil-forming process) and its presence may not be apparent at the ground surface.

Rock

Gypsiferous rock is considered an adverse construction condition and not a geologic hazard. We grouped gypsum-bearing bedrock units (table 6) into three susceptibility categories (GR_A, GR_B, and GR_C) on the Gypsiferous-Soil-and-Rock- Susceptibility Map (plate 8) based on the relative amount of gypsum present in the bedrock units that constitute each category. While there is a general decrease in the amount of gypsum present from GR_A to GR_C, all three susceptibility categories may contain abundant gypsum locally, and may have a significant potential for dissolution and collapse. The gypsiferous-rock categories are as follows:

GR_A These bedrock units contain abundant gypsum, often in laterally continuous horizons up to several feet thick, and they and the alluvial deposits derived from them are commonly associated with dissolution and collapse features. This category includes the Woods Ranch Member of the Toroweap Formation, Harrisburg Member of the Kaibab Formation, Shnabkaib Member of the Moenkopi Formation, and the Temple Cap Formation.

GR_B These bedrock units lack massive gypsum deposits, but contain thin to medium beds and veins of gypsum interspersed with other rock types. These units and the alluvial deposits derived from them, contain sufficient gypsum locally to cause foundation or other problems. This category includes the Seligman Member of the Toroweap Formation; Timpoweap, lower red, Virgin Limestone, middle red, and upper red members of the Moenkopi Formation; Moenkopi Formation undivided; lower member of the Kayenta Formation; and the Carmel Formation.

GR_C These bedrock units contain gypsum in greater or lesser amounts (see above), but due to geologic or topographic complexities, individual rock unit subdivisions could not be recognized in the field at the scale of our mapping and therefore were mapped as undifferentiated. The extent to which these bedrock units, or the alluvial deposits derived from them, contain gypsum is not known, but areas where these rock units crop out should be carefully investigated for gypsum if development is planned. This category includes Permian-age rocks undivided; Toroweap and Kaibab Formations undivided; Brady Canyon and Seligman Members of the Toroweap Formation undivided; Triassic-age rocks undivided; and the Kayenta, Iron Springs, Carmel, and Temple Cap Formations undivided.

Using This Map

The Gypsiferous-Soil- and Rock-Susceptibility Map (plate 8) shows the location of known and suspected gypsiferous soil and rock in the St. George–Hurricane metropolitan area. The map is intended for general planning purposes to indicate where gypsiferous soil and rock conditions may exist and special studies may be required. Regarding special studies, the UGS recommends performing a site-specific geotechnical foundation/geologic-hazards study for all development at all locations in the study area. Site-specific studies can resolve uncertainties inherent in generalized mapping and help ensure safety by identifying the need for special foundation designs or mitigation techniques. The presence and severity of gypsiferous soil and rock along with other geologic hazards and adverse construction conditions should be addressed in these investigations. If gypsiferous soil or rock is present at a site, appropriate design recommendations should be provided.

Map Limitations

The Gypsiferous-Soil- and Rock-Susceptibility Map (plate 8) is based on limited geologic and geotechnical data; site-specific studies are required to produce more detailed geotechnical information. The map also depends on the quality of those data, which varies throughout the study area. The mapped boundaries between hazard categories are approximate and subject to change with additional information. The susceptibility may be different than shown at any particular site because of geological variations within a map unit, gradational and approximate map-unit boundaries, and the small map scale. Additionally, gypsum-bearing bedrock units are locally covered by a thin veneer of unconsolidated deposits. Such areas may be susceptible to sinkhole development or collapse; however, because subsurface information is generally unavailable, those areas are not identified on this map. This map is not intended for use at scales other than the published scale, and is designed for use in general planning to indicate the need for site-specific studies.

Table 6. *Geologic units and NRCS soil categories known or likely to contain abundant gypsum.*

GYPSIFEROUS SOIL			
Unconsolidated Units	Map Symbols	Source of Data	Gypsiferous Soil Category
Gypcrete[1]	Qsg	UGS	GS_A
Mixed Alluvial and Eolian Deposits[1]	Qaeg	UGS	GS_A
Flood Plain and Alluvial-Fan Deposits[2]	Sa, Sb, Sc, Sd, Se (St. George Series)	NRCS	GS_B
Alluvial-Fan Deposits[2]	SH (Schmutz Loam)	NRCS	GS_B
GYPSIFEROUS ROCK			
Bedrock Units[1]	Map Symbols	Source of Data	Gypsiferous Rock Category
Woods Ranch Member/Toroweap Formation; Harrisburg Member/Kaibab Formation; Shnabkaib Member/Moenkopi Formation; Temple Cap Formation	Ptw, Pkh, TRms, Jtc, Jts	UGS	GR_A
Seligman Member/Toroweap Formation; Timpoweap, lower red, Virgin Limestone, middle red, and upper red members/ Moenkopi Formation; Moenkopi Formation undivided; lower member/ Kayenta Formation; Co-op Creek Limestone and Crystal Creek Members/Carmel Formation	Pts, TRmt, TRml, TRmv, TRmm, TRmu, TRm, Jkl, Jcco, Jcx	UGS	GR_B
Permian rocks undivided; Toroweap and Kaibab Formations undivided; Brady Canyon and Seligman Members/Toroweap Formation undivided; Triassic rocks undivided; Kayenta Formation undivided; Iron Springs, Carmel, and Temple Cap Formations undivided	Pu, Pkt, Ptbs, TRu, KJu, Jk	UGS	GR_C

[1]Refer to UGS geologic quadrangle maps for unit descriptions (see SOURCES OF DATA above and REFERENCES below).
[2] Refer to NRCS soil maps for a description of map units (see SOURCES OF DATA above and REFERENCES below).

Mitigation

Although potentially costly when not recognized and properly accommodated in project design and construction, problems associated with gypsiferous soil and rock rarely are life threatening. As with most adverse construction conditions, early recognition and avoidance is the most effective way to mitigate potential problems. However, gypsiferous soil and rock are widespread in the St. George - Hurricane metropolitan area and avoidance is generally not a viable or cost-effective mitigation option.

In Utah, soil-test requirements are specified in the soil and foundations provisions of IBC Chapter 18 (p. 343) and the foundations provisions of IRC Chapter 4 (p. 42), which are adopted statewide. IBC Section 1802.2.1 (p. 343) contains requirements for soil investigations in areas where questionable soil (soil classification, strength, or compressibility is in doubt) is present. IRC Section R401.4 (p. 67) states that the building official shall determine whether to require a soil test to determine the soil's characteristics in areas likely to have expansive, compressible, shifting, or other unknown soil characteristics. Where the presence of gypsiferous soil or rock is confirmed, possible hazard-reduction techniques include use of Type V sulfate-resistant cement for making concrete; soil removal and replacement with noncohesive, compacted backfill; use of special foundation designs such as drilled pier and beam foundations or stiffened slab-on-grade construction; careful site landscape and drainage design to keep moisture away from buildings and gypsum-bearing deposits; and the use of visqueen beneath concrete slabs to form a vapor and sulfate barrier (Keller and Blodgett, 2006).

BRECCIA PIPES AND PALEOKARST

The Colorado Plateau in southwestern Utah and northwestern Arizona is host to thousands of large solution-collapse breccia pipes (figure 7) (Wenrich and Sutphin, 1988) that have formed chiefly by dissolution of limestone. Most breccia pipes are thought to have their roots in the Redwall Limestone, which is present only in the deep subsurface in southwestern Utah. The breccia pipes are rubble-filled vertical tubes that form and project to the surface as overlying strata collapse into buried Redwall karst caverns that formed when the Redwall Limestone cropped out at the ground surface 300 million years ago.

A second zone of paleokarst features exists at the contact between the Harrisburg Member of the Kaibab Formation and the overlying Moenkopi Formation. These paleokarst features formed in both limestone and gypsum, and are at or close to the ground surface in some areas of southwestern Utah. Historic

Figure 7. *Breccia pipe (arrow) in the Kaibab and lower Moenkopi Formations in southwestern Utah.*

sinkholes, likely associated with this zone of paleokarst, have opened in or adjacent to the Virgin River and La Verkin Creek, and in some cases have intercepted all or part of the flow of those streams for considerable periods of time (Everitt and Einert, 1994; Lund, 1997; Milligan, 2000).

Most breccia pipes and paleokarst features in southwestern Utah are relict features and are no longer active. This inactivity is largely due to the region's current arid climate and deep water table. However, with the addition of water from irrigation, onsite wastewater disposal systems, canals and reservoirs, or other human-induced means, or construction above existing caverns, these relict features may reactivate locally resulting in subsidence or collapse and damage to structures, transportation and utility corridors, and reservoirs. Breccia pipes and paleokarst features also provide highly permeable pathways to the subsurface and are of concern for wastewater disposal and ground-water pollution.

Description

In the St. George–Hurricane metropolitan area, breccia pipes and paleokarst features are typically found where the Toroweap and Kaibab Formations, and to a lesser extent, where the Timpoweap and Virgin Limestone Members of the Moenkopi Formation crop out. Breccia pipes are not known to extend higher in the stratigraphic section than the Virgin Limestone Member of the Moenkopi Formation (Janice Hayden, UGS, verbal communication, 2006).

Classification

Breccia pipes and paleokarst features are considered adverse construction conditions and not geologic hazards. Areas where the Toroweap and Kaibab Formations, and the Timpoweap and Virgin Limestone Members of the Moenkopi Formation crop out and therefore, where a breccia pipe and paleokarst hazard may exist, are shown on the accompanying Breccia-Pipe- and Paleokarst-Susceptibility map (plate 9) as:

BP/PK Bedrock units that are known to contain breccia pipes and/or paleokarst features. These units include the Toroweap and Kaibab Formations, and the Timpoweap and Virgin Limestone Members of the Moenkopi Formation.

Using This Map

The Breccia-Pipe- and Paleokarst-Susceptibility Map (plate 9) shows the location of bedrock units in the St. George–Hurricane metropolitan area typically associated with breccia pipes and paleokarst features. The map is intended for general planning purposes to indicate where breccia pipes and paleokarst conditions may exist and special studies may be required. The UGS recommends performing a site-specific geotechnical foundation/geologic-hazards study for all development at all locations in the study area. Site-specific studies can resolve uncertainties inherent in generalized mapping and help ensure safety by identifying the need for special foundation designs or mitigation techniques. The presence and severity of breccia pipes and paleokarst features along with other adverse construction conditions and geologic hazards should be addressed in these investigations. If breccia pipes or paleokarst features are present at a site, appropriate design recommendations should be provided.

Map Limitations

The Breccia-Pipe- and Paleokarst-Susceptibility Map (plate 9) is based on limited geologic and geotechnical data; site-specific studies are required to produce more detailed geotechnical information. The map also depends on the quality of those data, which varies throughout the study area. The boundaries of the susceptibility category are approximate and subject to change with additional information. Small areas of localized susceptibility may exist throughout the study area, but their identification is precluded because of limitations of map scale. Additionally, gypsum-bearing units in the study area are locally covered by a thin veneer of unconsolidated deposits. Such areas may be susceptible to sinkhole reactivation or collapse (for example Big Round Valley [Milligan, 2000] south of Bloomington; figure 8); however, because subsurface information is generally unavailable, those areas are not identified on this

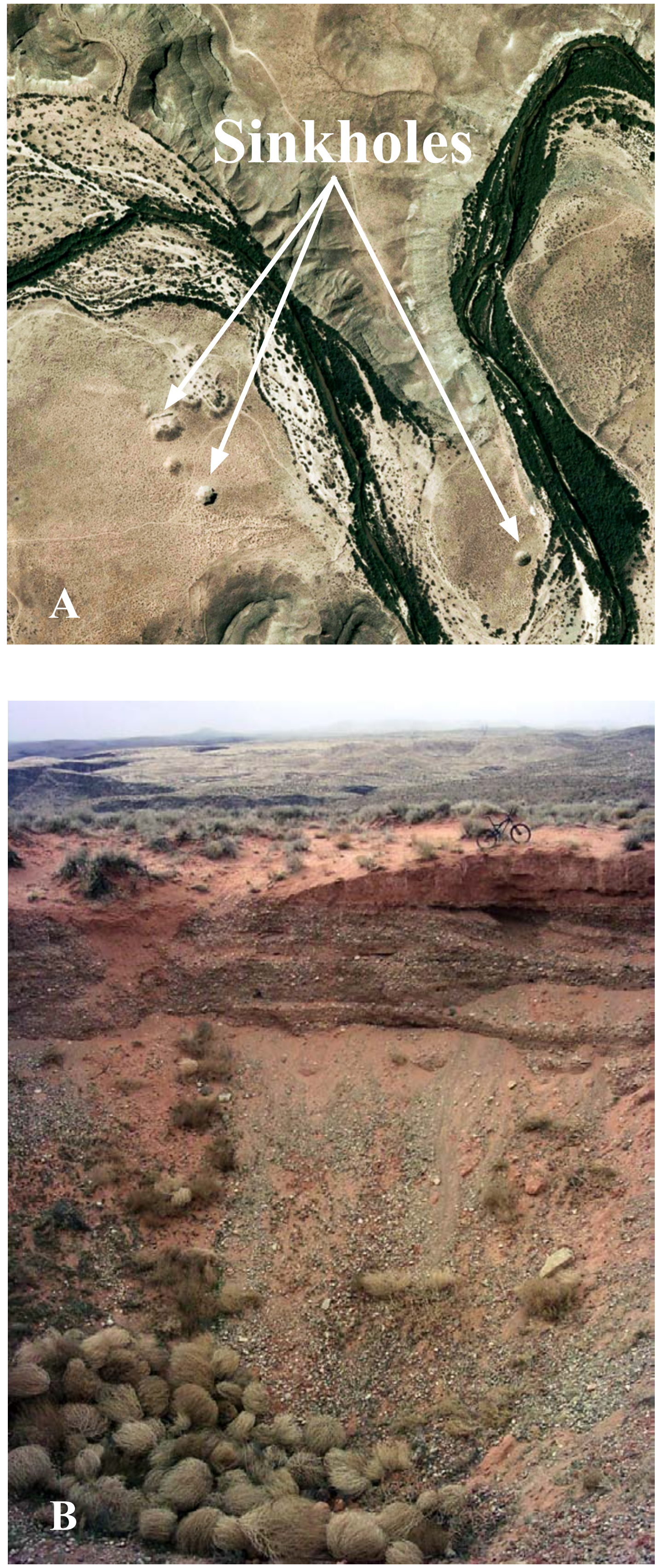

***Figure 8**. Sinkholes in Big Round Valley south of St. George, Utah, formed in an area underlain by gypsum-bearing bedrock; (A) aerial view of sinkholes, (B) close-up of a sinkhole, note bicycle on rim for scale.*

map. This map is not intended for use at scales other than the published scale, and is designed for use in general planning to indicate the need for site-specific studies.

Mitigation

Although potentially costly when not recognized and properly accommodated in project design and construction, problems associated with breccia pipes and paleokarst features rarely are life threatening. As with most adverse construction conditions, early recognition and avoidance is the most effective way to mitigate potential problems. However, breccia pipes and paleokarst terrain susceptible to subsidence and sinkhole formation are widespread in some areas of the St. George–Hurricane metropolitan area, and avoidance may not be a viable or cost-effective mitigation option, particularly for transportation and utility corridors and large reservoirs. Mitigation techniques include installing inverted aggregate filters, transit-mix plugs, various types of grouting, dynamic compaction, special foundation designs such as piles, and careful drainage design to keep water away from karst features (Fischer and McWhorter, 2006).

SHALLOW BEDROCK

Shallow bedrock exists throughout most of southwestern Utah, posing potential foundation and utility construction and wastewater disposal challenges. In general, unweathered bedrock formations provide incompressible foundations with high shear strengths, making mechanical compaction of these materials generally ineffective and unnecessary (Christenson and Deen, 1983). The principal problem associated with bedrock is difficulty of excavation, particularly in highly resistant, unweathered units. However, some bedrock formations in the St. George–Hurricane metropolitan area are soft, deeply weathered, and contain a high percentage of expansive clay minerals; chief among these being the Petrified Forest Member of the Chinle Formation (Blue Clay). Construction on these bedrock units may result in shrink/swell foundation problems unless care is taken with foundation design and preparation. Bedrock is not a suitable material for the installation of onsite wastewater disposal systems (Utah Department of Environmental Quality, 2006).

Description

Bedrock crops out at the ground surface or is present in the shallow subsurface (<10 ft) over much of the St. George–Hurricane metropolitan area making excavations for basements, foundations, underground utilities, and road cuts difficult in many areas (figure 9). Bedrock in the study area ranges from hard, resistant units that may require blasting to softer, less resistant units that typically can be excavated without or with only minimal blasting.

Figure 9*. Construction of a sewer line in an area of shallow bedrock in St. George; this excavation was made without blasting.*

Classification

Shallow bedrock is considered an adverse construction condition and not a geologic hazard. We grouped shallow bedrock on the Shallow-Bedrock–Susceptibility Map (plate 10) into three categories based upon degree of induration and depth of burial. The bedrock categories are as follows:

BR_H Hard: Areas where generally hard and resistant bedrock crops out at the ground surface. These bedrock units typically require blasting to excavate.

BR_S Soft: Areas where less resistant bedrock crops out at the ground surface. Even when fresh, these bedrock units typically can be excavated without blasting, although blasting may be required locally. Some rock units may contain expansive clay minerals and may be deeply weathered.

BR_B Buried: Areas where depth to bedrock is generally ≤10 feet beneath soil cover. In most areas the identity and degree of weathering of the underlying bedrock is unknown. However, many basalt flows in the study area, which consist of very hard and durable rock, are covered with a thin veneer of soil and fall into this category.

Using This Map

The Shallow-Bedrock-Susceptibility Map (plate 10) shows locations where bedrock crops out at the ground surface or is present in the shallow subsurface in the St. George–Hurricane metropolitan area. The map is intended for general planning purposes to indicate where adverse bedrock conditions may exist and special studies may be required. The UGS recommends performing a site-specific geotechnical foundation/geologic-hazards study for all development at all locations in the study area. Site-specific studies can resolve uncertainties inherent in generalized mapping and help ensure safety by identifying the need for special foundation designs or mitigation techniques. The presence and severity of bedrock conditions along with other adverse construction conditions and geologic hazards should be addressed in these investigations. If shallow bedrock is present at a site, appropriate design recommendations should be provided. Where onsite wastewater disposal systems are planned, system installation must meet the requirements of Utah Department of Environmental Quality Rule R317-4-5, Soil and Ground Water Requirements (Utah Department of Environmental Quality, 2006).

Map Limitations

The Shallow-Bedrock-Susceptibility Map (plate 10) is based on limited geologic and geotechnical data; site-specific studies are required to produce more detailed geotechnical information. The map also depends on the quality of those data, which varies throughout the study area. The boundaries of the susceptibility categories are approximate and small areas of shallow bedrock may exist throughout the study area, but their identification is precluded because of limitations of map scale. This map is not intended for use at scales other than the published scale, and is designed for use in general planning to indicate the need for site-specific studies.

Mitigation

Although potentially costly when not recognized and properly accommodated in project design and construction, problems associated with adverse bedrock conditions are not life threatening. As with most adverse construction conditions, early recognition and avoidance is the most effective way to mitigate potential problems. However, shallow bedrock is widespread in the St. George–Hurricane metropolitan area, and avoidance may not be a viable or cost-effective mitigation option. Where shallow bedrock is present, blasting may be required to excavate, and a sewer system may be required for waste-water disposal.

CALICHE

Caliche is a term broadly applied to calcareous material of secondary origin that typically accumulates through pedogenic processes in the shallow subsurface of soils in arid and semiarid climates (Bates and Jackson, 1987). Caliche is composed largely of soluble calcium carbonate ($CaCO_3$), but may include magnesium, silica, or gypsum. Caliche's physical characteristics range, depending on degree of development, from soft, thin, discontinuous coatings and filaments to strongly indurated and impermeable horizons up to several feet thick (figure 10). Other names commonly applied to these thick, impermeable caliche layers are hardpan, calcareous duricrust, or calcrete. Caliche is of concern for three reasons: first, because thick, well-indurated caliche horizons approach the hardness of rock, making excavation difficult, second, because as the soluble salts accumulate, they reduce soil permeability, which can affect the operation of individual wastewater disposal systems, or other engineering or agricultural applications that require free-draining soils, and third, because $CaCO_3$ is soluble, caliche may be subject to dissolution if subjected to prolonged wetting, which may cause a loss of internal volume and result in localized land subsidence and sinkhole formation.

Figure 10. *Well-developed caliche horizon (white) exposed in a test pit near Ivins.*

Table 7. *Geologic deposits known or likely to contain strongly indurated caliche (map category Ca).*

Type of Deposit	Map Units[1]
Stream and Terrace Alluvium	Qat_3, Qat_4, Qat_5, Qat_6, Qat_7, $QTat_7$, Tat_8, QTato, Qato, Qatb, Qas, Qagv, $Qagv_2$, Qagw, Qagi, QTag, Qag, Tag
Fan Alluvium	Qaf_2, Qaf_5, Qaf_6, Qafo, Qa/Qafo, Qaeo, Qaow, Qaec[2], Qao, Qab, Qabo, Qap, Qap_3, Qap_4, Qap_6, Qmfo
Eolian Deposits	Qes, Qea, Qea_2, Qea_3, Qes/Qaf_5, Qes/Qafo, Qeca, QTeca, Qecl, Qeo, Qec/Qb, Qec/Qbcp, Qec/Qbd, Qec/Qbg, Qec/Qbgw, Qec/Qbi, Qec/Qbr, Qec/Qbv_1, Qec/Qbv_2, Qec/Qbv_3

[1]Refer to UGS geologic quadrangle maps (see SOURCES OF DATA above and REFERENCES below) for a description of map units. [2]In the Pintura quadrangle only.

Description

While less common than shallow bedrock, strongly indurated caliche layers are also present in the St. George–Hurricane metropolitan area. Caliche forms progressively over time and therefore is typically better developed in older unconsolidated deposits. Because caliche forms in the subsurface, its presence can be difficult to recognize in the absence of test-pit or borehole information.

Classification

Caliche is considered an adverse construction condition and not a geologic hazard. The accompanying Caliche-Susceptibility Map (plate 11) shows areas where unconsolidated Quaternary and Tertiary deposits in the St. George–Hurricane metropolitan area (table 7) do or may contain strongly indurated caliche layers in the subsurface.

Ca Areas where caliche horizons have been identified or where older (Pleistocene) deposits are present which may contain caliche in the subsurface. Strongly indurated caliche layers may approach the hardness of bedrock and greatly reduce soil permeability.

Using This Map

The Caliche-Susceptibility Map (plate 11) shows where strongly indurated caliche either is or may be present in the St. George–Hurricane metropolitan area. The map is intended for general planning purposes to indicate where adverse caliche conditions may exist and special studies may be required. The UGS recommends performing a site-specific geotechnical foundation/geologic-hazards study for all development at all locations in the study area. Site-specific studies can resolve uncertainties inherent in generalized mapping and help ensure safety by identifying the need for special foundation designs or mitigation techniques. The presence and severity of caliche conditions along with other adverse construction conditions and geologic hazards should be addressed in these investigations. If indurated caliche is present at a site, appropriate design recommendations should be provided. Where onsite wastewater disposal systems are planned, system installation must meet the requirements of Utah Department of Environmental Quality Rule R317-4-5, Soil and Ground Water Requirements (Utah Department of Environmental Quality, 2006).

Map Limitations

The Caliche-Susceptibility Map (plate 11) is based on limited geologic and geotechnical data; site-specific studies are required to produce more detailed geotechnical information. The map also depends on the quality of those data, which varies throughout the study area. The boundaries of the susceptibility category are approximate and subject to change with additional information. Small, localized areas of caliche may exist throughout the study area, but their identification is precluded because of limitations of map scale. This map is not intended for use at scales other than the published scale, and is designed for use in general planning to indicate the need for site-specific studies.

Mitigation

Although potentially costly when not recognized and properly accommodated in project design and construction, problems associated with caliche are not life threatening. As with most adverse construction conditions, early recognition and avoidance is the most effective way to mitigate potential problems. However, caliche is widespread in the metropolitan area, and avoidance may not be a viable or cost-effective mitigation option. Where strongly indurated caliche is present, blasting may be required to excavate, and a sewer system may be required for waste-water disposal.

WIND-BLOWN SAND

Unless stabilized by natural vegetation or by artificial means, loose sand will move in response to high-velocity and long-duration wind. Wind transport (e.g., saltation; deBlij and Muller, 1996) winnows the sand, producing a well-sorted (poorly graded) deposit that typically consists of subrounded to rounded sand grains with diameters ranging from very fine to coarse sand (0.1 to 1.0 mm; Bates and Jackson, 1987). The fines content (silt and clay fraction) in wind-blown sand is generally less than 10 percent. Depending on topography, wind characteristics, and sand availability, blowing sand may accumulate in dunes or sand sheets, both of which may cover large areas.

If development encroaches into areas with sandy soil and disturbs the natural vegetative cover, wind-blown sand may migrate across roads and bury structures (Mulvey, 1992; Hayden, 2004). Stabilized sand dunes and sand sheets may react in the same manner if disturbed by construction. High winds can move fines by suspension and produce sand and dust storms that reduce visibility to near zero and sandblast vehicles and structures.

Description

Several sandstone formations crop out extensively within the St. George–Hurricane metropolitan area. Sand eroded from those bedrock units is the principal source of wind-blown sand in the study area. Chief among the sandstone formations is the Navajo Sandstone (figure 11), which consists of a thick (~2000 ft) sequence of lithified, mostly wind-blown sand of Jurassic age. The sand released by weathering and erosion from the Navajo Sandstone is in effect "fossil" dune sand that has the same size, sorting, and grain-shape characteristics of sand comprising modern sand dunes and sand sheets. Other bedrock formations that are less prolific, but still important sources of sand include the Moenave and Kayenta Formations, and the Shinarump Member of the Chinle Formation.

Figure 11. *Outcrop of the Navajo Sandstone with vegetation-stabilized Sand dunes in the foreground.*

Active Wind-Blown Deposits

Utah Geological Survey geologic maps (see SOURCES OF DATA) show that wind-derived sand deposits are common in the study area. Similarly, the NRCS mapped three soil units, the Mespun, Pintura, and Dune Land, which are comprised primarily of wind-blown sand (Mortensen and others, 1977). Both the UGS and NRCS mapping encompass what are chiefly geologically young, active or partially stabilized, wind-blown sand deposits characterized by dune or sand-sheet morphology; ripple marks; quickly migrating areas of sand accumulation and erosion; and very well-sorted, loose, sandy soil texture with few or no fines (figure 12).

Figure 12. *Sand dunes partially stabilized by vegetation near Ivins.*

Mixed-Unit Deposits

Through erosion, the Navajo Sandstone, and to a lesser extent other sandstone formations, contribute large quantities of already size-sorted sand. Once weathered from the rock, some of this sand is entrained almost immediately by the wind and incorporated into modern sand-dune and sand-sheet deposits. However, most of the sand is transported by a combination of mechanisms including wind, water, and gravity to form mixed-unit geologic deposits (figure 13). The characteristics of mixed-unit deposits typically reflect their dominant transport method. Mixed-unit deposits form a vast reservoir of size-sorted sand, but typically have higher fines content (up to 30%) than true wind-blown deposits. Mixed-unit deposits remain largely stable in their natural state, but may become susceptible to wind transport when disturbed. Although possessing a "sandy" appearance, mixed-unit deposits typically lack the characteristic morphology and texture of true wind-blown sand.

Figure 13. *Mixed-unit geologic deposit near Ivins containing a high percentage of size-sorted sand, but abundant fines (silt and clay) as well.*

Classification

Wind-blown sand is considered an adverse construction condition and not a geologic hazard, although during high wind events, blowing sand and dust may become a hazard to driving. We grouped wind-blown sand deposits and mixed-unit geologic deposits containing a wind-blown sand component (table 8) into one of three susceptibility categories on the Wind-Blown-Sand-Susceptibility Map (plate 12). Because wind-blown sand is considered an adverse construction condition and not a geologic hazard, the classification system presented below is a relative-susceptibility ranking, as opposed to a hazard-severity ranking such as those used on the geologic-hazard maps prepared for this study. The wind-blown-sand-susceptibility categories are as follows:

WBS_H High: Modern sand-dune or sheet-sand deposits, either active or stabilized by natural vegetation. These active wind-blown deposits or reactivated formerly stabilized deposits are highly susceptible to wind erosion and transport. The moving sand may form deposits that can surround houses and bury fields and transportation corridors.

WBS_M Moderate: Mixed-unit geologic deposits for which wind was the dominant transport mechanism. These units contain a high percentage of size-sorted sand, but also contain up to 30 percent fines incorporated into the deposit due to water or gravity transport. These units are generally stable in their natural state, but may destabilize if disturbed.

WBS_L Low: Mixed-unit geologic deposits which contain a wind-blown component, but for which the wind was not the dominant transport mechanism. Water and/or gravity transport predominate in these deposits, and they may contain in excess of 30 percent fines and thin horizons of fine- to medium-grained gravel. These units are generally stable in their natural state, but may destabilize locally if disturbed by construction. Also included in this category are older (Pleistocene) wind-blown and mixed-unit geologic deposits that have developed thick, indurated calcium carbonate (caliche) horizons over time that help to further stabilize the deposits, but which may become destabilized if disturbed.

Table 8. *Geologic deposits with a significant wind-blown sand component.*

Type of Deposit	Map Units[1]	Wind-Blown Sand Susceptibility Category
Modern Eolian Deposits	Qed, Qes, Qe/Qmsy, Qes/Qaf_5, Qes/Qafo	WBS_H
Young, Dominantly Eolian Mixed Units	Qea, Qea_1, Qec	WBS_M
Minor Eolian Mixed Units	Qae, Qaec, Qaeg, Qaeo	WBS_L
Older Eolian or Dominantly Eolian Mixed Units	Qeo, Qeca, QTeca, Qec_l, Qea_2, Qea_3, Qec/Qb, Qec/Qbcp, Qec/Qbd, Qec/Qbg, Qec/Qbgw, Qec/Qbi, Qec/Qbr, Qec/Qbv_1, Qec/Qbv_2, Qec/Qbv_3	WBS_L

[1]Refer to UGS geologic quadrangle maps (see SOURCES OF DATA above and REFERENCES below) for a description of map units.

Using This Map

The Wind-Blown-Sand-Susceptibility Map (plate 12) shows the location of areas susceptible to wind-blown sand in the St. George–Hurricane metropolitan area. The map is intended for general planning purposes to indicate where sand deposits susceptible to wind erosion may exist and where special studies may be required. The UGS recommends performing a site-specific geotechnical foundation/geologic-hazards study for all development at all locations in the study area. Site-specific studies can resolve uncertainties inherent in generalized mapping and help ensure safety by identifying the need for special foundation designs or mitigation techniques. The presence and severity of potential wind-blown-sand areas along with other adverse construction conditions and geologic hazards should be addressed in these investigations. If a potential for wind-blown sand is present at a site, appropriate design recommendations should be provided.

Map Limitations

The Wind-Blown-Sand-Susceptibility Map (plate 12) is based on limited geologic data; site-specific studies are required to produce more detailed geotechnical information. The map also depends on the quality of those data, which varies throughout the study area. The boundaries of the susceptibility categories are approximate and subject to change with additional information. Localized areas susceptible to wind-blown sand may exist throughout the study area, but their identification is precluded because of limitations of map scale. This map is not intended for use at scales other than the published scale, and is designed for use in general planning to indicate the need for site-specific studies.

Mitigation

Although potentially costly when not recognized and properly accommodated in project design and construction, problems associated with wind-blown sand rarely are life threatening. As with most adverse construction conditions, early recognition and avoidance is the most effective way to mitigate potential problems. However, sand deposits susceptible to wind erosion are widespread in the St. George–Hurricane metropolitan area, and avoidance may not be a viable or cost-effective hazard-reduction option.

In Utah, soil-test requirements are specified in the soil and foundations provisions of IBC Chapter 18 (p. 343) and the foundations provisions of IRC Chapter 4 (p. 42), which are adopted statewide. IBC Section 1802.2.1 (p. 343) contains requirements for soil investigations in areas where questionable soil (soil classification, strength, or compressibility in doubt) is present. IRC Section R401.4 (p. 67) states that the building official shall determine whether to require a soil test to determine the soil's characteristics in areas likely to have expansive, compressible, shifting, or other unknown soil characteristics. Where the presence of wind-blown sand is confirmed, possible mitigation techniques include vegetative stabilization and thatching, geotextiles, sand fences, and armor stone.

SOIL PIPING AND EROSION

Piping refers to the subsurface erosion of permeable, fine-grained, unconsolidated or semi-consolidated deposits by percolating ground water (Cooke and Warren, 1973; Costa and Baker, 1981; Black and others, 1999) (figure 14). Piping creates

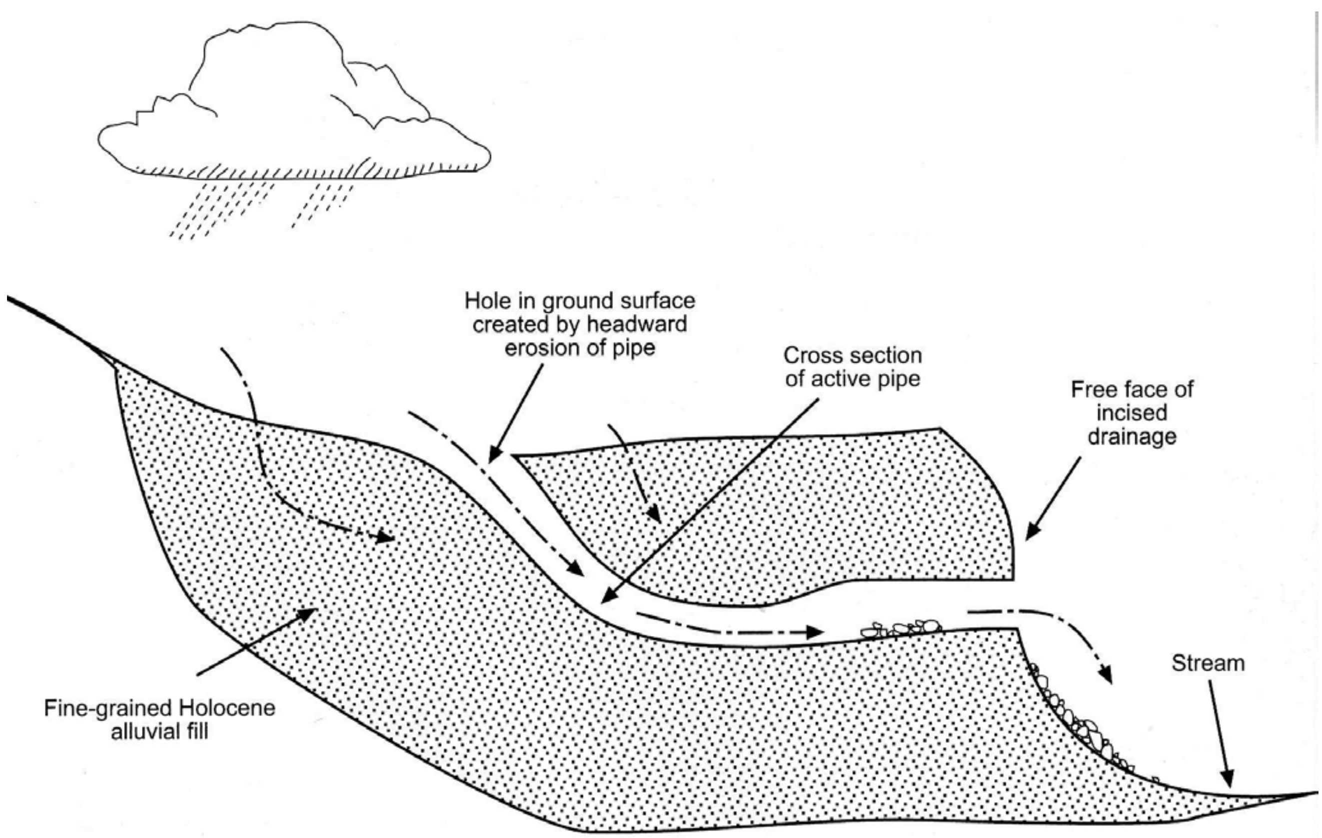

Figure 14. Cross section of a pipe in Holocene alluvium (after Black and others, 1999).

narrow, subterranean conduits that grow both in diameter and length as increasingly more subsurface material is removed and as the cavities trap greater amounts of ground-water flow. Piping eventually leads to caving and collapse of the overlying surficial materials (figure 15), and is an important process in the headward extension of gullies in the arid southwestern United States (Costa and Baker, 1981). For piping to take place, the following conditions are required: (1) fine-grained, noncohesive or poorly consolidated, porous materials, such as silt, some clay, fine sand, volcanic ash or tuff, and poorly indurated siltstone and claystone, (2) a sufficiently steep hydraulic gradient to cause ground water to percolate through the subsurface materials, and (3) a free face which intersects the permeable, water-bearing horizon and from which the water can exit the eroding deposit. The walls of an incised stream channel commonly provide the necessary free face, but human-made excavations such as cuts for canals or roads may also induce piping. Parker and Jenne (1967; in Costa and Baker [1981]) describe extensive damage to U.S. Highway 140 where it traverses dissected and extensively piped valley fill along Aztec Wash in southwestern Colorado.

Figure 15. *Collapsed pipe in fine-grained flood-plain alluvium.*

Christenson and Deen (1983) report piping at several locations within the St. George–Hurricane metropolitan area.

The characteristics that make soils susceptible to piping (fine-grained texture, little or no internal cohesion, and loose or poor consolidation) are also typical of highly erosive soils. Consequently, piping often develops in otherwise highly erodible soils.

Highly erosive soils are typically silts and clean sands that have little or no internal cohesion and are easily susceptible to detachment and movement by water and wind. In southern Utah, most erosion occurs during cloudburst storms and is caused by sheetwash and eventual channelization of runoff. If disturbed, highly erosive soils become even more susceptible to erosion, particularly when stabilizing vegetation is removed. Erosion is also an important issue along stream courses in the study area. In studies performed for the City of St. George (CH2MHILL, 1997) and the Washington County Water Conservancy District (JE Fuller Hydrology & Geomorphology, Inc., 2005, 2007) the Virgin and Santa Clara Rivers were identified as having high potential for lateral bank cutting and erosion. As the January 2005 flood on those two drainages forcefully demonstrated, such concern is well placed as more than 20 homes on stream terraces adjacent to the rivers were destroyed or damaged by bank erosion during the flood.

Description

Utah Geological Survey geologic maps (SOURCES OF DATA) show that fine-grained, noncohesive, loose sand and silt deposits are present in many areas of the St. George–Hurricane metropolitan area. They include wind-derived sand deposits and mixed-unit geologic deposits that contain a high percentage of “fossil” wind-blown sand derived from the weathering and erosion of the sandstone, or sandstone-bearing bedrock formations that crop out in the study area.

Classification

Soil susceptible to piping and rapid erosion is considered an adverse construction condition and not a geologic hazard. The Piping- and Soil-Erosion-Susceptibility Map (plate 13) shows the location of potentially pipeable and highly erosive fine-grained, noncohesive, loose to poorly consolidated sand and silt deposits. Because piping only occurs where susceptible soils exist in the presence of a free face and percolating ground water, these soils in and of themselves do not create piping susceptibility. Conversely, a change in conditions brought about either naturally or through the action of humankind can create the conditions necessary for piping to occur. While susceptible to erosion, these soils are generally stable in their natural, undisturbed state, but can quickly erode if disturbed or if drainage conditions change in an uncontrolled manner.

We grouped unconsolidated geologic deposits considered susceptible to piping and erosion (table 9) into a single susceptibility category, which is characterized as follows:

P&ES Soils susceptible to piping and erosion. Generally fine-grained, noncohesive, loose to poorly consolidated sand and silt deposits, landslide deposits, and some poorly consolidated siltstone and claystone. For piping to develop, a free face and percolating ground water are necessary requirements. The loose, noncohesive nature of erodible soils makes them highly susceptible to the effects of water and wind erosion, especially when disturbed from their natural conditions.

Table 9. *Geologic deposits susceptible to piping and erosion (map category P&ES).*

Type of Deposit	Map Units[1]
Stream Alluvium	Qal_1
Fan Alluvium	Qae, Qac, Qap_1, Qaec, Qaes, Qaeg
Eolian Deposits	Qes, Qed, Qea, Qea_1, Qec, Qe/Qmsy, Qes/Qaf_5, Qes/Qafo,
Landslide Deposits	Qms, Qmsy, Qmsm, Qmsh, Qmsc, Qmsb, Qmso
Poorly Consolidated Bedrock	Petrified Forest Mbr., Chinle Fm.; Shnabkaib Mbr. and red mbrs., Moenkopi Fm.; lower mbr., Kayenta Fm.; Kayenta Fm. undivided; Whitmore Point and Dinosaur Canyon Mbrs., Moenave Fm.

[1]Refer to UGS geologic quadrangle maps (see SOURCES OF DATA above and REFERENCES below) for a description of map units.

Using This Map

The Piping- and Soil-Erosion-Susceptibility Map (plate 13) shows the location of unconsolidated geologic deposits in the St. George–Hurricane metropolitan area that are susceptible to piping and erosion. The map is intended for general planning purposes to indicate where susceptible soils exist and where special studies may be required. The UGS recommends performing a site-specific geotechnical foundation/geologic-hazards study for all development at all locations in the study area. Site-specific studies can resolve uncertainties inherent in generalized mapping and help ensure safety by identifying the need for special foundation designs or mitigation techniques. The presence of soils susceptible to piping and erosion along with other adverse construction conditions and geologic hazards should be addressed in these investigations. If a potential for piping and erosion is present at a site, appropriate design recommendations should be provided.

Map Limitations

The Piping- and Soil-Erosion-Susceptibility Map (plate 13) is based on limited geologic and geotechnical data; site-specific studies are required to produce more detailed geotechnical information. The map also depends on the quality of those data, which varies throughout the study area. The boundaries of the areas shown as susceptible to piping and erosion are approximate and subject to change with additional information. Localized areas of piping and soil-erosion susceptibility may exist throughout the study area, but their identification is precluded because of limitations of map scale. This map is not intended for use at scales other than the published scale, and is designed for use in general planning to indicate the need for site-specific studies.

Mitigation

Although potentially costly when not recognized and properly accommodated in project design and construction, problems associated with piping and highly erosive soils rarely are life threatening. As with most adverse construction conditions, early recognition and avoidance is the most effective way to mitigate potential problems. However, soils susceptible to piping and erosion are widespread in the St. George–Hurricane metropolitan area, and avoidance may not be a viable or cost-effective mitigation option.

In Utah, soil-test requirements are specified in the soil and foundations provisions of IBC Chapter 18 (p. 343) and the foundations provisions of IRC Chapter 4 (p. 42), which are adopted statewide. IBC Section 1802.2.1 (p. 343) contains requirements for soil investigations in areas where questionable soil (soil classification, strength, or compressibility in doubt) is present. IRC Section R401.4 (p. 67) states that the building official shall determine whether to require a soil test to determine the soil's characteristics in areas likely to have expansive, compressible, shifting, or other unknown soil characteristics. Where the presence of soils susceptible to piping or rapid erosion is confirmed, possible mitigation techniques include minimizing disturbance of vegetated areas, controlling the flow of shallow ground water, and managing surface drainage onsite in a controlled manner.

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SECTION 8:
SHALLOW GROUND WATER

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SECTION 8:
SHALLOW GROUND WATER

INTRODUCTION

Ground water is water in saturated zones beneath the land surface in soil and rock at various depths. Ground water fills fractures and pore spaces in rocks and voids between grains in unconsolidated deposits (clay, silt, sand, and gravel). Ground water may exist under either unconfined (water table) or confined (artesian/pressurized) conditions, in regional aquifers or as local perched zones. Shallow ground-water levels are typically dynamic and fluctuate in response to a variety of conditions. Ground-water levels may rise or fall in response to seasonal variations in precipitation, long-term climatic change, irrigation, pumping, and the effects of urban development (lawn watering, roof and pavement runoff, septic-tank systems).

Ground water can be one of the most costly factors in construction and land development if it is not recognized and taken into consideration in the planning process (Shelton and Prouty, 1979). However, shallow ground water rarely if ever causes rapid, catastrophic property damage or is a threat to life safety; therefore, for purposes of this study, shallow ground water is considered an adverse construction condition and not a geologic hazard. Most construction-related ground-water problems occur when ground water is within 10 feet of the ground surface. Shallow ground water (≤10 feet; figure 1) can flood basements and other underground facilities, damage buried utility lines, and destabilize excavations (Black and others, 1999). Inundation of landfills, waste dumps, and septic-tank systems can impair the performance of those facilities and lead to ground-water contamination. Because of its ability to change the physical and chemical nature of rocks and soil, ground water can also induce volumetric change in expansive and collapsible soils, and is a major factor in slope instability (Ashland and others, 2005, 2006). During earthquakes, ground water within 50 feet of the ground surface may cause some soils to liquefy.

This study only considers shallow (≤10 feet), unconfined ground water in unconsolidated basin-fill deposits. Shallow ground water in rock generally poses few geotechnical problems. Foundations and conventional wastewater disposal systems in rock are uncommon and foundation stability is seldom appreciably reduced by saturated conditions. Additionally, determining if shallow ground water in rock is under water-table or confined conditions is often difficult.

***Figure 1**. Shallow, possibly perched, ground water in fine-grained valley-fill alluvium.*

SOURCES OF DATA

We evaluated shallow ground-water conditions using the following data: (1) 275 geotechnical reports obtained from municipalities in the study area and from the Utah Department of Transportation, (2) water-well driller's logs on file with the Utah Division of Water Rights, (3) the occurrence of wet or potentially wet soils mapped by the Natural Resources Conservation Service (NRCS; formerly the U.S. Soil Conservation Service) (Mortensen and others, 1977), (4) the distribution of unconsolidated geologic deposits typically associated with shallow ground water from nine digital Utah Geological Survey (UGS) 1:24,000-scale (1 inch = 2000 feet) geologic quadrangle maps covering the study area (Harrisburg Junction [Biek, 2003a], Hurricane [Biek 2003b], Pintura [Hurlow and Biek, 2003], Santa Clara [Willis and Higgins, 1996], St. George [Higgins and Willis, 1995], The Divide [Hayden, 2004], Washington [Willis and Higgins, 1995], Washington Dome [Hayden, 2005], and White Hills [Higgins, 1997]), and (5) unpublished UGS data on depth to water in the City of St. George.

The geotechnical and water-well data are unevenly distributed throughout the study area; geotechnical data are available only where development has already occurred, and water-well data are largely confined to agricultural areas. Consequently, detailed depth to ground water information is not available for much of the study area, including many areas where development may occur in the future. Regional ground-water information is provided by Cordova and others (1972) and Hecker and others (1988).

SHALLOW GROUND-WATER OCCURRENCE

Arid desert climate conditions characterize the St. George–Hurricane metropolitan area. Average annual precipitation at St. George is 8.25 inches for the period October 1, 1892, to December 31, 2005 (Western Regional Climate Center, 2006), and between June and September daytime temperatures commonly exceed 100° Fahrenheit. Low precipitation and high evaporation make water from all sources limited in the study area, and consequently shallow ground water is not widespread. Prior to settlement in the 1880s, shallow ground water was confined to flood-plain deposits along perennial streams and to the vicinity of springs and natural seeps. With the advent of agricultural irrigation and recent rapid urbanization, both perched and seasonally shallow ground water have developed in formerly dry areas. Perched ground water develops where water from irrigation or urban runoff percolates through thin, permeable, unconsolidated surface deposits and ponds on less permeable underlying bedrock or clay-rich layers. In addition, when water application rates exceed a soil's drainage capacity, a temporary shallow water table can develop until the water application stops and the soil has time to drain.

The 275 geotechnical consultant's reports collected for this study represent 5177 test pits or borings, of which 222 (4%) encountered ground water at depths ≤10 feet. The 222 occurrences represent 51 separate sites, or 19 percent of the sites for which geotechnical reports were available. Twenty-seven of the 235 water-well logs examined for this study recorded shallow ground water in unconsolidated deposits under probable unconfined conditions. The remaining wells either were dry, had depths to water >10 feet, reported ground water in bedrock, or lacked sufficient information to determine the conditions under which the ground water is present. Of the 78 geotechnical sites or water wells with shallow unconfined ground water in unconsolidated deposits, 15 (19%) are in areas mapped by the NRCS as having wet soils and shallow ground water. An additional 59 sites (76%) are in areas mapped by the NRCS as having potentially wet soils depending on local conditions. The remaining four sites (5%) are at locations not associated by the NRCS with shallow ground-water conditions.

Given the limited size and distribution of the existing ground-water data set, we could not establish a correlation between shallow ground water and individual geologic units. In most cases the number of test pits, borings, or wells recording shallow ground water in a given geologic unit were equaled or exceeded by dry recordings, or recordings of depths to water of >10 feet in the same unit. Dry or deep-water records are frequently situated between adjacent shallow ground-water measurements.

In addition to naturally wet areas mapped by the NRCS, areas of likely perched ground water chiefly related to irrigation, urbanization, or leakage from unlined irrigation canals exist locally within the study area. Naturally occurring springs or water migrating from bedrock aquifers into unconsolidated deposits in the shallow subsurface also create wet areas (UGS unpublished information). Although augmented by urban runoff, this is thought to be the principal source of the shallow ground water in St. George east of West Black Ridge and west of Interstate 15, where long-term evaporation of shallow ground water has caused formation of gypsiferous "water rock" in some areas (Christenson and Deen, 1983). Water rock consists of shallow, impermeable gypcrete formed at the water table that locally confines shallow ground water and creates artesian conditions.

In Ivins, shallow ground-water measurements cluster in an area from 200 to 600 South and from about 600 East to Main Street. Surficial deposits in this area are permeable, fine- to medium-grained sand with interbeds of silty sand, clayey sand, and clay. Bedrock is at shallow depths, probably everywhere less than 30 feet and typically less than 15 feet. Bedrock exposed along the east side of the shallow ground-water area is gently east-dipping mudstone and fine-grained sandstone of the Jurassic Dinosaur Canyon Member of the Moenave Formation that likely underlies the northern part of the shallow ground-water area. The Petrified Forest Member of the Chinle Formation, which consists chiefly of expansive, moderate- to high-plasticity clay and shale, underlies the southern part of the shallow ground-water area. Both of these bedrock formations have very low permeability. The shallow ground water likely results from infiltration of water from lawns, street and roof runoff, and other human-related sources, perching on the underlying, less permeable bedrock. The configuration of the bedrock surface beneath the overlying deposits is not known, but paleotopography on that surface may be concentrating ground water at low spots on the bedrock surface. Buried topography also may be directing some water from more urbanized parts of Ivins to the north and northwest to the wet area.

In the Santa Clara Heights section of Santa Clara, RB&G Engineering, Inc. (1994) documented a situation similar to that described above, where fine- to medium-grained sand deposits and Santa Clara River gravel deposits overlie the Petrified Forest Member of the Chinle Formation. Paleotopography on the buried Chinle surface collects and localizes subsurface water in preferred locations. Most of the shallow ground water likely comes from lawn watering and other urban runoff, although some ground water may be migrating into the area from the northwest along the sand/bedrock contact. Expansion of Chinle shale and clay wetted by shallow ground water in formerly dry areas has produced locally severe foundation problems in Santa Clara Heights, prompting the City of Santa Clara to install subsurface drains at strategic locations to lower ground-water levels. The addition of ground water has also contributed to several landslides around the edges of the Santa Clara bench.

Areas of shallow, perched ground water too small to map at 1:24,000 scale (1” = 2000 feet) exist in locations otherwise considered “dry” within the St. George–Hurricane metropolitan area, and demonstrate the relative ease with which perched ground water can develop where shallow permeable soils overlie less permeable bedrock. An example of such an area is the Sports Village in Green Valley atop a bench capped by calcified Santa Clara River gravels. Excavations have broken through the impermeable caliche cap, allowing infiltrating landscape-irrigation water to become perched on the underlying Petrified Forest Member of the Chinle Formation, causing shallow ground-water conditions and triggering landslides on the slopes surrounding the bench (Christenson, 1986).

We expect that as urbanization continues in the St. George–Hurricane metropolitan area, additional perched and seasonally shallow ground water will develop in formerly dry areas. Conversely, in areas where irrigated agricultural land is taken out of production and converted to urban uses, net water application rates may decrease (agricultural irrigation versus lawn watering) causing ground-water levels to locally drop or stabilize.

SHALLOW GROUND-WATER CLASSIFICATION

Soils in the study area that are either naturally wet or have a greater than normal potential to develop wet conditions are labeled SGW_1, SGW_2, and SGW_3 on the accompanying Shallow Ground-Water-Susceptibility Map (plate 14). Because shallow ground water represents an adverse construction condition and not a geologic hazard, the shallow ground-water classifications below do not represent relative severity rankings (Low, Medium, High) as is the case on the hazard maps prepared for this study. The shallow ground-water categories are as follows:

SGW_1 Naturally wet soils mapped by the NRCS (depth to ground water ≤60 inches), and soils mapped by the NRCS as poorly drained or frequently irrigated where water-well or geotechnical information indicates a significant area of permanent shallow ground water (≤10 feet). Construction in these areas will likely encounter shallow ground water at depths ≤10 feet, and basements and other water-sensitive underground facilities are not recommended without adequate drainage or other protection. Following development, lawn watering and other sources of urban runoff may cause ground-water levels to rise even higher in these areas.

SGW_2 Poorly drained, generally fine-grained soils mapped by the NRCS that may develop shallow ground water locally when rates of water application exceed the soil’s drainage capacity. Subsurface drains are frequently required to prevent these soils from becoming saturated. Because these soils naturally drain slowly, they may remain wet for most of the year, even though water is applied only during the growing season. Permanent shallow ground water is possible following urbanization.

SGW_3 Moderatly to freely draining soils mapped by the NRCS that are commonly irrigated for agricultural purposes. Where high rates of water application occur, these soils may develop seasonally shallow ground water, but typically drain quickly once water application stops or is reduced below the soil’s drainage capacity. Seasonal or transient shallow ground water is possible following urbanization.

USING THIS MAP

The Shallow-Ground-Water-Susceptibility Map (plate 14) shows the location of known and possible areas of shallow ground water in the St. George–Hurricane metropolitan area. The map is intended for general planning purposes to indicate where shallow ground water may be present and where special studies may be required. The UGS recommends a site-specific geotechnical foundation/geologic-hazards study for all development at all locations in the St. George–Hurricane metropolitan area. Site-specific studies can resolve uncertainties inherent in generalized hazard mapping and help ensure safety by identifying the need for special foundation designs or mitigation techniques. This is particularly true in the case of shallow ground water because our geotechnical database indicates that localized areas of shallow, perched ground water too small to show on the Shallow-Ground-Water-Susceptibility Map (plate 14) may be present anywhere within the study area. A site-specific investigation can establish the presence or absence of shallow ground water at a site, and if shallow ground water is present or is expected to be seasonally present, estimate the shallowest ground-water level expected. Doing so may require monitoring observation wells through more than one season and/or examining sediments exposed in test pits for evidence of seasonal ground-water fluctuations. If shallow ground water is present, or if the potential for seasonal shallow ground water exists, the consultant should provide appropriate design recommendations.

MAP LIMITATIONS

The Shallow-Ground-Water-Susceptibility Map (plate 14) is based on limited geologic, geotechnical, and hydrologic data; site-specific studies are required to produce more detailed geotechnical information. The map also depends on the quality of those data, which varies throughout the study area. Therefore, the map-unit boundaries are approximate and subject to change with additional information. Shallow ground-water conditions at any particular location may be different than shown because of geological or hydrologic variations within a map unit, gradational and approximate map-unit boundaries, and the generalized map scale. Localized areas of shallow, perched ground water may exist anywhere within the map area, but their identification is precluded because of data limitations and map scale. Seasonal and long-term fluctuations in weather patterns and changes in land use also may affect the depth to ground water at a site. This map is not intended for use at scales other than the published scale, and is designed for use in general planning to indicate the need for site-specific studies.

MITIGATION TECHNIQUES

Although potentially costly when not recognized and properly accommodated in project design, problems associated with shallow ground water rarely are life threatening. As with most adverse construction conditions, avoidance is the most effective way to mitigate possible problems. However, avoidance is not always a viable or cost-effective option. International Building Code section 1807 (International Code Council, 2006a) and International Residential Code section R406 (International Code Council, 2006b) contain dampproofing and waterproofing requirements for structures built in wet areas. Slab-on-grade construction is common in shallow ground-water areas as is placing fill on a site to raise building elevations where seasonal fluctuations in ground water may bring water very near or to the ground surface. Other possible ground-water mitigation techniques include installing well point systems, sump pumps, horizontal drains, vertical sand drains, or creating a ground-water barrier using sheet piling, cutoff walls, or grouting (Water and Power Resource Service, 1981; formerly and since the U.S. Bureau of Reclamation). However, pumping can be expensive, and pumps are subject to mechanical failure and electrical power outages. Where possible, a system of subsurface gravity drains to collect and carry ground water away is the preferred mitigation technique; however, drains require periodic cleaning and other long-term maintenance.

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SECTION 9:
EARTHQUAKE-GROUND-SHAKING HAZARD

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SECTION 9: EARTHQUAKE-GROUND-SHAKING HAZARD

INTRODUCTION

Ground shaking is the most widespread and frequently occurring earthquake hazard. Ground shaking presents the greatest worldwide seismic hazard, and the greatest risk is structural damage that results from earthquake ground motion (Yeats and others, 1997). Ground shaking is caused as seismic waves originating at the source of the earthquake radiate outward in all directions. The extent of property damage and loss of life due to ground shaking depends on factors such as (1) the strength of the earthquake, (2) the proximity of the earthquake to an affected location, (3) the amplitude, duration, and frequency of earthquake ground motions, (4) the nature of the geologic materials through which the ground motions travel, and (5) the design of engineered structures (Costa and Baker, 1981; Reiter, 1990).

A building need only withstand the vertical force of gravity to support its own weight. However, during an earthquake a building is also subjected to horizontal forces. Horizontal ground motions are typically the most damaging type of earthquake ground shaking, and are expressed in decimal fractions of the acceleration due to gravity (1 *g*). Horizontal ground motions as small as 0.1 *g* may cause damage to weak structures (buildings not specifically designed to resist earthquakes) (Richter, 1958), and such horizontal motions may reach values greater than that of gravity.

Large magnitude earthquakes typically cause more damage because they result in stronger ground shaking for longer time periods. The strength of ground shaking generally decreases with increasing distance from the earthquake epicenter because the earthquake's energy scatters and dissipates as it travels through the earth. However, in certain cases earthquake ground motions can be amplified and shaking duration prolonged by local site conditions (Hays and King, 1982; Wong and others, 2002). The degree of amplification depends on factors such as soil thickness and the nature of geologic materials.

Risk to public safety due to earthquake ground shaking can be reduced by incorporating building-code-based earthquake-resistant construction requirements in new construction and when retrofitting existing structures.

SOURCES OF DATA

The principal sources of information for this earthquake-ground-shaking analysis of the St. George–Hurricane metropolitan area were the U.S. Geological Survey (USGS) National Seismic Hazard Maps Web site at http://earthquake.usgs.gov/research/hazmaps/ and the International Building Code (International Code Council, 2006a) and International Residential Code (International Code Council, 2006b).

INTERNATIONAL CODE COUNCIL SEISMIC DESIGN

The 2006 International Building Code (IBC) (International Code Council, 2006a) and International Residential Code (IRC) (International Code Council, 2006b) provide design and construction requirements for resisting earthquake motions (loads) based on a structure's seismic design category.

International Building Code

Determining an IBC seismic design category begins by defining a site class based on the types and engineering properties of soil and rock present in the upper 100 feet beneath a proposed building site (IBC Section 1613.5.2, p. 303). The IBC defines Site Classes A through F (table 1). Site Classes A through E (hard rock to soft soil) may be defined on the basis of average shear-wave velocity, average standard penetration resistance (blow count), or average undrained shear strength (table1). Additionally, soils may be classified as Site Class E or F depending upon other geotechnical characteristics that make them particularly vulnerable to earthquake ground shaking (table 1).

Next, maximum considered earthquake ground motions (maximum spectral response accelerations) on rock (Site Class B) are obtained from either IBC figures 1613.5(1) or 1613.5(2) (p. 308–311), or from the USGS National Seismic Hazard Maps at http://earthquake.usgs.gov/research/hazmaps. Different structures are affected by different ground shaking frequencies, which, when matching the natural frequency of vibration of a structure (a function of building height and construction type),

Table 1. *IBC site-class definitions (modified from IBC table 1613.5.2).*

Site Class	**Soil Profile Name**	**Average Properties in Top 100 Feet**		
		Shear-Wave Velocity - V_s ft/s (m/s)	Standard Penetration Test - N (blows/ft)	Undrained Shear Strength - S_u (psf)
A	Hard rock	>5,000 (>1500)	n.a.	n.a.
B	Rock	2,500-5,000 (760-1500)	n.a.	n.a.
C	Very dense soil and soft rock	1,200-2,500 (360-760)	>50	>2,000
D	Stiff soil	600-1,200 (180-360)	15-50	1,000-2,000
E	Soft soil	<600 (<180)	<15	<1,000
		Any profile with more than 10 feet of soil having the following characteristics: 1. Plasticity index >20 2. Moisture content >40% 3. Undrained shear strength <500 psf		
F	---	Any profile containing soils having one or more of the following characteristics: 1. Soils vulnerable to potential failure or collapse under seismic loading such as liquefiable soils, quick and highly sensitive clays, collapsible weakly cemented soils 2. Peats and/or highly organic clays (>10 feet thick) 3. Very high plasticity clays (>25 feet thick with plasticity index>75) 4. Very thick (>120 feet) soft/medium stiff clays		

may cause resonance resulting in severe damage or collapse. Therefore, the IBC and USGS provide maximum spectral response accelerations for two periods of ground motion (0.2 sec and 1.0 sec), which together are appropriate for a wide range of building types. The 0.2 sec maximum spectral response acceleration (S_s) is appropriate when evaluating the effect of short-period (high-frequency) ground motions, which typically affect short buildings (1–2 stories). The 1.0 sec maximum spectral response acceleration (S_1) is appropriate when evaluating the effect of long-period (low-frequency) ground motions, which typically affect tall buildings (more than 2 stories).

Maximum spectral response accelerations are appropriate for a rock site (Site Class B), and must be adjusted for deamplification or amplification of earthquake ground motions due to other site-specific soil and rock conditions. Accelerations are adjusted using site coefficients. The IBC provides site coefficients (F_a and F_v) for each site class for both short period (F_a) and long period (F_v) ground motions. Site coefficients for the other site classes are calculated relative to the coefficient (1.0) for Site Class B. Site coefficients less than one indicate that ground motions will be less than those for Site Class B (deamplified). A site coefficient greater than one indicates that ground motions will be greater than those for Site Class B (amplified). The site coefficients for both short- and long-period ground motions for Site Class A (hard rock) are 0.8, indicating that ground shaking will be deamplified. The site coefficients for Site Classes C, D, and E (very dense soil or soft rock, stiff soil, and soft soil, respectively) range from 0.9 to 3.5, indicating that ground shaking may either be deamplified or amplified, depending upon the period and strength of ground motions; amplification generally increases as the period increases and soil or rock strength decreases. Because of the unique properties of soils in Site Class F, the IBC does not provide site coefficients for that site class. Instead, the IBC requires that site-specific geotechnical investigations and dynamic site-response analyses be performed to determine appropriate values.

Multiplying the site coefficients times the maximum spectral response accelerations produces the adjusted maximum considered earthquake spectral response accelerations (S_{MS} and S_{M1}) that account for ground motion amplification or deamplification due to site-specific soil or rock conditions. The adjusted maximum considered earthquake spectral response accelerations are then multiplied by 2/3 to arrive at design spectral response accelerations (S_{DS} and S_{D1}). The seismic design category for the structure is then determined by comparing the design spectral response acceleration with the proposed structure's IBC Occupancy Category (IBC table 1604.5; p. 281) using IBC tables 1613.5.6(1) and 1613.5.6(2) (p. 306). Buildings and structures are assigned the more severe seismic design category, regardless of the fundamental vibration period of the structure. The resulting seismic-design category determines the applicable seismic-design requirements for the structure.

This procedure is automated using the USGS Java Ground Motion Parameter Calculator available at http://earthquake.usgs.gov/research/hazmaps/design/ (check USGS Web site for most recent version of the calculator)

International Residential Code

The IRC applies to one- and two-family dwellings and townhouses. The IRC bases its seismic design categories on soil Site Class D (Section R301.2.2.1.1; p. 43) as defined in Section 1613.2 (p. 303) of the IBC. For soil conditions other than Site Class D, the short period design spectral response acceleration (S_{DS}) for a site is determined according to Section 1613.5 (p. 303) of the IBC. The resulting IBC SDS value is used to determine the IRC seismic design category using IRC table R301.2.2.1.1 (p. 43).

IBC AND IRC SEISMIC DESIGN CATEGORIES

Insufficient geotechnical data are available, both in terms of geographic distribution and depth, to prepare an IBC site class map for the St. George–Hurricane metropolitan area. Table 2 shows IBC seismic design categories for all IBC site classes for the communities of Hurricane, La Verkin, Leeds, Ivins, Santa Clara, St. George, Toquerville, and Washington. Values of S_S, S_1, S_{MS}, S_{M1}, S_{DS}, S_{D1}, and the resulting seismic design categories were obtained for this study using the USGS National Seismic Hazard Maps Java Ground Motion Parameter Calculator–Version 5.0.0 at http://earthquake.usgs.gov/research/hazmaps/design/. To use table 2 most effectively, it is necessary to make site-specific site class determinations for individual projects.

IBC Site Class

Determining an IBC site class requires characterizing the average soil and rock properties in the top 100 feet beneath a project site (IBC Section 1613.5.5; p. 304). Site-class designation may be made on the basis of average shear-wave velocity (v_s) in feet or meters per second (fps/mps), standard penetration resistance (N or N_{ch}) in blows per foot, or average soil undrained shear strength (s_u) in pounds per square foot (psf). Ashland and Rollins (1999) found poor correlation among v_s, N, and s_u along the Wasatch Front, and prefer using v_s only. Profiles containing distinctly different soil and/or rock layers within the top 100 feet must be subdivided into those layers and geotechnical parameters obtained for each layer. The values for the individual layers are then averaged in accordance with IBC Section 1613.5.5 (p. 304).

Rock Sites

The IBC requires that the hard-rock category (Site Class A) be supported by a shear-wave-velocity measurement either on site or from the same rock formation off site with an equal or greater degree of weathering or fracturing. Where hard-rock conditions extend to a depth of 100 feet, a surficial shear-wave-velocity measurement may be extrapolated to characterize the site (IBC Section 1613.5.5; p. 305). A shear-wave velocity for rock, Site Class B, may be measured on site or estimated by a qualified geotechnical professional for competent rock with moderate fracturing and weathering. For softer, more highly weathered or fractured rock, a shear-wave velocity shall either be obtained on site, or the material classified as Site Class C (IBC Section 1613.5.5; p. 305). A site shall not be classified as Site Class A or B if there is more than 10 feet of soil between the rock surface and the bottom of the spread footing or mat foundation.

Soil Sites

Site Classes C, D, and E (very dense soil and soft rock, stiff soil, and soft soil, respectively; IBC table 1613.5.2, p. 303; see also table 1 this report) are determined based on average values determined either for v_s, or N, or s_u (IBC table 1613.5.5, p. 305; see also table 1 this report). Standard penetration resistance (blow count) should not exceed 100 blows/foot. Where refusal (no further penetration) is met for rock or strongly indurated soil before a blow count of 100 is obtained, N shall be taken as 100 blows/foot.

Table 2. Seismic design categories for communities in the St. George–Hurricane metropolitan area by site class and IBC occupancy category; categories determined in May 2006 using USGS Java Ground Motion Parameter Calculator version 5.0.0; check the USGS Seismic Hazards Program Web site http://earthquake.usgs.gov/research/hazmaps/design/ for the most recent version of the calculator.

Site Class	Maximum Spectral Response Accelerations[1]		Site Coefficients[1]		Maximum Considered Spectral Response Accelerations[1]		Design Spectral Response Accelerations[1]		Seismic Design Category[2]				
									Occupancy Category				
									I	II		III	IV
	Short Period (S_s)	Long Period (S_1)	Short Period (F_a)	Long Period (F_v)	Short Period (S_{MS})	Long Period (S_{M1})	Short Period (S_{DS})	Long Period (S_{D1})	Buildings and Other Structures That Represent a Low Hazard to Human Life in the Event of Failure (IBC)	All Other Buildings and Structures Except Those Listed in Categories I, III, and IV (IBC)	One- and Two-Family Dwellings and Townhouses (IRC)	Buildings and Other Structures That Represent a Substantial Hazard to Human Life in the Event of Failure (IBC)	Buildings and Other Structures Designated as Essential Facilities (IBC)
Hurricane: Spectral response accelerations mapped at latitude 37.1517° longitude 113.2801°.													
A	0.586	0.191	0.80	0.80	0.469	0.153	0.312	0.102	B	B	B	B	C
B			1.00	1.00	0.586	0.191	0.390	0.127	C	C	C	C	D
C			1.16	1.609	0.683	0.07	0.455	0.205	D	D	C	D	D
D			1.331	2.037	0.780	0.388	0.520	0.259	D	D		D	D
D_{IRC}[3]	0.59	0.19	1.33	2.04			0.52				D_0		
E			1.528	3.228	0.895	0.615	0.597	0.140	D	D	D_0	D	D
F			Site-specific geotechnical investigation and dynamic site-response analysis shall be performed to determine appropriate values and seismic design categories										
Ivins: Spectral response accelerations mapped at latitude 37.1663° longitude 113.6657°.													
A	0.484	0.154	0.80	0.80	0.387	0.123	0.258	0.082	B	B	B	B	C
B			1.00	1.00	0.484	0.154	0.323	0.103	B	B	B	B	C
C			1.2	1.646	0.51	0.253	0.387	0.169	C	C	C	C	D
D			1.413	2.184	0.684	0.336	0.456	0.224	D	D		D	D
D_{IRC}[3]	0.48	0.15	1.41	2.18			0.46				C		
E			1.751	3.338	0.848	0.514	0.565	0.343	D	D	D_0	D	D
F			Site-specific geotechnical investigation and dynamic site-response analysis shall be performed to determine appropriate values and seismic design categories										

Table 2. *(continued).*

Site Class	Mapped Spectral Response Accelerations[1]		Site Coefficients[1]		Maximum Considered Spectral Response Accelerations[1]		Design Spectral Response Accelerations[1]		Seismic Design Category[2]				
	Short Period (S_s)	Long Period (S_1)	Short Period (F_a)	Long Period (F_v)	Short Period (S_{MS})	Long Period (S_{M1})	Short Period (S_{DS})	Long Period (S_{D1})	Occupancy Category				
									I	II		III	IV
									Buildings and Other Structures That Represent a Low Hazard to Human Life in the Event of Failure (IBC)	All Other Buildings and Structures Except Those Listed in Categories I, III, and IV (IBC)	One- and Two-Family Dwellings and Townhouses (IRC)	Buildings and Other Structures That Represent a Substantial Hazard to Human Life in the Event of Failure (IBC)	Buildings and Other Structures Designated as Essential Facilities (IBC)
La Verkin: Spectral response accelerations mapped at latitude 37.2086° longitude 113.2731°.													
A	0.599	0.194	0.80	0.80	0.479	0.155	0.320	0.103	B	B	B	B	C
B			1.00	1.00	0.599	0.194	0.399	0.129	C	C	C	C	D
C			1.166	1.606	0.695	0.311	0.463	0.209	D	D	C	D	D
D			1.321	2.025	0.791	0.392	0.528	0.261	D	D	C	D	D
D_{IRC}[3]	0.60	0.19	1.32	2.03			0.53				D_0		
E			1.502	3.219	0.900	0.623	0.600	0.416	D	D	D_0	D	D
F			Site-specific geotechnical investigation and dynamic site-response analysis shall be performed to determine appropriate values and seismic design categories										
Leeds: Spectral response accelerations mapped at latitude 37.2376° longitude 113.3646°.													
A	0.606	0.192	0.80	0.80	0.484	0.154	0.323	0.102	B	B	B	B	C
B			1.00	1.00	0.606	0.192	1.404	0.128	C	C	C	C	D
C			1.158	1.608	0.701	0.309	0.467	0.206	D	D	C	D	D
D			1.316	2.032	0.797	0.390	0.531	0.260	D	D		D	D
D_{IRC}[3]	0.61	0.19	1.32	2.03			0.53				D_0		
E			1.489	3.224	0.902	0.619	0.601	0.413	D	D	D_0	D	D
F			Site-specific geotechnical investigation and dynamic site-response analysis shall be performed to determine appropriate values and seismic design categories										

Table 2. *(continued).*

Site Class	Mapped Spectral Response Accelerations[1]		Site Coefficients[1]		Maximum Considered Spectral Response Accelerations[1]		Design Spectral Response Accelerations[1]		Seismic Design Category[2]				
									Occupancy Category				
									I	II		III	IV
	Short Period (S_s)	Long Period (S_1)	Short Period (F_a)	Long Period (F_v)	Short Period (S_{MS})	Long Period (S_{M1})	Short Period (S_{DS})	Long Period (S_{D1})	Buildings and Other Structures That Represent a Low Hazard to Human Life in the Event of Failure (IBC)	All Other Buildings and Structures Except Those Listed in Categories I, III, and IV (IBC)	One- and Two-Family Dwellings and Townhouses (IRC)	Buildings and Other Structures That Represent a Substantial Hazard to Human Life in the Event of Failure (IBC)	Buildings and Other Structures Designated as Essential Facilities (IBC)
Santa Clara: Spectral response accelerations mapped at latitude 37.1331° longitude 113.6454°.													
A	0.485	0.194	0.80	0.80	0.388	0.124	0.259	0.083	B	B	B	B	C
B			1.00	1.00	0.485	0.155	0.323	0.103	C	C	C	C	D
C			1.20	1.645	0.582	0.255	0.388	0.170	D	D	C	D	D
D			1.412	2.180	0.685	0.388	0.457	0.225	D	D	C	D	D
D_{IRC}[3]	0.48	0.155	1.41	2.18			0.46				D_0		
E			1.748	3.335	0.848	0.517	0.565	0.344	D	D	D_0	D	D
F			Site-specific geotechnical investigation and dynamic site-response analysis shall be performed to determine appropriate values and seismic design categories										
St. George: Spectral response accelerations mapped at latitude 37.0869° longitude 113.5849°.													
A	0.503	0.161	0.80	0.80	0.403	0.129	0.268	0.086	B	B	B	B	C
B			1.00	1.00	0.503	0.161	0.336	0.107	B	B	B	B	C
C			1.199	1.639	0.604	0.264	0.402	0.176	C	C	C	C	D
D			1.397	2.155	0.703	0.347	0.469	0.232	D	D		D	D
D_{IRC}[3]	0.50	0.161	1.40	2.16			0.47				C		
E			1.693	3.316	0.852	0.534	0.568	0.356	D	D	D_0	D	D
F			Site-specific geotechnical investigation and dynamic site-response analysis shall be performed to determine appropriate values and seismic design categories										

Table 2. *(continued).*

Site Class	**Mapped Spectral Response Accelerations**[1]		**Site Coefficients**[1]		**Maximum Considered Spectral Response Accelerations**[1]		**Design Spectral Response Accelerations**[1]		**Seismic Design Category**[2]				
									Occupancy Category				
									I	II		III	IV
	Short Period (S_s)	Long Period (S_1)	Short Period (F_a)	Long Period (F_v)	Short Period (S_{MS})	Long Period (S_{M1})	Short Period (S_{DS})	Long Period (S_{D1})	Buildings and Other Structures That Represent a Low Hazard to Human Life in the Event of Failure (IBC)	All Other Buildings and Structures Except Those Listed in Categories I, III, and IV (IBC)	One- and Two-Family Dwellings and Townhouses (IRC)	Buildings and Other Structures That Represent a Substantial Hazard to Human Life in the Event of Failure (IBC)	Buildings and Other Structures Designated as Essential Facilities (IBC)
Toquerville: Spectral response accelerations mapped at latitude 37.2493° longitude 113.2846°.													
A	0.618	0.198	0.80	0.80	0.494	0.158	0.329	0.105	B	B	B	B	C
B			1.00	1.00	0.618	0.198	0.412	0.132	C	C	C	C	D
C			1.153	1.602	0.712	0.317	0.475	0.211	D	D	C	D	D
D			1.306	2.01	0.807	0.397	0.538	0.265	D	D	C	D	D
D_{IRC}[3]	0.62	0.20	1.31	2.01			0.54				D_0		
E			1.465	3.207	0.905	0.634	0.603	0.422	D	D	D_0	D	D
F			Site-specific geotechnical investigation and dynamic site-response analysis shall be performed to determine appropriate values and seismic design categories										
Washington: Spectral response accelerations mapped at latitude 37.1329° longitude 113.5097°.													
A	0.531	0.171	0.80	0.80	0.430	0.137	0.286	0.091	B	B	B	B	C
B			1.00	1.00	0.537	0.171	0.358	0.114	C	C	C	C	D
C			1.185	1.629	0.637	0.279	0.424	0.186	C	C	C	C	D
D			1.37	2.116	0.736	0.362	0.491	0.241	D	D		D	D
D_{IRC}[3]	0.54	0.17	1.37	2.12			0.49				C		
E			1.626	3.287	0.873	0.562	0.582	0.375	D	D	D_0	D	D
F			Site-specific geotechnical investigation and dynamic site-response analysis shall be performed to determine appropriate values and seismic design categories										

Table 2. *(continued).*

[1] Maximum spectral response accelerations with a 2 percent probability of exceedance in 50 years (S_s and S_I), site coefficients (F_a and F_v), maximum considered spectral response accelerations (S_{MS} and S_{MI}), and 0.2 sec and 1.0/sec design spectral response accelerations (S_{DS} and S_{DI}) appropriate for the IBC obtained using Java Ground Motion Parameter Calculator – Version 5.0.0 at USGS National Seismic Hazard Map Web site http://earthquake.usgs.gov/research/hazmaps/design/. The Ground Motion Parameter Calculator is updated periodically; **check the USGS Web site for the most recent version of the calculator.**
[2] In accordance with IBC Section 1613.5.6, the seismic design category is the most severe category specified in IBC tables 1613.5.6(1) or 1613.5.6(2), irrespective of the fundamental period of vibration of the structure.
[3] D_{IRC} values of maximum spectral response accelerations with a 2 percent probability of exceedance in 50 years (S_s and S_I), site coefficients (F_a and F_v), and 0.2 sec design spectral response acceleration (S_{DS}) appropriate for the IRC obtained using Java Ground Motion Parameter Calculator – Version 5.0.0 at USGS National Seismic Hazard Map Web site http://earthquake.usgs.gov/research/hazmaps/design/. The Ground Motion Parameter Calculator is updated periodically; **check the USGS Web site for the most recent version of the calculator.** For soil or rock conditions other than site class D, short period design spectral response accelerations (S_{DS}) were determined in accordance with Section 1613.5 of the IBC; seismic design categories were then assigned in accordance with IRC table R301.2.2.1.1.

Site Class F consists of any soil profile with one or more of the characteristics listed in IBC table 1613.5.2 (IBC p. 303; see also table 1 this report). Although peat and very thick deposits of soft/medium stiff clays (thickness >120 feet) are uncommon in the St. George–Hurricane metropolitan area, such is not the case with high plasticity clay (plasticity index [PI] >75) and collapse-prone soil, both of which are comparatively common in the study area (see section on Problem Soils and Rock in the St. George–Hurricane Metropolitan Area). A site-specific geotechnical investigation and dynamic site-response analysis shall be performed for Site Class F soils to determine appropriate values and seismic design categories (International Code Council, 2006a).

Procedure for Determining Site Class

International Building Code Section 1613.5.5.1 (p. 305) provides a three-step procedure for classifying a site. The steps are as follows:

1 Check for the four categories of Site Class F requiring site-specific evaluation (table 1). If the site corresponds to any of those categories, classify the site as Site Class F and conduct a site-specific evaluation.

2 Check for the existence of a total thickness of soft clay >10 feet where the soft clay layer is defined by: average s_u <500 psf, moisture content ≥40 percent, and PI >20. If these criteria are satisfied, classify the site as Site Class E.

3 Categorize the site using one of the following three methods with average v_s, *N*, or s_u and computed as specified in IBC Section 1613.5.5. (p. 304). However, Ashland and Rollins (1999) prefer using average v_s , because they found poor correlation along the Wasatch Front among site classes calculated using v_s, *N*, and s_u.

3.1 Average v_s for the top 100 feet (average v_s method)

3.2 Average *N* for the top 100 feet (average *N* method).

3.3 Average *N* for cohesionless soil layers (PI <20) in the top 100 feet and average s_u for cohesive soil layers (PI >20) in the top 100 feet (average s_u method).

HAZARD REDUCTION

The hazard associated with earthquake ground shaking can be both widespread, depending on earthquake magnitude, and costly in terms of property damage, injury, and death depending on location. Ground shaking cannot be avoided, but meeting requirements for earthquake-resistant design and construction can reduce loss of life and damage to structures. The most effective method of mitigating earthquake ground shaking is through adoption of modern building codes that incorporate seismic-design provisions. In Utah, earthquake-resistant design requirements are specified in the seismic provisions of the IBC (Section 1613; p. 302) and IRC (Section R301.2.2; p. 42), which are adopted statewide. The Utah Geological Survey (UGS) strongly recommends that Washington County and the municipalities within the St. George–Hurricane metropolitan area adopt and enforce the most current version of both codes. Additionally, because a large portion of injuries during an earthquake are caused by falling objects resulting from ground shaking, the UGS recommends that heavy objects which may fall or topple over during an earthquake be secured to reduce injuries. Fire caused by damage to gas pipelines during an earthquake is also a significant ground-shaking related hazard.

Special studies are intended to ensure that buildings will be designed and constructed to resist the effects of earthquake ground motions. These effects may be particularly severe in areas subject to amplified ground motions. Because of uncertainties associated with the lack of data and critical role of site-class designations in building design, the IBC site class should be confirmed in the field for all projects as outlined in the IBC or IRC. In general, site class is determined by conducting geotechnical soil-foundation studies prior to construction.

For construction in areas underlain by rock subject to deamplification (Site Class A) or no amplification (Site Class B), site geologic studies are needed to confirm the mapped site class based on rock type. However, as amplification increases in Site Classes C, D, and E, more detailed subsurface studies should be conducted for all types of development intended for human occupancy. For construction in areas underlain by soil of Site Classes C, D, or E, special studies are needed to characterize site soil conditions. Studies in Salt Lake Valley have shown that site classes may vary locally at a site in adjacent boreholes (Ashland and McDonald, 2003), so an appropriate level of conservatism should be used when performing geotechnical studies, particularly at sites with variable geology and only a single borehole. The IBC requires that both site-specific geotechnical investigations and dynamic site-response analyses be performed in areas underlain by Site Class F materials. In some cases, as a default option, the IBC allows use of Site Class D except where the local building official determines that Site Class E or F is likely to be present.

Table 2 gives the seismic design categories generally appropriate for the communities within the St. George–Hurricane metropolitan area. However, because existing geotechnical information in the study area is limited both geographically and with depth, and because the USGS Java Ground Motion Parameter Calculator is updated periodically, the UGS recommends that IBC or IRC site classes be determined on a site-specific basis for new construction in the St. George–Hurricane metropolitan area using the most currently available USGS Java Ground Motion Parameter Calculator.

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