GEOLOGIC HAZARDS OF THE TICKVILLE SPRING QUADRANGLE, SALT LAKE AND UTAH COUNTIES, UTAH

by Jessica J. Castleton, Ben A. Erickson, Greg N. McDonald, and Gregg S. Beukelman

SPECIAL STUDY 163
UTAH GEOLOGICAL SURVEY
a division of
UTAH DEPARTMENT OF NATURAL RESOURCES
2018

Blank pages are intentional for printing purposes.

GEOLOGIC HAZARDS OF THE TICKVILLE SPRING QUADRANGLE, SALT LAKE AND UTAH COUNTIES, UTAH

by
Jessica J. Castleton, Ben A. Erickson, Greg N. McDonald, and Gregg S. Beukelman

Cover photo: *Step Mountain located at the mouth of Rose Canyon is a volcanic dike that exhibits columnar jointing.*

ISBN: 978-1-55791-950-2

UTAH DNR GEOLOGICAL SURVEY

SPECIAL STUDY 163
UTAH GEOLOGICAL SURVEY
a division of
UTAH DEPARTMENT OF NATURAL RESOURCES
2018

STATE OF UTAH
Gary R. Herbert, Governor

DEPARTMENT OF NATURAL RESOURCES
Michael Styler, Executive Director

UTAH GEOLOGICAL SURVEY
Richard G. Allis, Director

PUBLICATIONS
contact
Natural Resources Map & Bookstore
1594 W. North Temple
Salt Lake City, UT 84116
telephone: 801-537-3320
toll-free: 1-888-UTAH MAP
website: utahmapstore.com
email: geostore@utah.gov

UTAH GEOLOGICAL SURVEY
contact
1594 W. North Temple, Suite 3110
Salt Lake City, UT 84116
telephone: 801-537-3300
website: geology.utah.gov

CONTENTS

FIGURES

TABLES

PLATES

GEOLOGIC HAZARDS OF THE TICKVILLE SPRING QUADRANGLE, SALT LAKE AND UTAH COUNTIES, UTAH

by Jessica J. Castleton, Ben A. Erickson, Greg N. McDonald, and Gregg S. Beukelman

ABSTRACT

The Tickville Spring quadrangle, in the southwest portion of Salt Lake Valley and northern portion of Cedar Valley, is expected to experience a significant population increase in the next several decades. As urbanization expands into areas less suited for development, geologic hazards become an increasing concern in the planning, design, and construction of new facilities. This geologic-hazard study of the Tickville Spring quadrangle incorporates geologic, hydrologic, soil, and geotechnical information to identify geologic hazards, and where detailed, site-specific, geotechnical/geologic-hazard investigations are necessary.

This study provides maps and information for 10 geologic hazards: shallow groundwater, liquefaction, surface fault rupture, flooding, landsliding, rockfall, radon, collapsible soil, expansive soil and rock, and shallow bedrock. Historically, the most widespread annual hazard in Utah is flooding. Flooding is of special concern because it occurs frequently, can cause significant damage to facilities, and can be life threatening. Landslides and rockfalls are of growing concern as development increases on hillsides, where development is often favored due to scenic vistas and aesthetics. Large earthquakes are rare events in the Tickville Spring quadrangle, but the hazards associated with them (mainly ground shaking, surface fault rupture, 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 are typically localized in nature and rarely life threatening (except for indoor radon), though they are often costly when not recognized and properly addressed in project planning and design.

INTRODUCTION

This study provides maps and information for 10 geologic hazards in the Tickville Spring quadrangle. The quadrangle is in southwestern Salt Lake Valley and extends into the northern portion of Cedar Valley about 20 miles (32 km) from downtown Salt Lake City, and includes areas expected to grow in population in the coming decades. As the area's population grows, urbanization will increase; therefore, timely geologic information early in the planning and design process is critical to avoid or reduce risk from geologic hazards.

Purpose and Scope

Geologic-hazard mapping is a multidisciplinary, dynamic process that uses a variety of available data to create an integrated product intended for multiple uses. This study provides geotechnical engineers, engineering geologists, design professionals, building officials, developers, and the public with information on the types and locations of geologic hazards that may affect existing and future development in the Tickville Spring quadrangle (figure 1). We compiled data and created maps for this study at a scale of 1:24,000 (1 inch = 2000 feet) using a geographic information system (GIS). This approach resulted in geologic-hazard maps that incorporate data and methods from a variety of scientific disciplines including engineering geology, geomorphology, aerial-photography analysis, GIS technology, and geologic field mapping.

The geologic-hazard maps are designed as an aid for general planning to indicate areas where detailed, site-specific geotechnical/geologic-hazard investigations are recommended. The maps should not be enlarged for use at scales larger than 1:24,000, and are not a substitute for site-specific geotechnical/geologic-hazard investigations. These maps are based on a geologic-hazard analysis of the Tickville Spring quadrangle. The geologic hazards addressed are shallow groundwater, liquefaction, surface fault rupture, flooding, landsliding, rockfall, indoor radon potential, collapsible soil, expansive soil and rock, and shallow bedrock. Other unrecognized hazards may exist.

Both Salt Lake and Utah Counties have geologic hazard ordinances. The Salt Lake County Geologic Hazards Ordinance (Salt Lake County, 2017) requires, at minimum, investigation of surface-fault-rupture, liquefaction, debris-flow, landslide, and snow avalanche hazards prior to development. The Utah County Natural Hazards Overlay Zone (NHO) (Utah County, 2009) requires, at minimum, assessment of known special hazard areas including rockfall, debris flow, landslide, and surface fault rupture hazards prior to development. Both counties also address flood zoning in the ordinances. The Utah Geological Survey (UGS) provides recommendations for appropriate, minimum investigation techniques, standards, and report content for surface fault rupture, landslide, debris flow, land subsidence and rockfall hazards (Bowman and Lund, 2016).

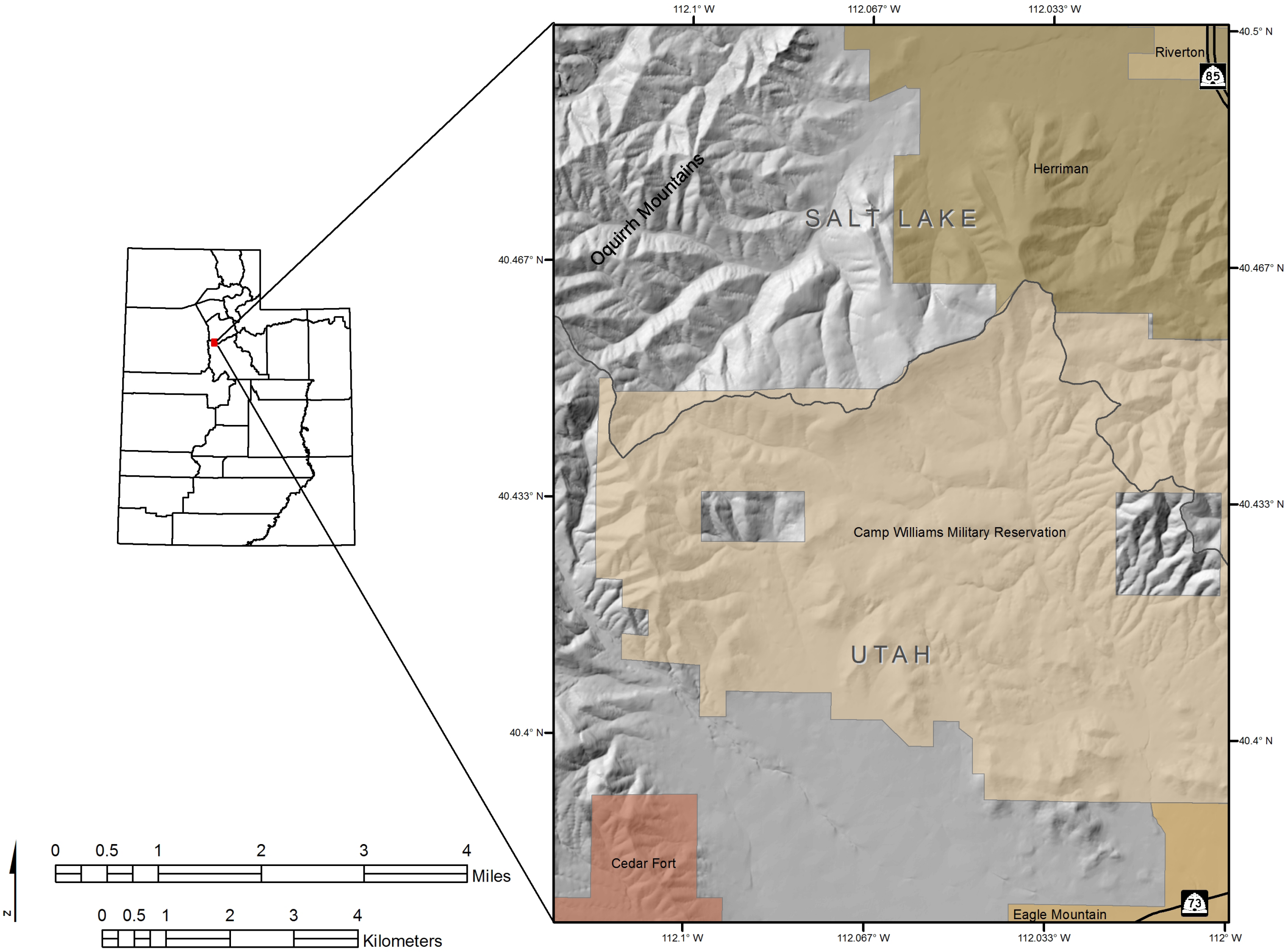

Figure 1. *Location map of the Tickville Spring quadrangle showing principal geographic features including boundaries of cities and towns (unshaded areas are unincorporated Salt Lake County), major transportation routes (AGRC, 2016), and 10 meter hillshade base (USGS, 2008, National Elevation Dataset [NED]).*

The scope of work for this study consisted of (1) identifying and reviewing geologic, hydrologic, and soils information available for the study area; (2) digitizing relevant geologic, hydrologic, and soils information; (3) compiling a digital geotechnical database incorporating test data, borehole logs, and other information from existing geotechnical/geologic-hazard reports in the study area; (4) field mapping; and (5) preparing this report and accompanying maps describing each geologic hazard. Hazards other than those mapped for this study may be present within the quadrangle and may affect existing and future development.

Previous Work

Christenson and Shaw (2008) compiled selected, existing geologic-hazard investigations for the Wasatch Front into a GIS database. Their maps include the Tickville Spring quadrangle and present information on debris flow, surface fault rupture, landslide, and liquefaction hazards. Other previous geologic-hazard investigations that encompass the Tickville Spring quadrangle include investigations of:

- earthquake site conditions (McDonald and Ashland, 2008),
- earthquake hazards associated with a scenario magnitude (M) 7 earthquake on the Salt Lake City segment of the Wasatch fault zone (including ground shaking, surface fault rupture, liquefaction, earthquake-induced landslides, and other geologic hazards) (Solomon and others, 2004),
- liquefaction (Anderson and others, 1994; Bartlett and others, 2005, 2006; Olsen and others, 2007; Hinckley, 2010), and
- radon-hazard potential (Black, 1996; mapping only includes part of the northern extent of the quadrangle).

Additionally, recent geologic mapping (Biek and others, 2005) and geotechnical/geologic-hazard investigations have greatly increased our understanding of the area's geology and hazards.

Setting

The Tickville Spring quadrangle includes portions of the cities of Herriman, Riverton, Cedar Fort, and Eagle Mountain. A large part of the quadrangle consists of private, state, and federally administrated land, including the Bureau of Land Management and the Department of Defense. The Mountain View Corridor highway (State Route 85) crosses the northeast corner of the Tickville Spring quadrangle (figure 1).

Elevation in the quadrangle ranges from approximately 7303 feet (2226 m) in the Oquirrh Mountains to 4800 feet (1463 m) in the northeast corner of the quadrangle. The study area is characterized by moderate precipitation, large daily temperature changes, cold damp winters, and warm dry summers. Average annual precipitation at the Garfield weather station, located approximately 25 miles (40 km) northwest of the town of Herriman and at approximately the same elevation, is 17.2 inches (43.6 cm) measured from November 1, 1924, to December 31, 2009 (Western Regional Climate Center [WRCC], 2014). Precipitation in the Oquirrh Mountains on the western border of the Tickville Spring quadrangle is more than 5 inches (13 cm) greater than in the valley, based on WRCC (2014) data for the Bingham Canyon weather station measured from December 1, 1940, to October 31, 1974. Most precipitation is associated with storms from the north Pacific Ocean during fall, winter, and spring. Winter precipitation occurs primarily as snow. Summer temperatures at lower elevations in the study area commonly exceed 90° Fahrenheit (°F) (32°C); the November 1, 1924, to December 31, 2009, average maximum temperature for July at the Garfield weather station is 91.5°F (33°C), and the January 1, 1948, to December 31, 2009, average maximum temperature for July at the Salt Lake International Airport weather station is 92.8°F (33°C) (WRCC, 2014). The dominant vegetation on the valley floor includes various types of perennial grasses. With increasing elevation along the valley margins, vegetation changes to a variety of shrubs, including sagebrush.

The 10 maps produced for this study use a U.S. Geological Survey (USGS) topographic base map published in 1997, which conforms to the North American Datum of 1983 (NAD 83). However, the boundary of the topographic base map conforms to the North American Datum of 1927 (NAD 27) resulting in a slight offset in boundaries and a gap on the west edge of the map that has no topographic data. The hazard mapping and all GIS data are in NAD 83.

Geology

Salt Lake Valley occupies a structural basin in the Basin and Range physiographic province (Stokes, 1977). The basin is bounded by the Wasatch Range on the east and the Oquirrh Mountains on the west. The Wasatch Range consists of a complex sequence of sedimentary, metamorphic, and igneous rocks ranging in age from Precambrian to Tertiary. The mountain range marks the western boundary of the Middle Rocky Mountains physiographic province and the eastern boundary of the Basin and Range physiographic province (Stokes, 1977). The Oquirrh Mountains are composed primarily of Pennsylvanian and Permian sedimentary rocks and Tertiary sedimentary and volcanic rocks. Additionally, hydrothermal fluids introduced in conjunction with Tertiary intrusive activity caused the precipitation of ore and gangue minerals in and surrounding the intrusions (Tooker, 1999), making the Oquirrh Mountains rich in valuable ore. The Oquirrh Mountains are home to the Bingham Canyon mine, which is located just beyond the northwest corner of the Tickville Spring quadrangle and is one of the largest copper mines in the world. The bedrock in the vicinity of the Tickville Spring quadrangle was deformed by Cretaceous to early Tertiary contractional faulting and folding of the Sevier orogeny (e.g., Willis; 1999; DeCelles, 2006; Schelling and others, 2007), extensional faulting during the late Eocene to middle Miocene (Constenius, 1996; Constenius and others, 2003), and middle Miocene to recent basin-and-range faulting (Zoback and others, 1981; Smith and Bruhn, 1984). The Wasatch fault zone (at the western base of the Wasatch Range), the West Valley fault zone (in the north-central portion of Salt Lake Valley), and the Oquirrh fault zone (at the western base of the Oquirrh Mountains) are the most prominent and youngest structures (Holocene age) associated with basin-and-range extensional faulting in the region.

Salt Lake Valley is in the Great Basin geographic area and has been characterized by internal drainage for much of the past 15 million years. The surficial valley sediments were mostly deposited by late Pleistocene Lake Bonneville, a large pluvial lake that covered much of northwestern Utah and adjacent parts of Idaho and Nevada (Gilbert, 1890; Oviatt and Shroder, 2016). The lake began to rise above levels comparable to those of Great Salt Lake after 35,000 years ago (CRONUS-Earth Project, 2005), and was in part contemporaneous with the most recent Rocky Mountain glacial advance, the Pinedale glaciation (Lips and others, 2005). Three major regional shorelines — Stansbury, Bonneville, and Provo — are associated with transgressive (rising) and regressive (lowering) phases of Lake Bonneville. The Bonneville and Provo shorelines are preserved within the Tickville Spring quadrangle. The Bonneville shoreline formed during the highest water elevation of Lake Bonneville and is evident in the southern part of the Tickville Spring quadrangle as the highest topographic bench on the valley margin. The elevation of the Bonneville shoreline was controlled by an overflow threshold at approximately 5092 feet (1552 m) near Zenda in southern Idaho. About 18,000 years ago (Miller and others, 2013), overflow and rapid erosion at the Zenda threshold resulted in catastrophic lowering of the lake by 340 feet (104 m) (Jarrett and Malde, 1987) in less than one year (O'Conner, 1993). Lake Bonneville then stabilized at a new lower threshold near Red Rock Pass, Idaho, and the Provo shoreline formed on the lower slopes of the Oquirrh Mountains. About 15,000 years ago, a warming climate induced further lowering of the lake level (Godsey and others, 2005), and Lake Bonneville began a decline to the current level of Great Salt Lake.

The Tickville Spring quadrangle is located on the westernmost extent of the east-west-trending Traverse Mountains, east of the Oquirrh Mountains at the south end of Salt Lake Valley. The Traverse Mountains are a salient and boundary between the Salt Lake City and Provo segments of the Wasatch fault zone. West of the Jordan Narrows, strata of the late Paleozoic Oquirrh Group were folded into northwest-trending synclines and anticlines during the Sevier orogeny about 140 to 150 million years ago. The Traverse Mountains are part of the upper plate of the Charleston-Nebo thrust sheet, a now faulted and dismembered thrust sheet showing 25 miles (40 km) of eastward displacement. In the west, the Traverse Mountains form the Tickville anticline, which is above the smaller Beef Hollow thrust fault (Biek, 2005).

After the Sevier orogeny, Tertiary intrusions, volcanic rocks, and younger basin-fill were deposited. In Eocene time, about 40 million years ago, the thrust belt collapsed westward along low-angle detachment faults. Volcanism associated with the collapse generated three groups of volcanic rocks. The oldest of these was erupted from the Bingham volcanic center, 37 to 40 million years ago. The Bingham volcanic cone likely towered above the current Bingham Canyon mine and has since eroded away. The second volcanic episode, 35 to 37 million years ago and making up the eastern extent of the Traverse Mountains, likely erupted from the Wasatch intrusive belt. The youngest volcanic episode occurred 30 to 33 million years ago and deposited andesitic to dacitic block and ash flow tuffs, lava flows, and intrusions (Biek, 2005).

Mid-Tertiary Basin and Range extensional tectonics created the current east-west-trending orientation of the Traverse Mountains. This east-west orientation is thought to be caused by a weak crustal tectonic boundary and contributes to the formation of the boundary between the Salt Lake City and Provo segments of the Wasatch fault zone on the eastern extent of the range (Biek, 2005).

More details on the stratigraphy, structure, and geologic resources of the Tickville Spring quadrangle and additional references are included on the geologic map of the quadrangle (Biek and others, 2005). Additionally, studies of the West Valley fault zone (Keaton and Currey, 1993; Keaton and others, 1993; Hylland and others, 2014), the Oquirrh fault zone (Lund, 1996), and the Oquirrh Mountains (Cook, 1961; Tooker and Roberts, 1998; Tooker, 1999) contain information regarding the geology of the area.

GEOLOGIC HAZARDS

The early recognition and mitigation of geologic hazards can reduce risk to life, property, and the economy. Hazard mapping is essential to identifying areas that need further investigations to determine hazard extent, risk, and mitigation measures. On an annual basis, the most common and damaging geologic hazard in Utah, which also affects the Tickville Spring quadrangle, is flooding. Because of the potentially wide distribution, frequent occurrence, and destructive nature, floods will likely be the principal geologic hazard in the quadrangle that planners and others will have to address in the future.

Landslides and rockfalls are of growing concern as development increases on hillsides, where development is often favored due to scenic vistas and aesthetics. Existing landslides in the quadrangle, especially older ones, can be difficult to recognize, and their stability remains suspect. Landslide identification and proper accommodation in project planning and design is critical to avoid slope-stability problems. Some bedrock units in the study area contain a high percentage of clay and are correspondingly weak and susceptible to landslides, especially when wet. The close correlation in the quadrangle between existing landslides and weak bedrock units provides ample warning that development on slopes underlain by landslide-susceptible bedrock must proceed with caution. Landslides are also associated with susceptible unconsolidated deposits. Conditions conducive to rockfall are present along the western boundary of the quadrangle, and damaging events are likely to increase as development moves into those areas, unless effective hazard-reduction measures are implemented.

Large, damaging earthquakes are rare in the Tickville Spring quadrangle, but active faults in the quadrangle and surrounding area are capable of producing earthquakes of M 7.0 or greater, resulting in an estimated short-term loss in the Wasatch Front region of over $33 billion, up to 2,500 deaths, 9,300 injuries, and 53,000 individuals displaced from housing (Pankow and others, 2015). 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 (160 km), north-south-trending zone of earthquake activity extending from northern Montana to northwestern Arizona (figure 2). Hazards associated with large earthquakes (ground shaking, surface fault rupture, landslides, rockfalls, and liquefaction) have the greatest potential for catastrophic property damage, economic disruption, and loss of life of any hazard in the study area. 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 (increased) or deamplified (decreased) depending on local soil and rock conditions (Reiter, 1990). Ground shaking is usually strongest near the earthquake epicenter and decreases away from that point. However, foundation conditions (type of soil or rock) and the type and quality of construction play large roles in determining the extent of ground shaking damage.

The Tickville Spring quadrangle may experience significant ground shaking due to movement on nearby faults, primarily the Wasatch and West Valley fault zones, but also possibly the

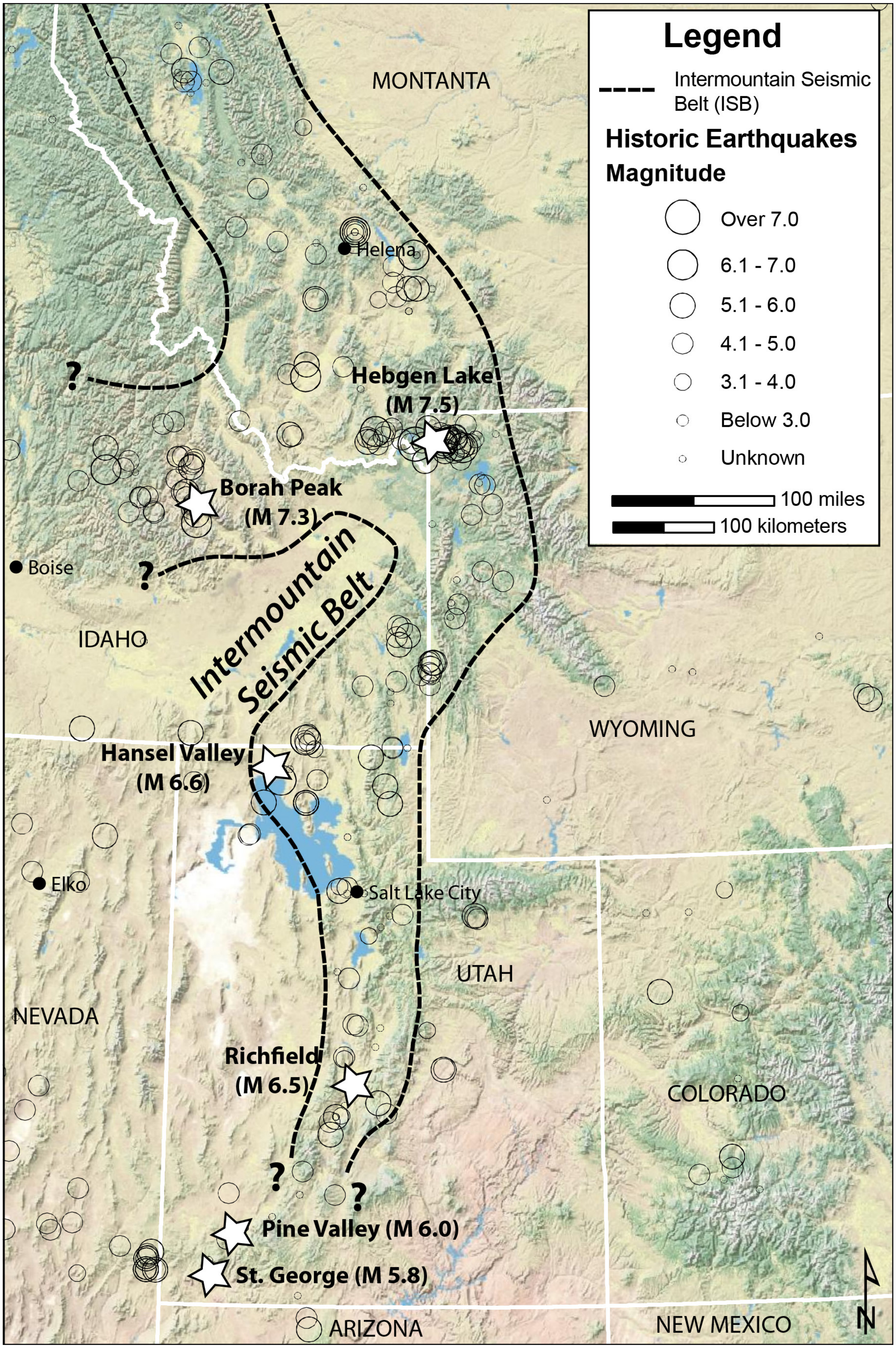

Figure 2. *The Intermountain Seismic Belt (ISB), earthquakes that produced surface faulting in the ISB (stars), and significant historical, non-surface faulting earthquakes in Utah (circles), with earthquake magnitude in parentheses (modified from Arabasz and others, 1992).*

Harkers fault in the adjoining Copperton quadrangle and an unnamed fault in the northwest part of the Tickville Spring quadrangle for which the time of latest movement is not known. Additionally, damaging ground shaking can occur during earthquakes that cannot be directly attributed to a specific fault (i.e., "background" earthquakes). Numerous earthquakes greater than M 4 have occurred in proximity to the Tickville Spring quadrangle over the past century, including the 1962 Magna M 5.2 earthquake and the 1992 Western Traverse Mountains M 4.2 earthquake (Christenson, 1992; University of Utah Seismograph Stations, 2010a; figure 3). The Magna earthquake resulted in minor damage to buildings in several cities and towns within one mile (1.6 km) to the southwest of the earthquake epicenter, which is approximately 5 miles (8 km) north of the Tickville Spring quadrangle (figure 3). Newspaper articles, photographs, and personal accounts of the Magna earthquake can be viewed on the University of Utah Seismograph Stations' (2010a) website. Eldredge and O'Brien (2001) also present photographs and discuss geologic effects and building damage from this earthquake. Additional information on earthquake preparedness and safety is found in the Utah Seismic Safety Commission (2008) handbook for earth¬quakes in Utah, *Putting Down Roots in Earthquake Country*, which is available online at https://www.utah.gov/beready/documents/roots_earthquake_low.pdf.

Several different studies related to ground shaking have been completed or are ongoing for Salt Lake Valley (Wong and others, 2002; McDonald and Ashland, 2008; Magistrale and others, 2009). For this reason, we did not complete a ground-shaking-hazard map or analysis for the Tickville Spring quadrangle. The effects of large earthquakes may be reduced through land-use planning, adoption and enforcement of modern seismic building codes (International Code Council, 2014a, 2014b), and disaster preparedness planning and drills.

The remaining geologic hazards considered in this report are typically localized in nature, and while often costly when not recognized and properly accommodated in project planning and design, problems associated with them are rarely life threatening. An exception is the hazard posed by elevated levels of indoor radon. Breathing radon over time increases the risk of lung cancer, but effective techniques are available for reducing indoor radon levels in existing construction and preventing dangerous levels in new construction.

Shallow Groundwater

Groundwater is in saturated zones beneath the land surface in soil and rock at various depths. Shallow groundwater levels typically are dynamic and fluctuate in response to a variety of conditions; groundwater levels may rise or fall in response to long-term climatic change, seasonal precipitation, irrigation, and the effects of development. Most development-related groundwater problems occur when water is within 10 feet (3 m) of the ground surface. Shallow groundwater can flood basements and other underground facilities, damage buried utility lines, and destabilize excavations. Groundwater inundation of landfills, waste dumps, and septic-tank/wastewater disposal systems can impair the performance of those facilities and lead to groundwater contamination. Groundwater can change the physical and chemical nature of rock and soil, cause soils susceptible to expansion and collapse to activate, and can be a contributing factor to slope instability (Wieczorek, 1996; Ashland and others, 2005, 2006). During moderate to large earthquakes, groundwater within approximately 50 feet (15 m) of the ground surface can cause liquefaction in sandy soils.

Groundwater may exist under unconfined (water table) or confined (artesian/pressurized) conditions, in regional aquifers, and/or as local perched zones. The deep unconfined and confined aquifers are commonly grouped together and called the principal aquifer (Thiros, 1995). Artesian pressure can force groundwater from the principal aquifer upward to the ground surface where it is discharged through springs and seeps. A shallow unconfined aquifer is typically present where confining layers overlie the principal aquifer (Thiros, 1995). Perched groundwater develops where water from precipitation, irrigation, and/or urban runoff percolates through thin, permeable, unconsolidated surface deposits and collects above less-permeable underlying layers.

Surficial deposits in the Tickville Spring quadrangle are highly variable and range from impermeable bedrock to moderately permeable lacustrine silt, sand, and gravel (Biek and others, 2005). Groundwater data in the quadrangle are limited to areas outside of recent development; therefore, perched water may extend outside of the mapped zone of shallow groundwater (plate 1). Perched groundwater and seasonally shallow groundwater may locally contribute to development problems in areas that do not have persistent shallow groundwater.

Our mapping focused on shallow groundwater including the principal aquifer where it is shallow, and locally unconfined or perched aquifers 50 feet (15 m) or less below the ground surface. However, the shallow-groundwater-potential map does not differentiate between aquifers and is not intended to model the deeper regional aquifer; instead, the map indicates the potential for shallow groundwater resulting from soil drainage capacity, geology, and hydrology.

To evaluate shallow groundwater potential (plate 1) we used six main sources of data: (1) recent UGS geologic mapping (Biek and others, 2005), (2) a geotechnical database compiled by the UGS, (3) previous groundwater investigations, (4) water-well drillers' logs on file with the Utah Division of Water Rights (UDWR, 2009), (5) private industry water-well data, and (6) the Natural Resources Conservation Service (NRCS) *Soil Survey Geographic (SSURGO) Database for Salt Lake Area, Salt Lake County, Utah* (NRCS, 2006).

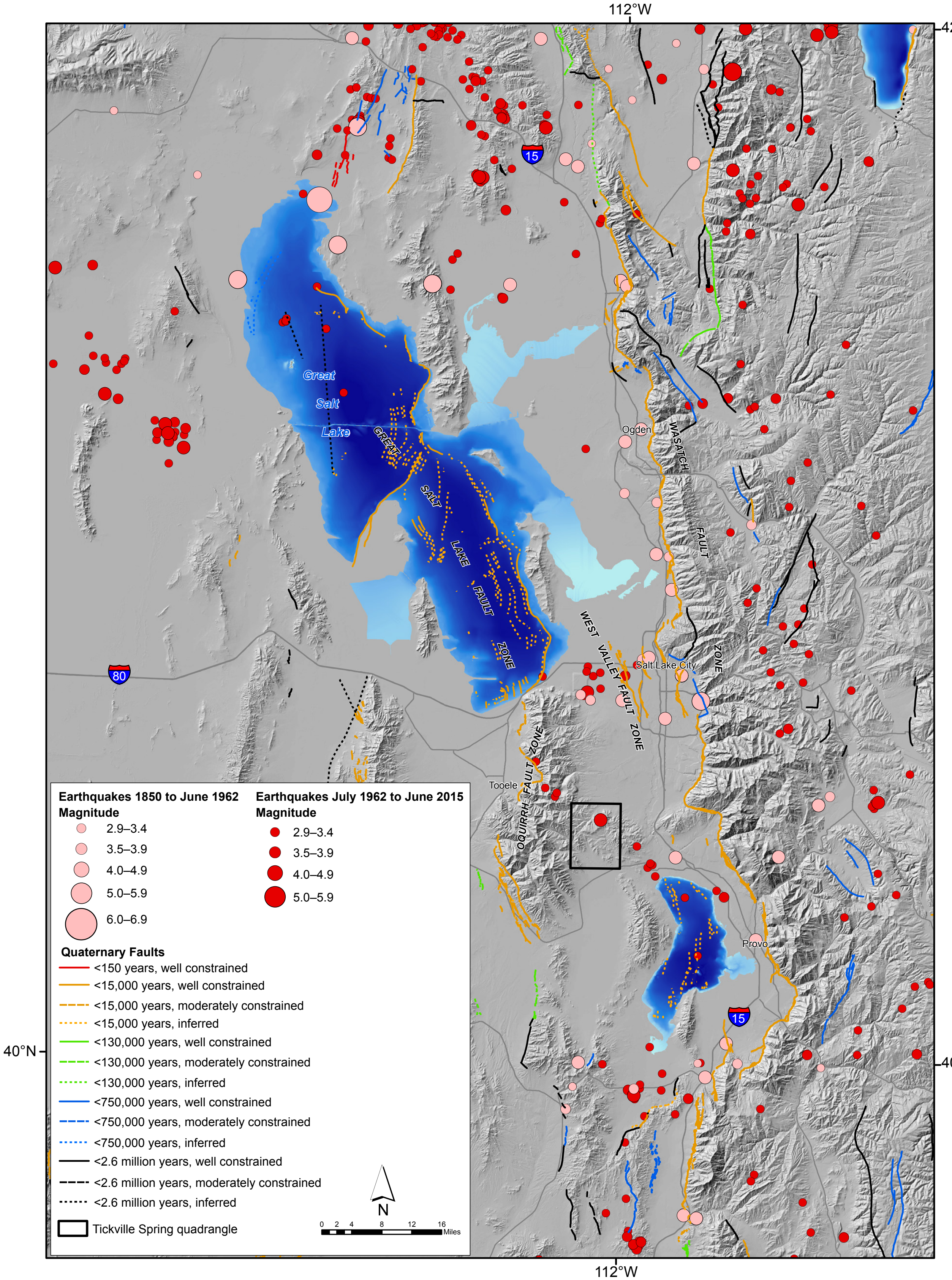

Figure 3. *Earthquake epicenters greater than or equal to M 4 in the Wasatch Front region from 1850 to 2009 (University of Utah Seismograph Stations, 2010b) and major Quaternary faults in the region (Black and others, 2003), including the Oquirrh fault zone (OFZ), West Valley fault zone (WVFZ), and Wasatch fault zone (WFZ). The area outlined in black shows the Tickville Spring quadrangle. Map base from NED 10-meter hillshade (USGS, 2008).*

We obtained groundwater-level data from geotechnical/geologic-hazard investigations and water-well logs and incorporated the data into a geotechnical database. The shallow groundwater mapping is based on geologic units using NRCS data and geotechnical data as modifiers. The NRCS maps the occurrence of wet or potentially wet soil conditions. Wet conditions are defined by the NRCS as soils in which depth to groundwater is less than 60 inches (152 cm), and potentially wet soil conditions are defined as poorly drained, fine-grained soils that may develop shallow groundwater locally when rates of water application exceed the soil's drainage capacity. The NRCS and geotechnical data were overlain with the geologic map to determine the shallow groundwater potential of each geologic unit, and the NRCS soil unit boundaries were used to modify the geologic unit where determined necessary. To account for temporal and seasonal fluctuations in groundwater, we used the most conservative (shallowest) depth to groundwater reported in an area.

Our shallow-groundwater-potential map (plate 1) is not intended to provide numerical depths to groundwater, but rather to indicate where shallow groundwater may affect development and contribute to other geologic hazards. We created three shallow-groundwater-potential categories to identify soil and rock units that are either naturally wet or have the potential to develop wet conditions. Only two of the shallow-groundwater-potential categories were identified on the Tickville Spring quadrangle; areas of permanent shallow groundwater less than 10 feet below the surface were not identified. Local areas of shallow groundwater less than 10 feet below the surface may exist. Areas mapped as bedrock are generally not considered to have shallow groundwater; however, some volcanic bedrock units can be highly weathered and contribute to shallow groundwater conditions. The categories define the conditions under which shallow groundwater may occur, but the categories do not represent relative severity rankings or actual depth to groundwater.

Liquefaction

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. Figure 4 illustrates the four principal types of liquefaction-induced ground failure. Liquefaction typically occurs within approximately 50 feet (15 m) of the ground surface (Seed, 1979), but the likelihood of liquefaction occurring in most deposits is very low when groundwater is deeper than about 30 feet (10 m) (Youd and Perkins, 1978; Youd and Gilstrap, 1999). However, perched groundwater, locally saturated soils, and changes in local and regional water management patterns, along with seasonal variations of the water table, must also be considered when evaluating the liquefaction hazard (Martin and Lew, 1999; California Geological Survey, 2008).

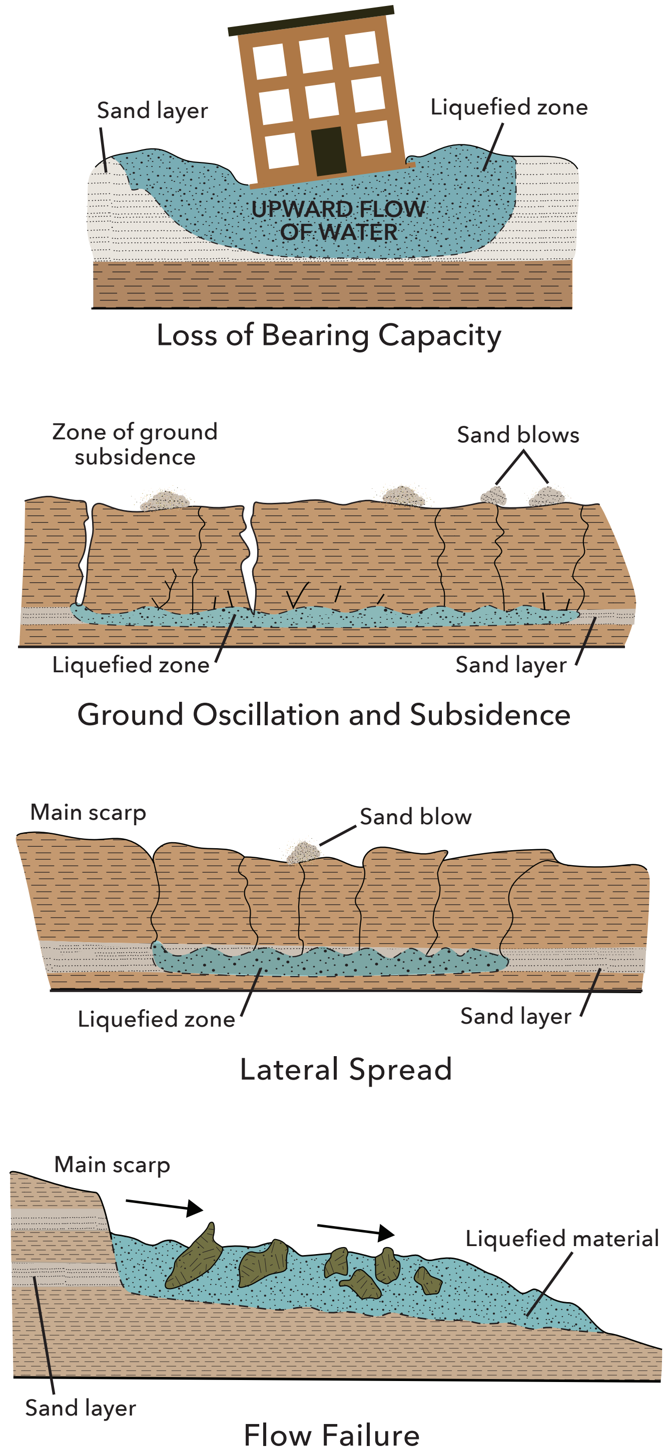

Figure 4. *Four principal types of liquefaction-induced ground failure. Arrows indicate direction of ground movement (modified from Youd, 1984).*

Liquefaction occurs when water-saturated, loose soil is subjected to strong ground shaking (Seed, 1979; Martin and Lew, 1999). Loose soils are typically sandy, have little clay, and have grains that do not readily adhere together, although some silty and gravelly soils are also susceptible to liquefaction. In general, an earthquake of M 5.0 or greater is necessary to induce liquefaction. Larger earthquakes are more likely to cause liquefaction, and it may occur at greater distances from the earthquake epicenter. All of the following conditions must be present for liquefaction to occur:

1. The soils must be submerged below the water table.
2. The soils must be loose/soft to moderately dense/stiff.
3. The ground shaking must be strong enough.
4. The duration of ground shaking must be sufficient for the soils to lose their shearing resistance.

To evaluate liquefaction susceptibility (plate 2) we used four main sources of data: (1) recent UGS geologic mapping (Biek and others, 2005), (2) a geotechnical database compiled by the UGS, (3) the NRCS *Soil Survey Geographic (SSURGO) Database for Salt Lake Area, Salt Lake County, Utah* (NRCS, 2006), and (4) shallow groundwater potential mapping completed for this study. We assigned a liquefaction susceptibility classification of low, very low, or not susceptible based on geologic and groundwater conditions; areas of high susceptibly were not present in the mapped area.

We used geologic mapping, NRCS soil data, and soil borehole logs from our geotechnical database to delineate unconsolidated geologic deposits typically associated with liquefaction. We evaluated each geologic map unit based on dominant grain-size distribution (fine to coarse grained), sorting (poorly to well sorted), and cementation (none to strong), and integrated these data with the groundwater data. Where depth to groundwater is likely 50 feet (15 m) or less, we classified the liquefaction susceptibility of the corresponding geologic unit as low, very low, or not susceptible based on textural characteristics and cementation (plate 2).

Geologic units that consist of well-sorted sand, silty sand, and gravel where depth to groundwater is less than or equal to 50 feet (15 m) below the ground surface are mapped as high (not mapped in the Tickville Spring quadrangle). Geologic units that consist of moderately to poorly sorted sand and gravel where depth to groundwater is less than or equal to 50 feet (15 m) below the ground surface are mapped as moderate. Geologic units that consist of poorly sorted sand and gravel where depth to groundwater is likely greater than 50 feet (15 m) below the ground surface, but shallow groundwater potential mapping identifies soil conditions likely to develop perched groundwater, are mapped as low susceptibility. Geologic units that consist of moderately to poorly sorted sand and gravel where depth to groundwater is greater than or equal to 50 feet (15 m) below the ground surface are mapped as low susceptibility. Areas of sandy to fine-grained soil and perched or seasonally high groundwater may increase liquefaction susceptibility within the low susceptibility areas (not mapped in the Tickville Spring quadrangle). Anderson and others (1994) emphasized that "perched groundwater is equal to true groundwater with respect to soil liquefaction," stating that "saturated granular material is the chief concern; the source of the saturation is immaterial." Bedrock areas are not susceptible to liquefaction.

The liquefaction susceptibility map (plate 2) does not integrate expected earthquake ground motions with soil characteristics and depth to groundwater, which is required to determine relative liquefaction potential (potential is equal to susceptibility plus opportunity) in susceptible soils. Probabilistic liquefaction potential and liquefaction-induced ground-failure mapping for the urban Wasatch Front is ongoing at the University of Utah in collaboration with the Utah Liquefaction Advisory Group (https://geology.utah.gov/hazards/earthquakes-faults/utah-earthquake-working-groups/liquefaction-advisory-group/) and other universities (Bartlett and others, 2005, 2006). The liquefaction susceptibility map also does not indicate if liquefaction of subsurface material will manifest at the ground surface, nor does it differentiate ground-failure type or amount, both of which are required to fully assess the hazard and evaluate mitigation techniques.

The liquefaction susceptibility map (plate 2) is intended for general planning purposes to indicate where liquefaction susceptibility may be present and to assist in designing liquefaction-hazard investigations. Minimum requirements for liquefaction investigations are detailed in the 2015 International Building Code (IBC) (International Code Council, 2014a) and are implied in the 2015 International Residential Code (IRC) (International Code Council, 2014b), which applies to the design and construction of one- and two-family dwellings and townhouses. The 2015 IBC Section 1803.5.11 requires a liquefaction evaluation if a structure is in Seismic Design Category C, D, E, or F, and 2015 IBC Section 1803.5.12 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. Although the IRC does not specifically mention liquefaction, IRC Section R401.4 leaves the need for soil tests up to the local building official in areas likely to have expansive, compressive, shifting, or other questionable soil characteristics, such as liquefiable soils.

IBC seismic design categories are described in IBC Section 1613.3.3. Seismic design categories are determined on a site-specific basis and vary throughout the Tickville Spring quadrangle depending on IBC Site Class, defined in IBC Section 1613.3.2; maximum considered earthquake ground motions; and the IBC Risk Category of the proposed structure. Risk Categories are based on the nature of the structure's use and occupancy and are described in IBC Section 1604.5 and table 1604.5. The IBC specifies four Risk Categories (I, II, III, and IV). Risk Category I includes buildings and other structures, such as temporary or storage facilities, that represent a low hazard to human life in the event of a failure. Risk Category II includes single and multi-family residences, and those buildings and other structures not listed in Risk Categories I, III, and IV, including single-family homes and townhomes. Risk Category III includes buildings and other structures, such as schools, that represent a substantial hazard to human life in the event of failure. Risk Category IV includes buildings and other structures designated as essential facilities, such as critical utility facilities and hospitals.

Table 1. *Liquefaction investigations and reports required prior to development approval in Salt Lake County. Modified from Salt Lake County Geologic Hazard Ordinance table 19.75.050 (Salt Lake County, 2010).*

Land Use and IBC Risk Correlation		**Liquefaction Potential**	
Land Use (Type or Facility)	**IBC Risk Category[1]**	**High and Moderate**	**Low and Very Low**
Critical and essential facilities as defined in Section 19.75.020 of the Salt Lake County Geologic Hazards Ordinance	IV	Yes	Yes
Industrial and commercial buildings (1 story and <5000 sq. ft.)	II	No[2]	No
Industrial and commercial buildings (>5000 sq. ft.)	III	Yes	No
Residential-single family lots/single family homes	II	No[2]	No
Residential subdivisions (>9 lots), and residential multi-family dwellings (4 or more units per acre)	II	Yes	No
Residential subdivisions (<9 lots), and residential multi-family dwellings (<4 units per acre)	II	No[2]	No

[1]International Code Council, 2014a

[2]Although a site-specific investigation is not required, the owner is required to file a disclosure notice prior to land-use approval.

The Salt Lake County Geologic Hazards Ordinance (Salt Lake County, 2017) stipulates the minimum requirements for liquefaction investigations prior to development. Table 1 shows the current Salt Lake County requirements based on intended land use and incorporates the corresponding IBC occupancy category. Martin and Lew (1999) provide guidelines for conducting both reconnaissance (screening) and detailed (quantitative) liquefaction investigations. In conjunction with the Salt Lake County requirements, we recommend at a minimum:

- reconnaissance investigations for all Occupancy Category II and III structures in all hazard areas,
- a detailed investigation for all Occupancy Category II and III structures when the reconnaissance investigation indicates the liquefaction hazard is moderate or greater, and
- a reconnaissance evaluation only for Occupancy Category I structures in moderate to high liquefaction-hazard areas.

No investigation is recommended for Occupancy Category I buildings in low, very low, or no susceptibility areas.

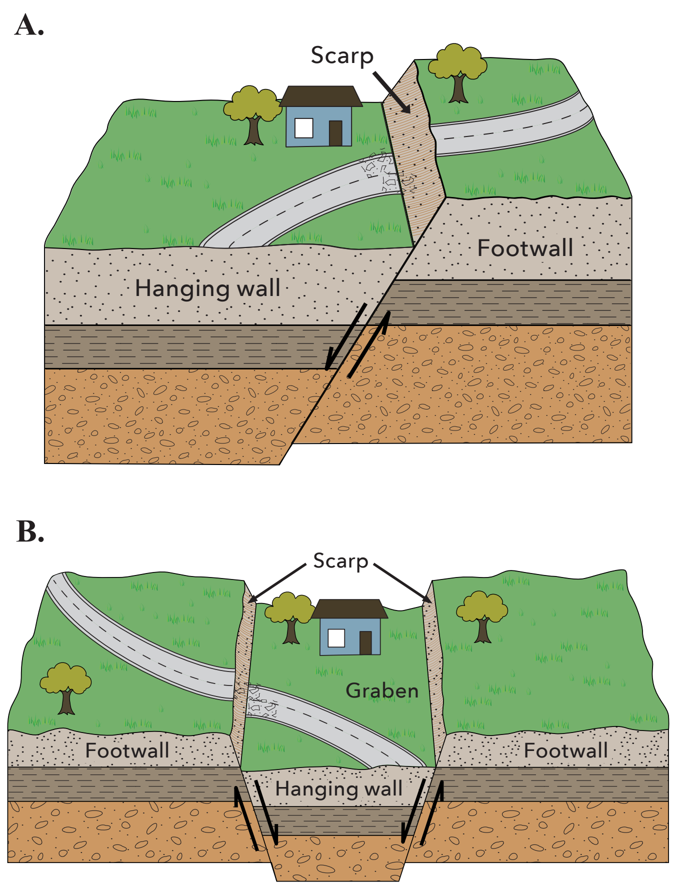

Figure 5. A. *Block diagram of a normal fault showing the relative movement of the hanging wall and footwall.* ***B.*** *Block diagram of a graben formed by two normal faults showing the relative movement of the hanging wall and footwall.*

Surface Fault Rupture

Among the potential damaging effects of large earthquakes is surface fault rupture, which occurs when fault movement at depth propagates upward along the fault to the ground surface. The resulting displacement of the ground surface may also produce ground cracking and warping, and may result in one or more fault scarps (figure 5A). Depending on the magnitude of the earthquake, fault scarps can range from a few inches to several feet high and extend for many miles along the fault trace. Local ground tilting and graben formation (figure 5B) by secondary faulting (antithetic faults) may accompany surface fault rupture, resulting in a zone of deformation along the fault trace that can be tens to hundreds of feet wide. Surface fault rupture, while of limited areal extent when compared to ground shaking, can have serious consequences for structures or other facilities that lie along or across the rupture path.

To evaluate the surface-fault-rupture hazard (plate 3) we used five main sources of data: (1) recent UGS geologic mapping (Biek and others, 2005), (2) the *Utah Quaternary Fault and Fold Database* (UGS, 2017), (3) the *Guidelines for Evaluating Surface-Fault-Rupture Hazards in Utah* (Lund and others, 2016), (4) aerial photograph interpretation, and (5) 0.5-meter bare-earth Light Detection and Ranging (lidar) data (Automated Geographic Reference Center [AGRC], 2006).

In California, the Alquist-Priolo Earthquake Fault Zoning Act (Bryant and Hart, 2007), 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)." California has a well-recognized earthquake hazard and was the first state to implement regulations designed to reduce risk from earthquake related hazards. The California "Holocene" standard is used in 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 Basin and Range Province, a time period longer than the Holocene is more appropriate for defining active faults because many 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 criterion, specifically 130,000 years, to define active faults in the Basin and Range Province. They base their recommendation on the observation that 6 to 8 (greater than 50%) of the 11 historical surface-faulting earthquakes in the Basin and Range Province occurred on faults that lacked evidence of Holocene activity, but which did have evidence of late Pleistocene activity.

Lund and others (2016) recommend adopting the fault activity classes defined by the Western States Seismic Policy Council (WSSPC) for the Basin and Range Province because of the difficulties in using a single "active" fault definition (WSSPC Policy Recommendation 11-2; first adopted in 1997 as WSSPC Policy Recommendation 97-1 and revised and readopted in 2002, 2005, 2008, 2011, and 2015; available at https://www.wsspc.org/public-policy/adopted-recommendations/ [WSSPC, 2015]). WSSPC Policy 15-3 recommends that the following definitions of fault activity be used to categorize potentially hazardous faults in the Basin and Range Province:

1. Late Pleistocene-Holocene fault — a fault that has moved within the past 15,000 years.
2. Late Quaternary fault — a fault that has moved within the past 130,000 years.
3. Quaternary fault — a fault that has moved within the past 2,600,000 years.

Based on recent UGS geologic mapping (Biek and others, 2005), we categorize normal faults (where the hanging wall has moved down relative to the footwall [figure 5A]) as well defined, concealed, or approximately located, and established special-study areas for surface-fault-rupture hazard (Lund and others, 2016) for each fault category. We consider a fault well defined if its trace is clearly detectable by a trained geologist as a physical feature at the ground surface (Bryant and Hart, 2007). We classified faults as well defined if UGS 1:24,000-scale mapping (Biek and others, 2005) shows them as solid lines, indicating that they are recognizable as faults at the ground surface. Although not well expressed at the surface, buried or approximately located Quaternary faults still may represent a significant surface-fault-rupture hazard and should be evaluated prior to development.

The surface-fault-rupture hazard map (plate 3) shows potentially active faults in the Tickville Spring quadrangle along which surface faulting may occur. A special-study area is shown around each fault, within which the UGS recommends performing a site-specific surface-fault-rupture-hazard investigation prior to development. The special-study areas established for well-defined faults extend 500 feet (150 m) on the downthrown side of the fault and 250 feet (75 m) on the upthrown side of the fault. Given their uncertain location, the special-study areas around buried or approximately located faults are broader, extending 1000 feet (300 m) from either side of the suspected fault. Lund and others (2016) provide recommendations for investigating and reporting surface-fault-rupture hazards, and procedures for establishing safe setback distances from active faults in Utah.

Two small unnamed faults mapped in the northwest corner of the quadrangle pose a potential surface-fault-rupture hazard (Biek and others, 2005). The unnamed faults are north-trending normal faults that cut late to middle Pleistocene alluvial-fan deposits; however, little else is known about these faults. The hazard from surface fault rupture should be investigated for all critical facilities within the special-study zones for these faults. Not all faults mapped on the geologic map were determined to be Quaternary faults. Mapped faults were included in the special-study zone if they were determined to be or possibly be Quaternary in age by the geologist that performed the geologic mapping.

Site-specific geotechnical/geologic-hazard investigations can resolve uncertainties inherent in the generalized surface-fault-rupture hazard map (plate 3) and help ensure safety by identifying the need for fault setbacks. The *Guidelines for Evaluating Surface-Fault-Rupture Hazards in Utah* (Lund and others, 2016; https://ugspub.nr.utah.gov/publications/circular/c-122.pdf) includes a detailed rationale for investigating and reporting surface-fault-rupture hazards, and procedures for establishing safe setback distances from potentially active faults. City and county officials, planners, and consultants should refer to the guidelines for details of conducting and reviewing investigations of surface-fault-rupture hazards. For well-defined faults, we recommend that investigations be performed in accordance with the UGS guidelines (Lund and others, 2016). Concealed and approximately located faults lack a clearly identifiable surface trace, and therefore may not be amenable to trenching, which is the standard hazard evaluation technique used to study well-defined faults (McCalpin, 2009). Where development is proposed in a special-study area for a concealed 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 published and unpublished maps, literature, and records concerning geologic units, faults, surface water and groundwater, previous subsurface investigations, and other relevant factors.
2. Use stereoscopic interpretation of aerial photographs and/or interpretation of lidar imagery to detect any subtle fault-related features expressed in the site topography, vegetation, or soil contrasts, and any lineaments of possible fault origin.
3. Perform a field evaluation of the proposed site and surrounding area to observe 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 excavate test pits to evaluate the age of deposits onsite to constrain the time of most recent surface faulting.

If the results of these investigations reveal evidence of possible surface-faulting-related features, those features should be trenched in accordance with the UGS guidelines (Lund and others, 2016). In addition, we recommend that construction excavations and cuts be carefully examined by a qualified geologist for evidence of faulting as development proceeds.

Flood Hazards

Flooding is the overflow of water onto lands that are normally dry and is the most commonly occurring natural hazard (Keller and Blodgett, 2006). Damage from flooding includes 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). Historically, flooding is the most prevalent and destructive (on an annual basis) hazard affecting Utah.

The flood hazard map (plate 4) shows areas in the Tickville Spring quadrangle that may be susceptible to flooding. Several creeks and ephemeral streams capable of flooding are at least partially within the quadrangle. These include Rose Creek, Butterfield Creek, Dry Canyon, Tickville Gulch, and ephemeral streams. Several smaller drainages also contribute to the flood hazard. Seasonal weather patterns that deliver moisture to northern Utah also contribute to a high flood hazard. The risk from flooding is significantly increased by wildfires because in burn areas, water infiltration decreases, and run-off and erosion increase. Human activities also increase the potential for flooding. These activities include placing structures and constrictions in floodplains, active alluvial fans, or erosion-hazard zones; developing without adequate flood and erosion control; poor watershed management practices (such as overgrazing or allowing indiscriminate off-road vehicle traffic); and the unintentional release of water from an engineered water-retention or conveyance structure (such as a dam or canal).

To evaluate the flood hazard (plate 4), we used six main sources of data: (1) Federal Emergency Management Agency (FEMA) National Flood Insurance Program Flood Insurance Rate Maps (FIRMs [FEMA, 2009]), (2) recent UGS geologic mapping (Biek and others, 2005), (3) active and historical debris-flow mapping conducted by the UGS, (4) aerial photography interpretation, (5) 0.5-meter lidar data (AGRC, 2006) to examine past and present drainage patterns, and (6) the National Hydrography Dataset (NHD) (USGS, 2016).

Geologic mapping is critical to determine the distribution of geologically young flood-related deposits, which aids in identifying flood-prone areas and evaluating their relative susceptibility to flooding and/or debris flows. Because of many variables contributing to flood hazard, including but not limited to precipitation intensity and duration, soil conditions, and topography, the geologic unit itself is not an absolute indicator of flood hazard susceptibility but rather a relative indicator. Geologic units assigned a flood hazard category on this map will likely demonstrate different flood susceptibility in other locations. Flood hazard categories were modified in geologic units where field observations, topographic and aerial photographic analysis warrant. Active floodplains and low terraces along perennial and larger ephemeral streams (normally dry stream channels with large catchment basins), active alluvial fans, and young lacustrine deltaic deposits are mapped as very high flood hazard. Stream channels, floodplains, low terraces along normally dry ephemeral streams, level 2 fan deposits and alluvial/colluvial deposits and talus in incised stream channels are mapped as high flood hazard. Active pediments and sloping depositional surfaces flanking ridges and other upland areas are mapped as moderate. Valley bottom lake Bonneville deposits, older pediments and stream- terrace deposits, minor ephemeral drainages, and over-steepened and incised tertiary volcanics subject to possible sheetfloods and minor flash floods from adjacent upland areas during cloudburst storms are mapped as low flood hazard. Bedrock that is highly weathered and incised and may be subject to flood hazards during cloudburst storms, and some landslide deposits are mapped as very low flood hazard. GIS data derived from the NHD delineate streams in drainages using GIS modeling based on a 30-meter National Elevation Dataset (NED)(USGS, 2016). These data were added to the map to indicate a high flood potential in drainages that have been identified by the NHD as having permanent or ephemeral flowing streams. Determining the actual extent of flooding is beyond the scope of this study and should be conducted as part of site-specific geologic hazard investigations. Small individual drainages were not mapped due to topographic complexities and scale limitations of the map.

Debris-flow and alluvial-fan deposits are also mapped on the flood map (plate 4). Debris-flow hazard is highly dependent on rainfall and snowmelt as well as sediment supply; therefore, debris flows may occur in areas mapped as moderate or low, and not only in areas with mapped active or historical debris-flow deposits. Post-wildfire flood hazard is considered high in areas having slopes greater than 17° (30%), based on the Salt Lake County Geologic Hazards Ordinance (Salt Lake County, 2017), and a site-specific debris-flow investigation should be performed. The potential for flooding is significantly increased by wildfires. Wildfire increases flood potential by decreasing saturation of water into the ground. The flood hazard may be mapped as very low or low in many areas with slopes greater than 17° (30%); however, exposed bedrock and sparse vegetation can increase the flood hazard in these locations.

Flood hazard associated with shallow groundwater was considered where data are available. Areas of potential shallow groundwater (less than 10 ft [3 m]) were mapped as high flood hazard potential. Interbedded clay, silt, sand, and gravel deposited during the Bonneville lake cycle give rise to a complex groundwater system.

Site-specific geotechnical/geologic-hazard flood investigations can resolve uncertainties in-herent in the generalized hazard map (plate 4) and help ensure safety by identifying the local flood and debris-flow hazard. UGS Circular 122, *Guidelines for the Geologic Investigation of Debris-Flow Hazards on Alluvial Fans in Utah* (Giruad, 2016; https://ugspub.nr.utah.gov/publications/circular/c-122.pdf), recommends minimum standards for performing debris-flow investigations in Utah.

FEMA-designated flood zones delineated on the FIRMs are overlain on our mapped hazard categories. FEMA, through its National Flood Insurance Program (NFIP), makes federally subsidized flood insurance available to individuals residing in participating communities. Not all areas in the Tickville Spring quadrangle have been mapped by FEMA, and FEMA may designate flood zones in the future. FIRMs are legal documents that govern the administration of the NFIP. Property owners should consult the appropriate FIRM directly when considering the purchase of NFIP flood insurance (https://msc.fema.gov). Flood insurance can also be purchased by landowners outside of mapped zone A designated by FEMA.

The flood-hazard-potential categories shown on the map are approximate and mapped boundaries are gradational. Localized areas of higher or lower flood hazard are likely to exist within any given map area, but their identification is precluded because of the generalized map scale, and nongeologic factors such as climate change, wildfire, removal of vegetation and/or topsoil, modification of waterways and/or the ground surface, unidentified areas of perched shallow groundwater, landscape irrigation, and stormwater control.

Landslide Hazards

Landslide is a general term that refers to the gradual or rapid movement of a mass of rocks, debris, or earth down a slope under the force of gravity (Neuendorf and others, 2005; Beukelman and Hylland, 2016). The term covers a wide variety of mass-movement processes, and includes both deep-seated and shallow slope failures. The moisture content of the affected materials when a slope fails can range from dry to saturated. However, high moisture content reduces the strength of most deposits susceptible to landslides and is often a contributing factor to landsliding.

Three broad factors, acting either individually or in combination, contribute to landsliding (Varnes, 1978; Wieczorek, 1996): (1) an increase in shear stress, (2) low material strength, and (3) a reduction of shear strength. Common factors that increase shear stress include adding mass to the top of a slope, removing support from the toe of a slope, transient stresses associated with earthquakes and explosions, and the long-term effects of tectonic uplift or tilting. Low material strength in rock or soil typically reflects the inherent characteristics of the material or is influenced by discontinuities (such as joints, faults, bedding planes, and desiccation fissures). Factors that reduce shear strength include both physical and chemical weathering, alteration, and the addition of water to a slope, which increases pore-water pressure and reduces the effective intergranular strength within the slope materials.

Although one or more of the above causes may make a rock or soil mass susceptible to landsliding, a trigger is required for landsliding to occur (Varnes, 1978; Cruden and Varnes, 1996). A trigger is an external stimulus or event that initiates landsliding either by increasing stresses or reducing the strength of slope materials (Wieczorek, 1996). Landslide triggers may be either static or dynamic. Static conditions include intense rainfall or prolonged periods of above-normal precipitation, rapid snowmelt, added water from irrigation or improper drainage, improper grading, and rapid erosion. Dynamic conditions include earthquakes and other ground shaking. Although frequently obvious, some triggers are subtle and not readily apparent. For example, a nearly imperceptible combination of weathering and gradual erosional undercutting can eventually cause landsliding.

To evaluate landslide susceptibility (plate 5), we used six main sources of data: (1) recent UGS geologic mapping (Biek and others, 2005), (2) landslide inventory mapping conducted by the UGS, (3) previous landslide investigations, (4) aerial photograph interpretation, (5) 0.5-meter lidar data (AGRC, 2006), and (6) field mapping and reconnaissance. We classify landslide susceptibility as high, moderate, or low. High landslide susceptibility consists of mapped landslides, as well as geologic units that have experienced previous landsliding elsewhere in Utah, that underlie slopes that equal or exceed a selected critical slope angle. Moderate landslide susceptibility consists of areas having slopes steaper than a selected critical slope angle and areas that have a geologic unit prone to landsliding and the slope is less steep than the critical slope angle. Low landslide susceptibility consists of areas having slopes with a critical angle lower than 10° and units not likely susceptible to landsliding.

In the Tickville Spring quadrangle, we applied critical slope angles of 10° and 20°, based on analysis of landslides in northern Utah within the same geologic units. To determine these slope angles, we used GIS to calculate the average slope of each mapped landslide included in the *Landslide Maps of Utah* (Elliott and Harty, 2010) in northern Utah. The landslide slopes were then exported to a spreadsheet based on geologic unit, and the average slope angle for each geologic unit was determined. Using the mean landslide slope plus or minus one standard deviation, we assigned a critical angle to geologic units in the Tickville Spring quadrangle. Similar methodology has been used in other landslide evaluation and susceptibility investigations in similar geologic units to define critical slope angles (Hylland and Lowe, 1997; Giraud and Shaw, 2007). We assigned a critical angle of 10° to Lake Bonneville deposits, Tertiary volcanic deposits, and other unconsolidated units, 17° to geologic deposits where no existing landslides are currently identified (Salt Lake County, 2017), and 20° to bedrock units where no existing landslides are currently identified.

Although earthquake-induced ground shaking increases the potential for landsliding in susceptible material, the relative landslide susceptibility of the slope material does not change. For example, slopes mapped as having moderate landslide susceptibility are more likely to fail during an earthquake than under static conditions; however, slopes having moderate landslide susceptibility are less likely to fail than slopes having high susceptibility under static or dynamic conditions.

The landslide-susceptibility map (plate 5) shows areas of relative landslide susceptibility where site-specific slope-stability conditions (material strength, orientation of bedding and/or fractures, groundwater conditions, erosion or undercutting, and slope loading) should be evaluated prior to development. A valid landslide-hazard investigation must address all pertinent conditions that could affect, or be affected by, the proposed development, including earthquake ground shaking, perched or irrigation-induced groundwater, and slope modifications. This can only be accomplished through the proper identification and interpretation of site-specific geologic conditions and processes (Beukelman and Hylland, 2016). The analysis of natural and modified slopes for static and/or seismic stability is a challenging geotechnical problem. Blake and others (2002) suggest that proper analysis requires characterization of surface topography, subsurface stratigraphy, groundwater levels and possible subsurface flow patterns, shear strength of materials through which the failure surface may pass, and 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:

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

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

Additionally, *Guidelines for Evaluating Landslide Hazards in Utah* (Beukelman and Hylland, 2016; https://ugspub.nr.utah.gov/publications/circular/c-122.pdf) recommends minimum standards for performing landslide-hazard evaluations in Utah. Minimum UGS recommendations for site-specific investigations for each landslide-susceptibility category in the Tickville Spring quadrangle are shown in table 2.

Salt Lake County's Zoning Ordinance Code prohibits development (including clearing, excavating, and grading) on slopes exceeding 30% (17°) and sets aside these areas as natural, private or public open space (Salt Lake County, 2010). Also, all roads are restricted from crossing slopes greater than 30% (17°) unless they meet specific requirements and gain authorization (Salt Lake County, 2010).

While it is possible to classify relative landslide hazard in a general way based on 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 significant or where landscape irrigation or onsite wastewater disposal systems may cause groundwater levels to rise (Ashland, 2003; Ashland and others, 2005, 2006) require a site-specific geotechnical/geologic-hazard investigation to evaluate the effect of development on slope stability.

Rockfall Hazards

Rockfall 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; Castleton, 2009). Rockfalls are a hazard because a boulder traveling at high speed can cause significant damage. Rockfalls can damage property, roadways, and vehicles, and pose a significant safety threat. Rockfall hazards are found where

Table 2. *Recommended requirements for site-specific landslide-hazard investigations in the Tickville Spring quadrangle.*

Landslide Susceptibility	Recommended Site-Specific Investigation
High	Detailed engineering, geologic and geotechnical-engineering investigation necessary.
Moderate	Geologic evaluation necessary; detailed engineering geologic and geotechnical-engineering investigation may be necessary.
Low	Geologic evaluation necessary; detailed geotechnical-engineering investigation generally not necessary.

a rock source exists above slopes steep enough to allow rapid downslope movement of dislodged rocks by falling, rolling, and bouncing. Most rockfalls originate on slopes steeper than 35° (Wieczorek and others, 1985; Keefer, 1993), although rockfall hazards may also be found on less-steep slopes.

Rockfall-hazard potential is based on a number of factors including geology, topography, and climate. Rockfall sources include bedrock outcrops or boulders on steep mountainsides or near the edges of escarpments, such as bluffs, terraces, and ancient shorelines. Talus cones and scree-covered slopes are indicators of a high rockfall hazard, although other areas are also vulnerable. Rockfalls may be initiated by frost action, rainfall, weathering and erosion of the rock or surrounding material, and root growth, though in many cases a specific triggering mechanism is not apparent. Rockfalls may also be initiated by ground shaking. Keefer (1984) indicated earthquakes as small as M 4 can trigger rockfalls.

The rockfall hazard map (plate 6) shows areas in the Tickville Spring quadrangle that may be susceptible to rockfall. Where no hazard is mapped, rockfall hazard is either absent or too localized to show on a 1:24,000-scale map. Each hazard category includes three components (figure 6): (1) a rockfall source, in general defined by geologic units that exhibit relatively consistent patterns of rockfall susceptibility throughout the study area; (2) an acceleration zone, where rockfall fragments detached from the source gain energy and momentum as they travel downslope, which often includes a talus slope, that becomes less apparent with decreasing relative hazard and is typically absent where the hazard is low; and (3) a runout zone, including gentler slopes that may be covered discontinuously by scattered large boulders that have rolled or bounced beyond the base of the slope.

To evaluate rockfall hazard (plate 6), we used five main sources of data: (1) recent UGS geologic mapping (Biek and others, 2005), (2) previous landslide investigations, (3) aerial photography interpretation, (4) 0.5-meter lidar data (AGRC, 2006), and (5) field mapping and reconnaissance. We assigned a hazard designation of high, moderate, or low, based on the following rockfall-source parameters: rock type, joints, fractures, orientation of bedding planes, and potential clast size, as determined by geologic mapping (Biek and others, 2005), as well as slope angle, acceleration zone, and a shadow angle of 20°. We evaluated slopes below rockfall sources for slope angle, vegetation, clast distribution, clast size range, amount of embedding, and weathering of rockfall boulders. Table 3 summarizes our recommended requirements for site-specific geotechnical/geologic-hazard investigations related to rockfall hazards to protect life and safety. Additionally, *Guidelines for Evaluating Rockfall Hazards in Utah* (Lund and Knudsen, 2016; https://ugspub.nr.utah.gov/publications/circular/c-122.pdf), recommends minimum standards for performing rockfall hazard investigations in Utah.

Radon Hazard

Radon is an odorless, tasteless, and colorless radioactive gas that is highly mobile and can enter buildings through small foundation cracks and other openings, such as utility pipes. The most common type of radon is naturally occurring and results from the radioactive decay of uranium, which is found in small concentrations in nearly all soil and rock. Air movement and open space dissipates radon gas outdoors, but indoor radon concentration may reach hazardous levels because of confinement and poor air circulation in buildings. Breathing any level of radon over time increases the risk of lung cancer, but long-term exposure to low radon levels is generally considered a small health risk. Smoking greatly increases the health risk due to radon because radon decay products attach to smoke particles and are inhaled into the lungs, greatly increasing the risk of lung cancer. The U.S. Environmental Protection Agency (U.S. EPA, 2009) recommends that action be taken to reduce indoor radon levels exceeding 4 picocuries per liter of air (pCi/L) and cautions that indoor radon levels less than 4 pCi/L still pose a health risk. In many cases radon hazard risk can be reduced.

Indoor radon levels are affected by several geologic factors including uranium content in soil and rock, soil permeability, and groundwater. Granite, metamorphic rocks, some volcanic rocks and shale, and soils derived from these rocks are generally associated with elevated uranium content contributing to high indoor radon levels.

Soil permeability and groundwater affect the mobility of radon from its source. If a radon source is present, the ability of radon to move upward through the soil into overlying buildings is facilitated by high soil permeability. Conversely, radon movement is impaired in soils having low permeability. Saturation of soil by groundwater inhibits radon movement by dissolving radon in the water and reducing its ability to migrate upward through the soil (Black, 1996).

Along with geologic factors, a number of non-geologic factors also influence radon levels in a building. Although the influence of geologic factors can be estimated, the influence of non-geologic factors, such as occupant lifestyle and home construction, are highly variable. As a result, indoor radon

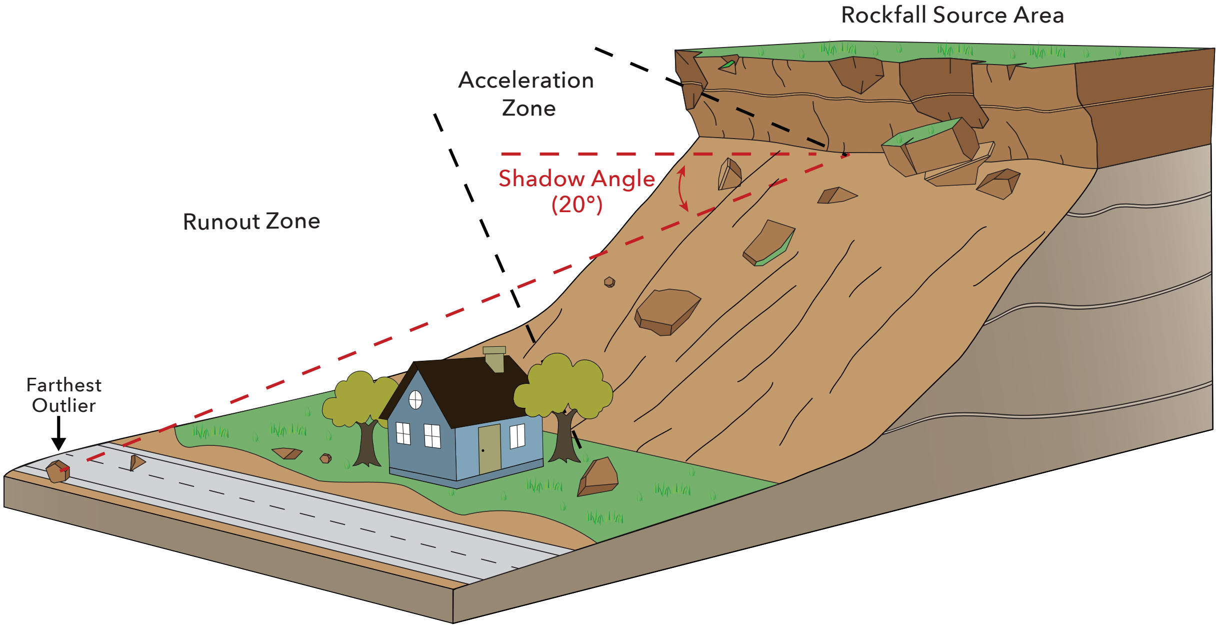

Figure 6. *Components of a characteristic rockfall path profile (modified from Lund and others, 2008).*

Table 3. *Recommended requirements for site-specific geotechnical/geologic-hazard investigations related to rockfall hazards to protect life and safety.*

Hazard Potential	**Classification of Buildings and Other Structures for Importance Factors**[1]				
	I		II	III	IV
	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	Buildings and other structures that represent a low hazard to human life in the event of failure
High, Moderate	Yes	Yes	Yes	Yes	No[2]
Low	Yes	Yes	Yes	Yes	No[2]
None	No	No	No	No	No

[1]Risk category from International Code Council, 2014a.
[2] Property damage possible, but little threat to life safety.

levels fluctuate and can vary in different structures built on the same geologic unit; therefore, the radon level must be measured in each building to determine if a problem exists. Testing is easy, inexpensive, and may often be conducted by the building occupant, but professional assistance is available (for more information, visit https://radon.utah.gov). Evaluation of actual indoor radon levels in the quadrangle was beyond the scope of this investigation.

To evaluate the radon-hazard potential (plate 7), we used five main sources of data to identify areas where underlying geologic conditions may contribute to elevated radon levels: (1) radon-hazard-potential studies where available, (2) soil permeability data from the NRCS *Soil Survey Geographic (SSURGO) Database for Salt Lake Area, Salt Lake County, Utah* (NRCS, 2006), (3) depth-to-groundwater mapping, and (4) recent UGS geologic mapping (Biek and others, 2005), and and (5) U.S. Geological Survey (USGS) National Uranium Resource Evaluation (NURE) Hydrogeochemical and Stream Sediment Reconnaissance Data (USGS, 2004). Using the geologic factors of uranium content, soil permeability, and depth to groundwater, we classified soil and rock units using a three-point system (table 4) into high (3 points), moderate (2 points), and low (1 point) hazard categories based on their potential to generate radon gas and the ability of the gas to migrate upward through the overlying soil and rock (after Black and Solomon, 1996). Points were assigned based on the shallow groundwater mapping (plate 1), permeability, and relative uranium content of mapped rock units in the Tickville Spring quadrangle.

Table 4. *Radon-hazard-potential classifications based on geologic factors affecting the ability of radon gas to migrate upward through the overlying soil and rock.*

Geologic Factors	**Radon hazard category**[1]		
	Low	**Moderate**	**High**
Uranium (ppm)	<2	2–3	>3
Soil permeability[2]	Impermeable (Hydraulic conductivity <0.6 in/hr [<4.23 µm/s])	Moderately permeable 0.6–6 in/hr (4.23–42.34 µm/s)	Highly permeable >6 in/hr (>42.34 µm/s)
Depth to groundwater	< 10 feet (3 m)	10–30 feet (3–9 m)	> 30 feet (9 m)

[1] Black (1996)
[2]NRCS (2006)

The NRCS reported hydraulic conductivity (Ksat) values of saturated soil for their soil units based on testing performed at representative locations (NRCS, 2006), and assigned permeability classes to their soil units based on the hydraulic conductivity of the unit. The hydraulic conductivity values of non-soil map units (water, borrow pits, and other artificial units as mapped by the NRCS) are reported as zero; however, they do not necessarily represent impermeable surfaces. Therefore, the hydraulic conductivity of adjacent units is assumed to apply to non-soil map units.

Saturation of soil by shallow groundwater (less than approximately 30 feet [9 m]) inhibits radon movement by dissolving radon in the water and reducing its ability to migrate upward through subgrade and foundation soil (Black, 1993). Our groundwater mapping focused on the principal aquifer where it is shallow and unconfined or artesian, and on locally unconfined or perched aquifers 30 feet (9 m) or less below the ground surface. Even in areas with very shallow groundwater, the source of radon may be above the water table or introduced from imported material. If the radon source was determined to be above the water table, then shallow groundwater no longer contributes to the inhibition of radon gas and we assigned a higher point value to the shallow groundwater factor.

The map of radon-hazard potential (plate 7) is intended to provide an estimate of the underlying geologic conditions that may contribute to the radon hazard. The map does not characterize indoor radon levels because they are also affected by highly variable non-geologic factors. The map can be used to indicate the need for testing indoor radon levels; however, we recommend testing in all existing structures. If professional assistance is required to test for radon or reduce the indoor radon hazard, a qualified contractor should be selected. The EPA provides guidelines for choosing a contractor and a listing of state radon offices in *Consumer's Guide to Radon Reduction* (U.S. EPA, 2010). The radon-hazard potential map is not intended to indicate absolute indoor radon levels in specific buildings. Although geologic factors contribute to elevated indoor-radon-hazard potential, other highly variable factors, such as building materials and foundation openings, affect indoor radon levels; therefore, indoor radon levels can vary greatly between structures located in the same hazard category. Additionally, the guidelines within the International Residential Code, Appendix F (International Code Council, 2014b), concerning radon control methods, should be followed for new construction.

The hazard-potential categories shown on the map are approximate and mapped boundaries are gradational. Localized areas of higher or lower radon potential are likely to exist within any given map area, but their identification is precluded because of the generalized map scale, relatively sparse data, and non-geologic factors such as variability in building construction. The use of imported fill for foundation material can also affect radon potential in small areas, because the imported material may have different geologic characteristics than native soil.

Collapsible Soil Susceptibility

Collapsible soils are relatively dry, low-density soils that decrease in volume or collapse under the load of a structure when they become wet. Collapsible soils may have considerable strength and stiffness in their dry natural state, but can settle up to 10% 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, structures, pavements, and underground utilities.

Collapsible soils are present in the Tickville Spring quadrangle and are typically geologically young materials, chiefly Holocene debris-flow sediments in alluvial fans and Pleistocene to Holocene lacustrine and colluvial deposits (plate 8). Collapsible soils typically have a high void ratio, a corresponding low unit weight (less than 80 to 90 lb/ft^3; Costa and Baker, 1981), and a relatively low moisture content (less than 15%; Owens and Rollins, 1990), all characteristics that result from the initial rapid deposition and drying of the sediments. Alluvial fans are an example of this depositional environment and in many cases have a high collapsible soil hazard. Intergranular bonds form between the larger grains (sand and gravel) of a collapsible deposit; these bonds develop through capillary tension or a binding agent such as silt, clay, or salt. Characteristically, collapsible soils consist of silty sand, sandy silt, and clayey sand (Williams and Rollins, 1991), although Rollins and Rogers (1994) identified collapse-prone gravel containing as little as 5% to 20% fines at several locations in the southwestern United States. Later wetting of the soil results in a loss of capillary tension or the softening of the bonding material, allowing the larger particles to slip past one another and form a denser structure. 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 fans. Therefore, soil collapse is often triggered by human activity related to urbanization, such as irrigation or wastewater disposal.

To evaluate collapsible-soil susceptibility (plate 8), we used two main sources of data: (1) recent UGS geologic mapping (Biek and others, 2005), and (2) the geotechnical database compiled by the UGS. First, we evaluated test data from the geotechnical database; swell/collapse tests (SCT), dry density, and moisture tests are all used to determine collapse potential. Next, we integrated geologic unit descriptions from recent UGS geologic mapping (Biek and others, 2005) with the geotechnical data to assign a susceptibility category to mapped geologic units. We classified unconsolidated geologic units into five categories based on their collapse potential.

Where geotechnical data provide evidence for high collapse susceptibility, as indicated by SCT results exhibiting collapse potential equal to or more than 3% (Jennings and Knight, 1975), we assigned two susceptibility categories: Highly Collapsible Soil, where SCT tests indicate collapse potential equal to or more than 5%, and collapsible Soil A, where SCT tests indicate collapse potential over 3% and less than 5%. For geologic units in which other geotechnical information (chiefly low density and moisture content) provide evidence for potentially collapsible soils, we delineated a collapsible Soil B category using geologic contacts. Where geotechnical data are lacking, we assigned geologic units having a genesis and texture conducive to collapse to the collapsible Soil C category. Finally, where older geologic units (Pleistocene) are mapped with no available geotechnical data, but having a genesis or texture permissive of collapse, we assigned the collapsible Soil D category. All susceptibility categories represent geologic units having a potential for collapse. Geologic units with SCT results indicating a demonstrated high percentage of collapse dictate that the geologic units containing the SCT test data are elevated above other similar geologic units lacking geotechnical test data. However, all mapped susceptibility categories may potentially exhibit a high percentage of collapse; therefore, site-specific investigations should be performed at all locations to resolve uncertainties inherent in the maps.

Expansive Soil and Rock Susceptibility

Expansive soil and rock swells as it gets wet, and shrinks as it dries out. These changes in volume can cause cracked foundations and other structural damage to buildings, structures, pavements, and underground utilities (figure 7), heaving and cracking of canals and road surfaces, and failure of wastewater disposal systems. Expansive soil and rock contains a significant percentage of clay minerals that can absorb water directly into their crystal structure when wetted. For soil having clay content greater than approximately 12% to 15%, the expansive nature of the clay begins to dominate and the soil is subject to swell. Sodium-montmorillonite clay can swell as much as 2000% 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 load imposed by many structures. Expansive soils are chiefly derived from weathering of clay-bearing rock formations and may be residual (formed in place) or transported (usually a short distance) and deposited in a new location. The principal transporting mechanisms are water and wind, but soil creep and mass-wasting processes can play important roles locally.

To evaluate susceptibility to expansive soil and rock (plate 9), we used three main sources of data: (1) recent UGS geologic mapping (Biek and others, 2005), (2) the geotechnical database compiled by the UGS, and (3) the NRCS *Soil Survey Geographic (SSURGO) Database for Salt Lake Area, Salt Lake County, Utah* (NRCS, 2006). We classified soil and rock units into three categories based on their potential for volumetric change: high, moderate, and low.

The NRCS (2006) assigned a linear extensibility value to soils. Linear extensibility is an expression of volume change that represents the change in length of an unconfined clod as moisture content is decreased from a moist to a dry state (NRCS, 2006). We compared the ratings presented by the NRCS with the laboratory test results in our geotechnical database. Correlations between the NRCS information and the geotechnical test data are generally good, but some discrepancies exist locally. Where geotechnical testing data show elevated levels of swell potential, we use geologic-map data to modify the boundaries between susceptibility categories.

Using geotechnical data in our database, we evaluated liquid limit (LL), plasticity index (PI), SCT tests, and expansion index data for swell potential. SCT tests are the most reliable indicator of swelling potential; we used them as the primary indicator of swell potential, and LL and PI tests in the absence of SCT data.

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 that categorize a soil's capacity to shrink or swell. Chen (1988) presented a correlation between swell potential and PI (table 5) that illustrates

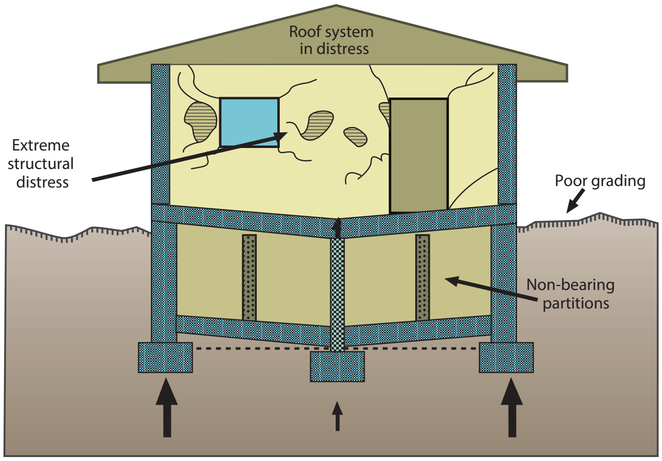

Figure 7. *Typical structural damage to a building from expansive soil and rock (after Black and others, 1999).*

Table 5. *Correlation between geotechnical tests of soils and expansive-soil susceptibility.*

Test	Susceptibility Category		
	Low	**Moderate**	**High**
SCT	0%–2%	2%–3%	> 3%
LL	0–30	20–50	> 45
PI[1]	0–15	10–35	> 20
Expansion Index[2]	0–50	51–90	> 91

[1]Chen (1988)
[2]Nelson and Miller (1992)

the use of PI as an indicator of swelling potential. The use of PI values can assist in selecting samples for swell/collapse testing. Chen (1988) placed the lower bound of soils with high swelling potential at a PI of 20, but also included soils with a PI between 20 and 35 in the moderate category. Therefore, using a PI between 20 and 35 from a site-specific geotechnical investigation as an indicator of high swell potential is conservative and may overestimate the potential for high swell values at the site. In contrast, the 2015 IBC and the 2015 IRC (International Code Council, 2014a, 2014b), which use PI as one of four criteria to determine if soils are considered expansive, include soils having a PI of 15 or greater in the expansive soil category. In general, PI values equal to or more than 20 can serve as a rough indicator of high swell potential and can be used to select samples for more extensive swell/collapse testing.

The Unified Soil Classification System (USCS) uses LL data when classifying fine-grained soils. The USCS classifies soils having an LL greater than 50 as highly plastic (capable of being permanently deformed without breaking); such soils typically contain expansive fat clays. The USCS classifies soils having an LL less than 50 as having low or medium plasticity.

We identified geologic units containing expansive clay minerals by examining geologic unit descriptions and geotechnical test data from the units. We classified them as having moderate or high swell potential depending on geotechnical test data from the unit and its corresponding NRCS classification. Due to the scale of our mapping, individual sites within any susceptibility category (high, moderate, low) may exhibit a high percentage of swell; therefore, site-specific geotechnical/geologic-hazard investigations should be performed at all locations to resolve uncertainties inherent on the map.

Shallow Bedrock

Bedrock formations that are not significantly fractured provide relatively incompressible foundations that have high shear strengths, making mechanical compaction of these materials generally ineffective and unnecessary (Christenson and Deen, 1983). The principal problem related to shallow bedrock is difficulty of excavation, particularly in highly resistant bedrock units. Shallow bedrock makes excavations for basements, foundations, underground utilities, and road cuts difficult, can cause areas of perched groundwater, and can create problems for wastewater disposal.

Resistant bedrock is exposed at the ground surface in many foothill locations of Utah. Less obvious are areas of shallow bedrock within valleys, where bedrock is overlain by a thin cover of unconsolidated Lake Bonneville and younger alluvial deposits.

To evaluate shallow-bedrock potential (plate 10), we used five main sources of data: (1) recent UGS geologic mapping (Biek and others, 2005), (2) the *NRCS Soil Survey Geographic (SSURGO) Database for Salt Lake Area, Salt Lake County, Utah* (NRCS, 2006), (3) the geotechnical database compiled by the UGS, (4) the Utah Division of Water Rights (UDWR) well information program WELLVIEW (UDWR, 2009), and (5) field mapping and reconnaissance. We classified shallow bedrock as hard or soft where exposed at the surface, and identified areas of buried shallow bedrock (less than 10 feet [3 m] below the surface). No soft bedrock was identified on the Tickville Spring quadrangle.

We used recent geologic mapping (Biek and others, 2005) to identify areas where bedrock is exposed at the ground surface, and qualitatively classified bedrock units based on geologic unit descriptions. After identifying bedrock outcrops, we used the restrictive layer data reported by the NRCS (2006) soil survey to identify areas of potentially shallow bedrock. The restrictive layer column identifies areas where bedrock is less than 6.5 feet (2 m) below the surface.

We used geotechnical borehole logs in the UGS geotechnical database in WELLVIEW (UDWR, 2009) to help identify areas of shallow bedrock. We compared the borehole logs with geologic mapping, NRCS soils mapping, and geotechnical testing information to confirm the existence of shallow bedrock where it was identified by NRCS and to identify other potential areas of shallow bedrock. Correlations between the borehole logs, geologic mapping, geotechnical data, and NRCS information are generally good, but some local discrepancies commonly exist.

MAP LIMITATIONS

The geologic-hazard maps accompanying this report are designed to provide geotechnical engineers, engineering geologists, design professionals, planners, building officials, developers, and the public with information on the geologic hazards that may affect existing and future development in the Tickville Spring quadrangle. Information provided herein includes the type and location of critical geologic hazards, and recommendations for site-specific investigations to mitigate the hazards. The maps indicate where detailed, site-specific geotechnical/geologic-hazard investigations should be performed. Additionally, the maps can aid local governments in developing geologic-hazards elements for their general land-use plans for development, re-development, planning, regulation, and design in Utah (Christenson and Ashland, 2007). We mapped 10 geologic hazards in the Tickville Spring quadrangle; however, other hazards may exist that may affect existing and future development.

We recommend performing site-specific geotechnical/geologic-hazard investigations for all development in the Tickville Spring quadrangle using the guidelines presented in UGS Circular 122 (Bowman and Lund, 2016). Site-specific geotechnical/geologic-hazard investigations can resolve uncertainties inherent in these generalized hazard maps and help ensure safety by identifying the need for hazard mitigation and/or special construction techniques. As with all maps, these geologic-hazard maps have limitations. The maps are not for use at scales other than 1:24,000, and are not a substitute for site-specific geotechnical/geologic-hazard investigations. The maps are based on limited geologic, geotechnical, and hydrologic data. The quality of each map depends on the quality of the data, which varies by hazard throughout the study area. Consequently, special-study-area boundaries shown on the maps are approximate and subject to change with additional information. Small, localized areas of geologic hazards may exist in a study area, but their identification may be precluded due to limitations of either data availability or map scale.

ADDITIONAL INFORMATION AND GUIDELINES

In addition to the information contained in this report, the UGS Earthquakes and Geologic Hazards web page at https://geology.utah.gov/hazards/ provides links to general information on geologic hazards in Utah. The UGS web page for consultants and design professionals (https://geology.utah.gov/about-us/geologic-programs/geologic-hazards-program/for-consultants-and-design-professionals/) provides links to recommended guidelines for geotechnical/geologic-hazard investigations and reports, UGS geologic-hazard maps and reports, geologic maps, groundwater reports, historical aerial photography, and other sources of useful information. The UGS has published updated guidelines (https://ugspub.nr.utah.gov/publications/circular/c-122.pdf) that include recommendations for appropriate, minimum investigation techniques, standards, and report content to ensure adequate geologic site characterization and geologic-hazard investigations (Bowman and Lund, 2016). The guidelines also provide a technical (scientific) basis for geologic-hazard ordinances and land-use regulations implemented by local jurisdictions. The UGS advises following the recommended guidelines when preparing site-specific engineering-geologic reports and conducting site-specific geotechnical/geologic-hazard investigations in Utah. Typically, geologic-engineering and geologic-hazard considerations would be combined in a single report, or included as part of a geotechnical report that also addresses site foundation conditions and other engineering aspects of the project.

ACKNOWLEDGMENTS

We thank Bill Lund (UGS, emeritus) and Barry Solomon (UGS, retired) for their work in developing the methods that this study incorporates. We also thank Steve Bowman, Tyler Knudsen, and Stephanie Carney for their thorough review of the report and maps. Finally, we thank Salt Lake and Utah Counties and the cities of Herriman, Riverton, and Eagle Mountain for aid in collecting geotechnical data and consultant's reports.

REFERENCES

Anderson, L.R., Keaton, J.R., Spitzley, J.E., and Allen, A.C., 1994, Liquefaction potential map for Salt Lake County, Utah, complete technical report: Utah Geological Survey Contract Report 94-9, 48 p. pamphlet, 9 plates, scales 1:24,000 and 1:48,000.

Arabasz, W.J., Pechmann, J.C., and Brown, E.D., 1992, Observational seismology and the evaluation of earthquake hazards and risk in the Wasatch Front area, Utah, *in* Gori, P.L., and Hays, W.W., editors, Assessment of regional earthquake hazards and risk along the Wasatch Front, Utah: U.S. Geological Survey Professional Paper 1500-D, 36 p.

Ashland, F.A., 2003, Characteristics, causes, and implications of the 1998 Wasatch Front landslides, Utah: Utah Geological Survey Special Study 105, 49 p.

Ashland, F.X., Giraud, R.E., and McDonald, G.N., 2005, Groundwater-level fluctuations in Wasatch Front landslides and adjacent slopes, northern Utah: Utah Geological Survey Open-File Report 448, 22 p.

Ashland, F.X., Giraud, R.E., and McDonald, G.N., 2006, Slope-stability implications of groundwater-level fluctuations in Wasatch Front landslides and adjacent slopes, northern Utah, *in* 40th Symposium on Engineering Geology and Geotechnical Engineering, May 24–26, 2006: Logan, Utah State University, 12 p.

Automated Geographic Reference Center, 2006, 2-meter bare earth LiDAR: Online, State Geographic Information Database, https://raster.utah.gov/, accessed March 2009.

Automated Geographic Reference Center, 2016, Roads and highway system: Online, State Geographic Information Database, https://gis.utah.gov/data/sgid-transportation/roads-system, accessed December 2016.

Bartlett, S.F., Ericksen, G., Leeflang, B., and Solomon, B.J., 2006, Probabilistic liquefaction potential and liquefaction-induced ground-failure maps for the urban Wasatch Front—Phase 3: Unpublished report to the U.S. Geological Survey, National Earthquake Hazards Reduction Program, award no. 06HQGR0015, 158 p.

Bartlett, S.F., Olsen, M.J., and Solomon, B.J., 2005, Probabilistic liquefaction potential and liquefaction-induced ground-failure maps for the urban Wasatch Front Phase 1: Unpublished report to the U.S. Geological Survey, National Earthquake Hazards Reduction Program, award nos. 04HQGR0025 and 04HQGR0026, 197 p.

Beukelman, G.S., and Hylland, M.D., 2016 Guidelines for evaluating landslide hazards in Utah, *in* Bowman, S.D., and Lund, W.R., editors, Guidelines for investigating geologic hazards and preparing engineering-geology reports, with a suggested approach to geologic-hazard ordinances in Utah: Utah Geological Survey Circular 122, p. 59–73.

Biek, R.F., 2005, The Traverse Mountains—new geologic maps and explosive suburban growth: Utah Geological Survey, Survey Notes v. 37, no. 2, p. 1–5.

Biek, R.F., Solomon, B.J., Smith, T.W., Keith, J.D., and Smith, T.W., 2005, Geologic map of the Tickville Spring quadrangle, Salt Lake and Utah Counties, Utah: Utah Geological Survey Map 214, scale 1:24,000.

Black, B.D., 1996, Radon-hazard potential of western Salt Lake Valley, Salt Lake County, Utah: Utah Geological Survey Special Study 91, 28 p.

Black, B.D., Solomon, B.J., and Harty, K.M., 1999, Geology and geologic hazards of Tooele Valley and the West Desert Hazardous Industry Area, Tooele County, Utah: Utah Geological Survey Special Study 96, 65 p., 6 plates.

Blake, T.F., Hollingsworth, R.A., and Stewart, J.P., editors, 2002, Recommended procedures for implementation of DMG Special Publication 117, Guidelines for analyzing and mitigating landslide hazards in California: Los Angeles, California, Southern California Earthquake Center, 125 p.

Bowman, S.D., and Lund, W.R., editors, 2016, Guidelines for investigating geologic hazards and preparing engineering-geology reports, with a suggested approach to geologic-hazard ordinances in Utah: Utah Geological Survey Circular 122, 203 p.

Bryant, W.A., and Hart, E.W., 2007, Fault-rupture hazard zones in California—Alquist-Priolo earthquake fault zoning act with index to earthquake fault zones maps: California Geological Survey Special Publication 42, 38 p., available online at ftp://ftp.consrv.ca.gov/pub/dmg/pubs/sp/Sp42.pdf.

California Geological Survey, 2008, Guidelines for evaluating and mitigating seismic hazards in California: California Geological Survey Special Publication 117A, 98 p., available online at http://www.conservation.ca.gov/cgs/shzp/webdocs/Documents/sp117.pdf.

Castleton, J.J., 2009, Rock-fall hazards in Utah: Utah Geological Survey Public Information Series 94, 3 p.

Chen, F.H., 1988, Foundations on expansive soils: Amsterdam, Netherlands, Elsevier, 463 p.

Christenson, G.E., compiler, 1992, The March 16, 1992 ML Western Traverse Mountains earthquake, Salt Lake County, Utah: Utah Geological Survey Open-File Report 255, 21 p.

Christenson, G.E., and Ashland, F.X., 2007, A plan to reduce losses from geologic hazards in Utah—recommendations of the Governor's Geologic Hazards Working Group, 2006–2007: Utah Geological Survey Circular 104, 30 p.

Christenson, G.E., and Deen, R.D., 1983, Engineering geology of the St. George area, Washington County, Utah: Utah Geological and Mineral Survey Special Study 58, 32 p., 2 plates.

Christenson, G.E., and Shaw, L.M., 2008, Geographic information system database showing geologic-hazard special-study areas, Wasatch Front, Utah: Utah Geological Survey Circular 106, 7 p., GIS data.

Constenius, K.N., 1996, Late Paleocene extensional collapse of the Cordilleran foreland fold and thrust belt: Geological Society of America Bulletin, v. 108, p. 20–39.

Constenius, K.N., Esser, R.P., and Layer, P.W., 2003, Extensional collapse of the Charleston-Nebo salient and its relationship to space-time variations in Cordilleran orogenic belt tectonism and continental stratigraphy, *in* Raynolds, R.G., and Flores, R.M., editors, Cenozoic systems of the Rocky Mountain region: Denver, Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, p. 303–353.

Cook, D.R., editor, 1961, Geology of the Bingham mining district and northern Oquirrh Mountains: Utah Geological Society Guidebook to Geology of Utah 16, 145 p.

Costa, J.E., and Baker, V.R., 1981, Surficial geology, building with the earth: New York, John Wiley & Sons, 498 p.

CRONUS-Earth Project, 2005, Draft sampling plan—Lake Bonneville shorelines sampling trip, July 7–10, 2005: Online, http://tesla.physics.purdue.edu/cronus/bonneville_shoreline_sampling_plan.pdf [CRONUS: Cosmic-Ray Produced Nuclide Systematics on Earth Project].

Cruden, D.M., and Varnes, D.J., 1996, Landslide types and processes, *in* Turner, A.K., and Schuster, R.L., editors, Landslides—investigation and mitigation: Washington, D.C., National Academy of Sciences, National Research Council, Transportation Research Board Special Report 247, p. 36–75.

DeCelles, P.G., 2006, Late Jurassic to Eocene evolution of the Cordilleran thrust belt and foreland basin system, western U.S.A.: American Journal of Science, v. 304, p. 105–168.

dePolo, C.M., and Slemmons, D.B., 1998, Age criteria for active faults in the Basin and Range Province, *in* Lund, W.R., editor, Proceedings volume, Basin and Range Province Seismic-Hazards Summit: Utah Geological Survey Miscellaneous Publication 98-2, p. 74–83.

Eldredge, S.N., and O'Brien, E.H., 2001, Photo essay of four Utah earthquakes 1921–1962: Utah Geological Survey Public Information Series 72, 22 p.

Elliott, A.H., and Harty, K.M., 2010, Landslide maps of Utah: Utah Geological Survey Map 246DM, 14 p., 46 plates, scale 1:100,000, DVD.

Federal Emergency Management Agency, 2009, National Flood Insurance Program, Flood Insurance Rate Map, Salt Lake County, Utah and incorporated areas: Federal Emergency Management Agency, Panel 275, scale 1"=2,000', available online at https://msc.fema.gov.

Gilbert, G.K., 1890, Lake Bonneville: U.S. Geological Survey Monograph 1, 438 p.

Giraud, R.E., 2016, Guidelines for the geologic investigation of debris-flow hazards on alluvial fans in Utah, *in* Bowman, S.D., and Lund, W.R., editors, Guidelines for investigating geologic hazards and preparing engineering-geology reports, with a suggested approach to geologic-hazard ordinances in Utah: Utah Geological Survey Circular 122, p. 75–91.

Giraud, R.E., and Shaw, L.M., 2007, Landslide susceptibility map of Utah: Utah Geological Survey Map 228DM, 11 p., 1 plate, scale 1:500,000.

Godsey, H.S., Currey, D.R., and Chan, M.A., 2005, New evidence for an extended occupation of the Provo shoreline and implications for regional climate change, Pleistocene Lake Bonneville, USA: Quaternary Research, v. 62, p. 212–223.

Hinckley, D.W., 2010, Liquefaction-induced ground displacement mapping for the Salt Lake Valley, Utah: Salt Lake City, University of Utah, M.S. thesis, 149 p.

Hylland, M.D., DuRoss, C.B., McDonald, G.N., Olig, S.S., Oviatt, C.G., Mahan, S.A., Crone, A.J., and Personius, S.F., 2014, Late Quaternary paleoseismology of the West Valley fault zone—insights from the Baileys Lake trench site, *in* DuRoss, C.B., and Hylland, M.D., Evaluating surface faulting chronologies of graben-bounding faults in Salt Lake Valley, Utah—new paleoseismic data from the Salt Lake City segment of the Wasatch fault zone and the West Valley fault zone—Paleoseismology of Utah, v. 24: Utah Geological Survey Special Study 149, p. 41–76, 8 appendices, 1 plate, CD.

Hylland, M.D., and Lowe, M., 1997, Regional landslide hazard evaluation using landslide slopes, western Wasatch County, Utah: Environmental and Engineering Geoscience, v. 3, no. 1, p. 31–43.

International Code Council, 2014a, 2015 International building code: Country Club Hills, Illinois, 706 p.

International Code Council, 2014b, 2015 International residential code—for one and two story dwellings: Country Club Hills, Illinois, 908 p.

Jarrett, R.D., and Malde, H.E., 1987, Paleodischarge of late Pleistocene Bonneville Flood, Snake River, Idaho, computed from new evidence: Geological Society of America Bulletin, v. 99, p. 127–134.

Jennings, J.F., and Knight, K., 1975, A guide to construction on or with materials exhibiting additional settlement due to "collapse" of grain structure: Sixth Regional Conference for Africa on Soil Mechanics and Foundation Engineering, Durban, South Africa, p. 99–104.

Keaton, J.R., 2005, Considering collapsible soil hazards for siting and design of natural gas pipelines [abs.]: Geological Society of America Abstracts with Programs, v. 37, no. 7, p. 328.

Keaton, J.R., and Currey, D.R., 1993, Earthquake hazard evaluation of the West Valley fault zone, Salt Lake City urban area, Utah: Utah Geological Survey Contract Report 93-7, 69 p.

Keaton, J.R., Currey, D.R., and Olig, S.J., 1993, Paleoseismicity and earthquake hazards evaluation of the West Valley fault zone, Salt Lake City urban area, Utah: Utah Geological Survey Contract Report 93-8, 55 p.

Keefer, D.K., 1984, Landslides caused by earthquakes: Geological Society of America Bulletin, v. 95, p. 406–421.

Keefer, D.K., 1993, The susceptibility of rock slopes to earthquake-induced failure: Bulletin of the Association of Engineering Geologists, v. 30, p. 353–361.

Keller, E.A., and Blodgett, R.H., 2006, Natural hazards—Earth's processes as hazards, disasters, and catastrophes: Upper Saddle River, New Jersey, Pearson Prentice Hall, 395 p.

Lips, E.W., Marchetti, D.W., and Gosse, J.C., 2005, Revised chronology of late Pleistocene glaciers, Wasatch Mountains, Utah [abs]: Geological Society of America Abstracts with Programs, v. 37, no. 7, p. 41.

Lund, W.R., editor, 1996, The Oquirrh fault zone, Tooele County, Utah—surficial geology and paleoseimicity—Paleoseismology of Utah, v. 6: Utah Geological Survey Special Study 88, 64 p., 2 plates.

Lund, W.R., Christenson, G.E., Batatian, L.D., and Nelson, C.V., 2016, Guidelines for evaluating surface-fault-rupture hazards in Utah, *in* Bowman, S.D., and Lund, W.R., editors, Guidelines for investigating geologic hazards and preparing engineering-geology reports, with a suggested approach to geologic-hazard ordinances in Utah: Utah Geological Survey Circular 122, p. 31–58.

Lund, W.R., and Knudsen, T.R., 2016, Guidelines for evaluating rockfall-hazards in Utah, *in* Bowman, S.D., and Lund, W.R., editors, Guidelines for investigating geologic hazards and preparing engineering-geology reports, with a suggested approach to geologic-hazard ordinances in Utah: Utah Geological Survey Circular 122, p. 111–123.

Lund, W.R., Knudsen, T.R., Vice, G.S., and Shaw, L.M., 2008, Geologic hazards and adverse construction conditions—St. George-Hurricane metropolitan area, Washington County, Utah: Utah Geological Survey Special Study 127, 105 p.

Magistrale, H., Olsen, K., and Pechmann, J., 2009, Construction and verification of a Wasatch Front community velocity model—collaborative research with San Diego State University and the University of Utah: Final technical report to the U.S. Geological Survey National Earthquake Hazards Reduction Program, award nos. 05HQGR0006, 05HQGR0011, 06HQGR0009, and 06HQGR0012, 14 p.

Martin, G.R., and Lew, M., editors, 1999, Recommended procedures for implementation of DMG Special Publication 117, Guidelines for analyzing and mitigating liquefaction hazards in California: University of Southern California, Southern California Earthquake Center, 63 p.

McCalpin, J.P., 2009, Paleoseismology (second edition): San Diego, Academic Press, 848 p.

McDonald, G.N., and Ashland, F.X., 2008, Earthquake site conditions in the Wasatch Front urban corridor, Utah: Utah Geological Survey Special Study 125, 41 p., 1 plate, scale 1:150,000, CD.

Miller, D.M., Oviatt, C.G., and McGeehin, J.P., 2013, Stratigraphy and chronology of Provo shoreline deposits and lake-level implications, late Pleistocene Lake Bonneville, eastern Great Basin, USA: Boreas, v. 42, p. 342–361. (Article first published online October 25, 2012, doi:10.1111/j.1502-3885.2012.00297.x.)

Natural Resources Conservation Service (NRCS), 2006, Soil survey geographic (SSURGO) database for Salt Lake area, Salt Lake County, Utah: Online, https://www.nrcs.usda.gov/wps/portal/nrcs/site/soils/home/, accessed September 2008.

Nelson, J.D., and Miller, D.J., 1992, Expansive soils, problems and practice in foundation and pavement engineering: New York, John Wiley & Sons, 259 p.

Neuendorf, K.K.E., Mehl, J.P., Jr., and Jackson, J.A., editors, 2005, Glossary of geology (fifth edition): Alexandria, Virginia, American Geological Institute, 800 p.

O'Conner, J.E., 1993, Hydrology, hydraulics, and geomorphology of the Bonneville Flood: Geological Society of America Special Paper 274, 83 p.

Olsen, M.J., Bartlett, S.F., and Solomon, B.J., 2007, Lateral spread hazard mapping of the northern Salt Lake Valley, Utah, for a M 7 scenario earthquake: Earthquake Spectra, v. 23, no. 1, p. 95–113.

Oviatt, C.G., and Shroder, J.F. Jr., editors, 2016, Lake Bonneville — A scientific update, *in* Shroder, J.F. Jr, editor, Developments in Earth Science Processes Volume 20, Elsivier, 696 p.

Owens, R.L., and Rollins, K.M., 1990, Collapsible soil hazard map for the southern Wasatch Front, Utah: Utah Geological and Mineral Survey Miscellaneous Publication 90-1, 34 p.

Pankow, K., Arabasz, W.J., Carey, R., Christenson, G., Groeneveld, J., Maxfield, B., McDonough, P.W., Welliver, B., and Youd, T.L., 2015, Scenario for a magnitude 7.0 earthquake on the Wasatch fault–Salt Lake City segment—hazards and loss estimate: Earthquake Engineering Research Institute, prepared for the Utah Seismic Safety Commission, 53 p.

Reiter, L., 1990, Earthquake hazard analysis issues and insights: New York, Columbia University Press, 254 p.

Rollins, K.M., and Rogers, G.W., 1994, Mitigation measures for small structures on collapsible alluvial soils: Journal of Geotechnical Engineering, v. 120, no. 9, p. 1533–1553.

Salt Lake County, 2017, Title 19, zoning, chapter 19.75, geologic hazards ordinance, Salt Lake County Municipal Code, Salt Lake County, Utah, codified through ordinance No. 1668, passed July 20, 2017 (Supplement No. 32 update 4).

Schelling, D.D., Strickland, D.K., Johnson, K.R., and Vrona, J.P., 2007, Structural geology of the central Utah thrust belt, *in* Willis, G.C., Hylland, M.D., Clark, D.L., and Chidsey, T.C., Jr., editors, Central Utah—diverse geology of a dynamic landscape: Utah Geological Association Guidebook 36, p. 1–29.

Seed, H.B., 1979, Soil liquefaction and cyclic mobility evaluation for level ground during earthquakes: Journal of the Geotechnical Engineering Division, American Society of Civil Engineers, v. 105 v. 2, p. 201–255.

Shelton, D.C., and Prouty, D., 1979, Nature's building codes: Colorado Geological Survey Special Publication 12, p. 37–40.

Smith, R.B., and Arabasz, W.J., 1991, Seismicity of the Intermountain Seismic Belt, *in* Slemmons, D.B., Engdahl, E.R., Zoback, M.D., and Blackwell, D.D., editors, Neotectonics of North America: Boulder, Colorado, Geological Society of America, Decade Map Volume, p. 185–228.

Smith, R.B., and Bruhn, R.L., 1984, Intraplate extensional tectonics of the eastern Basin-Range—inferences on structural style from seismic reflection data, regional tectonics, and thermal-mechanical models of brittle-ductile deformation: Journal of Geophysical Research, v. 89, p. 5733–5762.

Smith, R.B., and Sbar, M.L., 1974, Contemporary tectonics and seismicity of the western United States with emphasis on the Intermountain Seismic Belt: Geological Society of America Bulletin, v. 85, p. 1205–1218.

Solomon, B.J., Storey, N., Wong, I., Silva, W., Gregor, N., Wright, D., and McDonald,

G., 2004, Earthquake-hazards scenario for a M 7 earthquake on the Salt Lake City segment of the Wasatch fault zone, Utah: Utah Geological Survey Special Study 111DM, 59 p., 6 plates, scale 1:250,000.

Stauffer, N., 1992, Floods, *in* Eldredge, S.N., editor, Utah natural hazards handbook: Salt Lake City, Utah Division of Comprehensive Emergency Management, p. 42–45.

Stokes, W.L., 1977, Subdivisions of the major physiographic provinces in Utah: Utah Geology, v. 4, no. 1, p. 1–17.

Thiros, S.A., 1995, Chemical composition of groundwater, hydrologic properties of basin-fill material, and groundwater movement in Salt Lake Valley, Utah: Department of Natural Resources Technical Publication No. 110-A, 59 p.

Tooker, E.W., 1999, Geology of the Oquirrh Mountains, Utah: U.S. Geological Survey Open-File Report 99-571, 150 p.

Tooker, E.W., and Roberts, R.J., 1998, Geologic map of the Oquirrh Mountains and adjoining south and western Traverse Mountains, Tooele, Salt Lake, and Utah Counties: U.S. Geological Survey Open-File Report 98-581, 2 plates, scale 1:50,000.

University of Utah Seismograph Stations, 2010a, Personalizing the earthquake threat: Online, http://quake.utah.edu/wp-content/uploads/Personalizing-the-EQ-Threat-original-2.pdf, accessed April 2010.

University of Utah Seismograph Stations, 2010b, Earthquake catalog of Utah, 1850 to 2009: Salt Lake City, University of Utah Seismograph Stations.

U.S. Environmental Protection Agency, 2009, A citizen's guide to radon—the guide to protecting yourself and your family from radon: U.S. Environmental Protection Agency, U.S. Department of Health and Human Services, and U.S. Public Health Service, EPA 402/K-09/001, 15 p.

U.S. Environmental Protection Agency, 2010, Consumer's guide to radon reduction: U.S. Environmental Protection Agency, EPA 402/K-10/002, 12 p.

U.S. Geological Survey, 2016, National Hydrologic Dataset, GIS digital vector datasets: Online, https://nhd.usgs.gov/, accessed April 2015.

U.S. Geological Survey, 2008, National Elevation Dataset (NED), obtained from AGRC online at https://gis.utah.gov/data/elevation-terrain-data/10-30-meter-elevation-models-usgs-ned/, accessed 2010.

U.S. Geological Survey, 2004, National Uranium Resource Evaluation (NURE) hydrogeochemical and stream sediment reconnaissance data: Online, https://mrdata.usgs.gov/nure/sediment, accessed January 2016.

Utah Geological Survey, 2017, Quaternary fault and fold database: Online, https://geology.utah.gov/resources/data-databases/qfaults/, accessed October 2017.

Utah County, 2009, Utah County land use ordinance, chapter 5-12: Online, http://www.co.utah.ut.us/ordinances/index.asp, accessed September 2014.

Utah Division of Water Rights, 2009, Points of diversion database (well information program "WELLVIEW"): Online, https://www.waterrights.utah.gov/gisinfo/wrcover.asp (shapefile) and https://www.waterrights.utah.gov/cgi-bin/wellview.exe?Startup (WELLVIEW program), accessed September 2009.

Utah Seismic Safety Commission, 2008, Putting down roots in earthquake country—your handbook for earthquakes in Utah: Utah Seismic Safety Commission, 33 p.

Varnes, D.J., 1978, Slope movement types and processes, *in* Schuster, R.L., and Krizek, R.J., editors, Landslides—analysis and control: Washington, D.C., National Academy of Sciences, National Research Council, Transportation Research Board Special Report 176, p. 12–33.

Western Regional Climate Center, 2014, Climatological data summaries (Garfield [423097] and Salt Lake Intl AP [427598] locations): Online, https://wrcc.dri.edu/Climate/summaries.php, accessed September 2014.

Western States Seismic Policy Council, 2015, WSSPC Policy Recommendation 11-2—active fault definition for the Basin and Range Province: Western States Seismic Policy Council: Online, https://www.wsspc.org/public-policy/adopted-recommendations/, accessed June 2011.

Wieczorek, G.F., 1996, Landslide triggering mechanisms, *in* Turner A.K., and Schuster, R.L., editors, Landslides—investigation and mitigation: Washington, D.C., National Academy of Sciences, National Research Council, Transportation Research Board Special Report 247, p. 76–90.

Wieczorek, G.F., Wilson, R.C., and Harp, E.L., 1985, Map showing slope stability during earthquakes in San Mateo County, California: U.S. Geological Survey Miscellaneous Investigations Series Map I-1257-E, scale 1:62,500.

Williams, T., and Rollins, K.M., 1991, Collapsible soil hazard map for the Cedar City, Utah area: Utah Geological Survey Contract Report 91-10, 31 p., 4 plates.

Willis, G.C., 1999, The Utah thrust system—an overview, *in* Spangler, L.E., and Allen, C.J., editors, Geology of northern Utah and vicinity: Utah Geological Association Publication 27, p. 1–9.

Wong, I., Silva, W., Olig, S., Thomas, P., Wright, D., Ashland, F., Gregor, N., Pechmann, J., Dober, M., Christenson, G., and Gerth, R., 2002, Earthquake scenario and probabilistic ground shaking maps for the Salt Lake City metropolitan area, Utah: Utah Geological Survey Miscellaneous Publication 02-5, 50 p.

Yeats, R.S., Sieh, K., and Allen, C.R., 1997, The geology of earthquakes: New York, Oxford University Press, 568 p.

Youd, T.L., 1984, Geologic effects—liquefaction and associated ground failure: U.S. Geological Survey Open-File Report 84-760, p. 210–232.

Youd, T.L., and Gilstrap, S.D., 1999, Liquefaction and deformation of silty and fine-grained solids, *in* Seco e Pinto, P., editor, Proceedings of the Second International Conference on Earthquake Geotechnical Engineering: Lisbon, Portugal, 21–25 June 1999, p. 1013–1020.

Youd, T.L., and Perkins, D.M., 1978, Mapping liquefaction-induced ground failure potential: Journal of the Geotechnical Engineering Division, American Society of Civil Engineers, v. 104, p. 433–446.

Zoback, M.L., Anderson, R.E., and Thompson, G.B., 1981, Cenozoic evolution of the state of stress and style of tectonism of the Basin and Range Province of the western United States: Philosophical Transactions of the Royal Society of London, v. A300, p. 407–434