GEOLOGIC HAZARDS OF THE MOAB QUADRANGLE, GRAND COUNTY, UTAH

by Jessica J. Castleton, Ben A. Erickson, and Emily J. Kleber

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Cover photo: Image of northern Moab–Spanish Valley with Jurassic Navajo Sandstone in the foreground and vegetated Quaternary alluvial deposits on the valley floor. In the background, the Colorado River carves a path through the uplifted Triassic and Jurassic deposits bounding the valley to the west. Photo by Emily Kleber.

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CONTENTS

FIGURES

TABLES

PLATES

GEOLOGIC HAZARDS OF THE MOAB QUADRANGLE, GRAND COUNTY, UTAH

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ABSTRACT

The Moab 7.5-minute quadrangle is located in south-central Grand County, Utah. Currently, the area is experiencing rapid development and population growth that is expected to continue for the foreseeable future. As urbanization expands into areas less suited for development, geologic hazards become of increasing concern in the planning, design, and construction of new facilities and infrastructure. This geologic-hazard study of the Moab quadrangle uses available geologic, hydrologic, soil, and geotechnical information to identify where geologic hazards may exist and where detailed, site-specific, geotechnical/geologic-hazard investigations are necessary to protect health, welfare, and safety. This study provides maps and information for 13 geologic hazards: shallow groundwater, salt tectonics-related ground deformation, flooding, landsliding, rockfall, radon gas potential, collapsible soil, expansive soil and rock, corrosive soil and rock, soluble soil and rock, piping and erosion, wind-blown sand, 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 property and infrastructure, and can be life threatening. The surface and near-surface soils and rocks of the Moab–Spanish Valley are commonly salt-rich and have highly soluble minerals (i.e., easy to dissolve in water). The addition of water from development, mainly due to landscape irrigation and poor surface-runoff management, to previously dry areas will increase hazards related to soluble soils, other problem soils, and landslides. Landslides, debris flows, and rockfalls are of growing concern as development encroaches near and onto steep hillsides adjacent to cliffs, where development is often favored due to scenic vistas and aesthetics. With the exception of flooding, rockfall, and radon, geologic hazards identified in the Moab–Spanish Valley region are typically localized and are rarely life threatening. However, all geologic hazards are potentially costly when not recognized and properly addressed in project planning, design, construction, and maintenance.

INTRODUCTION

This study provides maps and information on 13 geologic hazards in the Moab 7.5-minute quadrangle, in south-central Grand County, Utah. The quadrangle encompasses the City of Moab municipality and the northern part of the Moab–Spanish Valley (figure 1), a northwest-southeast-trending graben formed from the collapse of a salt anticline. The Colorado River runs northeast to southwest through the northern part of the quadrangle. The Moab–Spanish Valley area has experienced rapid population growth in residential and commercial areas and is expected to see increasing growth in the coming decades. As the population grows and tourism increases in the area, urbanization will increase; therefore, comprehensive geologic information available early in the planning and design process is critical to avoid or reduce the risk from geologic hazards and protect public health, welfare, safety, and the local economy.

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 Moab quadrangle (figure 1). This mapping is best applied when used in conjunction with the Utah Geological Survey's (UGS) *Guidelines for Investigating Geologic Hazards and Preparing Engineering-Geology Reports, with a Suggested Approach to Geologic-Hazard Ordinances in Utah* (Bowman and Lund, 2016). We compiled the data and created the 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

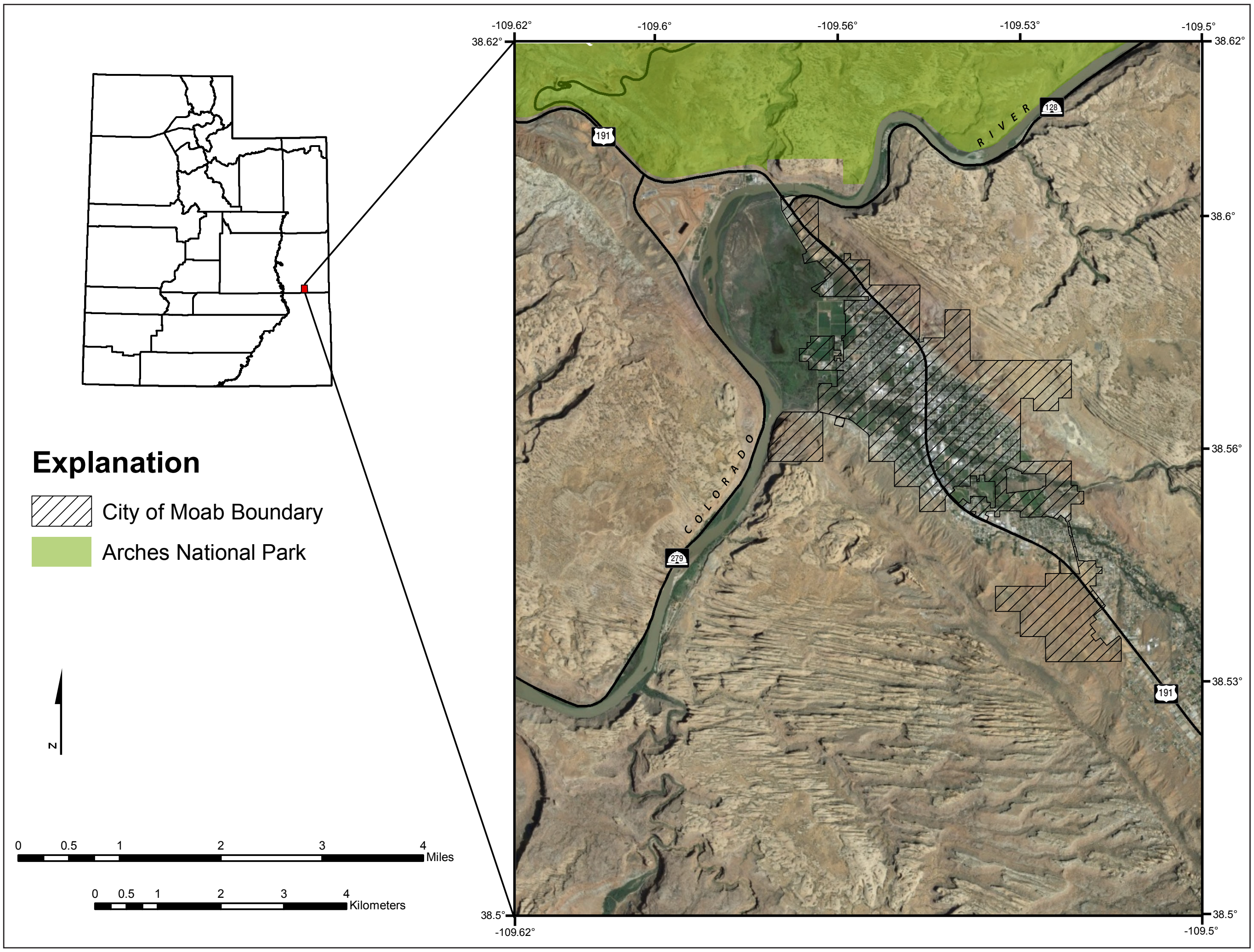

***Figure 1.** Location of the Moab quadrangle showing principal geographic features, including the boundary of the City of Moab and major transportation routes (base map from Utah Automated Geographic Reference Center, 2016).*

methods from a variety of scientific disciplines, including engineering geology, geotechnical engineering, geomorphology, imagery analysis, GIS technology, and geologic field mapping and reconnaissance.

The geologic-hazard maps (plates 1 through 13) are designed as aids 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. The maps are based on a geologic-hazard analysis of the Moab quadrangle. The geologic hazards addressed are shallow groundwater, salt tectonics-related ground deformation, flooding, landsliding, rockfall, radon potential, collapsible soil, expansive soil and rock, corrosive soil and rock, soluble soil and rock, piping and erosion, wind-blown sand, and shallow bedrock. Other hazards may exist.

In the state of Utah, counties and municipalities are encouraged to develop geologic hazard ordinances (Utah State Code, 2016). As of the writing of this report, no geologic hazard ordinances exist in Grand County or the City of Moab. Grand County does have an ordinance for flood damage prevention that applies to areas having a special flood hazard designation zone identified by the Federal Emergency Management Agency (FEMA) (Grand County, 2014).

Areas in Utah that have geologic hazard ordinances include Salt Lake, Utah, and Iron Counties. 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, 2017) requires, at minimum, assessment of known special hazard areas including rockfall, debris-flow, landslide, and surface-fault-rupture hazards prior to development. Iron County has incorporated geologic conditions into the zoning section of the county code (Iron County, 2016). These counties also address flood zoning in the ordinances.

The scope of work for this study consisted of (1) identifying and reviewing geologic, hydrologic, and soils information available for the quadrangle; (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; (4) field reconnaissance and mapping; and (5) preparing this report and accompanying maps describing each geologic hazard. Other hazards not identified, quantified, or mapped may be present within and near the quadrangle that may affect existing and future development.

Previous Work

Hylland and Mulvey (2003) completed a geologic-hazard study for the Moab–Spanish Valley area that included maps and a comprehensive report. Their maps included part of the Moab quadrangle and presented information on expansive soils, gypsiferous soils, alluvial-fan flooding, debris flows, collapsible soils, rockfall, shallow groundwater, fractured rock and subsidence associated with salt dissolution, and soils susceptible to piping and erosion. Other previous studies relevant to geologic hazards in the Moab quadrangle include:

- understanding subsurface brines and their movement in the Moab area (Mayhew and Heylman, 1965),
- radon-hazard potential (Sprinkel and Solomon, 1990),
- earthquake potential and seismic hazards of the Paradox Basin region (Wong and others, 1996),
- the earthquake potential of the Moab fault (Olig and others, 1996),
- modeling flooding of the Colorado River in relation to a large uranium mine tailings pile adjacent to the river (Kenney, 2005), and
- paleoseismic study of a normal fault attributed to salt-dissolution faulting on the southwest flank of Moab–Spanish Valley (Guerrero and others, 2014).

In addition, UGS geologic mapping (Doelling and others, 2002) and engineering consultant geotechnical/geologic-hazard investigations have increased our understanding of the area's geology and hazards.

Setting

The Moab quadrangle is in Grand County, Utah, which covers approximately 3694 square miles (9567 square kilometers [km^2]) in southeastern Utah. The quadrangle contains the City of Moab and the main entrance to Arches National Park. The Colorado River, which flows from northeast to southwest, bisects the northern part of the quadrangle (figure 1). Grand County has a population of about 9516 (U.S. Census Bureau, 2016), and is projected to grow to 13,098 by 2050 (Utah Foundation, 2014). The City of Moab is the most populated area within the county and has about 5235 people (U.S. Census Bureau, 2016). The Moab quadrangle consists of private, state, and federal property, and the largest land managers are the U.S. Bureau of Land Management, the National Park Service, and the U.S. Department of Energy (DOE). Due to the spectacular geology and unique setting, the Moab area receives more than one million tourists per year visiting Arches and Canyonlands National Parks, among other local and state parks and attractions (Kem C. Gardner Policy Institute, 2016).

Mining exploration, extraction, and remediation are part of the past and current economic activities in the area. Uranium and vanadium were prospected in Moab and the surrounding area in the 1910s and 1920s. Potash, manganese, oil, and natural gas have been extracted from geologic deposits in the Moab area over the past century. A notable mining-related deposit in the area is a large uranium mine tailings pile adjacent to the Colorado River. The Atlas Minerals Corporation created the tailings pile as part of a uranium-ore processing facility from the mid-1950s to 1984. This poses a significant contamination threat to the more than 50 million downstream users of Colorado River water. Atlas filed for bankruptcy in 1998, and in 2001, the U.S. Congress transferred the responsibility of site cleanup to the DOE (Shenton, 2016). As part of the Moab Uranium Mill Tailings Remedial Action (UMTRA) project, the DOE has removed approximately 52% of the estimated 16 million tons of contaminated mining tailings by railcar to a disposal site ~30 miles (48 km) to the north (Shenton, 2016). The tailings pile area within the Moab quadrangle geologic-hazard maps is labeled as "not mapped." This is due to the ongoing nature of the UMTRA project and studies pending in the area. For more information about the remediation history, progress, and hazards associated with the UMTRA tailings pile, visit www.moabtailings.org or www.gjem.energy.gov/moab.

In the Moab quadrangle, the Moab–Spanish Valley is bounded by ~500 to 1000-foot (~175–300 m) near-vertical cliffs of Pennsylvanian-age to Jurassic-age sedimentary rocks. Elevation in the quadrangle ranges from approximately 6315 feet (1925 m) along the southwestern rim of Moab–Spanish Valley to 3917 feet (1194 m) along the Colorado River. The area is characterized by low precipitation; large daily temperature changes; cold, dry winters; and hot, dry summers. Average annual precipitation in the Moab area from January 1893 to June 8, 2016, is 9 inches (23 cm) (Western Regional Climate Center [WRCC], 2016). Precipitation in the Moab area falls fairly equally throughout the year, only varying within ~0.6 inch (1.5 cm) from month to month (minimum: 0.42 inch [1.07 cm] in June; maximum: 1.03 inches [2.62 cm]). Summer precipitation is primarily from monsoonal patterns that bring high winds and moisture from the Gulf of Mexico and the Pacific Ocean. Summer temperatures in the area commonly exceed 90°F (32.2°C); the January 1893 to June 8, 2016, average maximum temperature for July is 98.2°F (36.7°C), and the January 1893 to June 8, 2016, average maximum temperature for January is 42.4°F (5.7°C) (WRCC, 2016).

We present the distribution of geologic hazards using a U.S. Geological Survey Moab quadrangle 1:24,000-scale topographic base map published in 1997, which conforms to the North American Datum of 1983 (NAD 83).

Geology

The Moab quadrangle is within the Colorado Plateau physiographic province, which overall is characterized as a broadly uplifted region of relatively undeformed, "layer-cake" sedimentary strata. Geologically, the quadrangle is in the fold-and-fault belt of the asymmetric Paradox Basin, which was made structurally complex by faulting and salt-diapir movement and salt dissolution. The Paradox Basin developed in mid-Pennsylvanian through early Permian time along the southwest flank of the Uncompahgre Uplift (Stevenson and Baars, 1986). As the Uncompahgre Uplift rose, the basin subsided along northwest-trending normal faults while strata of the Pennsylvanian Paradox Formation—which is rich in evaporite minerals, including halite, potash, and magnesium salts—were deposited. Salts have low density, and under pressure from layers of younger strata deposited above, salt in the Paradox Formation moved upward along fractures and faults as large diapirs, creating long, northwest-trending salt-cored anticlines. The Moab–Spanish Valley is part of a series of northwest-trending valleys in southeastern Utah and southwestern Colorado formed from collapsed salt anticlines in the Paradox Basin. Dissolution of the salt core in the anticlines caused collapse of the overlying strata. Timing of anticline collapse is poorly constrained, but is thought to have occurred in the late Pliocene to early Pleistocene (Doelling, 2001). The Moab–Spanish Valley is about 17 miles (27 km) long and 0.5 to 1.5 miles (0.8–2.4 km) wide, and is bounded by steep cliffs of Pennsylvanian-age to Jurassic-age sedimentary rocks.

The geology of the Moab 7.5-minute quadrangle is complex, thus, a detailed discussion of the regional geology of the area is beyond the scope of this report. Detailed information on the geology of the greater Moab–Spanish Valley area can be found in Doelling (1985, 2001), Doelling and others (1988, 2002), Huffman and others (1996), Doelling and Morgan (2000), and Doelling and Kuehne (2013a, 2013b, 2013c). The following descriptions of geologic units in the quadrangle are modified from Doelling (2001), Doelling and others (2002), and Hylland and Mulvey (2003) (figure 2).

The oldest rock unit exposed in the quadrangle is the Middle Pennsylvanian Paradox Formation, which is dominated by evaporite minerals but also contains carbonate rocks, silty sandstone, and black shale (figure 2).

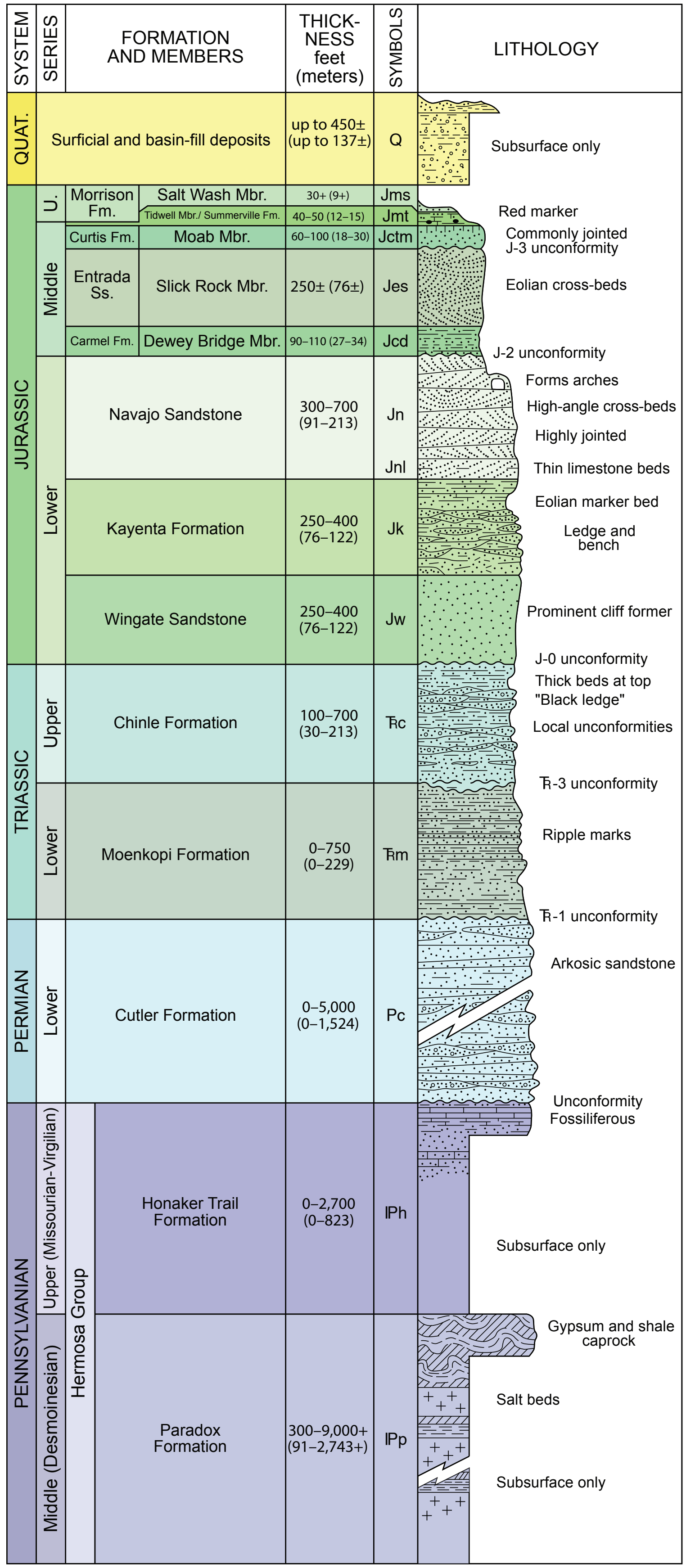

Figure 2. *Lithological column of geologic units exposed in the Moab quadrangle (after Doelling and others, 2002).*

The Paradox outcrops appear pale yellowish gray, pale greenish gray, and grayish white to light gray with patches of dark gray (figure 3). Within the Moab–Spanish Valley, the Paradox Formation is exposed in two discontinuous bands along the northeastern and southwestern margins. In the northern part of the quadrangle, the Upper Pennsylvanian Honaker Trail Formation and the overlying Lower Permian Cutler Formation crop out south of the Arches National Park visitor center. The Honaker Trail Formation is composed of grayish sandstone, siltstone, and limestone. The Cutler Formation forms cliffs and slopes composed of red-brown and maroon cross-bedded sandstone and conglomerate with thin siltstone and limestone beds.

The Lower Triassic Moenkopi Formation forms steep slopes and ledges above the Cutler Formation and consists of brown, micaceous sandstone, siltstone, mudstone, and shale (figure 2). Overlying the Moenkopi is the Upper Triassic Chinle Formation, also a slope-forming unit. The Chinle is gray-red to red-brown sandstone, siltstone, conglomeratic sandstone, and mudstone (figure 2). Capping these formations are cliffs of the

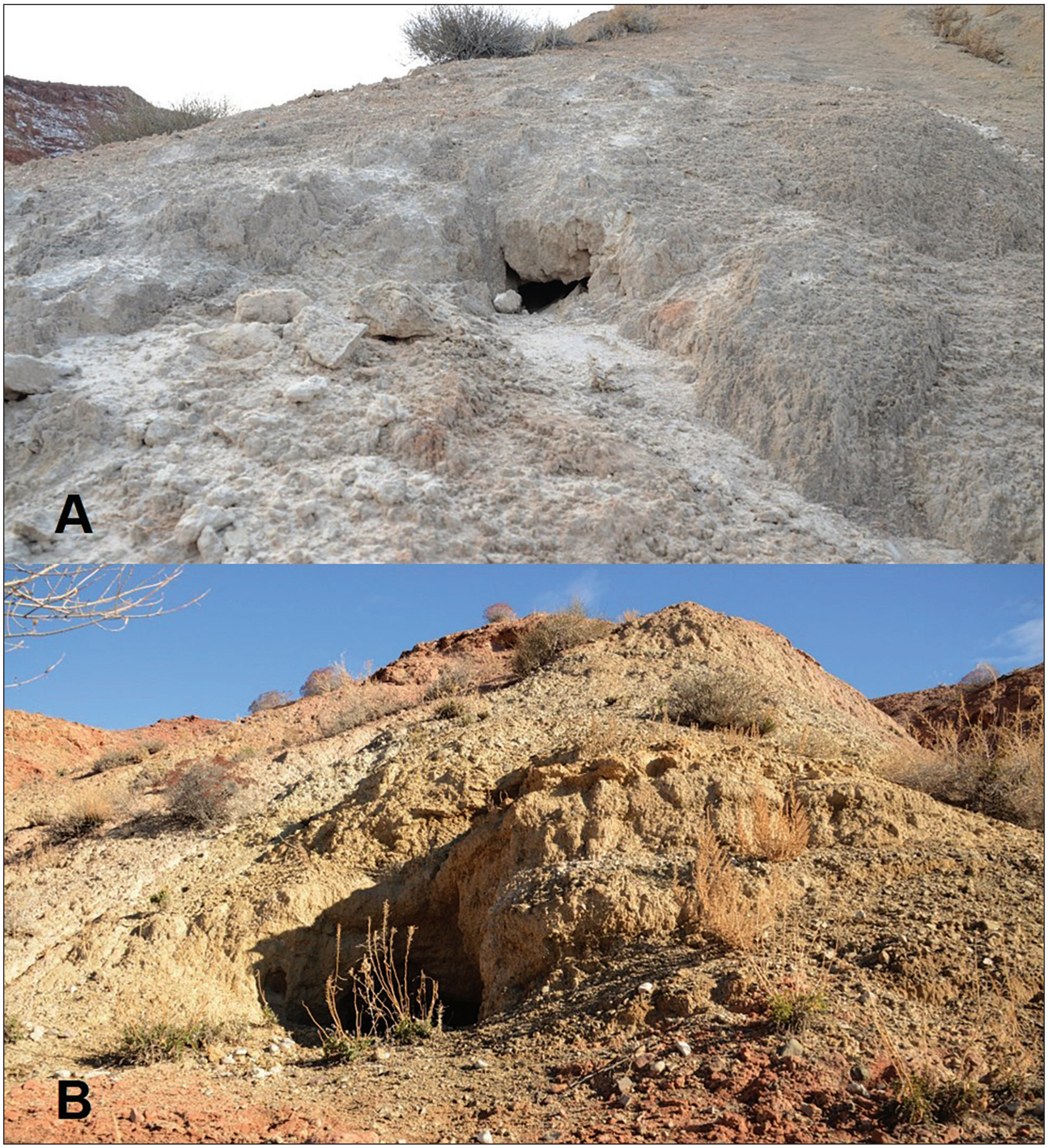

Figure 3. *Paradox Formation exposures on the margins of the Moab–Spanish Valley that have varying degrees of color appearance. (A) Example of light to dark gray Paradox Formation. (B) Example of pale yellowish gray, and pale greenish gray Paradox Formation.*

Lower Jurassic Wingate Sandstone and Kayenta Formation. The Wingate is composed of fine-grained, well-sorted sandstone and forms the massive, dark-brown cliffs south and west of Moab, and along the Colorado River north of Moab. On top of the Wingate is the Kayenta Formation, a ledge and step-like, lavender-gray and dark-brown sandstone (figure 2). The Kayenta Formation caps many of the cliffs bordering Moab–Spanish Valley. The Lower Jurassic Navajo Sandstone overlies the Kayenta, forming an irregular surface of pale-orange to light-gray sandstone fins, hills, and swales on the northeastern and southwestern sides of Moab–Spanish Valley.

Overlying the Navajo Sandstone is a Middle to Upper Jurassic sequence of mostly sandstone units exposed in and near Arches National Park. These rocks include the Dewey Bridge Member of the Carmel Formation, the Slick Rock Member of the Entrada Sandstone, the Moab Member of the Curtis Formation, the Summerville Formation, and the Tidwell and Salt Wash Members of the Morrison Formation (figure 2). Most of the arches in Arches National Park are formed in sandstone of the Dewey Bridge, Slick Rock, and Moab Members. Strata of the Summerville and Morrison Formations, exposed in only a small part of the study area within Arches National Park, generally consist of red to brown sandstone and siltstone and gray limestone overlain by pale yellow-gray sandstone interbedded with green and red mudstone and siltstone (figure 2).

The floor of Moab–Spanish Valley is composed of Quaternary fill and surficial deposits derived from the nearby La Sal Mountains and local valley slopes and transported by the Colorado River, Dry Creek, Pack Creek, and smaller, local drainages. Debris flows and rockfalls from the cliffs bounding the valley produce prominent colluvium and talus slopes. Downslope of these deposits are alluvial fans derived from erosion of upstream channel deposits and slope sediments. The alluvial-fan deposits interfinger with stream alluvium of Mill and Pack Creeks and the Colorado River in the interior of the valley. The valley-bounding cliffs give way to broad, flat plateaus of highly jointed and deeply eroded sandstone. Quaternary eolian sand deposits are present on the valley floor and the upper plateau areas.

GEOLOGIC HAZARDS

Early recognition and mitigation of geologic hazards can reduce risk to life, property, and the economy. Since 1847, an estimated 5797 fatalities have occurred due to geologic hazards in Utah (Bowman and Lund, 2016) (table 1). Radon gas exposure and subsequent lung cancer has been Utah's most deadly geologic hazard, with over 5372 fatalities (data from 1973–2012), followed by landslide hazards with 337 documented fatalities, and flooding hazards with 101 documented fatalities (Bowman and Lund, 2016). As debris flows are both a landslide and flooding hazard, fatalities are listed in both hazard categories. Hazard mapping is essential to identify areas that need further investigation to determine hazard extent, risk, and mitigation measures. In almost all cases, it is more cost effective to identify and characterize geologic hazards and then implement appropriate mitigation in project design and construction, rather than rely on additional maintenance over the life of the project (Bowman and Lund, 2016).

On an annual basis, the most common and damaging geologic hazard in Utah, and the Moab quadrangle, is flooding. Because of their potentially wide distribution, frequent occurrence, and destructive nature, floods will likely be the principal geologic hazard in the quadrangle that planners, land owners, and others will have to address in the future.

The Moab quadrangle has significant gypsiferous, corrosive, expansive, and collapsible soil and rock, and piping and erosion potential due to the mineralogy of surficial geologic units and their weathering by-products. Significant hazard potential exists from the proximity and exposure of the Paradox, Moenkopi, and Chinle Formations to surface and groundwater. The Paradox, Moenkopi, and Chinle Formations contain various amounts of soluble minerals. The mostly salt-based minerals such as gypsum, potash, and halite present collapse, piping, corrosion, and erosion issues. The dissolution of subsurface soluble-mineral deposits can create underground voids. Depending on the location and size of voids in relation to the ground surface, they can present a significant collapse hazard. Small voids may coalesce over time, creating larger voids and forming sinkholes. These units also contain sulfates which can degrade unprotected construction materials over time, and uranium which decays to dangerous radon gas.

Landslides, rockfalls, alluvial-fan flooding, and debris flows are of growing concern as development increases on hillsides, where development is often favored due to scenic vistas. Some bedrock units in the quadrangle contain a high percentage of clay and are correspondingly weak and susceptible to landslides, especially when wet. 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. One landslide was identified in the Moab quadrangle (plate 4). New landslides could develop if groundwater conditions on slopes change due to human- or climate-induced conditions, such as landscape irrigation, wastewater disposal fields, infiltration basins, and/or increased precipitation. Conditions conducive to rockfall are present along the valley-forming cliffs. Damaging rockfalls are a hazard in many locations in the quadrangle. Damaging events are likely to increase as development moves into those areas, unless effective hazard-reduction measures are implemented. Alluvial-fan flooding occurs when a concentrated amount of water, usually from a cloudburst rainstorm, is captured in a drainage or slot canyon, picks up debris in turbulent flow, then deposits debris on an alluvial fan due to the increase in surface area, shallowing of the slope angle, and slowing of

Table 1. *Summary of known geologic-hazard fatalities in Utah (from Bowman and Lund, 2016).*

Geologic Hazard		**Fatalities**			
Landslide Hazards					
Landslides[1]		4	1.2%	337	5.7%
Rockfall		15	4.5%		
Debris Flows[2]		15	4.5%		
Snow Avalanches[3]		303	89.8%		
Earthquake Hazards					
Ground Shaking		2	100%	2	< 0.1%
Flooding Hazards					
Flooding		81	80.1%	101	1.7%
Debris Flows[2]		15	14.9%		
Dam and Water Conveyance Structure Failure[1]		5	5.0%		
Problem Soils					
Radon Gas[4]	1973–2001	1460[5]	--	5372	92.6%
	2002–2011	3816[6]			
	2012	96[5]			
Total:		**5797**			

[1]Because of uncertainty in event initiation, three fatalities are listed in both the "Landslides" and "Dam and Water Conveyance Structure Failure" categories.

[2]Debris flows are both a landslide and flooding hazard.

[3]The majority of post-1950 snow avalanche fatalities are in the backcountry from human-induced avalanches; however, many have occurred near or in developed areas where appropriate mitigation measures should be used.

[4]Limited data are available and contain various assumptions; exact number of fatalities is unknown.

[5]Based on World Health Organization general estimate that 14% of lung cancer cases are attributable to radon gas (Sasha Zaharoff, Utah Department of Health, written communication, 2015) and data from http://epht.health.utah.gov/epht-view/query/result/ucr/UCRCntyICDO2/Count.html.

[6]Utah Environmental Public Health Tracking Network (2015).

the flow. These occur most often on mapped Holocene alluvial fans. Debris flows in the Moab quadrangle can be caused by precipitation that falls far away from the deposition area, traveling great distances at fast speeds.

Geologic and geomorphic mapping and seismic interpretation indicate the presence of fault scarps in the Moab–Spanish Valley that are attributed to subsurface movement associated with salt tectonics (Olig and others, 1996; Guerrero and others, 2014). In Utah, most earthquakes are associated with the Intermountain Seismic Belt (ISB) (Smith and Sbar, 1974; Smith and Arabasz, 1991; Bowman and Arabasz, 2017), an approximately 100-mile-wide (160 km), north-south-trending zone of earthquake activity extending from northern Montana to northwestern Arizona; however, the Moab–Spanish Valley is outside that zone. Most earthquakes in Moab–Spanish Valley cannot be attributed to movement on known faults and have regionally been smaller than magnitude 5 (Wong and others, 1996). Along the margins of the Moab–Spanish Valley, some fault scarps have been investigated to determine their movement history (Guerrero and others, 2014). The fault scarps most likely formed from diapirism and/or collapse due to salt dissolution (Doelling and others, 2002). Fault locations and displacements were likely influenced by the extent of the underlying Paradox Formation, the mechanical strength of overlying layers of rock, and changes in hydrostatic base level over time (Guerrero and others, 2014). The periodicity and magnitude of earthquakes that likely produced the fault scarps in the Moab–Spanish Valley are poorly understood due to the complexities of salt-related tectonics. In western Colorado, a paleoseismic study of the Hogback monocline (~140 miles northeast of Moab) and adjacent faults showed their movement was caused by salt dissolution and diapirism, and modeling showed the faults able to cause a significant earthquake (M_w 6, [moment magnitude]) with a rupture area as large as 77 square miles (200 km^2) (Gutiérrez and others, 2014). We did not complete a ground-shaking-hazard analysis or map for the Moab quadrangle. The origin of mapped faults cannot currently be discerned between tectonic- or salt-dissolution-related faulting due to the lack of requisite information, so any ground-shaking model would not be accurate.

Shallow groundwater, wind-blown sand, and shallow bedrock are typically localized in nature. While potentially costly when not recognized and properly accommodated in project planning, design, and maintenance, these hazards are rarely life threatening. By contrast, hazards posed by rockfall, flooding, and elevated levels of indoor radon gas can be life threatening. Breathing radon gas over time significantly 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 (U.S. Environmental Protection Agency [U.S. EPA], 2010).

Shallow Groundwater

Groundwater is in saturated zones beneath the land surface in soil and rock at various depths. Shallow groundwater levels are typically 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 these facilities and lead to groundwater contamination. Groundwater can change the physical and chemical nature of rock and soil, cause soils and rocks 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 Moab quadrangle are highly variable and range from impermeable to moderately permeable bedrock and soils (clay, silt, sand, and gravel) (Doelling and others, 2002). Groundwater data in the quadrangle are limited outside areas of recent development; therefore, perched water or unknown groundwater conditions 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 not having persistent shallow groundwater. Areas of localized perched shallow groundwater may result from the addition of water from landscape irrigation and stormwater control. The addition of post-development water may cause sinkholes by soil piping or the dissolution of subsurface evaporite minerals and contribute to damage from collapsible and expansive soils. Groundwater in the Moab–Spanish Valley area is contained in two aquifers, the Glen Canyon aquifer and the unconsolidated valley-fill aquifer (Lowe and others, 2007). The shallow-groundwater-potential map does not differentiate between aquifers and is not intended to model the deeper regional aquifer; instead it 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) UGS geologic mapping (Doelling and others, 2002), (2) a geotechnical database of information from consultant geotechnical and geologic hazard reports compiled by the UGS, (3) previous groundwater studies, (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 Grand County, Utah—Central Part (UT624)*; *Canyonlands Area, Utah—Parts of Grand and San Juan Counties (UT633)*; and *Arches National Park, Utah (UT687)* (NRCS, 2016a, 2016b, 2016c).

We obtained groundwater-level data from geotechnical/geologic-hazard studies and water-well logs and incorporated the data into a geotechnical database. The shallow groundwater mapping is based on geologic unit 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. Geotechnical data that indicate where depth to groundwater was observed to be shallow (less than or equal to 10 feet [3 m]) was obtained from geotechnical borehole and water-well logs. The NRCS and geotechnical data were overlain with the geologic map to determine the shallow groundwater potential of each geologic unit, and 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 on 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. Areas mapped as bedrock are generally not considered to have shallow groundwater; however, some bedrock units can be highly weathered and fractured, 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.

The shallow-groundwater-potential categories shown (plate 1) are approximate and mapped boundaries are gradational. Localized areas of higher or lower groundwater are likely to exist within any given map area, but their identification is precluded because of the generalized map scale, relatively sparse data, unidentified areas of perched shallow groundwater, and non-geologic factors such as landscape irrigation and stormwater control.

Salt Tectonics-Related Ground Deformation and Faulting

The Moab–Spanish Valley is a graben formed by the collapse of a salt-cored anticline that was created by diapirism (figure 4) in the salt-rich Paradox Formation (Guerrero and others, 2014). The valley formed due to the dissolution of salt deposits at depth, causing the rock above to collapse or subside downward, forming a valley (Doelling and others, 2002). Processes such as salt diapirism—the upward movement of salt due to its low density and plastic nature—and salt dissolution have resulted in ground deformation, including the development of fractures, folds, joints, grabens, and faults along the valley margins of the Moab–Spanish Valley. The resulting displacement of the ground surface may also produce ground cracking, surface warping, and multiple, complex scarps. De-

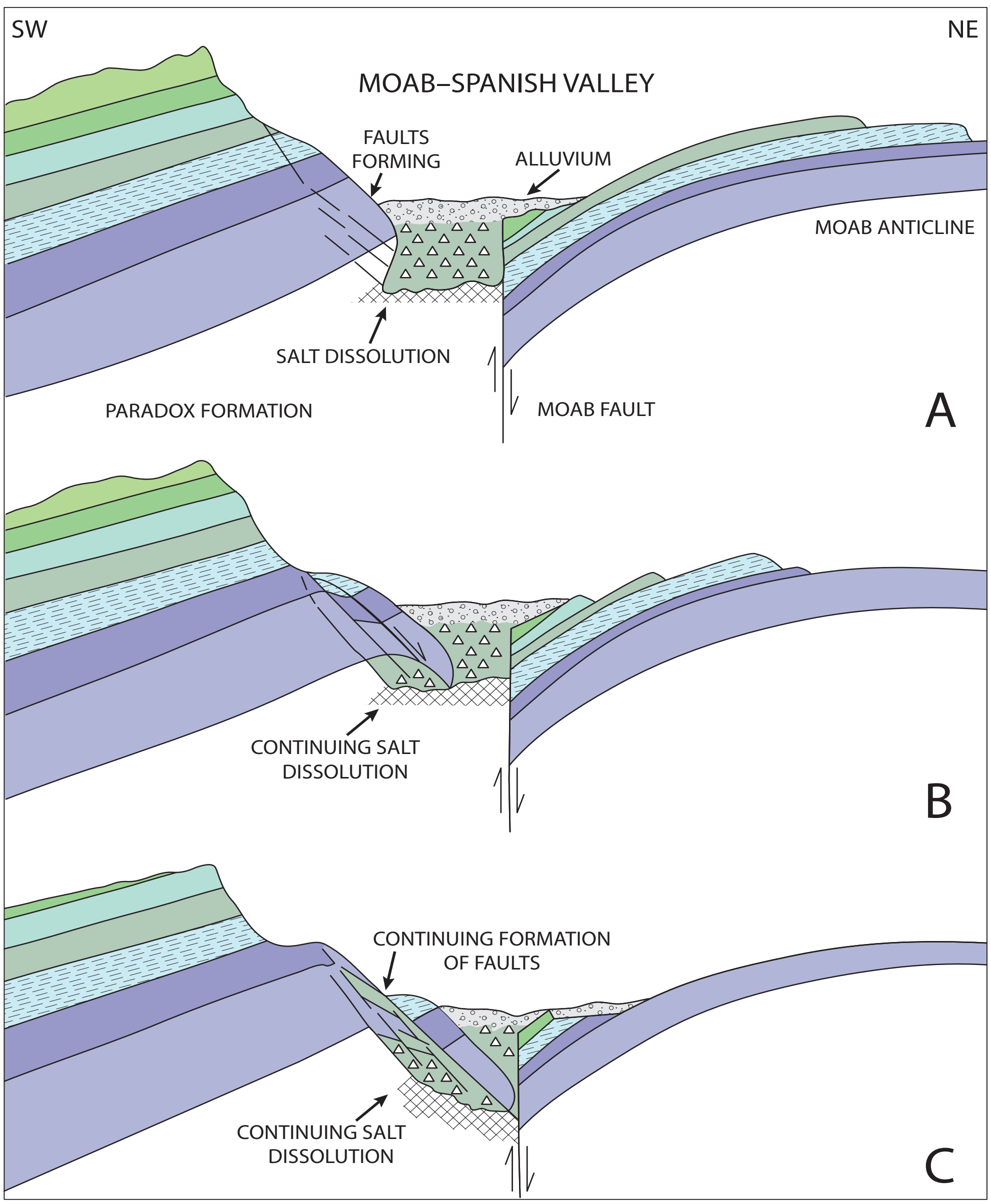

Figure 4. *Formation of salt-dissolution-related faulting over time in the Moab–Spanish Valley area. Cross section trends southwest-northeast across the northern Moab–Spanish Valley area and the Moab anticline (modified from Baars and Doelling, 1987).*

pending on the magnitude of subsurface movement, scarps can range from a few inches to several feet high and extend for many miles along a fault trace or deformation zone. Local ground tilting and graben formation (figure 5) by secondary gravitational faulting may result in a deformation zone along the fault trace that can be tens to hundreds of feet wide. Surface fault rupture related to gravitational faulting can cause damage similar to that of tectonic-related surface fault rupture and can have serious consequences for structures or other facilities that lie along or across the rupture path. The extent of the underlying Paradox Formation, the mechanical strength of geologic strata, and changes in hydrostatic base level over time (Guerrero and others, 2014) affect subsurface displacement and subsequent surface faulting. Unpredictable failure rates related to underground salt movement make the hazard very difficult to quantify.

To evaluate the salt tectonics-related ground-deformation hazard (plate 2), we used five main sources of data: (1) UGS geologic and hazard mapping (Doelling and others, 2002; Hylland and Mulvey, 2003), (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 photography interpretation, and (5) a recent paleoseismic investigation (Guerrero and others, 2014).

Compared to tectonically generated earthquakes and associated fault systems, there is significantly less research and literature about the magnitude of earthquakes created by salt-dissolution faulting. Due to the unpredictable nature of salt tectonics, we mapped an area of ground deformation based on analysis of geologic units, mapped faults, and existing ground deformation. Ground deformation in this area may be severe. Continued ground deformation, subsidence, possible surface fault rupture, and other hazards, such as sinkhole formation, ground cracking, differential settlement, and widespread subsurface erosion (piping), can occur in the ground deformation zone. Geologic mapping by Doelling and others (2002) shows potentially active salt-dissolution normal faults (where the hanging wall has moved down relative to the footwall) along which additional salt-tectonic-related surface faulting and movement may occur. Due to the unknown nature of these faults, we show mapped faults on the salt tectonics-related ground- deformation hazard map (plate 2) and categorize them as well defined, concealed, or approximately located, in accordance with the *Guidelines for Evaluating Surface-Fault-Rupture Hazards in Utah* (Lund and others, 2016). 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) and UGS 1:24,000-scale mapping (Doelling and others, 2002) shows them as solid lines, indicating that they are recognizable as faults at the ground surface. Although not well expressed at the surface, approximately located or buried faults (Doelling and others, 2002) may still represent a significant ground-deformation and surface-fault-rupture hazard and should be evaluated prior to development. Approximately located faults are shown as a dashed line, and buried faults are shown as a dotted line. Also mapped is the potential for valley floor subsidence that can cause tilting and/or damage to structures due to differential settlement, lateral earth pressures, ground cracks or displacements in fractured rock, and/or ground collapse, including sinkhole formation. The plateaus and canyon areas are subject to regional and local subsidence potential resulting in fracturing and displacement of rock. Fractures weaken the rock and can lead to unstable conditions in road cuts and tunnels, increase potential for aquifer contamination, and increase susceptibility to rockfall and slope instability.

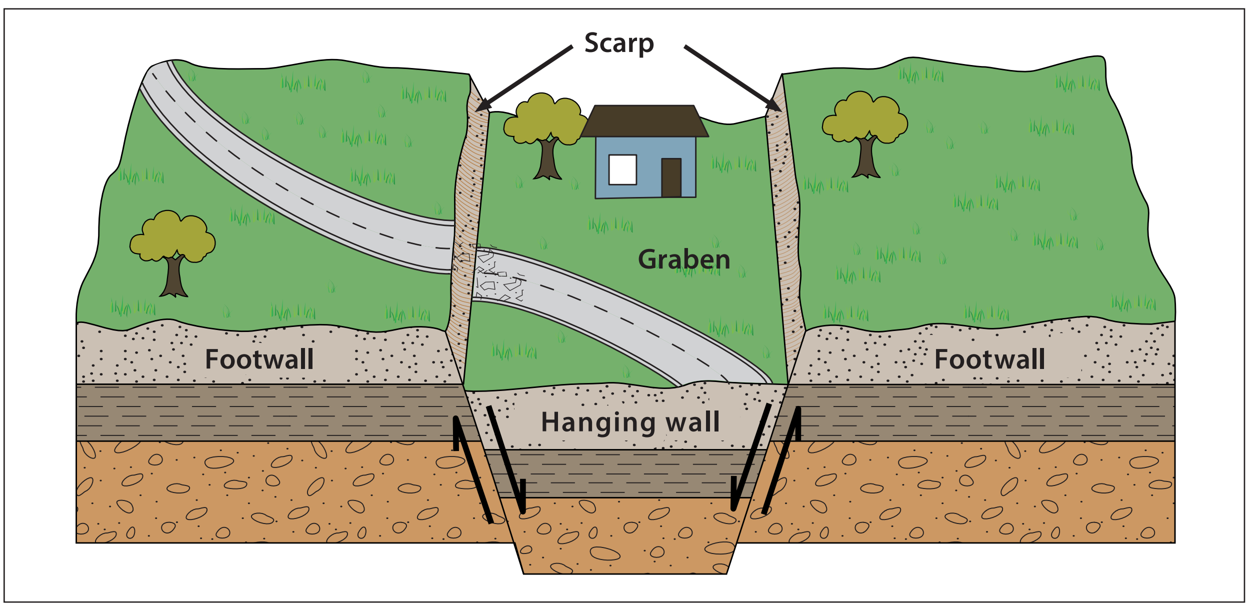

Figure 5. *Diagram of a graben formed by two normal faults showing the relative movement of the hanging wall and footwall.*

Paleoseismic investigations in two trenches by Guerrero and others (2014) in the Moab–Spanish Valley indicate nine faulting events over the past ~4500 years. Closed-interval slip rates from the paleoseismic data are highly variable; vertical slip rates range from 1.0 to 15.5 mm/yr (average 3.07 mm/yr), and recurrence intervals range from 73 to 815 years (average 316 years) (Guerrero and others, 2014). For comparison, the range of mean, Holocene, closed-interval slip rates for each of the five central segments of the Wasatch fault zone is 1.3–2.0 mm/yr (Working Group on Utah Earthquake Probabilities, 2016). Using statistical analyses from paleoseismic data, Guerrero and others (2014) indicate faults in the Moab–Spanish Valley that ruptured the surface do not behave like tectonically driven faults, having comparatively higher slip rates and higher slip per event in relation to their length. Although not tectonically driven, faults in the Moab–Spanish Valley can produce damaging earthquakes and surface rupture on a relatively short timescale (Gutierrez and others, 2014).

In addition to the graben-bounding normal faults, the trace of the Moab fault is inferred to trend northwest-southeast down the middle of the Moab–Spanish Valley (Doelling and others, 2002). Unlike other faults in the region, this fault is believed to be primarily related to Tertiary extensional tectonics but shows no evidence of movement related to extensional tectonism in the Quaternary (Olig and others, 1996). The last period of major tectonic activity on the Moab fault occurred during the Laramide orogeny (>35 Ma; Solum and others, 2005). The Moab fault is unlikely to be a source of significant modern earthquakes.

The salt tectonics-related ground deformation hazard map (plate 2) shows potentially active faults in the Moab quadrangle along which salt tectonic-related ground deformation and surface faulting may occur. The UGS recommends a site-specific ground deformation and surface-fault-rupture-hazard investigation be performed in the areas identified as having severe ground-deformation potential prior to development. Because of the lack of paleoseismic data and the poorly understood mechanisms of Quaternary salt-dissolution-related faulting in the Moab quadrangle, we based the zone of concern on the mapped soluble geologic units at the surface and where they are likely within 50 feet or less from the surface (Doelling and others, 2002). Valley floor and plateau subsidence can occur where soluble rock is present beneath the surface. The inferred trace of the Moab fault is shown on plate 2, but does not include a special study zone due to the pre-Quaternary age of latest major fault activity (Olig and others, 1996; Solum and others, 2005), based on the limited data available.

Deformation due to salt can occur anywhere within the quadrangle, but the margins of the valley have the potential for the most damaging deformation. Pre-development investigations present many challenges. Traditional geotechnical investigations could worsen the risk associated with shallow subsurface soluble deposits. Drilling, test pits, and trenches may introduce water at depth, increasing the risk of salt tectonic-related ground deformation, including surface rupture from faulting, as well as sinkhole formation and piping and erosion, all discussed in detail within this report. We recommend that completed borings be appropriately grouted to prevent conducting water into the subsurface. Test pits should be excavated with caution, but if necessary, non-native fill of geologic material without soluble salts and other minerals should be used as backfill and appropriately compacted. Geophysical investigation methods to determine displacement, voids, and salt tectonics-related structures are recommended to limit potential water exposure to the subsurface.

The most conservative approach to prevent damage in these areas is avoidance of development. Where avoidance is not possible, disclosure of the hazard and the associated risk should be mandatory. Currently, no investigational methodology can determine the frequency or extent of risk to development from salt tectonics. This risk should be clearly defined to potential land owners and disclosed.

The areas of ground deformation, valley floor subsidence, and plateau subsidence related to salt tectonics shown on plate 2 are approximate and mapped boundaries are based on an estimated deformation zone determined by interpreting geologic units on the surface and at depth, and the distance from mapped faults. Localized areas of deformation where surface rupture may occur are likely to exist anywhere within the quadrangle, but their identification is precluded because of the generalized map scale and relatively sparse data.

Salt tectonics-related faulting and ground deformation does not necessarily preclude development in the area, but it should cause significant concern for the design and construction of structures and facilities. A high amount of risk is associated with development in these areas and should be addressed in site-specific geotechnical/geophysical investigations, engineering design, and communication with potential land users. Disclosure of the risks associated with development and limited mitigation options should be mandatory. If the risk is understood and assumed by land users and owners, then site-specific geotechnical (with precautions noted above) and/or geophysical investigations are recommended to determine the extent of subsurface damage, voids, and salt tectonics-related structures until the processes involved in salt-dissolution-related faulting are further understood. Engineering design should account for potential differential movement. The extent of vertical displacement is unknown at this time, except for fault scarp heights, and investigations should be focused on determining possible displacement on salt tectonics-related faults in the area. In these areas, other salt-dissolution and diapirism-related hazards include soluble soil and rock (plate 9), which can cause sinkholes and subsidence; corrosive soil and rock (plate 10); and piping and erosion (plate 11). These additional hazards should also be addressed in a comprehensive geologic hazard/getotechnical investigation.

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 (Utah Division of Homeland Security, 2008). Historically, flooding is the most prevalent and destructive (on an annual basis) hazard affecting Utah.

The flood hazard map (plate 3) shows areas in the Moab quadrangle that may be susceptible to flooding. Within the quadrangle, several drainages are known to be capable of flooding and include the Colorado River, Courthouse Wash (figure 6), Pack Creek, Mill Creek, North Fork Mill Creek, Moab Canyon, Kane Springs Canyon, Grandstaff Canyon, and Pritchett Canyon. Several small ephemeral drainages contribute to the flood hazard as well. Seasonal weather patterns that deliver moisture to southeastern Utah, particularly during the late summer monsoon season, also contribute to a high flood hazard and flash flood hazard. Types of seasonal floods that typically occur are riverine (stream) floods, flash floods/debris flows, and sheet floods. Flash flooding in the area can be very localized when intense rain accumulates on the plateaus and quickly floods slot canyons and overwhelms infrastructure in the valley (figure 7). The potential for flooding is increased by human activities, such as placing structures and constrictions in floodplains, active alluvial fans, or erosion-hazard zones; developing without adequate flood and erosion control; and the unintentional release of water from an engineered water-retention or conveyance structure (such as a dam or canal).

To evaluate flood hazard (plate 3), we used six main sources of data: (1) FEMA National Flood Insurance Program Flood Insurance Rate Maps (table 2) (FIRMs) (FEMA, 2016), (2) UGS mapping (Doelling and others, 2002; Hylland and Mulvey, 2003), (3) aerial photography interpretation, (4) 10-meter National Elevation Dataset (NED) (USGS, 2016a) and 0.5-meter lidar data (Bowen Collins & Associates, Inc., 2015) where available, to examine past and present drainage patterns, (5) the National Hydrography Dataset (NHD) (USGS, 2016b), and (6) a geotechnical database compiled by the UGS that includes unpublished consultant's reports having updated flood mapping (Bowen Collins & Associates, Inc., 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 in the Moab quadrangle 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. Small ephemeral drainages and slot canyons may be mapped as low flood hazard; however, these drainages have a high flash-flood hazard. The NHD delineates streams in drainages using GIS modeling based on 30-meter NED data (USGS, 2016b). 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 likely to occur in the very high and high categories and can occur anywhere in the quadrangle (plate 3). 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 degrees (30%), based on the Salt Lake County Geologic Hazards Ordinance (Salt Lake County, 2017), and a debris-flow site-specific 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 degrees (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 (< 10 ft [3 m]) were mapped as high flood hazard potential.

Site-specific geotechnical/geologic-hazard flood investigations can resolve uncertainties inherent in the generalized hazard map (plate 3) and help ensure safety by identifying the local flood and debris-flow hazard. Chapter 5 of UGS Circular 122, *Guidelines for the Geologic Investigation of Debris-Flow Hazards on Alluvial Fans in Utah* (Giraud, 2016), 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 (table 2, plate 3). FEMA, through its National Flood Insurance Program

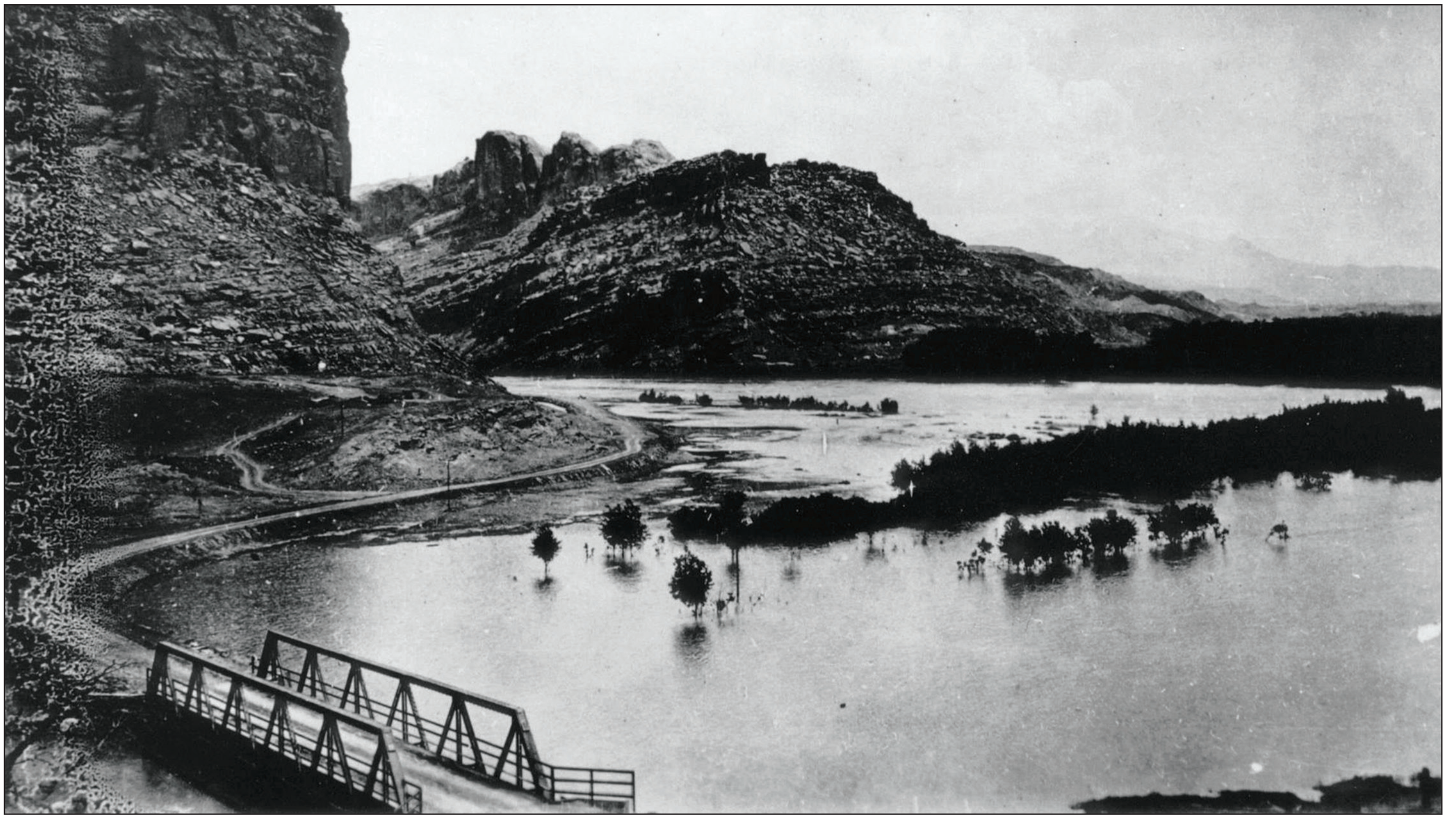

Figure 6. *Colorado River flooding into the mouth of Courthouse Wash in 1917, looking to the east. Photograph from Dan O'Laurie museum collection, Museum of Moab, used with permission.*

Figure 7. *Flooding over Arches National Park service road near park entrance. (photo: July 19, 2017).*

Table 2. FEMA FIRM panel information and effective dates.

DFIRM ID[1]	FIRM ID[2]	Panel	Suffix[3]	FIRM Panel	Effective Date	Scale	LOMR Date[4]
49019C	49019C_269	1759	D	49019C1759D	4/2/2009	6000	
49019C	49019C_293	1758	D	49019C1758D	4/2/2009	6000	
49019C	49019C_296	1766	D	49019C1766D	4/2/2009	6000	
49019C	49019C_295	1767	D	49019C1767D	4/2/2009	6000	11/14/2016
49019C	49019C_294	1754	D	49019C1754D	4/2/2009	6000	
49019C	49019C_76	1775	D	49019C1775D	4/2/2009	24000	11/14/2016

[1]Digital Flood Insurance Rate Map (DFIRM) ID is the digitized version and consolidation of existing FIRM data.

[2]Insurance Rate Map (FIRM) ID is the panel reference of specific areas used since the 1970s.

[3]Suffix indicates the number of times a panel has been revised.

[4]Letter of Map Revision (LOMR) Date indicates official modifications to the FIRM.

(NFIP), makes federally subsidized flood insurance available to individuals residing in participating communities. Not all areas on the Moab 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 (FEMA, 2016). Flood insurance can also be purchased by landowners outside of mapped zone A designated by FEMA.

The flood-hazard-potential categories shown on plate 3 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 non-geologic 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). 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 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, 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 factors 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.

Landslides are categorized based on how they move: topple, fall, slide, spread, or flow (Cruden and Varnes, 1996). In the Moab area, the common types of landslides are fall and topple. Fall and topple movements are due to exposed rigid bedrock being affected by slow erosional processes; fractures and jointing of rock faces are precursors to these types of events. Falls are associated with weakened rock detaching from cliff faces or overhangs and falling or sliding to the valley floor. Topples are like falls, but have a rotational aspect. When a weakened rock column dislodges, it rotates away from the rock face, tumbling down the slope. Falling rock attributed to fall and topple movements are addressed on the rockfall hazard map (plate 5).

Flow, spread, and slide movements are possible in Moab–Spanish Valley area, but require high subsurface water content to trigger movement. Due to the arid climate, these types of movement are less likely, except around perennial rivers and creeks. Flow-, spread-, and slide-type landslides typically undergo either rotational and/or translational movement. Rotational slides move on a concave sliding surface, resulting in back-tilted areas at the head of the slide, and they can be shallow or deep seated and can move very slowly or rapidly. Translational slides form on planar surfaces and slide out over the original ground surface. The sliding surface can form on bedding planes, faults, joints, or other discontinuities.

To evaluate landslide susceptibility (plate 4), we used five main sources of data: (1) UGS geologic and hazard mapping (Doelling and others, 2002; Hylland and Mulvey, 2003), (2) aerial photography interpretation, (3) 10-meter NED (USGS, 2009) and 0.5-meter lidar data (Bowen Collins & Associates, Inc., 2015) where available, (4) analysis of mapped landslides in similar geologic conditions, and (5) field mapping and reconnaissance. We classify landslide susceptibility as high, moderate, or low. High landslide susceptibility consists of mapped landslides, geologic units that have experienced previous landsliding elsewhere in Utah as identified by geologic mapping, and that underlie slopes that equal or exceed a determined critical slope angle. Moderate landslide susceptibility consists of areas having steep slopes in a geologic unit with material that may be susceptible to landsliding but has no prior landslides, and in geologic units with material that is highly susceptible to landsliding where the slope is slightly lower than the critical angle. Low landslide susceptibility consists of areas having slopes below the critical angle in units not likely susceptible to landsliding.

In the Moab quadrangle, we applied critical slope angles of 10 and 22 degrees based on analysis of landslides in southern Utah within similar 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 southern 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 mean landslide slope plus or minus one standard deviation, we assigned critical angles to geologic units in the Moab quadrangle. Similar methodology has been used in other landslide evaluation and susceptibility investigations in similar geologic units to define critical slope (Hylland and Lowe, 1998; Giraud and Shaw, 2007; Lund and others, 2008; Knudsen and Lund, 2013; Knudsen and others, in review). We assigned a critical angle of 10 degrees for Quaternary deposits along the Colorado River and its tributaries (Pack Creek and Mill Creek), smaller tributaries (Courthouse Wash and Grandstaff Canyon), and ephemeral drainages. We assigned a critical angle of 22 degrees to the Chinle and Moenkopi Formations and deposits originating from them. Geologic units that were not determined to be landslide prone were not assigned a critical angle.

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 4) shows areas of relative landslide susceptibility where site-specific slope-stability conditions (material strength, orientation of bedding and/or fractures, groundwater conditions, and erosion or undercutting) should be evaluated prior to development. A valid landslide-hazard study 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 study can only be accomplished through the proper identification and interpretation of site-specific geologic conditions and processes. Chapter 4 of UGS Circular 122, *Guidelines for Evaluating Landslide Hazards in Utah* (Beukelman and Hylland, 2016), recommends minimum standards for performing landslide-hazard evaluations in Utah. The guidelines outline a phased approach to slope-stability investigations, beginning with a geologic evaluation and progressing through reconnaissance and detailed geotechnical-engineering evaluations as needed based on the results of the previous phase. Table 3 summarizes minimum UGS recommendations for site-specific investigations for each landslide-susceptibility category in the Moab quadrangle; see Beukelman and Hylland (2016) for more information.

Table 3. *Recommended requirements for site-specific landslide-hazard investigations in the Moab quadrangle; see Beukelman and Hylland (2016) for more information.*

Landslide Susceptibility	Recommended Site-Specific Study
High	Detailed engineering geologic and geotechnical-engineering study necessary.
Moderate	Geologic evaluation and reconnaissance-level geotechnical-engineering study necessary; detailed engineering geologic and geotechnical-engineering study may be necessary.
Low	Geologic evaluation and reconnaissance-level geotechnical-engineering study necessary; detailed geotechnical-engineering study generally not necessary.

Some local governments in Utah have created and maintain geologic-hazard-specific ordinances to limit the impact of landslides. Salt Lake County's Zoning Ordinance Code prohibits development, including clearing, excavating, and grading, on slopes exceeding 17 degrees (30%) and sets aside these areas as natural private or public open space (Salt Lake County, 2010). Also, all roads are restricted from crossing slopes steeper than 17 degrees (30%) unless they meet specific requirements and gain authorization (Salt Lake County, 2017).

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 study to evaluate the effect of development on slope stability and recommend appropriate design and mitigation measures.

The landslide-hazard-susceptibility categories shown on plate 4 are approximate and mapped boundaries are gradational. Localized areas of higher or lower landslide susceptibility are likely to exist within any given map area, but their identification is precluded because of the generalized map scale and non-geologic factors, such as modification of slopes, unidentified areas of perched shallow groundwater, landscape irrigation, and stormwater control.

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). Rockfalls are a hazard because dislodged rocks traveling at high speed can cause considerable damage. Rockfalls can damage property, roadways, and vehicles, and pose a significant safety threat. Rockfall hazards occur where a rock source exists above slopes steep enough to allow rapid downslope movement of dislodged rocks by falling, rolling, and/or bouncing (figure 8). Most rockfalls originate on slopes steeper than 35 degrees (Wieczorek and others, 1985; Keefer, 1993), although rockfall hazards may be found on less-steep slopes.

Rockfall-hazard potential is based on a number of factors, including geology, topography, and climate. Rockfall sources

Figure 8. *Steep cliffs are a rockfall source and dislodged rocks fall, roll, and/or bounce down steep slopes below the source. Rocks traveling at high speed can cause significant damage and injury or death. (photo: Moab Rim trail east of the Colorado River).*

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 talus cones and scree-covered slopes are indicators of a high rockfall hazard, although other areas are also vulnerable. Rockfalls may be initiated by thermal cycling (solar heating of the rock, Collins and Stock, 2016), 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) indicates earthquakes as small as M_w 4 can trigger rockfalls.

The rockfall hazard map (plate 5) shows areas in the Moab 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 9): (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—this zone often includes a talus slope, which becomes less apparent with decreasing relative hazard and is typically absent where the hazard is low; and (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 5), we used four main sources of data: (1) UGS geologic and hazard mapping (Doelling and others, 2002; Hylland and Mulvey, 2003), (2) aerial photography interpretation, (3) 0.5-meter lidar data (Bowen Collins & Associates, Inc., 2015) where available, and (4) 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 mapping (Doelling and others, 2002; Hylland and Mulvey, 2003) and field reconnaissance, as well as slope angle, acceleration zone, and a shadow angle of 20 degrees. The shadow angle was determined through field reconnaissance and aerial photography analysis of rockfall deposits and their source. The shadow 20-degree angle was calculated for boulders originating in the Curtis Formation, the Entrada Sandstone, and the Wingate Sandstone. Rockfalls originating in the Navajo Sandstone and the Kayenta Formation have larger shadow angles, around 28 to 30 degrees. To be conservative we applied the 20-degree shadow angle across the map area. We evaluated slopes below rockfall sources for slope angle, vegetation, clast distribution, clast size range, amount of embedding, and weathering of rockfall boulders. Table 4 summarizes our recommended requirements for site-specific geotechnical/geologic-hazard investigations related to rockfall hazards to protect life and safety. Chapter 7 of UGS Circular 122, *Guidelines for Evaluating Rockfall Hazards in Utah* (Lund and Knudsen, 2016), recommends minimum standards for performing rockfall-hazard evaluations in Utah.

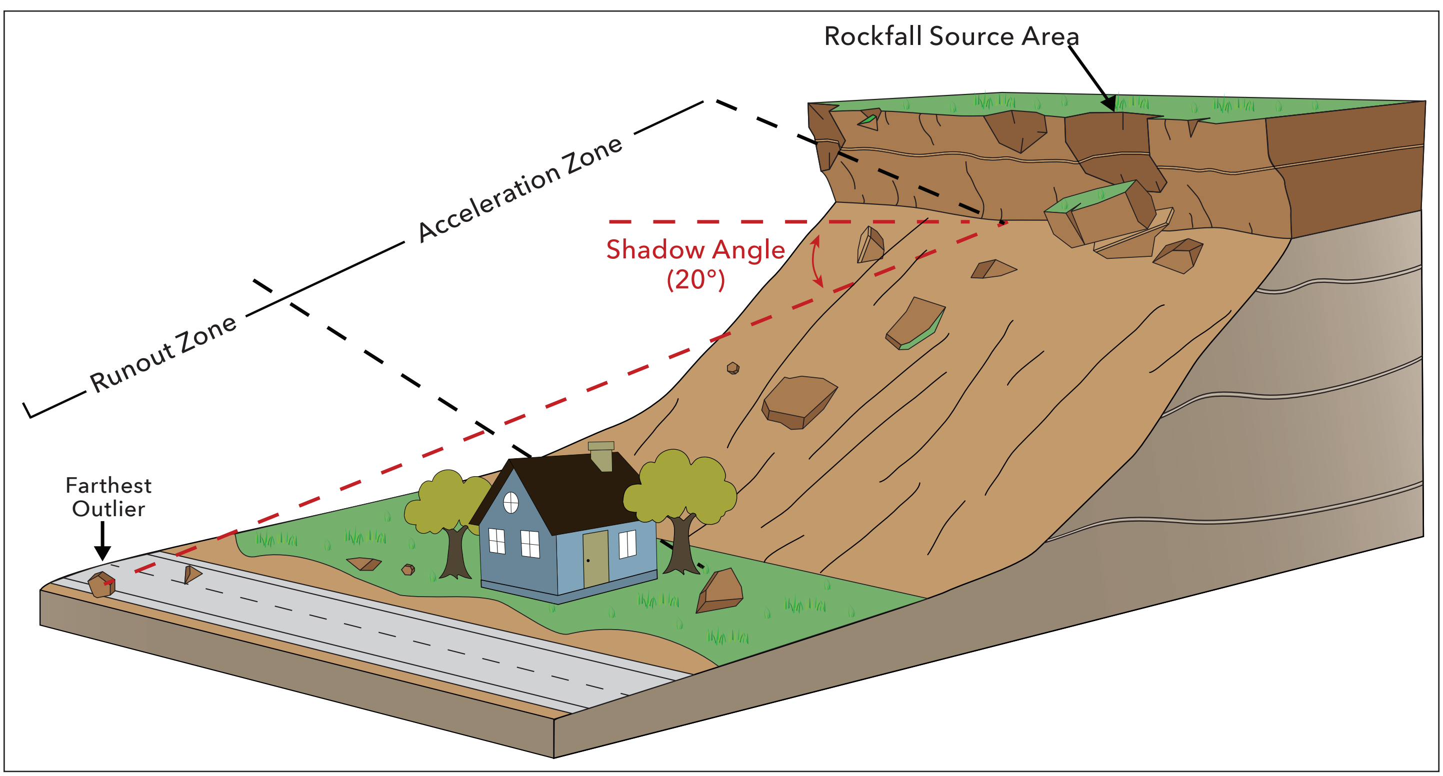

Figure 9. *Components of a characteristic rockfall-path profile (after Lund and others, 2008).*

Table 4. *Recommended requirements for site-specific rockfall hazards investigations 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.

The rockfall-hazard-potential categories shown on plate 5 are approximate and mapped boundaries are gradational. Localized areas of higher or lower rockfall potential are likely to exist within any given map area, but their identification is precluded because of the generalized map scale and non-geologic factors such as cuts, fills, or other modifications to the natural terrain.

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. Although outdoor radon concentrations rarely reach dangerous levels because air movement and open space dissipate the gas, indoor radon concentrations may reach hazardous levels because of confinement and poor air circulation in buildings and other confined spaces. 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 (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 significant health risk.

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, shale, hydrothermally altered rocks, 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 and Solomon, 1996). However, if the source of the radon gas is above or within the groundwater table, shallow groundwater may not reduce the movement of radon. Long-term exposure to water with dissolved radon is also dangerous (drinking, etc.).

Along with geologic factors, non-geologic factors also influence radon levels in a building or other confined space. Although the influence of geologic factors can be estimated, the influence of non-geologic factors, such as occupant lifestyle and structure construction and maintenance, are highly variable. As a result, indoor radon levels fluctuate and can vary in different structures built on the same geologic unit; therefore, the radon level must be measured in each structure 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 study.

To evaluate the radon-hazard potential (plate 6), we used four main sources of data to identify areas where underlying geologic conditions may contribute to elevated radon levels: (1) soil permeability data from the NRCS *Soil Survey Geographic (SSURGO) Database for Grand County Utah—Central Part (UT624)*; *Canyonlands Area, Utah—Parts of Grand and San Juan Counties (UT633)*; and *Arches National Park, Utah (UT687)* (NRCS, 2016a, 2016b, 2016c), (2) depth-to-groundwater mapping (this study), and (3) UGS geologic and hazard mapping (Doelling and others, 2002; Hylland and Mulvey, 2003) and (4) 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 5) 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 Moab quadrangle which were summed together to report indoor radon hazard potential (table 6).

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.

Geologic mapping is important for identifying geologic units having high uranium content, particularly outside of areas covered by previous investigations where radiometric data are limited. In the Moab quadrangle, the most uranium-rich bedrock units are the Permian Honaker Trail and Cutler Formations (Black, 1993; Doelling and others, 2002; Hylland and Mulvey, 2003), the Triassic Moenkopi Formation (Black, 1993; Hylland and Mulvey, 2003), the Mossback and Shinarump Members of the Triassic Chinle Formation (Finch, 1954; Black, 1993; Doelling and others, 2002; Hylland and Mulvey, 2003), and the Tidwell and Salt Wash Members of the Jurassic Morrison Formation (Finch, 1954; Mohammad, 1986; Doelling and Kuehne, 2013). All alluvium and colluvium from locally derived uranium-bearing geologic units (Doelling and others, 2002), as well as alluvium interpreted to be from the intrusive igneous La Sal Mountains, were assigned a point value of 3 for their undetermined, but possible, uranium content (Hylland and Mulvey, 2003). Any areas where uranium ore or waste products have been stored warrant a detailed site-specific study; these areas can emit very high concentrations of radon, even in open air.

Table 5. *Soil geologic factors that contribute to radon hazard potential. Soil permeability from NRCS data. Groundwater depth from shallow groundwater mapping in this study. Uranium data from unpublished reports and NURE (modified from Black and Solomon, 1996).*

Factor	Point Value		
	1	2	3
Uranium (ppm, estimated)	<2	2–3	>3
Permeability (Ksat, in/hr)	Low 0.06–0.6	Moderate 0.6–6.0	High 6.0–20.0
Groundwater depth (feet)	<10	10–30	>30

Table 6. *Radon hazard potential mapping criteria and indoor radon potential (from Black and Solomon, 1996).*

Category	Point range	Potential indoor radon concentration (pCi/L) estimate*
Low	3–4	< 2
Moderate	5–7	2–4
High	8–9	> 4

* Indoor radon concentrations are highly dependent upon structure design and construction.

The NRCS reported hydraulic conductivity (Ksat) values of saturated soil for their soil units based on testing performed at selected locations (NRCS, 2016a, 2016b, 2016c) and assigned permeability classes to their soil units based on the hydraulic conductivity of the unit (table 5). 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.

The map of radon-hazard potential (plate 6) 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 be completed in all existing structures and other confined spaces. 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 the *Consumer's Guide to Radon Reduction* (EPA, 2010). The Utah Department of Environmental Quality (DEQ, 2017) provides information on radon mitigators and ordering test kits on their website at https://deq.utah.gov/ProgramsServices/programs/radiation/radon/.

The tailings pile area within the Moab quadrangle is labeled on the geologic-hazard maps as "not mapped." This is due to the ongoing nature of that project and studies pending in the area. For more information about the remediation history, progress, and hazards associated with the tailings pile, visit www.moab-tailings.org or www.gjem.energy.gov/moab.

The radon-hazard potential map (plate 6) is not intended to indicate absolute indoor radon levels in specific structures. Although geologic factors contribute to elevated indoor-radon-hazard potential, other highly variable factors, such as building materials, construction methods, and foundation openings, affect indoor radon levels; therefore, indoor radon levels can vary greatly between structures located in the same hazard category.

The hazard-potential categories shown on plate 6 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 at the site.

Collapsible Soil Susceptibility

Collapsible soils are relatively dry, low-density soils that decrease in volume or collapse under the load of a building or infrastructure when they become wet. Collapsible soils may have considerable strength and stiffness in their dry natural state, but can settle up to 10 percent of the susceptible deposit thickness when they become wet for the first time following deposition (Costa and Baker, 1981; Rollins and Rogers, 1994; Keaton, 2005) causing damage to property, structures, pavements, and underground utilities.

Collapsible soils are present in the Moab quadrangle and are typically geologically young materials, chiefly Holocene debris-flow sediments in alluvial fans and Pleistocene to Holocene colluvial deposits (plate 7). Collapsible soils typically have a high void ratio, a corresponding low unit weight (<80 to 90 lb/ft^3; Costa and Baker, 1981), and a relatively low moisture content (<15 percent; 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 sands, sandy silts, and clayey sands (Williams and Rollins, 1991), although Rollins and Rogers (1994) identified collapse-prone gravels containing as little as 5 to 20 percent fines (U.S. Standard #200 sieve) 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 into 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, wastewater disposal, and/or surface drainage changes.

To evaluate collapsible-soil susceptibility (plate 7), we used two main sources of data: (1) UGS geologic and hazards mapping (Doelling and others, 2002; Hylland and Mulvey, 2003), and (2) a geotechnical database compiled by the UGS. First, we evaluated test data from the geotechnical database; swell/collapse tests (SCT), dry density, and moisture tests were all used to determine collapse potential. Next, we integrated geologic-unit descriptions from UGS geologic and hazard mapping (Doelling and others, 2002; Hylland and Mulvey, 2003) with the geotechnical data to assign a susceptibility category to mapped geologic units. We classified unconsolidated geologic units into four 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 percent (Jennings and Knight, 1975), we assigned two susceptibility categories: highly collapsible soil, where SCT tests indicate collapse potential equal to or more than 5 percent, and collapsible soil A, where SCT tests indicate collapse potential over 3 percent and less than

5 percent. Where geotechnical data are lacking, we assigned geologic units that have 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 that have a genesis or texture permissive of collapse, we assigned them to the collapsible soil D category. Geologic units in which other geotechnical information (chiefly low density and moisture content) provide evidence for potentially collapsible soils, would be delineated as collapsible soil B; however, there is no collapsible soil B mapped in the Moab quadrangle. 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.

The collapsible-soil-susceptibility categories shown on plate 7 are approximate and mapped boundaries are gradational. Localized areas of soil having higher or lower collapse 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 disturbed land, changes in drainage and water runoff patterns, landscape irrigation, and wastewater control. 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 (figure 10), structures, pavements, and underground utilities, 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. When clay content is greater than approximately 12 to 15 percent, the expansive nature of the clay dominates, and the soil is subject to swell. Some sodium-montmorillonite clay can swell as much as 2000 percent upon wetting (Costa and Baker, 1981). The resulting expansion forces can be greater than 20,000 pounds per square foot (Shelton and Prouty, 1979) and can easily exceed the loads imposed by 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 or wind, but soil creep and mass-wasting processes can play important roles locally.

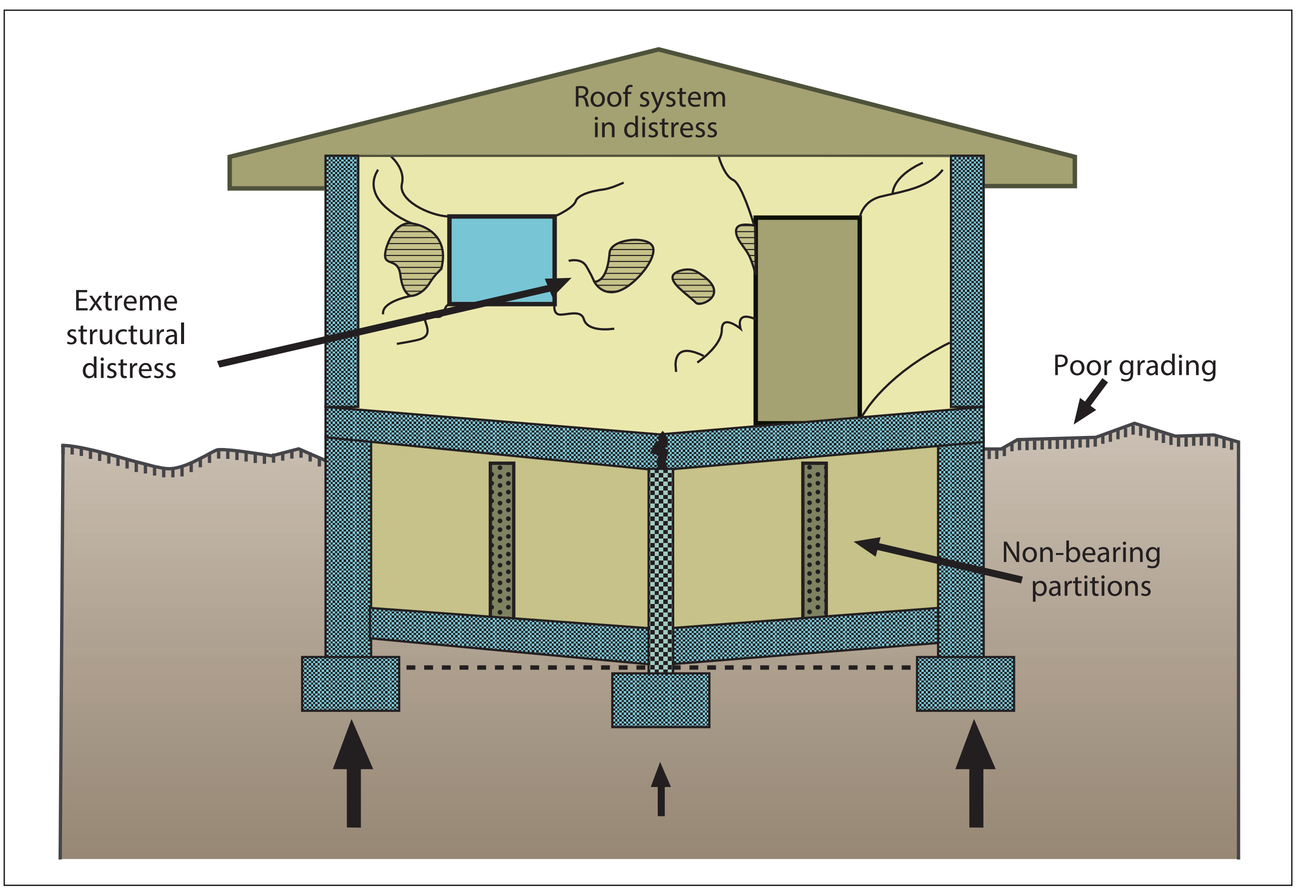

Figure 10. *Typical structural damage to a building from expansive soil (after Black and others, 1999).*

To evaluate expansive soil and rock susceptibility (plate 8), we used three main sources of data: (1) UGS geologic and hazard mapping (Doelling and others, 2002; Hylland and Mulvey, 2003), (2) a geotechnical database compiled by the UGS, and (3) the NRCS *Soil Survey Geographic (SSURGO) Database for Grand County, Utah—Central Part (UT624)*; *Canyonlands Area, Utah—Parts of Grand and San Juan Counties (UT633)*; and *Arches National Park, Utah (UT687)* (NRCS, 2016a, 2016b, 2016c). We classified soil and rock units into three categories based on their potential for volumetric change: high, moderate, and low (table 7).

The NRCS (2016a, 2016b, and 2016c) 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. 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 used 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 included in the NRCS data (NRCS, 2016a, 2016b, 2016c) 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. Table 7 shows the correlation between these geotechnical tests and expansive soil and rock susceptibility.

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 that illustrates the use of PI as an indicator of swelling potential (table 7). 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. The 2015 International Building Code (IBC) and International Residential Code (IRC) (International Code Council, 2014a, 2014b), adopted in Utah, 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.

Table 7. *Correlation between geotechnical tests of soils and expansive-soil susceptibility.*

Test	Susceptibility Category		
	Low	Moderate	High
Swell-Collapse[1] (SCT)	0–2%	2–3%	> 3%
Liquid Limit (LL)	0–30	20–50	> 45
Plasticity Index[2] (PI)	0–15	10–35	> 20
Expansion Index[3] (EI)	0–50	51–90	> 91

[1] Jennings and Knight (1975)

[2] Chen (1988)

[3] Nelson and Miller (1992)

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 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 units 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. The expansion of material may lead to underground void spaces where further erosion will increase void volume and tunneling (figure 11). Over time, a shrink-swell cycle can erode potentially large subsurface caverns and result in collapse (Dunne, 1990). A key indicator of surficial expansive material is the textural change when water is introduced and then removed. When the expansive material swells with water then shrinks after water removal, the surface becomes disturbed over several cycles; the result is clod aggregation at the surface, resembling popcorn (figure 12) (Hylland and Mulvey, 2003). In the Moab quadrangle, both the Chinle and Paradox Formations are susceptible to expansion (as evident in surface texture [figure 12]), near-surface cracking, and subsurface voids (figure 11).

The expansive-soil-and-rock-susceptibility categories shown on plate 8 are approximate and mapped boundaries are gradational. Localized areas of soil and rock having higher or lower expansive susceptibility 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 disturbed land, changes in drainage and water runoff patterns, landscape irrigation, and wastewater control. 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.

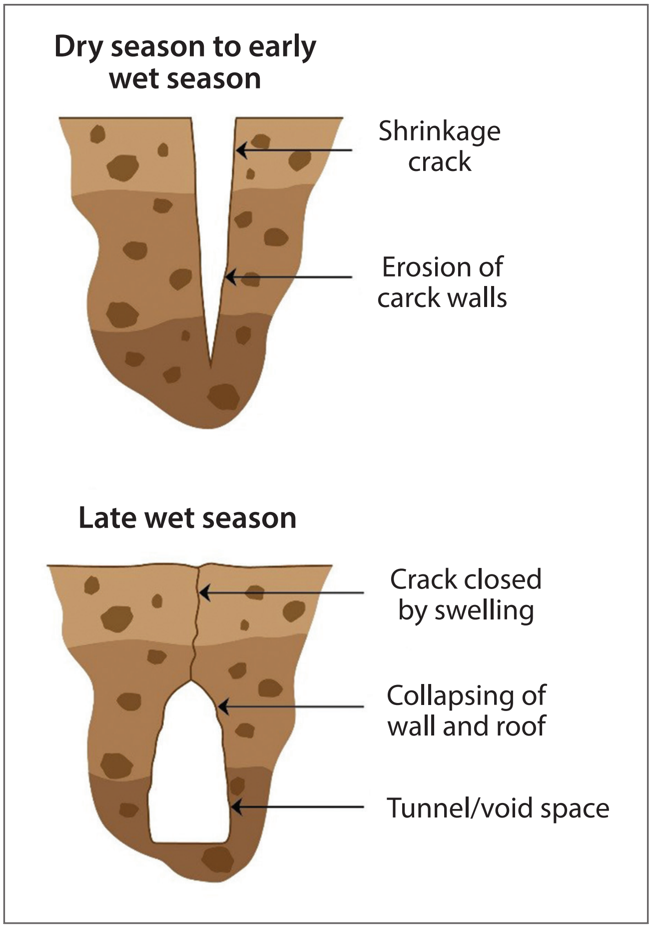

Figure 11. *Subsurface void formation due to shrink-swell of soils having a high clay content. Voids may continue to enlarge in the subsurface and propagate to the surface, creating a sinkhole hazard (modified from Dunne, 1990).*

Figure 12. *"Popcorn" texture with evaporite precipitation in soils derived from the Chinle and Paradox Formations (photo: base of cliffs on the southwest side of the Moab Valley).*

Soluble Soil and Rock

Soluble soil and rock are subject to dissolution and reduced soil and rock strength, which can cause considerable damage to structures, foundations, and infrastructure. Soil and rock containing salt, gypsum, and limestone are susceptible to dissolution, which is associated with karst, sinkholes, and subsidence. Gypsum ($CaSO_4 \cdot 2H_2O$)-bearing soil and rock are highly soluble. Changes in surface-water flow and groundwater can quickly dissolve gypsiferous material, resulting in cavities that can collapse, either propagating to the surface or causing local or regional subsidence. Where the amount of gypsum is greater than 10 percent, dissolution can result in localized land subsidence and sinkhole formation (Mulvey, 1992; Muckel, 2004; Santi, 2005). Gypsum dissolution can be greatly accelerated by application of water from sources like reservoirs; septic-tank and wastewater drain fields; street, roof, or parking-lot runoff; and irrigation (Martinez and others, 1998). Care should be taken in areas of gypsiferous materials to avoid surface-flow- and groundwater-regime changes. Surface flow should be directed to areas where it will not percolate into the material below. Landscape irrigation is discouraged, and storm drain infrastructure should be regularly maintained to prevent leaks and sealed pipes should be considered. Gypsum is a weak material that has low bearing strength and is not suited as subgrade or foundation soil.

Other evaporite minerals with high salt content, including halite (NaCl), anhydrite ($CaSO_4$), carnallite ($KMgC_{l3} \cdot 6H_2O$), and sylvite (KCl), are common in the Moab quadrangle and surrounding area (Mayhew and Heylman, 1965). These minerals are highly soluble and are intermixed with gypsum in the Paradox Formation.

Limestone and rock made up of mostly calcium carbonate ($CaCO_3$) and soils derived from them are moderately susceptible to dissolution. Karst terrain is common in areas of limestone rock. Climate, water, and human activity are factors in chemical weathering resulting in limestone dissolution. The arid climate of east-central Utah contributes to slow rates of limestone dissolution. However, changing surface-flow and groundwater regimes and/or increased precipitation due to climate change could accelerate dissolution of limestone-bearing rocks in the Moab area.

To evaluate soluble soil and rock (plate 9), we used three main sources of data: (1) UGS geologic and hazard mapping (Doelling and others, 2002; Hylland and Mulvey, 2003), (2) a geotechnical database compiled by the UGS, and (3) the NRCS *Soil Survey Geographic (SSURGO) Database for Grand County Utah—Central Part (UT624)*; *Canyonlands Area, Utah—Parts of Grand and San Juan Counties (UT633)*; and *Arches National Park, Utah (UT687)* (NRCS, 2016a, 2016b, 2016c).

We classified soil and rock units into eight categories based on their potential for dissolution: highly soluble rock (HSR); highly soluble soil (HSS); gypsiferous rock (GR) A, B, and C; gypsiferous soils (G_S); and limestone rock (LR) A and B.

HSR and HSS categories include the Paradox Formation which contains significant amounts of gypsum and other salts and alluvial-fan deposits. The depth to the Paradox Formation along the eastern and western margins of the Moab–Spanish Valley is not well constrained and caution should be taken during development to limit the removal of surface material along the valley margins, and to limit the addition or change the rate of water application. The Paradox Formation poses a dissolution hazard, even at depth, as cavities can form and propagate to the surface creating sinkholes and subsidence (figure 13). Additionally, varying layers of unconsolidated deposits can conceal gypsum and salt-bearing material. The thickness of the unconsolidated deposits can range from a thin veneer to several hundred feet (Doelling and others, 2002). The concealed gypsum-salt deposits contribute to sinkhole susceptibility and are exposed or are at shallow depth below the surface primarily along the valley-edge areas.

The classification system for soluble soil and rock that can contribute to dissolution and collapse hazard is a relative susceptibility ranking as opposed to a hazard-severity ranking. Soluble rock and soil hazard category GR_A poses a significant hazard due to dissolution. The Chinle Formation along the valley margins has been deformed due to uplift in the salt-cored anticline region of the Moab–Spanish Valley. This deformation has incorporated gypsum and salt from the Paradox Formation into the Chinle, increasing the dissolution and collapse hazard. Category GR_B may contain gypsum and other soluble salts locally and has a significant potential for dissolution and collapse. Category GR_C includes talus and alluvial material that may be composed of units with significant gypsum and salt content. This category represents a thin cover above rock and soil units that pose a significant dissolution and collapse hazard. Caution should be taken when removing soil or surficial deposits in this category, as it could expose soil or bedrock below that has an increased dissolution and collapse hazard. Category GS includes soils lacking significant geotechnical data, but have been identified by the NRCS (2016a, 2016b, and 2016c) as gypsum-bearing soils.

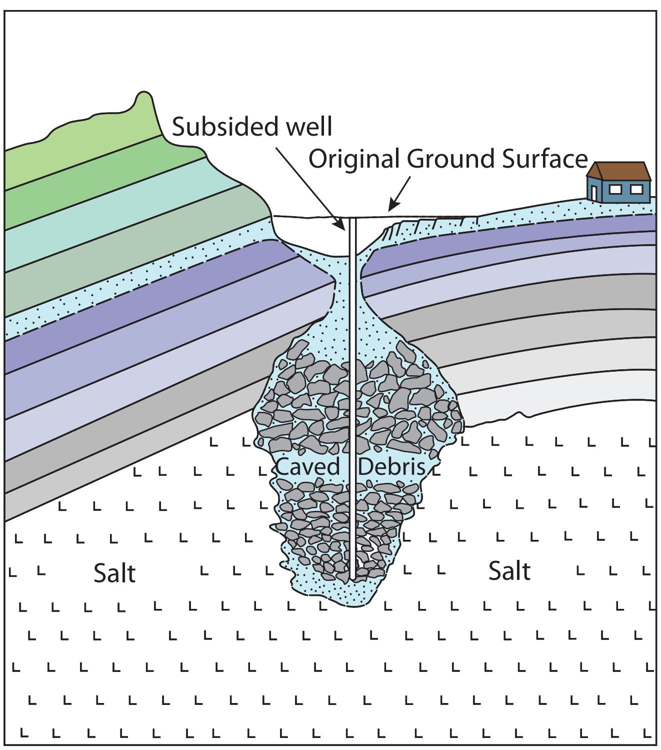

Figure 13. *Representation of sinkhole formation due to salt dissolution near a subsided well. Dissolution can occur in a similar manner due to groundwater dissolution and percolating surface water (modified from Dunrud and Nevins, 1981).*

Geologic units consisting of limestone or interbedded carbonate rocks are mapped as LRA and LRB. The solubility of these units is relatively lower than the solubility of gypsum- and salt-bearing units; however, the potential for dissolution and collapse is still present and could increase from land-use modification, introducing and concentrating surface water, and groundwater-regime changes due to development.

The soluble-soil-and-rock-hazard categories shown on plate 9 are approximate and mapped boundaries are gradational. Localized areas of higher or lower soluble soil and rock hazard 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 landscape irrigation and stormwater control.

Corrosive Soil and Rock

Corrosion of Portland cement concrete (PCC) occurs from a chemical reaction between a base (concrete) and a weak acid (sulfate, sodium, or magnesium in soil or water) (Muckel, 2004). Soil and rock with high gypsum content is associated with corrosion of concrete. Gypsum is soluble and along with associated sulfates, such as sodium sulfate and magnesium sulfate, can dissolve in water to form a weak acid solution that is corrosive to concrete and metals in areas where the amount of soil gypsum is one percent or greater (Muckel, 2004). Sulfate-induced corrosion of unprotected concrete slabs, walls, masonry blocks, and buried infrastructure is widespread in arid regions of Utah (figure 14). Corrosion of steel (metals) occurs from an electrochemical process that results from contact between steel (metals) and soluble chloride salts found in soil or water (White and others, 2008).

To evaluate corrosive soil and rock (plate 10), we used three main sources of data: (1) UGS geologic and hazard mapping (Doelling and others, 2002; Hylland and Mulvey, 2003), (2)

Figure 14. *Evaporite precipitation and corrosion on concrete masonry unit wall (photo: northeast valley margin, February 23, 2017).*

a geotechnical database compiled by the UGS, and (3) the NRCS *Soil Survey Geographic (SSURGO) Database for Grand County Utah—Central Part (UT624)*; *Canyonlands Area, Utah—Parts of Grand and San Juan Counties (UT633)*; and *Arches National Park, Utah (UT687)* (NRCS, 2016a, 2016b, 2016c).

We classified soil and rock units into five categories based on their potential for corrosion of concrete and metals: corrosive rock A (CR_A), corrosive rock B (CR_B), corrosive soil A (CS_A), corrosive soil B (CS_B), and buried or concealed corrosive soil or rock (CS_C). Site-specific investigations prior to development should include testing for sulfate and gypsum content and pH of soils. Other testing may be required; however, specialized corrosion engineering consultants are recommended. It is important to include testing for sulfates in geotechnical investigations, as sulfates can degrade concrete over time. Concrete masonry unit walls, foundations, and other structures, where high sulfate levels are found, should follow applicable American Concrete Institute, IBC, and IRC standards, such as the use of Type V (sulfate resistant) cement.

The corrosive-soil-and-rock-potential categories shown on plate 10 are approximate and mapped boundaries are gradational. Localized areas of soil having higher or lower corrosive potential are likely to exist within any given map area, but their identification is precluded because of the generalized map scale and relatively sparse data. All mapped categories may exhibit corrosive potential; therefore, site-specific investigations should be performed at all locations to resolve uncertainties inherent in the maps.

Piping and Erosion

Piping and erosion can cause significant damage to roads, canals, earth-fill dams, structures, bridges, culverts, and farmland. Rapid erosion may occur when susceptible materials are exposed to running water or wind. Monsoonal storms typically bring intense rainfall and high winds. Heavy rain can quickly erode fine-grained sediment. Slope runoff that becomes channelized can form gullies (figure 15) and erode steep banks of streams and rivers. Erosional gullies can contribute to the piping hazard. Piping, also referred to as tunnel erosion, is subsurface erosion by groundwater that moves through permeable, non-cohesive layers in unconsolidated materials and exits at a free face (figure 16). Fine-grained sand, silt, and clay particles are removed by the subsurface flow of water, creating void space. An exit point at a free face may not always be obvious. Entrained silt and clay can travel with the subsurface groundwater flow for long distances, enter the regional groundwater regime, and exit as seeps and springs or into streams and rivers.

Soil and rock susceptible to piping and erosion are prevalent in the Moab quadrangle. The Chinle Formation and the Paradox Formation are highly susceptible to piping and erosion, as well as other geologic units that have high silt and clay content or high evaporite mineral content. Soil and un-

Figure 15. *Gully erosion in slope underlain by Chinle Formation (photo: northeast valley margin).*

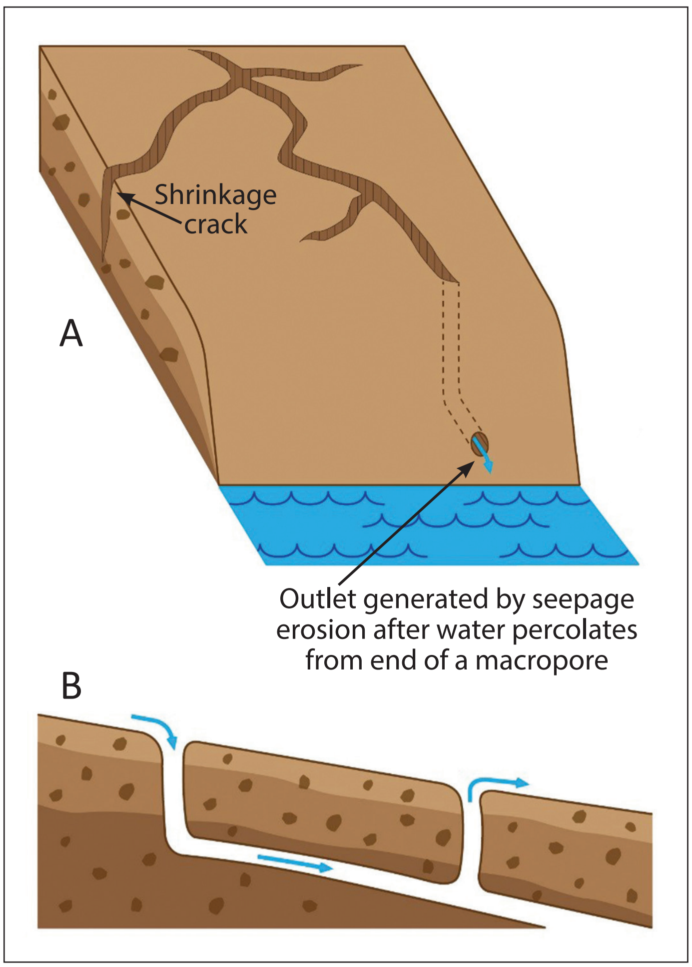

Figure 16. *(A) Piping erosion caused by water entering cracks as expansive soils dry. (B) Clay particles are suspended and evaporites dissolve in solution and move with subsurface water flow creating void spaces. Outlets may not be obvious as water may carry sediment a significant distance through a network of tunnels or into the larger, regional groundwater flow (modified from Dunne, 1990).*

consolidated rock with high shrink-swell potential are also highly susceptible to piping and erosion. Clay shrinkage cracks allow water to easily penetrate below the surface (figure 16); as the soil hydrates and swells, the cracks can close leaving subsurface voids that form near-surface sinkholes and ground subsidence.

To evaluate piping and erosion (plate 11), we used three main sources of data: (1) recent UGS geologic and hazard mapping (Doelling and others, 2002; Hylland and Mulvey, 2003), (2) a geotechnical database compiled by the UGS, and (3) the NRCS *Soil Survey Geographic (SSURGO) Database for Grand County Utah—Central Part (UT624)*; *Canyonlands Area, Utah—Parts of Grand and San Juan Counties (UT633);* and *Arches National Park, Utah (UT687)* (NRCS, 2016a, 2016b, 2016c).

We classified soil and rock units into four categories based on their potential for piping and erosion: highly susceptible rock (HSr), highly susceptible soil (HSs), susceptible rock (Sr), and susceptible soil (Ss). The presence of these units in and of themselves does not create a piping and erosion hazard. However, a change in conditions brought about naturally or through human activity, such as cut-and-fill construction techniques, can create the conditions necessary for piping to occur. While susceptible to erosion, these units are generally stable in their natural, undisturbed state, but can quickly erode if disturbed or if surface-water drainage conditions change in an uncontrolled manner.

The piping-and-erosion-susceptibility categories shown on plate 11 are approximate and mapped boundaries are gradational. Localized areas of soil with higher or lower piping and erosion susceptibility are likely to exist within any given map area, but their identification is precluded because of the generalized map scale and relatively sparse data. All mapped susceptibility categories may potentially exhibit piping and erosion; therefore, site-specific investigations should be performed at all locations to resolve uncertainties inherent in the maps.

Wind-Blown Sand

In southeast Utah, there are significant amounts of loose sand and seasonal winds that make wind-blown sand a viable hazard in the Moab quadrangle. Even a few inches of sand on a road can be very dangerous (Stipho, 1992). In the Moab quadrangle, wind-blown sand can cause damage to infrastructure, by burial and/or sandblasting effect, and create unsafe driving conditions. Dust storms commonly occur due to wind associated with the monsoonal season that affects southern Utah and northern Arizona. The most important factors for wind-blown sand hazard are (1) a source of sand grains, (2) a source of wind at a threshold speed, and (3) proximity to areas likely to be affected by wind-blown-sand hazard.

In desert regions, up to 98 percent of dry, non-cohesive sand grains picked up by winds can travel up to 1 meter (3 feet) above the surface (Stipho, 1992). Studies in other arid regions (Stipho, 1992; Sherman and Nordstrom, 1994) indicate the threshold shear velocity, or wind speed needed to initially move a sand grain, is a function of the sand grain diameter. According to these studies, a wind speed of 0.5 mph (0.2 m/s) is required to initiate movement of a 0.2 mm sand grain, the standard sand size in NRCS reports (NRCS, 2016a, 2016b, 2016c). To transport sand within 3 feet (1 meter) of the surface, wind speeds more than 9 mph (4 m/s) are required (Sherman and Nordstrom, 1994).

The average annual wind speed (1998–2006) from the Moab-Canyonlands airport, about 14 miles north of the City of Moab, is 6.3 mph (2.8 m/s) (WRCC, 2006). Monitoring from 1992 to 2002 indicates that western wind directions are dominant throughout the year, with the exception of June through August when more southern and eastern winds prevail from summer monsoon storms (WRCC, 2006). The average monthly wind speed for the period of 1996–2006 varied from 3.7 mph (1.6 m/s) in December to 9.2 mph (4.1 m/s) in April (WRCC, 2006). Monthly average wind speeds indicate local transportation of sand grains is possible, given that the initiation wind speed for sand grain movement is 0.5 mph (0.2 m/s). This may indicate a more significant local hazard of wind-blown sand for mapped eolian deposits close to infrastructure or development. However, wind-blown-sand deposits that interfere with infrastructure most often occur from storm-related winds, which are typically above average wind speeds, and are the most likely to cause more massive sand migration and adverse road conditions for drivers.

To evaluate wind-blown-sand susceptibility (plate 12), we used four main sources of data to identify areas where geologic and historical environmental conditions may contribute to elevated wind-blown-sand hazard susceptibility: (1) percentage of soil sand (<0.2 mm grain size) data from the NRCS *Soil Survey Geographic (SSURGO) Database for Grand County Utah—Central Part (UT624)*; *Canyonlands Area, Utah—Parts of Grand and San Juan Counties (UT633)*; and *Arches National Park, Utah (UT687)* (NRCS, 2016a, 2016b, 2016c), (2) historical wind-speed and direction data (WRCC, 2006; National Renewable Energy Laboratory [NREL], 2012), (3) UGS geologic and hazard mapping (Doelling and others, 2002; Hylland and Mulvey, 2003), and (4) studies from other desert (Stipho, 1992; Lund and others, 2008) and coastal areas (Sherman and Nordstrom, 1994). Using the geologic factors contributing to the supply and distribution of potential wind-blown sand, we classified soil and rock units into high, moderate, and low susceptibility hazard categories.

The NRCS data were particularly useful because of the detailed sand percentages available for the different soil map units. However, it should be noted that these data are only representative of the top 5 feet (1.5 m) of soil. Any removal of soil for development or construction should be reassessed for wind-blown-sand hazard. In coastal environments, wind-blown sand hazard is often mitigated by stabilizing deposits with vegetation (Sherman and Nordstrom, 1994), but this may not be applicable in deserts where water is scarce and should not be added to the surface. Armoring deposits with appropriate sized and graded gravel, cobbles, and/or boulders may be needed.

We evaluated sand source areas within and adjacent to the Moab quadrangle. The highest contribution to sand in the Moab quadrangle is from geologically young eolian deposits and areas that have been disturbed, including talus slopes, landslides, and developed areas. A majority of this sand is derived from the Navajo Sandstone. Soil units with high concentrations of sand, as reported in NRCS (NRCS, 2016a, 2016b, and 2016c) and geologic-map data (Doelling and others, 2002), include geologically young and modern eolian and dry-alluvium deposits, which have greater than 50 percent sand (<0.2 mm sized particles). We mapped talus slopes and sandy geologic units having a low quantity of sandy soil (<50% sand with <0.2 mm sized particles), and up to 30 percent of fines (0.125 mm [0.005 in] to 0.2 mm [0.008 in]) as moderate for wind-blown-sand susceptibility. Areas having low soil sand quantity (<50%) and on mapped sandstones, which are mainly on the broad, flat Navajo Sandstone exposed at higher elevations in the quadrangle, were classified as low susceptibility to wind-blown sand.

Although distal sources of sand were not mapped, there is still a possibility that sand and dust could be transported from regional active dune fields, dried playas in southern Utah, and other areas of small, easily mobilized sediment. In western Utah, dust from dried playas, agricultural lands, and other barren and/or disturbed areas can contain bacteria, viruses, or fungi (Hahnenberger and Nicholl, 2014). Evaluating dust and related biological hazards was beyond the scope of our mapping.

The wind-blown-sand-hazard susceptibility categories shown on plate 12 are approximate and mapped boundaries are gradational. Localized areas of higher or lower wind-blown sand susceptibility 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 infrastructure and design. The use of imported fill for foundation material can also affect wind-blown-sand susceptibility in small areas, because the imported material may have different geologic characteristics than native soil at the site.

Shallow Bedrock

Exposed bedrock is abundant in the Moab area. Less obvious are areas of shallow bedrock within the Moab–Spanish Valley, where bedrock is overlain by a thin cover of younger unconsolidated deposits. Bedrock formations that are not significantly fractured and are strong and stiff usually have satisfactory bearing-capacity and settlement characteristics; however, large loads may exceed the rock bearing capacity and specialized rock mechanics engineering will be required (Goodman, 1980). The principal problem related to shallow bedrock is difficulty of excavation, particularly in highly resistant bedrock units, which often require blasting. Shallow bedrock makes excavations for basements, foundations, underground utilities, and road cuts difficult, can cause areas of perched groundwater, and create problems for wastewater disposal. Not accounting for shallow bedrock in project design may lead to excessive, unaccounted for construction cost, contract change orders, and project delays.

To evaluate shallow-bedrock potential (plate 13), we used four main sources of data: (1) UGS geologic and hazard mapping (Doelling and others, 2002; Hylland and Mulvey, 2003), (2) the NRCS *Soil Survey Geographic (SSURGO) Database for Grand County Utah—Central Part (UT624)*; *Canyonlands Area, Utah—Parts of Grand and San Juan Counties (UT633)*; and *Arches National Park, Utah (UT687)* (NRCS, 2016a, 2016b, 2016c), (3) a geotechnical database compiled by the UGS, and (4) 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).

We used UGS geologic and hazard mapping (Doelling and others, 2002; Hylland and Mulvey, 2003) 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 (2016a, 2016b, and 2016c) soil survey to identify areas of potentially shallow bedrock. The NRCS restrictive layer column identifies areas where bedrock is found less than 6.5 feet (2 m) below the surface.

We also used geotechnical borehole logs in the UGS geotechnical database 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 the 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 may exist.

The shallow-bedrock-potential categories shown on plate 13 are approximate and mapped boundaries are gradational. Localized areas of shallow bedrock are likely to exist within any given map area, but their identification is precluded because of the generalized map scale, relatively sparse data, and limited subsurface data.

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 general public with information on the geologic hazards that may affect existing and future development in the Moab quadrangle. Information provided herein includes the type and location of critical geologic hazards, and recommendations for site-specific investigations to confirm the presence of, investigate in detail, and develop mitigation for the hazards. Additionally, the maps can aid local governments in developing geologic-hazard elements in their general land-use plans for development, re-development, planning, regulation, and design in Utah. We mapped 13 geologic hazards in the Moab quadrangle; however, other hazards may exist that could affect existing and future development.

We recommend performing site-specific geotechnical/geologic-hazard investigations for all development in the 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 available geologic, geotechnical, and hydrologic data. The quality of each map depends on the quality of the data, which varies by hazard throughout the quadrangle. Consequently, geologic hazard boundaries shown on the maps are approximate and subject to change with additional information. Small, localized areas of geologic hazards may exist in the quadrangle, but their identification may be precluded due to limitations of data availability and/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 advises following the recommended guidelines when preparing site-specific engineering-geologic reports and conducting site-specific geotechnical/geologic-hazard investigations in Utah (Bowman and Lund, 2016). 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 geoengineering aspects of the project.

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