GEOLOGIC HAZARDS OF BRYCE CANYON NATIONAL PARK AND VICINITY, GARFIELD AND KANE COUNTIES, UTAH

by Tyler R. Knudsen

SPECIAL STUDY 178
UTAH GEOLOGICAL SURVEY
UTAH DEPARTMENT OF NATURAL RESOURCES
In cooperation with the Bryce Canyon Association and the National Park Service
2026

Blank pages are intentional for printing purposes.

GEOLOGIC HAZARDS OF BRYCE CANYON NATIONAL PARK AND VICINITY, GARFIELD AND KANE COUNTIES, UTAH

by Tyler R. Knudsen

Cover photo: *May 23, 2006, rockfall on the Wall Street section of the Navajo Loop Trail in Bryce Canyon National Park. Photo courtesy of Kristin Legg (National Park Service).*

Suggested citation:
Knudsen, T.R., 2026, Geologic hazards of Bryce Canyon National Park and vicinity, Garfield and Kane Counties, Utah: Utah Geological Survey Special Study 178, 45 p., 15 plates, scale 1:24,000, https://doi.org/10.34191/SS-178.

Mapping available at https://maps.geology.utah.gov/hazards

SPECIAL STUDY 178
UTAH GEOLOGICAL SURVEY
UTAH DEPARTMENT OF NATURAL RESOURCES
In cooperation with the Bryce Canyon Association and the National Park Service
2026

STATE OF UTAH
Spencer J. Cox, Governor

DEPARTMENT OF NATURAL RESOURCES
Joel Ferry, Executive Director

UTAH GEOLOGICAL SURVEY
Darlene Batatian

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

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

This mapping was funded by the Utah Geological Survey and the Bryce Canyon Association, and facilitated by the U.S. Department of the Interior, National Park Service. The views and conclusions contained in this document are those of the author and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the Bryce Canyon Association or the U.S. Government. These maps and explanatory information are submitted for publication with the understanding that the Bryce Canyon Association and the United States Government are authorized to reproduce and distribute reprints for their use.

CONTENTS

FIGURES

TABLES

PLATES

GEOLOGIC HAZARDS OF BRYCE CANYON NATIONAL PARK AND VICINITY, GARFIELD AND KANE COUNTIES, UTAH

by Tyler R. Knudsen

ABSTRACT

The extraordinary geological character of Bryce Canyon National Park attracts more than 2 million visitors annually. Geologic processes that shaped this dramatic landscape are still active today and can be hazardous to property and life. The purpose of this study is to provide the National Park Service (NPS) and other land managers with geographic information system (GIS)-based information on the kind and location of geologic hazards that may affect existing and future development and visitor and employee safety in Bryce Canyon National Park and surrounding area. The Utah Geological Survey (UGS) conducted a geologic-hazard investigation of a 265-square-mile (686 km^2) area centered on the park. The study area encompasses Bryce Canyon National Park, the Town of Tropic, Bryce Canyon City, and recreational areas within the adjoining Dixie National Forest and Grand Staircase-Escalante National Monument. Available geologic, hydrologic, soil, and geotechnical information were used to identify where geologic hazards may exist and where site-specific geotechnical/geologic-hazard investigations are necessary to protect health, welfare, and safety. This study provides maps and information for 14 geologic hazards: rockfall, landslide, flooding/debris flow, shallow groundwater, surface faulting, liquefaction, collapsible soil, piping and erosion, wind-blown sand, soluble rock, corrosive soil and rock, expansive soil and rock, shallow bedrock, and radon.

Erosional processes dominate the Bryce Canyon region. Mass wasting (rockfalls, landslides, and debris flows) along and below the steep eastern escarpment of the Paunsaugunt Plateau (Pink Cliffs) create the principal geologic hazards with which visitors, park employees, planners, residents, and public safety personnel must contend. Rockfall hazard is particularly acute along parts of Bryce Canyon's increasingly visited Navajo Loop Trail and other "under-the-rim" trails that access the rapidly eroding Pink Cliffs. The UGS encourages the NPS to continue, and enhance where possible, informational signage, preventative search and rescue (PSAR) volunteer programs, weather-triggered trail closures, and slope-deformation monitoring to reduce the probability of a visitor-rockfall encounter. New geologic mapping completed for this study shows that landslides are common throughout much of the study area where clay-rich Cretaceous strata crop out on slopes. Headward erosion and canyon entrenchment via stream scouring (primarily floods) along the Paria River and its tributaries also present a widespread hazard to humans and infrastructure within the study area.

Although large earthquakes are rare in the Bryce Canyon area, strong ground shaking, surface faulting, and liquefaction are possible. New geologic mapping shows that the Paunsaugunt fault has displaced unconsolidated Pleistocene deposits at a minimum of three locations in the study area, indicating that the fault is Quaternary-active and should be considered hazardous. Excluding the effects of a rare, large earthquake, the remaining geologic hazards considered in this report are typically localized, and though potentially costly when not recognized and properly accommodated in project planning and design, the problems associated with them are rarely life threatening.

INTRODUCTION

This study provides maps and information on 14 geologic hazards near Bryce Canyon National Park (BCNP) in southwest Utah. The 265-square-mile (686 km^2) BCNP geologic-hazard study area (hereafter, "Bryce Canyon study area") encompasses the park and surrounding areas that include Bryce Canyon City, the Town of Tropic, and public lands managed by the Dixie National Forest (DNF) and the Grand Staircase-Escalante National Monument (GSENM) (Figure 1).

Bryce Canyon National Park is centered on the precipitous eastern escarpment of the Paunsaugunt Plateau that is part of the High Plateaus subsection of the Colorado Plateau physiographic province (Figure 1, inset; Stokes, 1977). The gently north-tilted surface of the Paunsaugunt Plateau sits at an average elevation of about 8200 feet (2500 m) and is drained northeastward by the East Fork Sevier River that empties into the Great Basin. Below the eastern rim of the Paunsaugunt Plateau, elevation drops steeply 1000 to 2000 feet (305–610 m) to dissected tablelands characterized by incised benches, entrenched canyons, and broad alluvial valleys drained by the Paria River system that empties into the Colorado River near Lees Ferry, Arizona. Elevation in the study area ranges from 9120 feet (2780 m) at Rainbow Point in southern BCNP (Figure 2) to 6080 feet (1855 m), where the Paria River exits the map area southeast of Tropic. Due to the large elevation variation within the Bryce Canyon study area, climatic conditions are also widely varied. For example, the BCNP Visitor Center at an elevation of about 8000 feet (~2440 m) receives an average annual precipitation of 15.24 inches (39 cm), whereas Tropic, at an elevation of

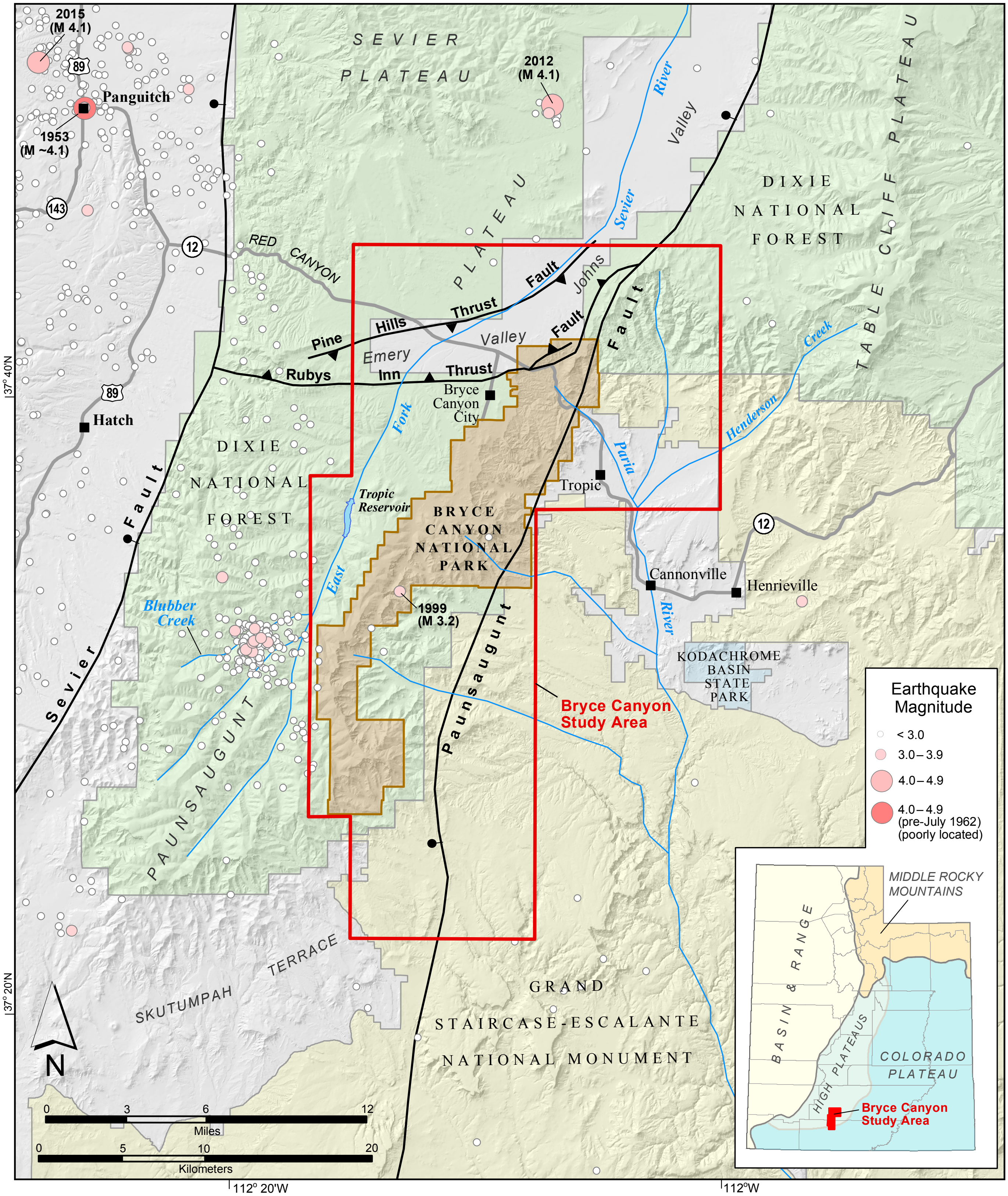

Figure 1. *Bryce Canyon study area boundary, principal physical and hydrologic features, federal-land management boundaries, Quaternary-active faults, and roads (gray lines). Earthquake epicenters from the University of Utah Seismograph Stations (2022a). Inset shows physiographic provinces. Shaded relief base map generated from ESRI, USGS, and NOAA elevation data.*

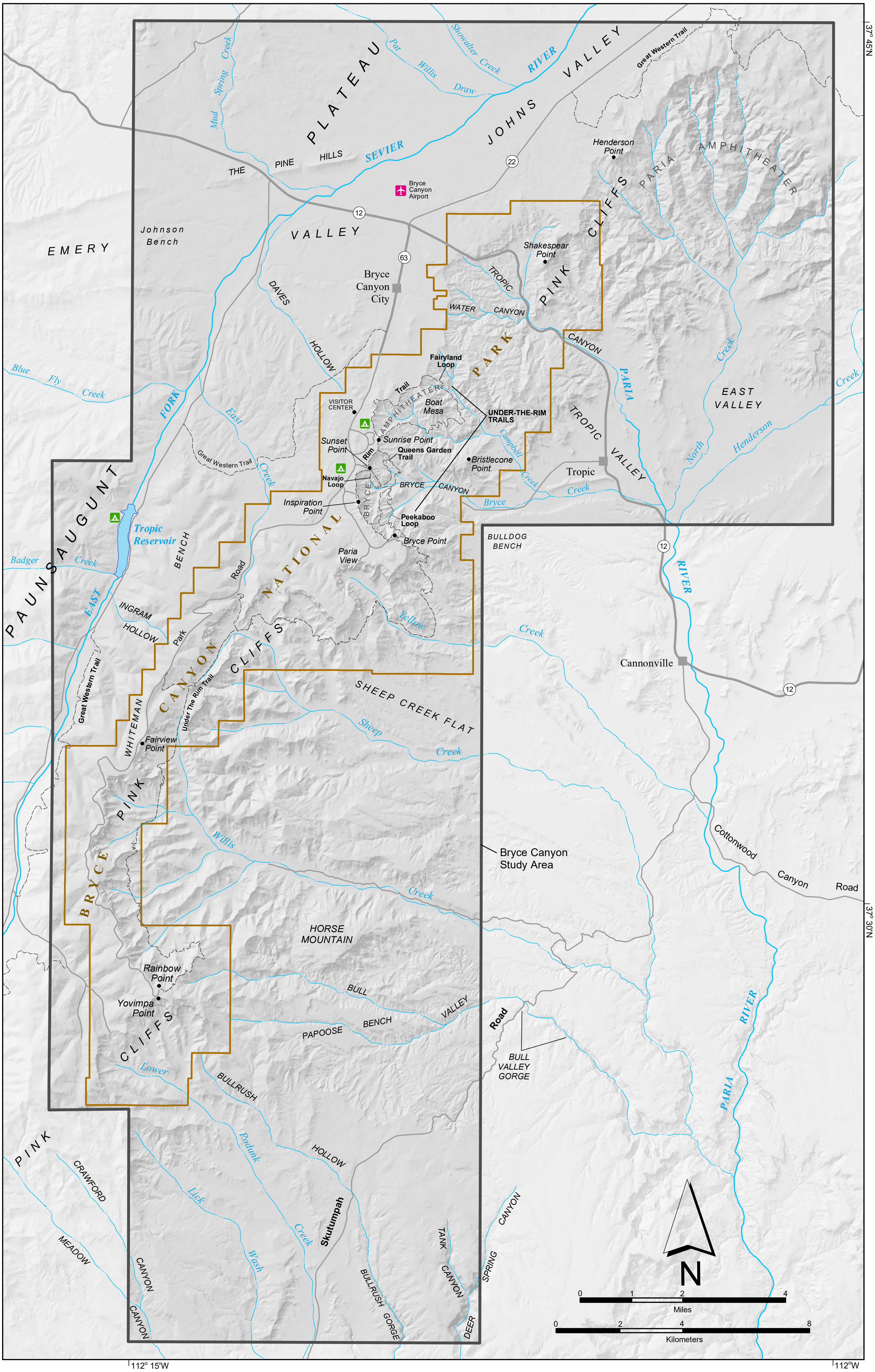

Figure 2. *Bryce Canyon study area physical relief map showing study boundary, principal physical and hydrologic features, roads (solid gray lines), and trails (dashed gray lines). Shaded relief base map generated from ESRI, USGS, and NOAA elevation data.*

6300 feet (1920 m), receives an average annual precipitation of 12.07 inches (31 cm) (Western Regional Climate Center, 2022). BCNP's relatively high elevation ensures subfreezing nighttime temperatures through much of the year, and its high number of cloud-free days allow for effective solar radiation to consistently raise daytime temperatures above freezing (Lindquist, 1980; Davis and Pollock, 2024). These frequent freeze-thaw cycles play a prominent role in weathering and erosion within the park.

Known for its colorful and intricately eroded landscape, BCNP has attracted millions of visitors since its establishment as a National Monument in 1923. From the 1990s through the mid-2000s, BCNP averaged about 1 million visitors annually (National Park Service [NPS], 2024). Visitation has more than doubled over the past two decades, peaking at nearly 2.7 million visitors in 2018. Many of these visitors hike at least one of BCNP's popular under-the-rim-trails (Navajo Loop, Peekaboo Loop, Queens Garden, and Fairyland Loop trails) that descend into the Bryce Amphitheater (Figure 2)—an area prone to frequent rockfalls that are a part of the natural cliff-retreat process. Increased visitation to these trails increases the likelihood of a rockfall-visitor encounter. Visitation to recreation areas within adjacent lands managed by the DNF and the GSENM have also increased over the past decade. Recreation on DNF land within the study area is centered on Tropic Reservoir (Figure 2) which offers fishing, boating, hiking, and a campground. Additionally, the multi-use Great Western trail (Figure 2) passes west of BCNP mainly within the DNF. Within the GSENM, the graded dirt Skutumpah Road traverses the southeastern part of the study area (Figure 2) and provides access to increasingly popular hikes at Willis Creek, Bull Valley Gorge, and Lick Wash.

The geologic processes that shaped the Bryce Canyon study area's rugged topography remain active today and can be hazardous to visitors, employees, residents, and infrastructure. Erosional geologic processes dominate the Bryce Canyon region. Mass wasting (landsides, rockfalls, and debris flows) along and below the steep eastern Paunsaugunt Plateau margin (Pink Cliffs) create the principal geologic hazards with which visitors, planners, public safety personnel, and employees in BCNP must contend. Headward erosion and canyon entrenchment via stream scouring (primarily floods) along the Paria River and its tributaries also present a widespread hazard to humans and infrastructure within the study area. Except for the effects of a rare large earthquake, the remaining geologic hazards considered in this report are typically localized, and while potentially costly when not recognized and properly accommodated in project planning and design, the problems associated with them are rarely life threatening.

Purpose and Scope

Geologic-hazard mapping is a multidisciplinary process that uses a variety of available data to create an integrated product intended for multiple uses. The purpose of this study is to provide the NPS and other land managers with geographic information system (GIS)-based information on the kind and location of geologic hazards that may affect existing and future development and visitor, employee, and resident safety in the Bryce Canyon study area. Data were compiled and hazard maps created for this study at a scale of 1:24,000 (1 inch = 2000 feet) using GIS. This methodology resulted in geologic-hazard mapping that incorporates data and methods from a variety of scientific disciplines, including geology, engineering geology, geotechnical engineering, geomorphology, imagery analysis, GIS analyses, and geologic reconnaissance and field mapping. Available geologic maps at the outset of this study (e.g., Bowers, 1991; Doelling, 2008; Biek et al., 2015) lacked sufficient detail and/or an emphasis on unconsolidated geologic deposits that are critical to effective geologic-hazard mapping. Therefore, this study was preceded with new geologic mapping at 1:24,000 scale (Knudsen et al., in preparation) that added significant geological detail with a focus on mass wasting (talus, landslides, and debris flows), fluvial deposits, and fault locations.

This geologic-hazard mapping is designed as an aid for general planning to indicate where detailed, site-specific geotechnical/geologic-hazard investigations are recommended. The maps should not be enlarged for use at scales greater than 1:24,000, and are not a substitute for site-specific geotechnical/geologic-hazard investigations. Geologic hazards addressed are rockfall, landslide, flooding and debris flow, shallow groundwater, surface-fault rupture, liquefaction, collapsible soil, piping and erosion, wind-blown sand, soluble rock, corrosive soil and rock, expansive soil and rock, shallow bedrock, and radon.

The scope of work for this study consisted of (1) identifying and reviewing geologic, hydrologic, and soils information available for the study area, (2) digitizing relevant geologic, hydrologic, and soils information, (3) compiling a digital geotechnical database incorporating test data, borehole logs, and other information from the limited number of geotechnical/geologic-hazard reports available for the study area, (4) field reconnaissance and mapping, and (5) preparing maps and this accompanying report that characterize each geologic hazard. Considering the map scale and limited geotechnical data, the special-study area boundaries shown on the maps accompanying this report are considered approximate and subject to change as additional information becomes available. Furthermore, small, unrecognized areas of hazard may exist in the study area, but their identification was precluded by limitations of data availability or map scale.

The Utah Geological Survey (UGS) provides recommendations for appropriate, minimum investigation techniques, standards, and report content for surface-fault rupture, landslide, debris flow, geologic radon, and rockfall hazards (Bowman and Lund, 2020). Bowman and Lund (2020) also present a suggested approach to implementing geologic-hazard ordinances in Utah that can be implemented at the municipality or county level.

Geology

Many researchers have studied the geology of the Bryce Canyon region (for geologic reference lists, see Doelling, 2008; Biek et al., 2015; Davis and Pollock, 2024; and Knudsen, in preparation). The discussion provided in this report is limited to a brief description of the geologic units, structures, and conditions pertinent to geologic hazards within the Bryce Canyon study area. For readers interested in greater detail about the general geology of the study area, see Gregory (1951), Bowers (1991), DeCourten (1994), Biek et al. (2015), and Davis and Pollock (2024).

Exposed bedrock in the Bryce Canyon study area consists of a sequence of sedimentary rock layers ranging in age from Early Jurassic (about 170 million years ago) to Eocene (about 38 million years ago) (Figure 3). These rock units represent about a 7500-foot (2290 m) section of marine and continental depositional environments; rock types include limestone, mudstone, claystone, shale, sandstone, conglomerate, and evaporite deposits. Much of BCNP, including its high-use areas, is dominated by the brightly colored limestone, sandstone, mudstone, and minor conglomerate of the Paleocene to Eocene Claron Formation (Figure 4). On the surface of the Paunsaugunt Plateau, Claron strata typically weather to gentle, colluvium-covered slopes. Along the plateau's rim, Claron strata are sculpted into steep-walled amphitheaters adorned with vertical spires, hoodoos, and fins that form the Pink Cliffs. Below the precipitous Pink Cliffs, the Paria River and its tributaries have carved deep canyons into the mudstone-rich Cretaceous section (Figure 5) that includes the Wahweap Formation, Straight Cliffs Formation, Tropic Shale, and Naturita Formation (formerly, the Dakota Formation). At lower elevations to the east within the GSENM, the terrain is dominated by broad, deeply dissected benches formed primarily on alternating red and white "banded" strata of the Jurassic Entrada Sandstone and gypsum-rich Carmel Formation. The white, cross-bedded Jurassic Navajo Sandstone is exposed in the deeply incised Deer Range Canyon and Bullrush Gorge near the southeast corner of the map area.

Some bedrock units in the Bryce Canyon study area, particularly the mudstone-rich Cretaceous units, contain a high percentage of clay and are correspondingly weak and moisture sensitive, making them susceptible to landslides and volumetric change (shrink/swell). The John Henry and Smoky Hollow Members of the Straight Cliffs Formation, the Tropic Shale, and the Naturita Formation are prone to landsliding where exposed on steep to moderate slopes. Landslides in these units have coalesced to form large complexes north-northwest of Tropic and along parts of Meadow Canyon, Crawford Canyon, and Lick Wash near the southwest corner of the study area. More competent, cliff-forming rock formations, such as the Claron Formation and Navajo Sandstone, are cut by joint sets, faults, and deformation shear bands (Davis, 1999; Davis and Pollock, 2024), which make many areas in the study area susceptible to rockfall.

Unconsolidated Quaternary geologic units in the study area are of limited aerial extent and thickness due to the dominance of erosive geomorphic processes. Stream alluvium and terrace deposits of different ages are present along larger drainages, including the East Fork Sevier River, the Paria River, and their larger tributaries. Alluvial pediment deposits blanket much of Emery and Johns Valleys. Aprons of mixed alluvial-fan and colluvial deposits floor much of Tropic Valley and Bryce Creek Canyon. Depending on clay content, alluvial-fan material may be locally moisture sensitive and prone to either swell or collapse.

The Rubys Inn and Pine Hills thrust faults are major east-west-trending, mid-Tertiary thrust faults that cross the northern part of the study area and define the margins of Emery and Johns Valleys (Figure 1) (e.g., Lundin, 1989; Bowers, 1991; Davis, 1999; Biek et al., 2015; Davis and Pollock, 2024). The faults generally place upper Cretaceous strata onto the Paleogene pink member of the Claron Formation. North of State Route (SR)-12, the Rubys Inn fault splays into two sections (Figure 1; Lundin, 1989), each placing resistant Claron pink member over softer pink or white member strata. Erosional undercutting of the softer lower-plate strata has resulted in significant rockfall hazard to SR-12 (Reed, 2020). Research over the past 30 years has shown that the Rubys Inn and Pine Hills thrust faults are part of the larger Paunsaugunt thrust fault system that developed in response to gravitational spreading of the Marysvale volcanic field about 20 to 30 million years ago (e.g., Nickelsen et al., 1992; Davis and Rowley, 1993; Merle et al., 1993; Davis, 1999; May et al., 2011; Leavitt et al., 2011; Biek et al., 2015; Davis and Pollock, 2024).

Uplift and subsequent erosion of the greater Colorado Plateau region began in the early Tertiary (about 65 Ma) and continue to the present (Hunt, 1956; Lucchitta, 1979; Anderson et al., 2024). Erosional processes were greatly accelerated by the onset of the Basin and Range extension at about 17 Ma (Stewart, 1978), and integration of the upper Colorado River system to the Gulf of California in the past 6 million years (Lucchitta, 1979; Young and Spamer, 2001; Karlstrom et al., 2014; Anderson et al., 2024; Davis and Pollock, 2024).

The Paunsaugunt Plateau is bounded by the Sevier fault (Lund et al., 2008a; Biek et al., 2015, p. 86 for discussion) on the west and the Paunsaugunt fault (Bowers, 1991; Biek et al., 2015; Davis and Pollock, 2024, p. 89 for discussion) on the east (Figure 1); both are large-displacement, down-to-the-west, Basin-and-Range normal faults. The Paunsaugunt fault traverses the length of the Bryce Canyon study area and extends southward, en-echelon, for an additional 65 miles (105 km; Doelling, 2008) into northern Arizona, where it is known as the West Kaibab fault. The Paunsaugunt fault has produced a remarkable example of an obsequent or inverted fault scarp where it defines the eastern margin of the Paunsaugunt Plateau. An obsequent fault scarp is a scarp that forms on the downthrown or hanging-wall side of a normal fault rather than on the upthrown or footwall side of the fault, which is opposite of

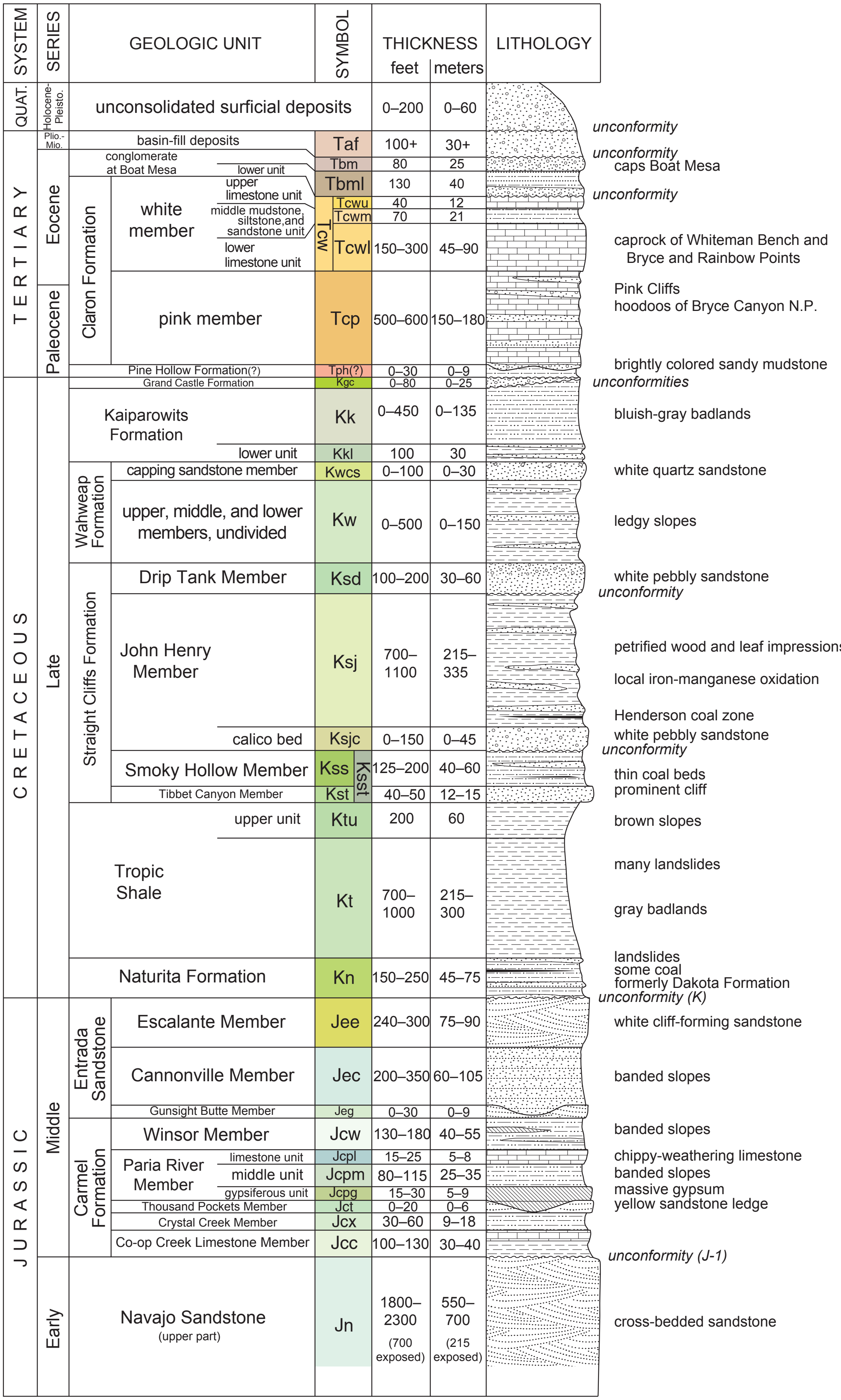

Figure 3. *Lithologic column of geologic units that crop out in the Bryce Canyon study area; from Knudsen et al. (in preparation).*

Figure 4. *Northeast-directed view from the Navajo Loop Trail of the stunning colors and textures of the Tertiary Claron Formation exposed along BCNP's Pink Cliffs.*

Figure 5. *Mud Canyon is typical of several deeply entrenched and steep-walled canyons carved into the mudstone-rich Cretaceous section of the Bryce Canyon study area. Relatively weak rock units and steep slopes are conducive to landslides, rockfalls, and debris flows View is to the east.*

what would be expected. This type of scarp is possible where differential erosion rates of rocks juxtaposed across a fault exceed the vertical tectonic slip rate of the fault. At BCNP, the Paunsaugunt fault juxtaposes the more resistant Claron Formation in its hanging wall against non-resistant Cretaceous rocks in its footwall. The Paria River and its tributaries are quickly eroding the softer footwall Cretaceous rocks, leaving the more resistant Claron strata at a higher elevation (Bowers, 1991; Biek et al., 2015; Davis and Pollock, 2024). Development of the obsequent Paunsaugunt fault scarp is one of many geologic conditions that have combined to form the unique landscape along BCNP's Pink Cliffs. The rapid headward erosion of the Paria River system into the Paunsaugunt Plateau has produced extremely steep and locally unstable terrain that is prone to rockfalls, landslides, and debris flows.

GEOLOGIC HAZARDS

Early recognition and mitigation of geologic hazards can reduce risk to life, property, and the economy. 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, 2020).

On an annual basis, the most common and potentially damaging geologic hazards in the Bryce Canyon study area are flash floods, debris flows, rockfalls, and landslides. Because of their wide distribution, frequent occurrence, and destructive nature, these hazards are the principal geologic hazards in the study area that planners and others should consider addressing. Due to the abundance of easily eroded, clay-rich bedrock units exposed in the study area, flash floods can quickly erode and entrain a large amount of sediment, transforming them into destructive debris flows. Conditions conducive to rockfall are present along the Pink Cliffs and are particularly hazardous along BCNP's heavily used under-the-rim trails that access the Bryce Amphitheater section of the Pink Cliffs. New geologic mapping (Knudsen et al., in preparation) revealed dozens of previously unmapped landslides throughout the deeply dissected Cretaceous outcrop belt below the Pink Cliffs. The close correlation in the study area between existing landslides and weak bedrock units provides ample warning that development on slopes underlain by landslide-susceptible bedrock must proceed with caution. 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.

Large, damaging earthquakes are rare in the Bryce Canyon study area, but active faults in and around the study area can produce earthquakes of magnitude (M) 6.5 or greater. Earthquakes in southwestern Utah are typically associated with the Intermountain Seismic Belt (ISB) (Smith and Sbar, 1974; Smith and Arabasz, 1991; Bowman and Arabasz, 2017), an approximately 100-mile-wide, north-south-trending zone of earthquake activity extending from northern Montana to northwestern Arizona (Figure 6). Ground shaking is the most widespread and typically most damaging earthquake hazard (Yeats et al., 1997). Strong ground shaking can last from several seconds to minutes and can be amplified (increased) or deamplified (decreased) depending on local soil and rock conditions (Reiter, 1990). Ground shaking is usually strongest near the earthquake epicenter and decreases away from that point. However, foundation conditions (type of soil or rock) and the type and quality of construction play large roles in determining the extent of ground shaking damage (Hays and King, 1982; Wong et al., 2002).

Ground shaking in the Bryce Canyon study area could result from an earthquake generated by movement on a mapped fault, or from an earthquake on a concealed fault. Most earthquakes on the Colorado Plateau cannot be attributed to movement on known faults (Wong and Humphrey, 1989; Wong et al., 1996). Although the maximum magnitude of these "background earthquakes" could theoretically approach M 6.5 (the lower limit of surface-fault rupture on the Colorado Plateau), historical earthquakes in in the Bryce Canyon region have been much smaller (Figure 1). However, the Sevier fault (Lund et al., 2008a; Knudsen et al., 2021) and Paunsaugunt fault (this study, see Surface-Fault Rupture section) have produced large, surface-rupturing earthquakes during the Quaternary (past 2.6 million years) and are considered seismically active. Between 1962—when the first regional seismic network was installed to record earthquakes in Utah—and 2016, only about a dozen earthquakes have been recorded within the Bryce Canyon study area (Figure 1) (University of Utah Seismograph Stations [UUSS], 2022a), the largest being a M 3.2 tremor recorded in 1999. All remaining earthquakes recorded in the study area were < M 2.0. Just west of the study area near Blubber Creek, a pronounced swarm of about 150 minor (< M 3.3) earthquakes (Figure 1) was recorded over the past two decades, peaking at about 50 earthquakes in 2008. Only three earthquakes in the M 4.0–4.1 range have been reported in the greater Bryce Canyon region (Figure 1) and they caused little to no damage (Murphy and Cloud, 1984, p. 10; Associated Press, 2015; UUSS, 2022b). Precariously balanced landforms (balanced rocks, hoodoos, spires, etc.) have been used in the southwestern U.S. to constrain the time elapsed since the occurrence of an earthquake strong enough to topple such landforms (e.g., Brune, 1993, 1994; Brune and Whitney, 2000; Haddad and Arrowsmith, 2011). BCNP's abundant hoodoos indicate that considerable time has elapsed since the area has experienced a strong earthquake. However, any earthquake-timing data gleaned from BCNP's hoodoos may be limited due to their short life expectancy caused by rapid cliff-retreat rates of about 2 feet (~0.6 m) per century in the Pink Cliffs (Lindquist, 1980).

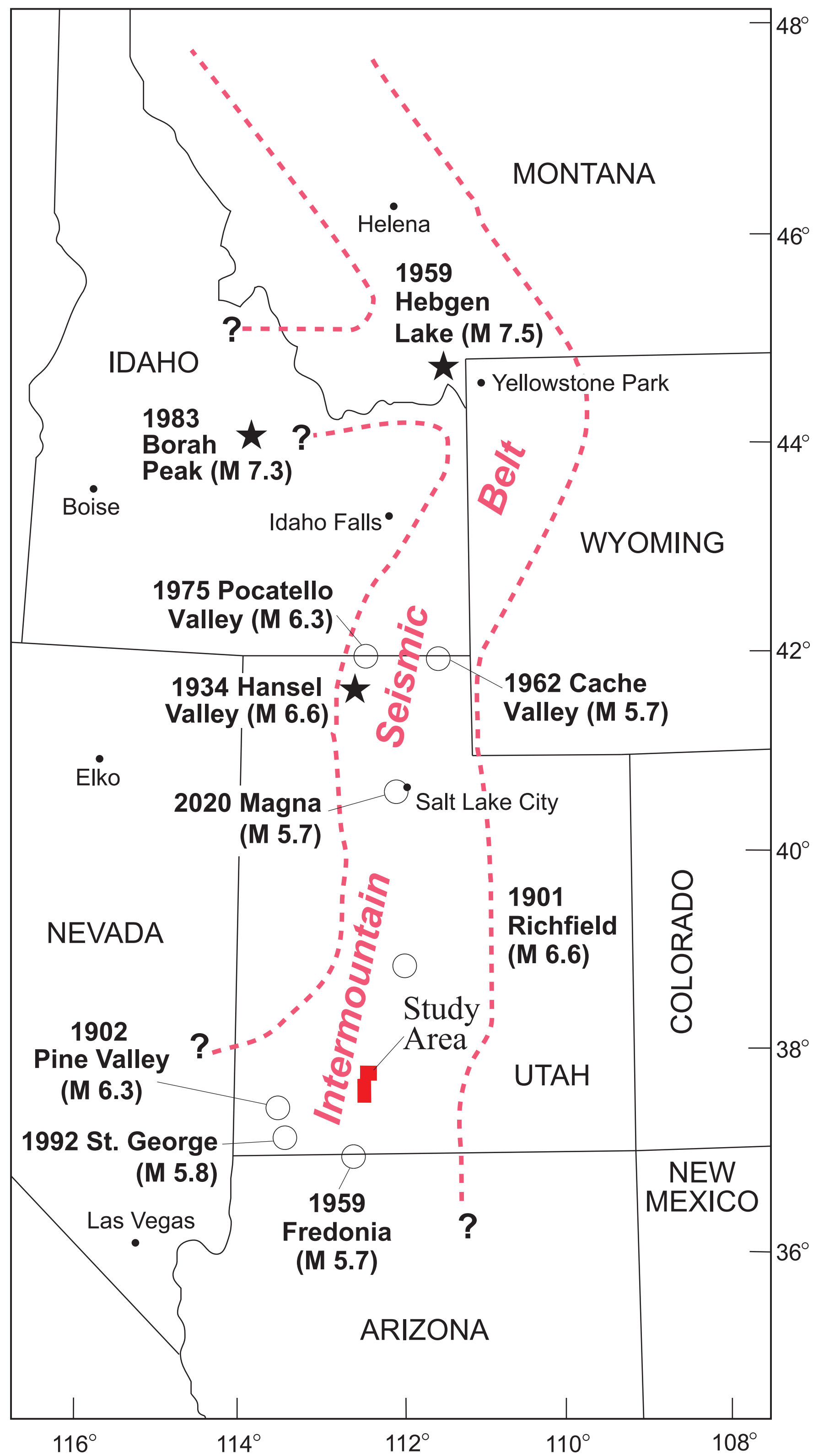

Figure 6. *The Intermountain Seismic Belt and major historical ISB earthquakes. Stars indicate surface-faulting earthquakes; modified from Arabasz et al. (1992).*

Insufficient geotechnical data exist to prepare an earthquake site conditions map for the Bryce Canyon study area. However, risk to public safety due to earthquake ground shaking can be reduced by incorporating building-code-based earthquake-resistant construction requirements in new construction and when retrofitting existing structures. In Utah, earthquake-resistant design requirements are specified in the seismic provisions of the 2021 International Building Code (IBC; International Code Council [ICC], 2020a), which are adopted statewide. Additional information on earthquake preparedness and safety is found in the Utah Seismic Safety Commission (2022) handbook for earthquakes in Utah, *Putting Down Roots in Earthquake Country*, which is available online at https://ugspub.nr.utah.gov/publications/non_lib_pubs/putting-down-roots.pdf.

Rockfall

Rockfall is a natural mass-wasting process that involves the dislodging and downslope movement of individual rocks and rock masses (Varnes, 1978; Cruden and Varnes, 1996; Loew et al., 2022). Rockfalls pose a threat because falling or rolling boulders can damage property and cause injury or loss of life (Smith and Petley, 2009). At least 20 deaths directly attributable to rockfalls have occurred in Utah since 1850 (Bowman and Lund, 2020). Rockfall hazard exists where a source of rock is present above slopes steep enough to allow rapid downslope movement of dislodged rocks by falling, rolling, and bouncing. Most rockfalls originate on slopes steeper than 35° (Wieczorek et al., 1985; Keefer, 1993), although rockfall hazards may be found on less-steep slopes.

Rockfall hazard is based on several factors including geology, topography, and climate. Rockfall sources include bedrock outcrops or boulders on steep mountainsides or steep escarpments such as bluffs, cliffs, and terraces. Rockfall frequency typically rises with increasing fracture density of the source area (Loew et al., 2022). Talus cones and scree-covered slopes are indicators of a high rockfall hazard, although other areas are also vulnerable. Rockfalls may be initiated by freeze-thaw conditions, rainfall, weathering and erosion of the rock or surrounding material, root growth, and thermal expansion (e.g., Collins and Stock, 2016), though in many cases, a specific triggering mechanism is not apparent. Rockfalls may also be initiated by ground shaking. Keefer (1984) indicated that earthquakes as small as magnitude 4.0 can trigger rockfalls. In Utah, the 1988 M 5.2 San Rafael Swell earthquake triggered multiple rockfalls (Figure 7) (Case, 1988), and the 1992 M 5.8 St. George earthquake caused numerous rockfalls in Washington County (Black et al., 1995).

Slope modifications, such as cuts for roads, trails, and building pads, or clearing of slope vegetation for development, can increase or create a local rockfall hazard. Although not well documented, rockfalls in Utah generally occur more frequently during spring and summer months, likely due to spring snowmelt, summer thunderstorms, and large daily temperature variations (Case, 2000; Castleton, 2009). Along the Bryce Amphitheater,

Figure 7. *Dust clouds from numerous rockfalls triggered by the 1988 M 5.2 San Rafael Swell earthquake in central Utah. The Bryce Canyon area has similar canyon and mesa topography and can expect similar rockfall activity during moderate to strong earthquakes (> M 4.5). Photo courtesy of Terry Humphrey, Bureau of Land Management.*

rockfalls appear to occur most frequently during periods of rapid snowmelt or heavy precipitation (Bilderback, 2015).

Determining the severity of rockfall hazard requires evaluating the characteristics of three hazard components (Figure 8): (1) a rockfall source, in general defined by bedrock 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 momentum as they travel downslope—this zone often includes a talus slope, which becomes less apparent with decreasing relative hazard, and (3) a runout zone or rockfall shadow, which includes gentler slopes where boulders roll or bounce before coming to rest beyond the base of the slope (Evans and Hungr, 1993; Wieczorek et al., 1998). Where appropriate, I used shadow angles (the angle formed between a horizontal line and a line extending from the base of the rock source to the outer limit of the runout zone [Evans and Hungr, 1993; Wieczorek et al., 1998]) to establish the boundaries of areas subject to rockfall hazard in the study area (Figure 8). Shadow angles vary based on rock type, boulder shape, slope steepness, slope roughness, and rock source height. Shadow angles measured for dozens of representative rockfall boulders in the study area showed that a shadow angle of 22° is generally applicable in the study area and defines a hazard zone sufficiently wide to include the limits of rockfall debris that accumulates at the base of cliffs and steep slopes.

The geology of the Bryce Canyon study area is conducive to widespread rockfall hazard. Rockfalls in the study area are particularly prevalent in the following two scenarios: (1) along much of the Pink Cliffs where headward erosion of the Paria River and its tributaries have carved steep-walled and hoodoo-filled amphitheaters into the Claron Formation, and (2) where resistant bedrock units form ledges above easily eroded bedrock units. Erosion of the softer underlying units and subsequent undercutting of the more resistant bedrock formations trigger many rockfalls. Resistant-over-nonresistant bedrock pairs include the Tibbett Canyon Member of the Straight Cliffs Formation over Tropic Shale, Claron Formation over Wahweap Formation, Claron Formation over Kaiparowits Formation, lower limestone unit of the white member over the pink member of the Claron Formation, and where the Ruby's Inn thrust fault places relatively resistant pink member over easily eroded white member in upper Tropic Canyon (Reed, 2020). The relatively resistant Conglomerate at Boat Mesa that caps Boat Mesa has also produced historical rockfalls (Figure 9). On a smaller scale, ledges within some slope-forming units, such as the upper part of the Straight Cliffs Formation (Smoky Hollow, John Henry, and Drip Tank strata) and the Wahweap Formation can also create a rockfall hazard. Talus deposits blanket steep to moderate slopes throughout much of the study area. These deposits are derived from upslope ledges and cliffs and consist chiefly of accumulations of poorly sorted, coarse, angular rockfall blocks of various sizes. The widespread distribution of talus and the direct relation of talus deposits to the rockfall process attest to the widespread extent of the rockfall hazard in the study area.

Rockfalls pose a significant hazard to BCNP visitors that hike the popular under-the-rim trails (e.g., Greco, 2005; Thornberry-Ehrlich, 2005; Baril et al., 2018, p. 85). Rockfall hazard is particularly acute along the Navajo Loop Trail that traverses the narrow, vertical-walled Wall Street and Two Bridges canyons (Greco, 2005; Harp and Greco, 2010; Bilderback, 2015; Moore, 2015). Rockfalls in Wall Street that required lengthy trail closures for repair occurred in April 1984 and May 2006 (Harp and Greco, 2010) (Figure 10). Since 2010, the NPS

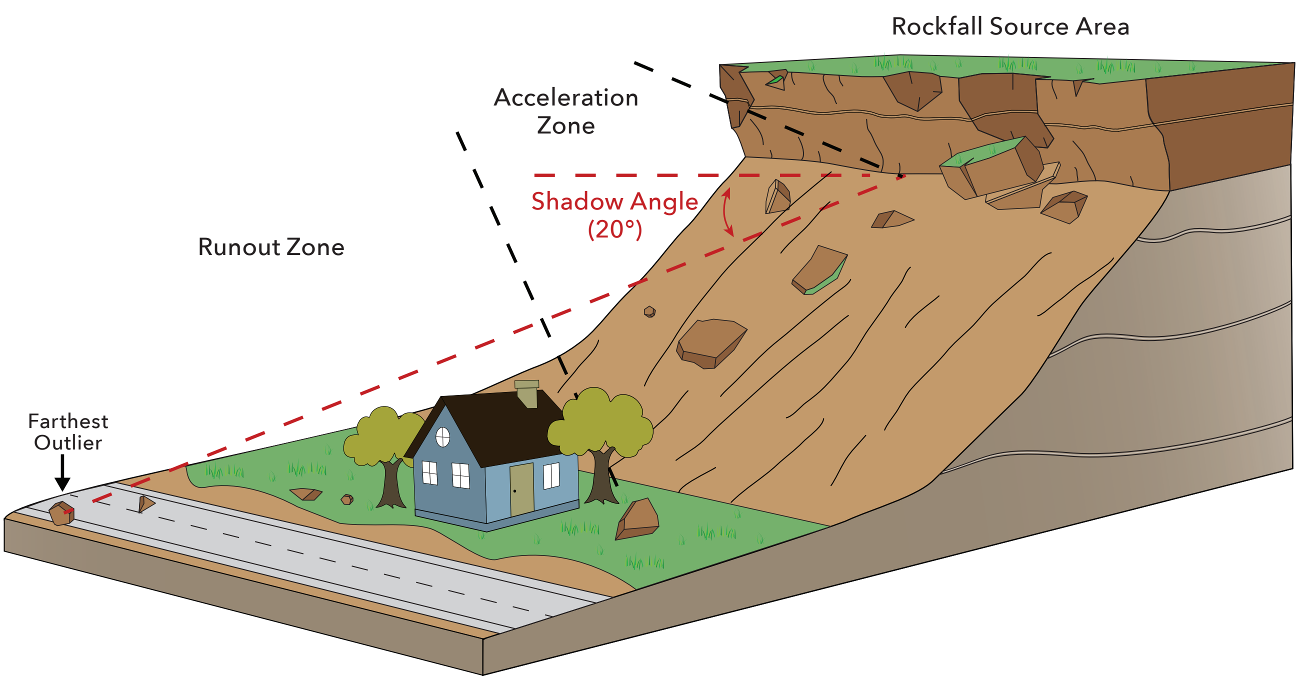

Figure 8. *Components of a characteristic rockfall path profile (modified from Lund et al., 2008b).*

Figure 9. *May 6, 2013, photo taken by a BCNP visitor that witnessed a rockfall near the southeast edge of Boat Mesa. The rockfall, sourced from the capping Conglomerate at Boat Mesa, did not affect any nearby trails or visitors. View is to the northeast. Photo courtesy of the NPS.*

Figure 10. *May 23, 2006, rockfall on the Wall Street section of the Navajo Loop Trail that forced its closure for 14 months. No injuries were reported. Photo courtesy of Kristin Legg (NPS).*

routinely closes Wall Street as a precautionary measure in winter months when precipitation combines with overnight freezing temperatures to produce frequent rockfalls (Gonder, 2010). The NPS also installed signage at the entrances to Wall Street in 2010 that warns visitors of the rockfall hazard. The sharp increase in park visitation over the past decade has further increased the probability of a hazardous rockfall-visitor encounter. Starting in 2016, BCNP began using Preventative Search and Rescue (PSAR) volunteers to alert visitors of the various risks that may be encountered while hiking under-the-rim trails. The UGS encourages the enhancement of the PSAR program and that volunteers explicitly advise visitors to reduce their exposure to rockfall by limiting their time spent in high rockfall-hazard areas, such as Wall Street and Two Bridges canyons. Periodic visual, photographic, and terrestrial lidar surveys (e.g., Kromer et al., 2015; Lefu and Nokwe, 2020) and installation of crack meters (Moore, 2015) along the Navajo Loop Trail can also be deployed by park personnel to help detect subtle slope deformations and incipient signs of failure, which can be used as warning signals to increase visitor safety by implementing trail closures or scaling of unstable rock.

Four main sources of data were used for the rockfall-hazard evaluation in the study area: (1) recent UGS 1:24,000-scale geologic mapping of the Bryce Canyon study area (Knudsen et al., in preparation), (2) interpretation of stereo aerial photographs (air photos) (1993 National Aerial Photography Program [NAPP] and 2011 National Agricultural Imagery Program [NAIP] from the U.S. Geological Survey's [USGS] EarthExplorer [https://earthexplorer.usgs.gov/]) and digital orthophotos (2009, 2016, and 2021 NAIP available from the Utah Geospatial Resource Center [UGRC; https://gis.utah.gov/data/aerial-photography/naip/]), (3) 1-meter bare-earth lidar-derived imagery (UGRC, 2018, 2019) that covers the study area, and (4) field reconnaissance and mapping.

The rockfall-hazard maps (Plates 1A and 1B) show places in the Bryce Canyon study area that are susceptible to rockfall. Rockfall-hazard designations of very high (VH), high (H), moderate (M), or low (L) are based on the following rockfall-source parameters: rock type, orientation, and density of discontinuities (bedding planes, joints, fractures, faults), and presence of overhanging rock masses. Slope characteristics evaluated below rockfall sources include slope angle, a shadow angle of 22°, vegetation, clast distribution, clast size range, and weathering of rockfall boulders. Plate 1B shows detailed (1:10,000 scale) rockfall hazard of BCNP's high-use areas, including the under-the-rim trails. Where no hazard is mapped, rockfall hazard is either absent or too localized to show at the map scale. Table 1 summarizes the UGS's recommended requirements for site-specific geotechnical/geologic-hazard investigations related to rockfall hazards to protect life and safety. Additionally, *Guidelines for Evaluating Rockfall Hazards in Utah* (Lund and Knudsen, 2020), recommends minimum standards for performing rockfall-hazard investigations in Utah.

Landslides

Rock and soil units susceptible to landsliding are widespread in parts of the Bryce Canyon study area. *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 et al., 2011). Landslide material typically moves as a coherent or semi-coherent mass with little internal deformation, and movement occurs on either a curved (rotational slide) or planar (translational slide) rupture surface (Highland and Bobrowsky, 2008). Occasionally, individual landslides may involve multiple types of movement if conditions change as the displaced material moves downslope. For example, a landslide may initiate as a rotational slide and then become a translational slide as it progresses downslope. The moisture content of the affected materials when a slope fails can range from dry to saturated. High moisture content reduces the strength of most deposits susceptible to landslides and is often a contributing factor to slope failures. Figure 11 shows the position and terms used for the different parts of a landslide.

Three factors acting 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, adding water to a slope, transitory stresses from earthquakes and explosions, and 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 (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 slope materials.

Although one or more of the above causes may make a rock or soil mass susceptible to landsliding, a trigger is required for landsliding to occur (Varnes, 1978; Cruden and Varnes, 1996). A trigger is an external stimulus or event that initiates landsliding either by increasing stresses or reducing the strength of slope materials (Wieczorek, 1996). Landslide triggers may be static or dynamic. Static conditions include intense rainfall or prolonged periods of above-normal precipitation, rapid snowmelt, added water from irrigation or septic systems, 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 (McColl, 2022). For example, a nearly imperceptible combination of weathering and gradual erosional undercutting can eventually cause landsliding.

The landslide susceptibility evaluation for this study used four main sources of data: (1) recent UGS 1:24,000-scale

Table 1. *Recommended requirements for site-specific rockfall-hazard investigations for modified IBC risk category of buildings and other structures (modified from ICC [2020a] and 2021 IBC table 1604.5).*

Mapped Hazard Potential	IBC Risk Category[1]				
	I	II(a)	II(b)	III	IV
	Buildings and other structures that represent a low hazard to human life in the event of failure	Single family dwellings, apartment complexes and condominiums (<10 dwelling units), and campgrounds	Buildings and other structures except those listed in I, II(a), III, and IV	Buildings and other structures that represent a substantial hazard to human lives in the event of failure	Buildings and other structures designated as essential facilities
Very High, High, Moderate	No[2]	Yes	Yes	Yes	Yes
Low	No[2]	Yes	Yes	Yes	Yes
None	No	No	No	No[3]	No[3]

[1] See ICC (2020a) chapter 3, Occupancy Classification and Use and chapter 16, Structural Design, table 1604.5 for a complete list of structures/facilities included in each IBC Risk Category. Check table 1604.5 if a question exists regarding which Risk Category a structure falls under. For purposes of these recommendations, Risk Category II has been divided into subcategories II(a) and II(b) to reflect the lower hazard associated with single family dwellings, apartment complexes and condominiums with <10 dwelling units, and campgrounds.

Risk Category I—includes but not limited to agricultural facilities, certain temporary facilities, and minor storage facilities;

Risk Category II(a)—single family dwellings, apartment complexes, condominiums (<10 dwelling units), and campgrounds;

Risk Category II(b)—buildings and other structures except those listed in Risk Categories I, II(a), III, and IV; includes, but not limited to:

a. many business, factory/industrial, and mercantile facilities;
b. public assembly facilities with an occupant load < 300 (e.g., theaters, concert halls, banquet halls, restaurants, community halls);
c. adult education facilities such as colleges and universities with an occupant load < 500;
d. other residential facilities (e.g., boarding houses, hotels, motels, care facilities, dormitories with >10 dwelling units).

Risk Category III—includes, but not limited to:

a. public assembly facilities with an occupant load > 300, schools (elementary, secondary, day care);
b. adult education facilities such as colleges and universities with an occupant load > 500;
c. Group I-2 occupancies (medical facilities without surgery or emergency treatment facilities) with an occupant load > 50;
d. Group I-3 occupancies (detention facilities, for example: jails, prisons, reformatories) with an occupant load > 5;
e. any other occupancy with an occupant load > 5000;
f. power-generating stations, water treatment plants, wastewater treatment facilities, and other public utility functions not included in risk category IV;
g. buildings and other structures not included in risk category IV that contain quantities of toxic or explosive materials.

Risk Category IV—includes, but not limited to:

a. Group I-2 occupancies having surgery or emergency treatment facilities;
b. fire, rescue, ambulance, and police stations, and emergency vehicle garages;
c. designated emergency shelters; emergency preparedness, communication, and operations centers and other facilities required for emergency response;
d. power-generating stations and other public utility facilities required as emergency backup facilities for Risk Category IV structures;
e. buildings and other structures containing quantities of highly toxic materials;
f. aviation control towers, air traffic control centers, and emergency aircraft hangars;
g. buildings and other structures having critical national defense functions;
h. water storage facilities and pump structures required to maintain water pressure for fire suppression.

[2] Property damage possible, but little threat to life safety.

[3] Investigations are recommended if IBC Risk Category III and IV facilities are adjacent to areas where bedrock crops out on steep slopes, even if not near a mapped rockfall-hazard area, to ensure that a previously unknown rockfall hazard is not present. If a hazard is found, a comprehensive investigation is recommended.

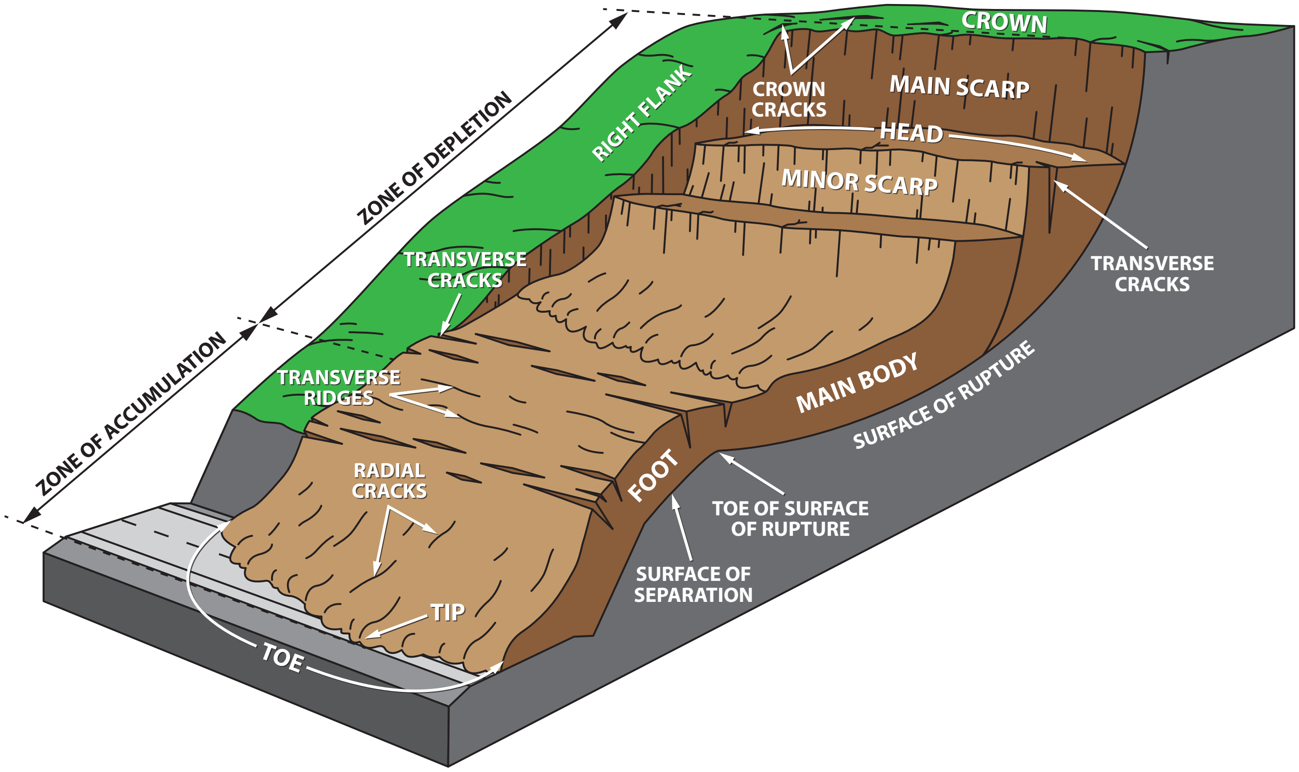

***Figure 11.** Diagram of an idealized landslide showing commonly used landslide morphology nomenclature (modified from Cruden and Varnes, 1996).*

geologic mapping of the Bryce Canyon study area (Knudsen et al., in preparation), (2) interpretation of stereo air photos (1993 NAPP and 2011 NAIP from the USGS's EarthExplorer [https://earthexplorer.usgs.gov/]) and digital orthophotos (2009, 2016, and 2021 NAIP from the UGRC [https://gis.utah.gov/data/aerial-photography/naip/]), (3) 1-meter bare-earth lidar-derived imagery (UGRC, 2018, 2019) that covers the study area, and (4) field reconnaissance and mapping.

Geologic mapping completed for this study (Knudsen et al., in preparation) revealed dozens of previously unrecognized landslides within the Bryce Canyon study area. Landslides are commonly found within clay-rich Cretaceous units exposed within the deeply entrenched canyons carved by the Paria River and its tributaries. The Naturita Formation, Tropic Shale, Smoky Hollow and John Henry Members of the Straight Cliffs Formation, Wahweap Formation, and the Kaiparowits Formation are the most prolific landslide producers in the study area. Most of the landslides formed on Cretaceous strata are in remote areas seldom visited, although a few have either damaged or threaten infrastructure. A periodically active landslide formed on the Wahweap Formation near the head of Tropic Canyon in BCNP has repeatedly damaged State Route (SR) 12. Most recently, landslide damage to SR 12 in 2017 prompted extensive repair and highway reconstruction at a cost of about $3 million (Davidson, 2017). Knudsen et al. (in preparation) mapped a 3.25-acre (13,000 m^2) landslide in the northwest corner of section 2, T. 37 S., R. 3 W. near Tropic formed on the Tropic Shale. This historically active landslide's main scarp is within 50 feet (15 m) of one of Tropic City's water tanks, and its toe is within a few tens of feet of a house and outbuildings (Figure 12). Shallow landslides formed on Tertiary Claron Formation, generally too small to map at 1:24,000-scale, frequently affect the popular under-the-rim trails (Figure 13). These landslides are commonly associated with cuts, fills, and other slope modifications made during trail construction.

Geologic units in the study area are assigned to three broad landslide-susceptibility categories ranging from highly susceptible to least susceptible based on the perceived strength characteristics, relative percentage of strong versus weak lithologies in each unit, and the general abundance of mapped landslides present in each unit in southern Utah. Bedrock units consisting chiefly of weak rock types (claystone, mudstone, siltstone, and gypsum) are more susceptible to slope instability than rock units consisting of stronger rock types (sandstone, conglomerate, limestone). Table 2 summarizes the susceptibility categories.

Table 2 also shows average ground-surface slope angles measured for representative landslides in each of the susceptibility categories. Considering the broad scale of this study and the intended use of the maps as land-use planning tools, the lowest measured landslide slope angle for each susceptibility category was used as the critical slope angle for that category. The critical slope angle is the minimum slope above which landsliding typically occurs in a particular

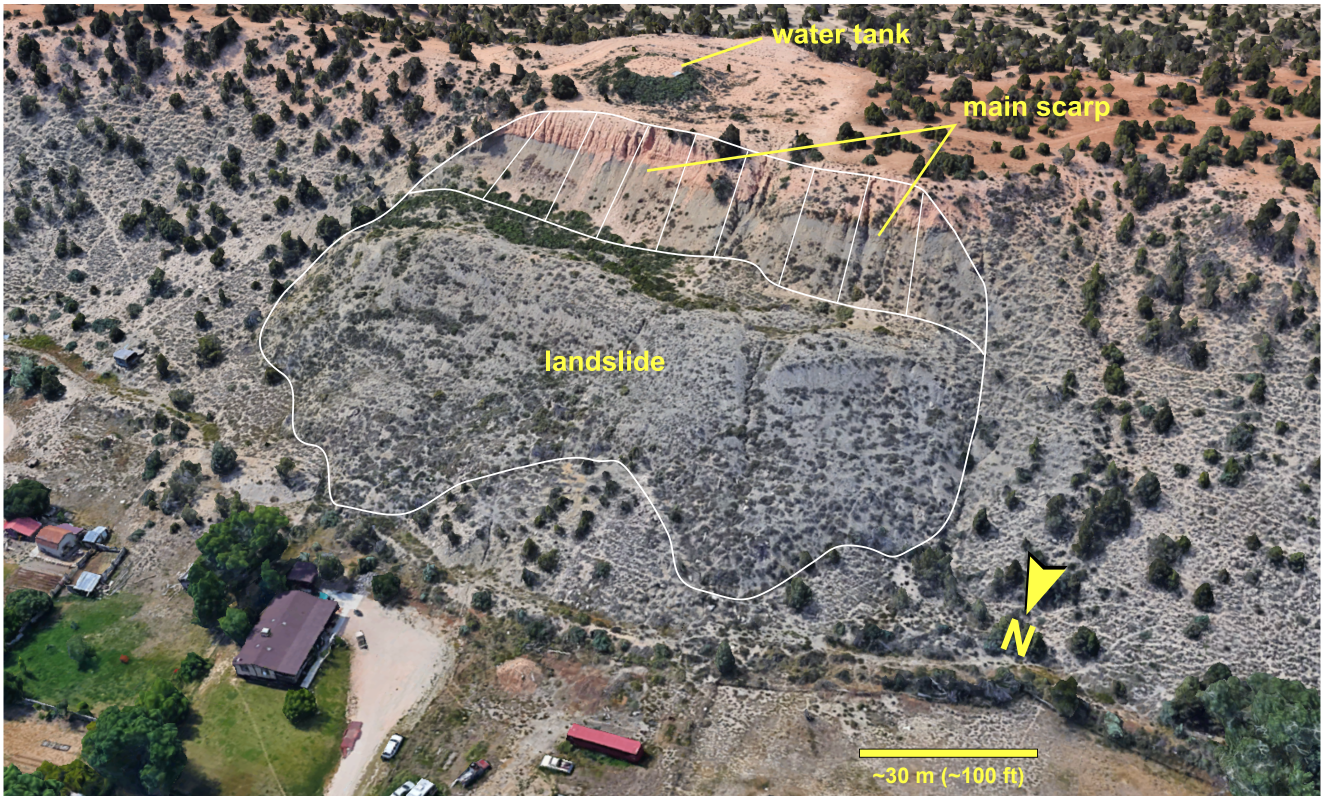

Figure 12. Oblique, southeast-directed Google Earth image of a landslide formed in gray clay-rich Tropic Shale near structures in Tropic. Orange deposit capping mesa and exposed in upper part of the main scarp is older (Pleistocene) pediment alluvium.

Figure 13. Damage to the Navajo Loop Trail due to shallow landsliding in the Claron Formation. Such shallow landslides are commonly associated with modifications made to the natural slope during trail construction. Photo taken April 3, 2020.

susceptibility category (Hylland and Lowe, 1997; Giraud and Shaw, 2007). To characterize landslide hazard in the Bryce Canyon study area, I used the three landslide-susceptibility categories combined with the critical slope angles determined for each category. Since existing landslides are the most likely units to initiate new landslides (Ashland, 2003), I assigned all mapped landslides to the highest hazard category (H) regardless of slope. In addition to mapped landslides, the high landslide-hazard category includes highly landslide-prone geologic units that crop out on slopes at or above a critical angle of 8° (Table 2). Moderate landslide hazard (M) includes moderately landslide-prone units that crop out on slopes at or above a critical angle of 15°, and highly landslide-prone geologic units that crop out on slopes less than 8°. Low landslide hazard (L) includes geologic units of low landslide-prone susceptibility that crop out on slopes at or above a critical angle of 20°, and moderately landslide-prone geologic units that crop out on slopes less than 15°.

The landslide-hazard map (Plate 2) shows areas of relative landslide susceptibility where site-specific slope-stability conditions (material strength, orientation of discontinuities, groundwater conditions, and erosion or undercutting) should be evaluated prior to development. The UGS recommends that a landslide-hazard investigation be made for all new buildings for human occupancy and for modified IBC Risk Category II(a), II(b), III, and IV facilities (Table 1604.5 [ICC, 2020a]) that are proposed on slopes or in mapped landslide-hazard areas (Beukelman and Hylland, 2020). The level of investigation needed at a given site depends on the relative hazard and the nature of the proposed development. Recommendations for site-specific investigations in each landslide-hazard category are given in Table 3. The UGS recommends that investigations be conducted for all IBC Risk Category III and IV facilities in slope areas, whether near a mapped landslide-hazard area or not, to ensure that previously unknown landslides are not present (Beukelman and Hylland, 2020). If a hazard is found, the UGS recommends a comprehensive investigation be conducted. In some instances, an investigation may become necessary when existing infrastructure is discovered to be on or adjacent to a landslide.

A landslide-hazard investigation must address all pertinent conditions that could affect, or be affected by, the proposed development, including earthquake ground shaking, perched or irrigation-induced groundwater, and slope modifications. The investigation can only be accomplished through the proper identification and interpretation of site-specific geologic conditions and processes. Chapter 4 of UGS Circular 128, *Guidelines for Evaluating Landslide Hazards in Utah* (Beukelman and Hylland, 2020), 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.

Flood and Debris Flow

Flooding is the overflow of water onto land that is normally dry. Flooding has been the most economically destructive natural hazard in Utah (Utah Department of Public Safety, 2024). Damage from flooding includes inundation of land and structures, erosion, deposition of sediment and debris, and the force of the water itself, which can damage or destroy property

Table 2. *Landslide susceptibility categories and their critical slope angle for landslide-susceptible geologic units in the Bryce Canyon study area.*

Susceptibility Category	Geologic Unit	Critical Slope Angle	Comments
High	Existing landslides[1], Naturita Formation, Tropic Shale, Smoky Hollow and John Henry Members of the Straight Cliffs Formation, Wahweap Formation, Kaiparowits Formation, Pine Hollow Formation	8°	These units contain abundant bentonitic clay, which is expansive and has low shear strength. These unit includes the greatest number of landslides in the study area and surrounding region.
Moderate	Carmel Formation, Entrada Sandstone, Claron Formation, Conglomerate at Boat Mesa, younger unconsolidated surficial units	15°	These units contain varying amounts of gypsum, shale, claystone, mudstone, siltstone, or a combination of these rock types that imparts weak shear strength to the units, at least locally, and makes them susceptible to landsliding. These units contain the second greatest number of landslides in the study area and surrounding region.
Low	Remaining bedrock units, and older partially consolidated surficial units exclusive of the Navajo Sandstone[2]	20°	These geologic units either contain a higher percentage of stronger rock types, crop out on slopes too gentle to generate landslides, or generate failures that are too small to map at 1:24,000 scale. As a result, they exhibit few or no mapped landslides.

[1]Existing landslides are not slope dependent.

[2]Mass wasting in the Navajo Sandstone is limited to rockfalls and therefore, mass-wasting hazards associated with Navajo Sandstone are discussed in the Rockfall Hazard section of this study.

Table 3. *Recommendations for site-specific landslide-hazard investigations for all new buildings for human occupancy and for modified IBC Risk Category II(a), II(b), III, and IV facilities (see Table 1).*

Landslide-Hazard Category	Recommended Site-Specific Study
High	Detailed engineering geologic and geotechnical-engineering investigation necessary.
Moderate	Geologic evaluation necessary; detailed engineering geologic and geotechnical-engineering investigation may be necessary.
Low	Geologic evaluation necessary; detailed geotechnical-engineering investigation generally not necessary.
None	None for modified IBC Risk Category II(a) and II(b) facilities. Geologic evaluation recommended for Risk Category III and IV facilities near slopes even if not mapped as a landslide-hazard area, to ensure previously unknown landslides are not present. If a hazard is found, a comprehensive investigation is recommended.

and take lives (Stauffer, 1992; Utah Division of Homeland Security, 2008). Historical accounts of damaging floods affecting BCNP and communities in the study area date back to the mid-nineteenth century (e.g., Woolley, 1946; Butler and Marsell, 1972; Utah Division of Comprehensive Emergency Management, 1981) and provide ample evidence for the destructive power and life-threatening nature of flooding in the study area.

The Bryce Canyon study area's high flood hazard results from the complex interaction of the area's rugged topography and seasonal weather patterns typical of the Southwest. Two principal types of floods occur in the study area: riverine (stream) floods and flash floods. Riverine flooding along major drainages in southwestern Utah is usually regional in nature, lasts for several hours or days, commonly takes place on perennial streams, and typically can be predicted days to weeks in advance. Riverine floods usually result from rapid melting of the winter snowpack or from prolonged heavy rainfall. Flash floods are sudden, intense, localized events that occur in response to heavy rainfall that often accompanies convective, monsoonal thunderstorms. Because thunderstorms result from strong convective cells produced by differential atmospheric heating, flash floods typically occur in summer and early fall in southern Utah. Flash floods in the Bryce Canyon study area can affect both perennial and ephemeral drainages and alluvial fans.

Wildfires significantly increase the risk from flooding because of a decrease in the ability of water to infiltrate soil, and an increase in runoff and erosion in burn areas (Neary et al., 2005). Human activities, such as placing structures and constrictions in floodplains, on active alluvial fans, or in erosion-hazard zones; developing without adequate flood and erosion control; poor watershed management practices (overgrazing, poorly managed off-road vehicle traffic); and unintentional release of water from engineered water-retention or conveyance structures (such as a dam or canal) also increase the potential for flooding.

The Bryce Canyon study area is drained by two major drainage basins: the Paria River and the East Fork Sevier River (Figure 2). The Paria River and its larger tributary drainages, including Henderson Creek, North Creek, Tropic Canyon, Campbell Creek, Bryce Creek, Yellow Creek, Sheep Creek, Willis Creek, Bull Valley, Bull Rush, Lower Podunk Creek, and Meadow Canyon drain relatively large areas (> 5 mi^2 [> 13 km^2]) of the Paria Amphitheatre and Pink Cliffs, and are highly prone to significant riverine flooding. Except for Henderson Creek, which heads at an elevation near 10,000 feet on the Table Cliff Plateau (Figure 1), the Paria River and its tributaries have relatively low mean elevations in the study area and consequently contain smaller snowpacks. Therefore, flash floods due to intense thunderstorms or prolonged precipitation events are more likely to cause flooding along those drainages than springtime snowmelt. The East Fork Sevier River and its larger tributaries including Showalter Creek, Pat Willis Draw, Mud Spring Creek, Bluefly Creek, East Creek, and Badger Creek drain large areas (> 5 mi^2 [> 13 km^2]) of the central Paunsaugunt Plateau (Figure 2) and are subject to flash floods. The East Fork drainage has a higher mean elevation and correspondingly larger snowpack compared to the Paria River system and is therefore subject to springtime snowmelt floods as well as flash floods. However, the flood hazard along the East Fork Sevier River below Tropic Reservoir has been reduced since the reservoir's completion in 1936.

Remaining drainages in the Bryce Canyon study area are mostly ephemeral, except where springs produce perennial flow. The most intense and unpredictable floods in the study area are thunderstorm-induced flash floods in small- to medium-sized watersheds characterized by ephemeral stream flow and normally dry stream channels. Extremely narrow "slot" canyons are of particular concern during heavy rainstorms due to their lack of escape routes and the limited visibility of hikers to detect approaching storms. Deer Range Canyon and Bull Rush Gorge near the southeast corner of the mapped area are narrow canyons deeply incised into Navajo Sandstone that can be extremely hazardous during intense rainstorms. However, these canyons are infrequently visited compared to the nearby (but just outside the study area) narrow gorges of Willis Creek, Bull Valley Gorge, and Lick Wash. Within BCNP, the Wall Street and Two Bridges slot canyons typically convey hundreds of visitors daily, but because these canyons only drain a 1- to-2-acre (4000–8000 m^2) area, flooding is rarely a concern; rockfalls present a greater hazard to visitors in those canyons during intense thunderstorms. Within the Bryce Amphitheater, flood hazard intensifies downslope where numerous rivulets higher on the amphitheater's headwall converge into larger trunk streams that can carry significant volumes of floodwater. Visitor safety and trail damage are of particular concern where the under-the-rim trails cross or run alongside Bryce Creek and Campbell Creek.

Four main sources of data were used for the evaluation of flood hazard in the study area: (1) Federal Emergency Management Agency (FEMA) Flood Insurance Rate Maps (FIRMs) community panel numbers 4900650675B, 4900650700B, 4900650900B, 4900650925B, 4900710001A, 4900830003B, 4900830004B, and 4900830012B from FEMA's National Flood Hazard Layer (https://msc.fema.gov/nfhl), (2) the distribution of young, water-deposited geologic units shown on recent UGS 1:24,000-scale geologic mapping of the Bryce Canyon study area (Knudsen et al., in preparation), (3) interpretation of stereo air photos (1993 NAPP and 2011 NAIP from the USGS's EarthExplorer [https://earthexplorer.usgs.gov/]) and digital orthophotos (2009, 2016, and 2021 NAIP from the UGRC [https://gis.utah.gov/data/aerial-photography/naip/]), and (4) 1-meter bare-earth lidar-derived imagery (UGRC, 2018, 2019) that covers the study area.

Geologic mapping is critical to determine the distribution of geologically young flood-related deposits, which aid in identification of flood-prone areas and evaluation of their relative susceptibility to flooding and/or debris flows. Because many variables contribute to flood hazard, including but not limited to, precipitation intensity and duration, soil conditions, and topography, geologic units themselves are not absolute indicators of flood-hazard susceptibility, but rather provide a relative indication of hazard. Large parts of the study area undergoing active erosion consist primarily of exposed bedrock and lack mappable alluvial deposits. Flood-hazard evaluation in these areas was based primarily on drainage size, drainage gradient, general permeability of geologic substrate, clay content of geologic substrate (for evaluating debris-flow potential), and evidence of past flooding observed on aerial photography and lidar imagery, or in the field. Young (Holocene) stream, floodplain, and low terrace deposits along perennial streams, and larger (≥ 5 mi^2 [≥ 13 km^2] drainage basin) ephemeral streams are mapped as very high flood hazard (VH) on Plate 3. Stream deposits along smaller ephemeral streams (generally < 5 mi^2 [< 13 km^2] drainage basin), active alluvial-fan deposits, and mixed alluvial/colluvial deposits are mapped as high flood hazard (H). Minor (< 2 mi^2 [< 5 km^2] drainage basin) tributary ephemeral drainages, active pediments and sloping depositional surfaces flanking ridges and other upland areas, and level-2 alluvial fans and terraces (surfaces incised by active drainages) are mapped as moderate hazard (M). Older, inactive pediments and alluvial-fan deposits subject to possible sheetfloods and minor flash floods from adjacent upland areas during cloudburst storms are mapped as low flood hazard (L). Due to topographic complexities and scale limitations, flood hazard could not be mapped for some smaller channels, particularly in complexly eroded slickrock and badland areas. It is important to note that a flash flood can occur in, or issue from any drainage whether depicted or not on the flood- and debris-flow hazard map.

Floodwaters typically contain a large amount of sediment ranging in size from clay to boulders. As the proportion of sediment increases, flash floods transform into debris floods and finally into debris flows. A debris flow moves as a viscous fluid capable of scouring and transporting large boulders, trees, and other heavy debris over long distances. Like flash floods, debris flows are fast moving and under some conditions can exceed 35 miles (56 km) per hour (USGS, 1997). Their high density and speed make debris flows particularly dangerous to life and destructive to property. Debris flows can destroy buildings, roads, and bridges, and are capable of depositing thick layers of mud, rock, and other debris. The volume and frequency of debris flows depend on several factors, including the amount of sediment in a drainage basin that is available for erosion and transport, the magnitude and frequency of storms, the amount of vegetation in the drainage, and soil conditions (Costa and Wieczorek, 1987; Costa, 1988; Coe et al., 2008; Giraud, 2020). Drainage basins that have experienced recent wildfire are generally more susceptible to debris flows (Gartner et al., 2005; Giraud, 2020). Sediment carried by a debris flow can be deposited anywhere on an active alluvial-fan surface. The active fan surface includes those areas where modern deposition, erosion, and alluvial-fan flooding may occur. In general, those parts of the fan surface where sediment has been deposited during the Holocene are considered active (Cohen and Gibbard, 2019), unless proven otherwise. Typically, the upper part of an active alluvial fan has a higher debris-flow hazard due to greater velocities, impact pressures, burial depths, and event frequency (Giraud, 2020). In the Bryce Canyon study area, debris flows occur periodically in the steep-walled, entrenched canyons that drain the eastern escarpment of the Paunsaugunt Plateau. These canyons are incised into easily erodible bedrock units that produce relatively large sediment volumes. Such bedrock units include the Claron Formation, Wahweap Formation, upper Straight Cliffs Formation (particularly the John Henry and Smoky Hollow Members), Tropic Shale, and Naturita Formation.

Site-specific geotechnical/geologic-hazard flood investigations can resolve uncertainties inherent in the generalized flood- and debris-flow hazard map and help ensure safety by identifying the local flood and debris-flow hazard. The UGS recommends that a debris-flow-hazard investigation be made for all new buildings for human occupancy and for modified IBC Risk Category II(a), II(b), III, and IV facilities (see Table 1, modified from IBC Table 1604.5 [ICC, 2020a]) on or adjacent to alluvial fans. Chapter 5 of UGS Circular 128, *Guidelines for the Geologic Investigation of Debris-Flow Hazards on Alluvial Fans in Utah* (Giraud, 2020), recommends minimum standards for performing debris-flow investigations in Utah.

The Federal Emergency Management Agency (FEMA), through its National Flood Insurance Program (NFIP), designates flood zones on its Flood Insurance Rate Maps (FIRMs) and makes federally subsidized flood insurance available to individuals in participating communities. Most FEMA flood zone maps covering the Bryce Canyon study area were produced in the 1980s and have not been updated. Scanned copies of available FIRMs can be downloaded from the FEMA National Flood Hazard Layer (NFHL; https://msc.fema.gov/nfhl). Not all areas of the Bryce Canyon study area have been mapped by FEMA, and FEMA may designate additional flood zones in the future. FIRMs are legal documents that govern the administration of the NFIP. Property owners should consult the appropriate FIRM when considering the purchase of NFIP flood insurance. Flood insurance can also be purchased by landowners outside of mapped FEMA flood zones.

The flood-hazard-potential categories shown on Plate 3 are approximate and mapped boundaries are gradational. Localized areas of higher or lower flood hazard may exist within any given map area, but their identification may be precluded because of the 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.

Shallow Groundwater

Groundwater saturates porous zones in soil and rock at various depths beneath the land surface. Shallow groundwater levels are typically dynamic and fluctuate in response to a variety of conditions: groundwater levels may rise or fall in response to seasonal precipitation, irrigation, the effects of development, and long-term climatic change. 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 et al., 2005, 2006). During moderate to large earthquakes, groundwater within approximately 50 feet (15 m) of the ground surface may 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. Artesian pressure can force groundwater from the principal aquifer upward to the ground surface where it is discharged through springs and seeps. 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. Perched groundwater and seasonally shallow groundwater may locally contribute to development problems in areas that do not have 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 contribute to damage from collapsible and expansive soils.

UGS mapping focuses on groundwater 50 feet (15 m) or less below the ground surface. The shallow groundwater susceptibility map (Plate 4) indicates the potential for shallow groundwater resulting from soil drainage capacity, geology, and hydrology.

The shallow groundwater evaluation for this study used seven sources of data: (1) UGS 1:24,000-scale geologic mapping of the Bryce Canyon study area (Knudsen et al., in preparation), (2) interpretation of stereo air photos (1993 NAPP and 2011 NAIP from the USGS's EarthExplorer [https://earthexplorer.usgs.gov/]) and digital orthophotos (2009, 2016, and 2021 NAIP from the UGRC [https://gis.utah.gov/data/aerial-photography/naip/]), (3) previous groundwater investigations conducted in the study area, including Marine (1963), Carpenter et al. (1967), Thiros and Brothers (1993), Ott (1996), Doremus and Kreamer (1999), and Wallace et al. (2021), (4) water-well drillers' logs on file with the Utah Division of Water Rights (2021), (5) water-level measurements for a limited number of wells by the USGS available through their National Water Information System database (https://maps.waterdata.usgs.gov/mapper/index.html), (6) U.S. Department of Agriculture (USDA) National Resources Conservation Service's (NRCS) *Soil Survey of Panguitch Area, Utah, Parts of Garfield, Iron, Kane, and Piute Counties* (Swenson and Bayer, 1990) and *Soil Survey of Grand Staircase-Escalante National Monument Area, Parts of Kane and Garfield Counties, Utah* (Sutcliffe, 2005), and (7) a limited number of unpublished, site-specific geotechnical reports completed for projects in the Bryce Canyon study area.

The shallow-groundwater-susceptibility map (Plate 4) is based on a geotechnical database that includes geologic units, NRCS soil data, and groundwater-level data obtained from geotechnical/geologic-hazard investigations and water-well logs. 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 (< 1.5 m), and potentially wet soil conditions are defined as poorly drained, fine-grained soils that may develop shallow groundwater locally when rates of water application exceed the soil's drainage capacity. The NRCS and geotechnical data were overlain with the geologic map to determine the shallow groundwater potential of each geologic unit, and the NRCS soil unit boundaries were used to modify the geologic unit where necessary. To account for temporal and seasonal fluctuations in groundwater, the most conservative (shallowest) depth to groundwater is reported in susceptible areas. I used the presence of phreatophytic vegetation (typically cottonwood, willow, or tamarisk with roots extending to the water table) and springs to identify additional areas of potentially shallow groundwater.

Three shallow-groundwater categories are used to identify soil and rock units that are either naturally wet or have the potential to develop wet conditions. Areas with evidence for shallow groundwater at less than 10 feet (< 3 m) below the ground surface are mapped as S1 on the shallow-groundwater-susceptibility map (Plate 4). Areas that have shallow groundwater at depths of 10 to 50 feet (3–15 m) are mapped as S2. Map unit S3 indicates areas where groundwater is likely greater than 50 feet (> 15 m) from the surface but may develop seasonal shallow groundwater after development. The shallow-groundwater categories define the conditions under which shallow groundwater may occur, but the categories do not represent relative severity rankings or actual depth to groundwater.

In the Bryce Canyon study area, shallow groundwater (< 50 feet [< 15 m]) is common in unconsolidated deposits along the East Fork Sevier River, Paria River, and their larger tributaries. Occurrences of shallow groundwater were also found along some predominantly ephemeral streams, notably: Showalter Creek, Shinglemill Swale, Syrett Hollow, East Creek, North Creek, Henderson Creek, Bryce Creek, Yellow Creek, Sheep Creek, Willis Creek, and Lower Podunk Creek (Plate 4).

The shallow-groundwater categories shown on Plate 4 are approximate and mapped boundaries are gradational. Localized areas of higher or lower groundwater may exist within any given map area, but their identification is precluded because of the map scale, relatively sparse data, unidentified areas of perched shallow groundwater, and non-geologic factors such as landscape irrigation and stormwater control.

Surface Fault Rupture

Among the potentially damaging effects of large earthquakes (> M 6.5) is surface fault rupture, which occurs when fault movement at depth propagates upward along the fault to the ground surface. The resulting displacement of the ground surface may produce a zone of ground cracking and warping and can result in one or more fault scarps (Figure 14A). Depending on the magnitude of the earthquake, fault scarps can range from a few inches to several feet high and extend for many miles along the fault trace. Local ground tilting and graben formation (Figure 14B) by secondary faulting (antithetic faults) may accompany surface fault rupture, resulting in a zone of deformation along the fault trace that can be tens to hundreds of feet wide. Surface fault rupture, while of limited areal extent when compared to ground shaking, can have serious consequences for structures or other facilities that lie along or across the rupture path.

The surface-fault-rupture-hazard evaluation for this study used five sources of data: (1) UGS 1:24,000-scale geologic mapping of the Bryce Canyon study area (Knudsen et al., in preparation), (2) interpretation of stereo air photos (1993 NAPP and 2011 NAIP from the USGS's EarthExplorer [https://earthexplorer.usgs.gov/]) and digital orthophotos (2009, 2016, and 2021 NAIP from the UGRC [https://gis.utah.gov/data/aerial-photography/naip/]), (3) 1-meter bare-earth lidar-derived imagery (UGRC, 2018, 2019) that covers the study area, and (4) *Guidelines for Evaluating Surface-Fault-Rupture Hazards in Utah* (Lund et al., 2020a).

In California, the Alquist-Priolo Earthquake Fault Zoning Act (Bryant and Hart, 2007), regulates development along known active faults, and defines an "active" fault as one that has had "surface displacement within Holocene time (about the past 11,700 years)." Because California has a well-recognized earthquake hazard and was the first state to implement regulations designed to mitigate those hazards, the California "Holocene" standard has found its way into many regulations in other parts of the country, even in areas where the Holocene is not the best time frame against which to measure surface-faulting recurrence. DePolo and Slemmons (1998) argued that in the Basin and Range Province, a period longer than the Holocene is more appropriate for defining active faults, because most faults there have surface-faulting recurrence intervals (average repeat times) that approach or exceed 10,000 years. They advocated a Late Pleistocene age criterion, specifically 130,000 years, to define active faults in the Basin and Range Province. They based their recommendation on the observation that 6 to 8 (> 50%) of the 11 historical surface-faulting earthquakes in the Basin and Range were on faults that lacked evidence of Holocene activity but had evidence of Late Pleistocene activity.

Because of the difficulties in using a single "active" fault definition, the Western States Seismic Policy Council (WSSPC) has defined the following fault activity classes (WSSPC Policy Recommendation 21-3, 2021; first adopted in 1997 as WSSPC Policy Recommendation 97-1, and revised and readopted in 2005, 2008, 2011, 2018, and 2021 [WSSPC, 2021]). The UGS recommends following the WSSPC (2021) definitions of activity class:

Latest Pleistocene-Holocene fault – a fault whose movement in the past 15,000 years before present has been large enough to break the ground surface.

Late Quaternary fault – a fault whose movement in the past 130,000 years before present has been large enough to break the ground surface.

Quaternary fault – a fault whose movement in the past 2.6 million years before present has been large enough to break the ground surface.

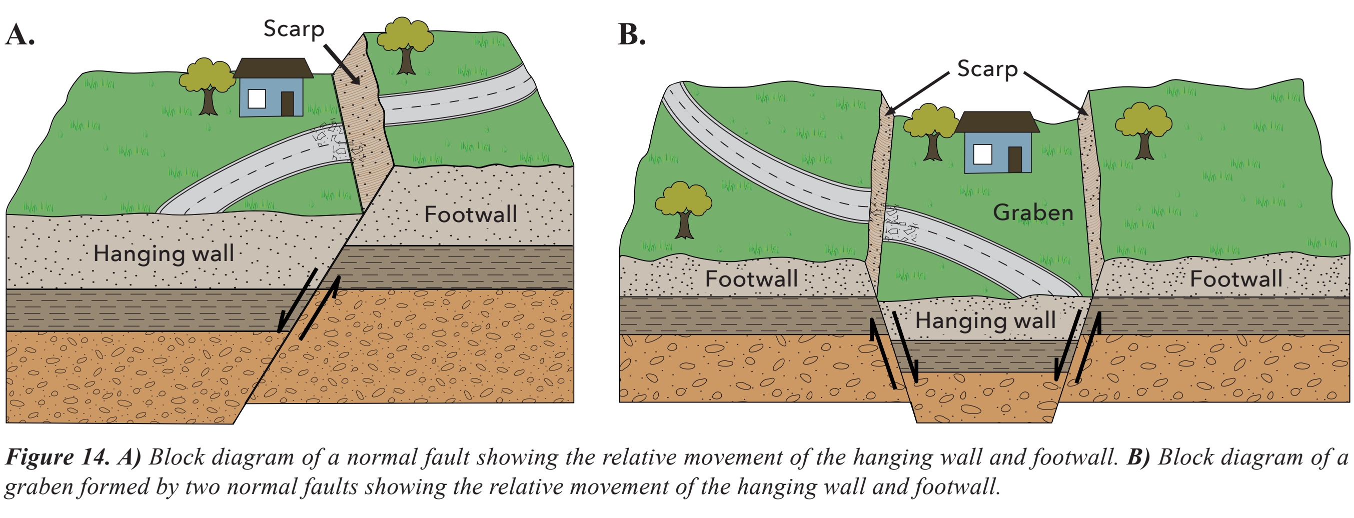

***Figure 14. A)** Block diagram of a normal fault showing the relative movement of the hanging wall and footwall. **B)** Block diagram of a graben formed by two normal faults showing the relative movement of the hanging wall and footwall.*

The last two classes are inclusive: Holocene faults are included within the definition of Late Quaternary faults, and both Holocene and Late Quaternary faults are included in Quaternary faults. The UGS recommends that in the absence of information to the contrary, all Quaternary faults be considered Holocene unless there are adequate data to confidently assign them to the Late Quaternary or Quaternary activity classes (Lund et al., 2020a).

Based on recent UGS geologic mapping (Knudsen et al, in preparation), normal faults in the study area are categorized as well defined, concealed, or approximately located. Based on Lund et al. (2020a), surface-fault-rupture-hazard study areas are established for each fault category. A fault is considered well defined if its trace is clearly detectable by a trained geologist as a physical feature at the ground surface (Bryant and Hart, 2007). Normal-slip faults in the study area are classified as well defined if UGS 1:24,000-scale mapping shows them as solid lines, indicating that they are recognizable as faults at the ground surface. Although not well expressed at the surface, buried, or approximately located Quaternary faults still may represent a significant surface-fault-rupture hazard and should be evaluated prior to development.

The surface-fault-rupture hazard map (Plate 5) shows potentially active faults in the Bryce Canyon study area along which surface faulting may occur. A special-study area is shown around each fault, within which the UGS recommends performing a site-specific surface-fault-rupture-hazard investigation prior to development. The special-study areas established for well-defined faults extend 500 feet (152 m) on the downthrown side of the fault and 250 feet (76 m) on the upthrown side of the fault. Given their uncertain location, the special-study areas around buried or approximately located faults are broader, extending 1000 feet (305 m) from either side of the suspected fault. Lund et al. (2020a) provide recommendations for investigating and reporting surface-fault-rupture hazards, and procedures for establishing safe setback distances from active faults in Utah.

The Paunsaugunt fault is the largest fault in the study area (both in terms of vertical displacement and length) and has experienced the most recent surface rupture. Currently, most of the Paunsaugunt fault in Utah, including all fault sections in the study area, is not included in the UGS database of Quaternary-active, potentially hazardous faults (UGS, 2022). However, mapping completed for this study shows that Quaternary-age deposits are locally displaced by the Paunsaugunt fault in the Bryce Canyon area, and that the fault should be considered hazardous. In addition to scarps mapped or mentioned by Bowers (1991) at Bulldog Hollow and Papoose Bench, additional scarps were discovered during geologic mapping completed for this study (Knudsen et al., in preparation; Plate 5). The Bulldog Hollow scarp is within BCNP in the NE ¼ of section 8, T. 37 S., R. 3 W., at the head of Bulldog Hollow (Plate 5). The approximately 12-foot-high (~4 m) and 360-foot-long (110 m) scarp is formed on old pediment alluvium (geologic map unit Qapo) broadly estimated to be Pleistocene in age by Knudsen et al. (in preparation). The Papoose Bench scarp is formed on Pleistocene pediment alluvium (Qapo1) at the west end of Papoose Bench between Promontory Creek and Papoose Creek in sections 26 and 35, T. 38 S., R. 4 W. (Plate 5). The highly eroded and subdued scarp is less than 5 feet (< 1.5 m) high and is about 750 feet (~230 m) long. The newly discovered Sheep Creek Flat scarp at the west end of Sheep Creek Flat (Figure 15; Plate 5) is the most continuous Paunsaugunt fault scarp formed on unconsolidated deposits in the Bryce Canyon study area. The scarp is formed on Pleistocene pediment alluvium (Qapo) and is as much as 6 feet (2 m) high and is 0.8 mile (1.3 km) long. The remaining Paunsaugunt fault scarps discovered in the study area may be bedrock cored (a bedrock fault-line scarp draped by a thin and unbroken mantle of surficial deposits) and would require additional investigation to determine if unconsolidated Quaternary deposits are displaced by the fault. The Shakespear Point scarp is 0.25 mile (0.4 km) southeast of Shakespear Point (Plate 5) and is formed on old colluvium (Qco) estimated by Knudsen et al. (in preparation) to be Late Pleistocene in age. The poorly preserved scarp faces uphill and is less than 5 feet (< 1.5 m) high and is about 300 feet (~90 m) long. The scarp continues southward an additional 150 feet (45 m) in bedrock. The Henderson Point scarp is 0.5 mile (0.8 km) north of Henderson Point in the NE ¼ of section 35, T. 35 S., R. 3 W., and is formed on middle to late Pleistocene alluvial-fan deposits (Qafo of Knudsen et al. [in preparation]). The scarp is highly eroded, probably less than 15 feet (< 5 m) high and is about 600 feet (~180 m) long.

Subdued scarp morphologies and a lack of displaced Holocene deposits along the Paunsaugunt fault indicate that the recurrence interval between surface-faulting earthquakes is likely long (> 10,000 years), providing ample time for scarp erosion and the development of an obsequent (inverted) scarp along much of the fault (see Geology section above). With relatively little infrastructure along the trace of the Paunsaugunt fault in the study area, seismically induced rockfalls and landslides would likely have a larger impact on human safety and infrastructure than would surface fault rupture, during a surface-faulting earthquake. However, SR-12 and adjacent buried utilities could be damaged by a surface-faulting earthquake where they cross the Paunsaugunt fault in Tropic Canyon. A Paunsaugunt fault surface rupture may also alter flows or damage water collection infrastructure at fault-controlled springs near the mouth of Bryce Creek Canyon that are critical to Tropic's water supply.

The 1.6-mile-long (2.6 km), near-vertical Fairyland fault is buried by unbroken Middle Eocene Conglomerate at Boat Mesa strata (Bowers, 1991; Biek et al., 2015; Knudsen et al., in preparation) indicating that the fault has not moved since Middle Eocene time (about 40 million years ago) and is therefore not included on the surface-fault-rupture hazard

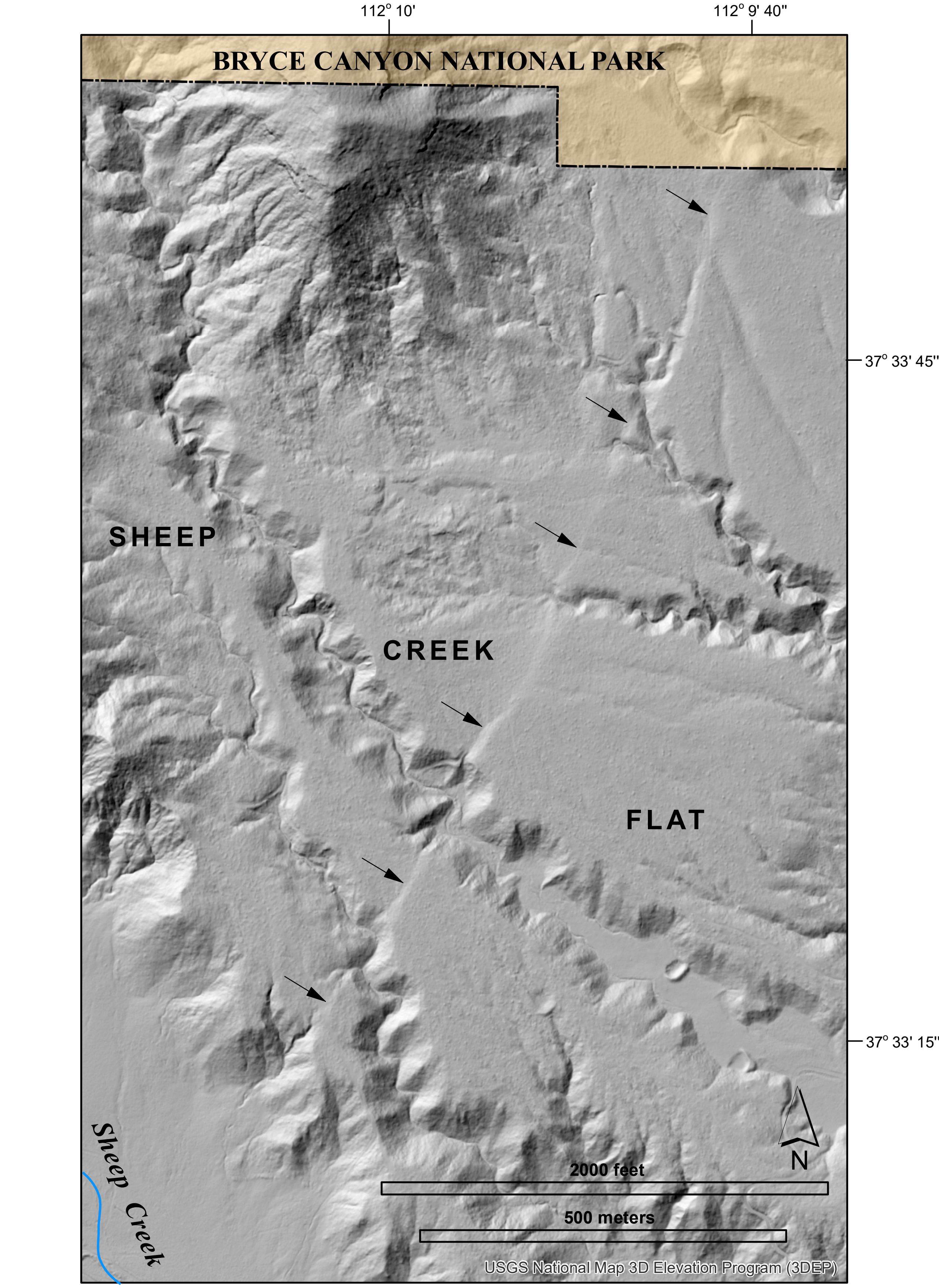

Figure 15. *WNW-facing Paunsaugunt fault scarp (arrows) formed on Pleistocene pediment alluvium at Sheep Creek Flat. Lidar-derived image produced from the USGS 3D Elevation Program (3DEP) viewer (https://apps.nationalmap.gov/3depdem/).*

map. Remaining normal faults in the Bryce Canyon study area, including some splays of the Paunsaugunt fault and the Peekaboo fault, lack definitive timing information and are mapped with an "undetermined" age on Plate 5. The UGS recommends treating these faults as Quaternary active until proven otherwise.

Site-specific geotechnical/geologic-hazard investigations can resolve uncertainties inherent in the generalized surface-fault-rupture hazard map and help ensure safety by identifying the need for fault setbacks. The *Guidelines for Evaluating Surface-Fault-Rupture Hazards in Utah* (Lund et al., 2020a; https://ugspub.nr.utah.gov/publications/circular/c-128.pdf) includes a detailed rationale for investigating and reporting surface-fault-rupture hazards, and procedures for establishing safe setback distances from potentially active faults. City and county officials, planners, and consultants should refer to the guidelines for details about conducting and reviewing investigations of surface-fault-rupture hazards. For well-defined faults, investigations should be performed in accordance with the UGS guidelines (Lund et al., 2020a). Concealed and approximately located faults lack a clearly identifiable surface trace, and therefore may not be amenable to trenching, which is the standard hazard evaluation technique used to study well-defined faults (McCalpin, 2009). Where development is proposed in a special-study area for a concealed or approximately located fault, the UGS recommends that at a minimum the following tasks be performed to better define the surface-fault-rupture hazard in those areas:

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

If the results of these investigations reveal evidence of possible surface-faulting-related features, those features should be trenched in accordance with the UGS guidelines (Lund et al., 2020a). In addition, construction excavations and cuts should be carefully examined by a qualified geologist for evidence of faulting as development proceeds.

Liquefaction

Liquefaction and liquefaction-induced ground failures are major causes of earthquake damage (Keller and DeVecchio, 2019). Upon liquefaction, a soil loses its strength and ability to support the weight of overlying structures or sediments. Figure 16 illustrates the four principal types of liquefaction-induced ground failure. Liquefaction typically occurs within approximately 50 feet (15 m) of the ground surface (Seed, 1979), but the likelihood of liquefaction occurring in most deposits is very low when groundwater is deeper than about 30 feet (10 m) (Youd and Perkins, 1978; Youd and Gilstrap, 1999). However, perched groundwater, locally saturated soils, and changes in local and regional water management patterns, along with seasonal variations of the water table, must also be considered when evaluating liquefaction hazard (Martin and Lew, 1999; California Geological Survey, 2008).

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

- The soils must be saturated.
- The soils must be loose/soft to moderately dense/stiff.
- The ground shaking must be intense.
- The duration of ground shaking must be sufficient for the soils to lose their shearing resistance.

The liquefaction susceptibility evaluation for this study used four main sources of data: (1) UGS 1:24,000-scale geologic mapping of the Bryce Canyon study area (Knudsen et al., in preparation), (2) NRCS *Soil Survey of Panguitch Area, Utah, Parts of Garfield, Iron, Kane, and Piute Counties* (Swenson and Bayer, 1990) and *Soil Survey of Grand Staircase-Escalante National Monument Area, Parts of Kane and Garfield Counties, Utah* (Sutcliffe, 2005), (3) a limited number of unpublished, site-specific geotechnical reports completed for projects in the Bryce Canyon study area, and (4) shallow-groundwater-potential mapping completed for this study.

Liquefaction susceptibility classifications of very high, high, moderate, low, and very low are based on geologic and groundwater conditions. The susceptibility classifications incorporate information on dominant grain-size distribution (fine to coarse grained), sorting (poorly to well sorted), and cementation (none to strong) of each geologic unit, along with depth to groundwater data. Geologic units that consist of well-sorted sand, silty sand, and gravel where

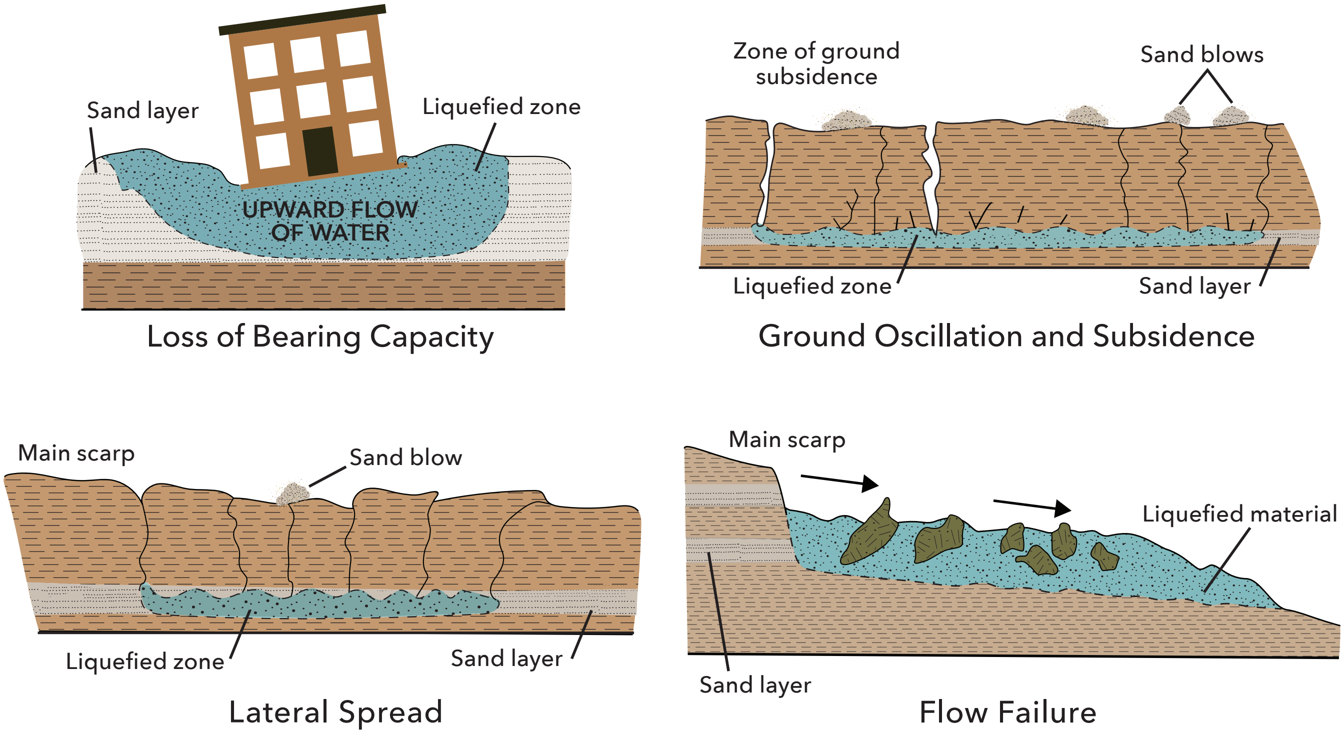

Figure 16. *Four principal types of liquefaction-induced ground failure; arrows indicate direction of movement (modified from Youd, 1984).*

depth to groundwater is less than or equal to 10 feet (≤ 3 m) below the ground surface were assigned to the very high liquefaction susceptibility category (VH). These same units, but where depth to groundwater is likely 10 to 50 feet (3–15 m) below the ground surface, were assigned to the high susceptibility category (H). Geologic units that consist of moderately to poorly sorted sand and gravel where depth to groundwater is less than or equal to 50 feet (≤ 15 m) below the ground surface were mapped as moderate (M). Geologic units that consist of poorly sorted sand and gravel where depth to groundwater is likely greater than 50 feet (> 15 m) below the ground surface, but shallow groundwater potential mapping identified soil conditions likely to develop perched groundwater, were mapped as low susceptibility (L). Geologic units that consist of moderately to poorly sorted sand and gravel where depth to groundwater is greater than or equal to 50 feet (≥ 15 m) below the ground surface were also mapped as low susceptibility (L). Geologic units consisting of very poorly sorted material where depth to groundwater may be less than 50 feet (< 15 m) below the ground surface were mapped as very low susceptibility (VL). Unclassified areas on the liquefaction susceptibility map include areas of exposed or shallow (≤ 5 feet [≤ 1.5 m) bedrock, unconsolidated geologic deposits with textural or cementation characteristics that generally preclude liquefaction, and areas where depth to groundwater is estimated to be greater than 50 feet (≥ 15 m). Unclassified areas are considered to have no liquefaction susceptibility. However, areas of liquefaction susceptibility too small to show at the scale of the map prepared for this study may exist locally within unclassified areas.

The liquefaction-susceptibility map (Plate 6) shows areas where liquefaction may be possible in the Bryce Canyon study area. However, the mapping is based on limited information about the textural characteristics of unconsolidated geologic units and the distribution and depth of groundwater in the study area. The mapping does not integrate the effect of earthquake ground motions with material characteristics and depth to groundwater, which is required to determine relative liquefaction potential in susceptible deposits. Consequently, the map does not differentiate ground-failure types or amounts, which are needed to fully assess the hazard and evaluate possible mitigation techniques.

Plate 6 is intended for general planning and design purposes to indicate where a liquefaction hazard may exist and to assist in liquefaction-hazard investigations. Soil-test requirements are specified in chapter 18 (Soils and Foundations) of the 2021 IBC (ICC, 2020a) and chapter 4 (Foundations) of the 2021 International Residential Code (IRC; ICC, 2020b). IBC Section 1803.2 requires a geotechnical investigation be performed in accordance with IBC sections 1803.3 through 1803.5. Section 1803.3 requires an investigation to evaluate liquefaction, and Section 1803.5.11 requires a liquefaction evaluation for structures in Seismic Design Categories C, D, E, or F. In general, seismic design categories in the study area for structures built on unconsolidated materials fall into Seismic Design Categories C and D, thus triggering the IBC requirement for a liquefaction investigation. Although the IRC does not specifically mention liquefaction, IRC Section R401.4 states that the local building official determines whether to require soil tests in areas likely to have expansive, compressive, shifting, or other unknown soil characteristics, such as liquefiable soils.

International Building Code seismic design categories are determined on a site-specific basis and vary throughout the study area depending on IBC site class, maximum considered earthquake ground motions, and the IBC risk category of the proposed structure. Because the risk to human life and the requirement that certain essential structures remain functional during natural or other disasters varies by occupancy category, the UGS recommends the following levels of liquefaction-hazard investigation for the different IBC risk categories (Table 4) in areas identified on Plate 6 as susceptible. Detailed (quantitative) subsurface investigations should be performed for modified Risk Category II(a), II(b), III, and IV facilities (modified from IBC table 1604.5 [ICC, 2020a]), and reconnaissance (screening) investigations for Risk Category I facilities. Additionally, a reconnaissance investigation should be performed for Risk Category II(a), II(b), III, and IV structures in areas mapped as not susceptible to liquefaction followed by a detailed investigation if a liquefaction hazard is determined to be present. Investigations are not recommended for Risk Category I structures in non-susceptible areas. Martin and Lew (1999) provide guidelines for conducting both reconnaissance and detailed liquefaction investigations.

Collapsible Soil

Collapsible (hydrocompactible) soils are relatively dry, low-density soils that decrease in volume or collapse under the load of a structure when they become wet. Collapsible soils may have considerable strength and stiffness in their dry natural state but can settle up to 10% of the susceptible deposit thickness when they become wet for the first time following deposition (Costa and Baker, 1981; Rollins and Rogers, 1994; Keaton, 2005), causing damage to property, structures, pavements, and underground utilities. Collapsible soils are common throughout the arid southwestern United States and are commonly geologically young materials, chiefly debris-flow deposits in Holocene-age (past 11,700 years) alluvial fans, and some wind-blown, lacustrine, and colluvial deposits (Owens and Rollins, 1990; Mulvey, 1992; Santi, 2005).

Collapsible soils typically have a high void ratio, corresponding low unit weight (Costa and Baker, 1981), and relatively low moisture content (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 they typically have a high collapsible-soil hazard. Intergranular bonds form between the larger grains (sand and gravel) of a collapsible deposit; these bonds develop through capillary tension or a binding agent such as silt, clay, or salt. Characteristically, collapsible soils consist of silty sand, sandy silt, and clayey sand (Williams and Rollins, 1991), although Rollins and Rogers (1994) identified collapse-prone gravel containing as little as 5% to 20% fines at several locations in the southwestern United States. Post-deposition wetting of the soil results in a loss of capillary tension or the softening, weakening, or dissolving of the bonding agent, allowing the larger particles to slip past one another into a denser structure (Williams and Rollins, 1991) (Figure 17).

Table 4. *Recommended requirements for site-specific liquefaction-hazard investigations for modified IBC risk category of buildings and other structures (see table 1; modified from ICC [2020a] and IBC table 1604.5).*

Mapped Liquefaction Susceptibility	IBC Risk Category[1]				
	I	II(a)	II(b)	III	IV
	Buildings and other structures that represent a low hazard to human life in the event of failure	Single family dwellings, apartment complexes and condominiums (<10 dwelling units), and campgrounds	Buildings and other structures except those listed in I, II(a), 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
Very High	Reconnaissance	Detailed[2]	Detailed[2]	Detailed[2]	Detailed[2]
High	Reconnaissance	Detailed[2]	Detailed[2]	Detailed[2]	Detailed[2]
Moderate	Reconnaissance	Detailed[2]	Detailed[2]	Detailed[2]	Detailed[2]
Low	None	Reconnaissance[3]	Reconnaissance[3]	Detailed[2]	Detailed[2]
Very Low	None	Reconnaissance[3]	Reconnaissance[3]	Reconnaissance[3]	Reconnaissance[3]
None	None	Reconnaissance[3]	Reconnaissance[3]	Reconnaissance[3]	Reconnaissance[3]

[1] See ICC (2020a) chapter 3, Occupancy Classification and Use (p. 45) and chapter 16, Structural Design, table 1604.5 (p. 364) for a complete list of structures/facilities included in each IBC Risk Category. Check table 1604.5 if a question exists regarding which Risk Category a structure falls under.

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

[3] A reconnaissance investigation should be followed by a detailed investigation if a liquefaction hazard is determined to be present.

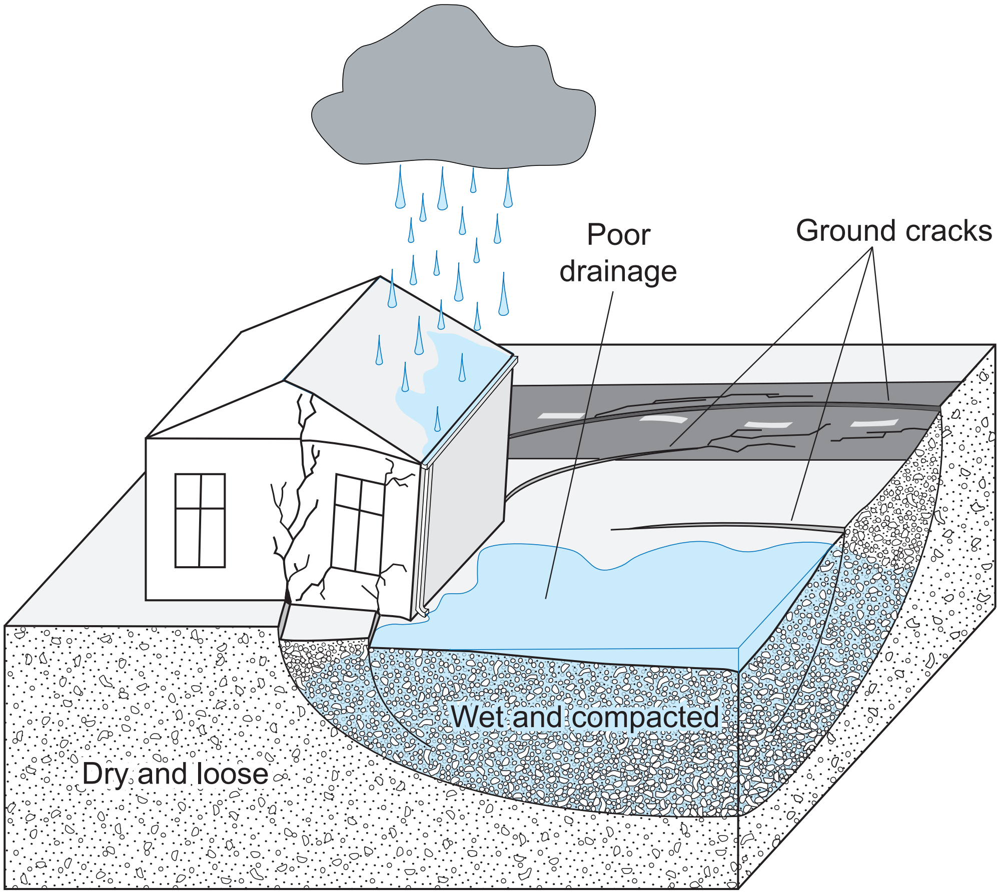

Figure 17. *Diagram of differential settlement and resulting structural damage due to the addition of excess water to collapsible soils (modified from Love, 2001).*

Naturally occurring deep percolation of water into collapsible deposits is uncommon after deposition due to the arid conditions in which the deposits typically form, and the steep gradient of many alluvial-fan and colluvial surfaces. Therefore, soil collapse is usually triggered by human activity such as irrigation, development, and/or wastewater disposal. Collapsible soils have caused costly damage to infrastructure in Utah, including a cement plant near Leamington (Rollins et al., 1992), flood-control structures near Monroe (Smith and Deal, 1988), and dozens of public and private structures in Cedar City (Kaliser, 1978). In 2001, collapsible soils damaged the Zion National Park greenhouse soon after its construction (Figure 18) as soils below and around the building were wetted by excess irrigation water (Lund et al., 2010). Although clear examples of infrastructure damage due to collapsible soils are lacking in the Bryce Canyon study area, several unconsolidated geologic units within the study area have physical characteristics indicative of potentially collapsible soils.

The evaluation of collapsible-soil susceptibility in the study area used four sources of data: (1) UGS 1:24,000-scale geologic mapping of the Bryce Canyon study area (Knudsen et al., in preparation), (2) NRCS *Soil Survey of Panguitch Area, Utah, Parts of Garfield, Iron, Kane, and Piute Counties* (Swenson and Bayer, 1990) and Soil S*urvey of Grand Staircase-Escalante National Monument Area, Parts of Kane and Garfield Counties, Utah* (Sutcliffe, 2005), (3) a limited number of unpublished, site-specific geotechnical reports completed for projects in the Bryce Canyon study area, and (4) aerial photograph interpretation and field mapping to identify areas that are periodically inundated with water, such as heavily irrigated agricultural areas, which reduces collapse potential.

I grouped unconsolidated geologic units that may be prone to collapse into five susceptibility categories on the collapsible-soil-susceptibility map (Plate 7). The categories are based on limited geotechnical data, and whether the deposit genesis or texture is permissive of collapse. Due to the lack of geotechnical information in the study area, the classification system presented here employs a relative susceptibility ranking as opposed to a hazard-severity ranking.

Common soil characteristics measured by geotechnical engineers to identify collapsible soils include swell/collapse test (SCT) data, density, and moisture content. With sparse geotechnical data available in the Bryce Canyon study area, I relied on geologic unit descriptions and NRCS soil analyses and descriptions to identify areas potentially susceptible to liquefaction. The unconsolidated geologic units shown on UGS geologic maps are defined by geomorphology (landform), genesis, age, and to a lesser extent texture.

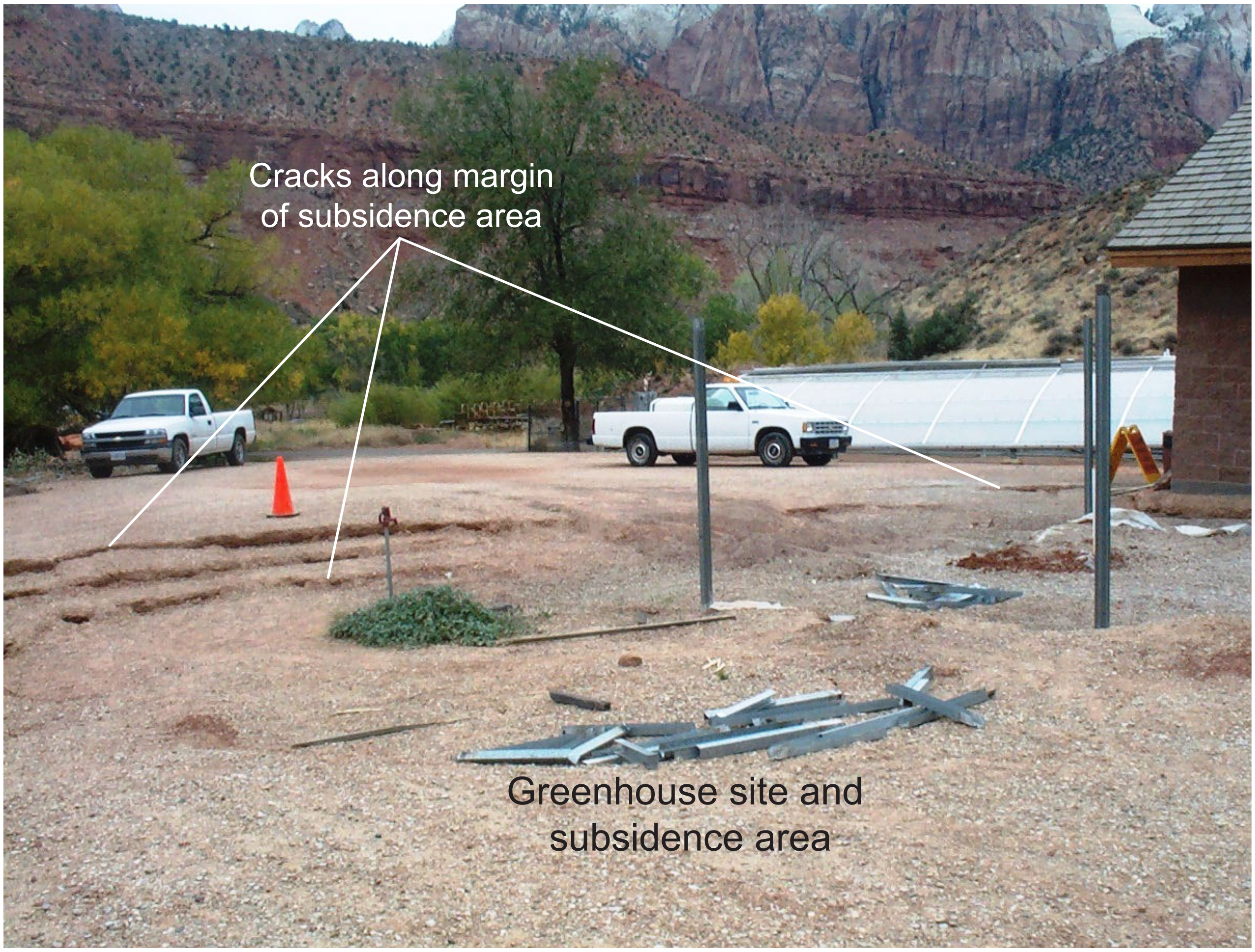

Figure 18. *Zion National Park greenhouse damaged by collapsible soils in 2001. Photo courtesy of the NPS.*

Rapidly deposited, Holocene-age alluvial units (typically geologic-map unit Qaf_1) with reported low densities (< 85 lbs/ft^3), abundant fine-grained material in the clay to fine-sand range as reported by the NRCS are mapped as highly collapsible (H) on Plate 7. Late Pleistocene to Holocene alluvial-fan units (Qafy and some Qafc) with a genesis and texture permissive of collapse or reported (in geotechnical reports) collapse data indicate values > 3% are mapped as collapsible soil 1 (SU1) (Plate 7). Unconsolidated geologic units that either (1) lack collapse data but have other geotechnical information (chiefly low unit weight and moisture content) indicative of collapse-susceptible material, or (2) collapse data indicate values < 3%, are mapped as collapsible soil 2 (SU2). Unconsolidated deposits where no geotechnical data are available but have a genesis or texture susceptible to collapse (chiefly geologically young alluvial, colluvial, and eolian deposits) are mapped as collapsible soil 3 (SU3). Finally, Pleistocene geologic units with no available geotechnical data, but with a genesis or texture permissive of collapse, are assigned to collapsible soil category 4 (SU4). Because of their age, SU4 deposits have experienced greater exposure to natural wetting and may have already experienced collapse, or the deposits may have become cemented by secondary calcium carbonate or other soluble minerals, making them less susceptible to collapse.

The collapsible-soil-susceptibility map (Plate 7) is intended for general planning and design purposes to indicate where collapsible-soil conditions may exist and where special investigations are recommended. The susceptibility categories are approximate and mapped boundaries are gradational. Localized areas of soil having higher or lower collapse potential may 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. Site-specific investigations can resolve uncertainties inherent in generalized mapping and help identify the need for special design, site grading and soil placement, and/or mitigation techniques. The presence and severity of collapsible soil, along with other geologic hazards, should be addressed in these investigations. If collapsible soil is present at a site, appropriate design and construction recommendations should be provided.

Piping and Erosion

Piping refers to the subsurface erosion of permeable, fine-grained, unconsolidated, or poorly consolidated deposits by percolating groundwater (Cooke and Warren, 1973; Costa and

Baker, 1981) (Figure 19). Piping creates narrow, subterranean conduits that enlarge both in diameter and length as increasingly more subsurface material is removed and as the cavities trap greater amounts of groundwater flow. Piping eventually leads to caving and collapse of the overlying surficial materials and is an important process in the headward extension of gullies in the arid southwestern United States (Costa and Baker, 1981). Soil erosion and gully formation are widely recognized as one of the greatest threats to land degradation and loss of productive agricultural lands (García-Ruiz et al., 2017).

For piping to take place, the following conditions are required: (1) fine-grained, non-cohesive or poorly consolidated, porous materials, such as some silt and clay; fine sand; poorly consolidated, typically sandy siltstone, mudstone, or claystone; and volcanic ash or tuff, (2) a sufficient thickness of susceptible material in which pipes may form, (3) a sufficiently steep hydraulic gradient to cause groundwater to percolate through the subsurface materials, and (4) a free face that intersects the permeable, water-bearing horizon and from which the water can exit the eroding deposit (Parker, 1963; Costa and Baker, 1981). The walls of an incised stream channel commonly provide the necessary free face, but human-made excavations, such as canal banks or road cuts, may also contribute to piping.

The characteristics that make soil or rock susceptible to piping (fine-grained texture, little or no internal cohesion, and loose or poor consolidation) are also typical of highly erodible materials. Consequently, piping often develops in and is an indicator of otherwise highly erodible deposits. In the Bryce Canyon study area, most erosion occurs during thunderstorms and is caused by sheetwash and eventual channelization of runoff. If disturbed, highly erodible soil or rock become even more susceptible to erosion, particularly when stabilizing vegetation and/or desert pavement is removed or disturbed.

UGS geologic maps show that poorly consolidated, often highly weathered, fine-grained bedrock units and clay-rich landslide deposits are widely distributed throughout the Bryce Canyon study area (Knudsen et al., in preparation) and are prone to piping and erosion. Fine-grained, non-cohesive, sand and silt deposits are also present in many areas (Figure 20). Unconsolidated erosion-prone units include eolian, alluvial, and mixed-unit geologic deposits that contain a high percentage of wind-blown sand.

Three main sources of data were used to evaluate piping and erosion in the study area: (1) UGS 1:24,000-scale geologic mapping of the Bryce Canyon study area (Knudsen et al., in preparation), (2) NRCS *Soil Survey of Panguitch Area, Utah, Parts of Garfield, Iron, Kane, and Piute Counties* (Swenson and Bayer, 1990) and *Soil Survey of Grand Staircase-Escalante National Monument Area, Parts of Kane and Garfield Counties, Utah* (Sutcliffe, 2005), and (3) a limited number of unpublished, site-specific geotechnical reports completed for projects in the Bryce Canyon study area.

I grouped soil and rock units susceptible to piping and erosion in the study area into two categories. Susceptible soil (SS) on the piping-and-erosion-susceptibility map (Plate 8) includes eolian, alluvial, and mixed-unit deposits that contain a high percentage of fine-grained, non-cohesive, loose to poorly

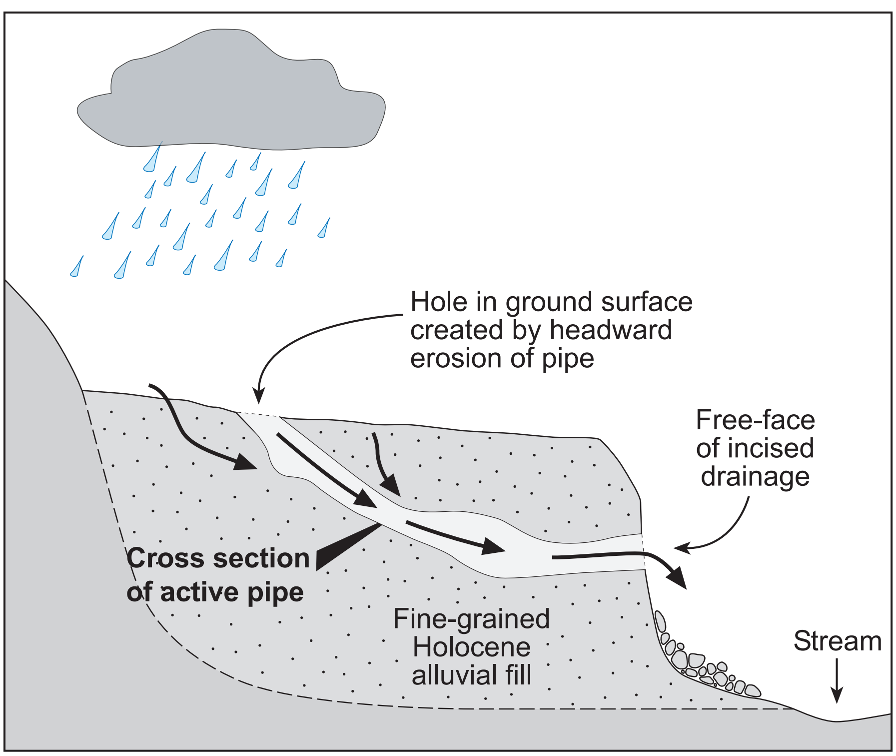

Figure 19. *Cross section of a pipe in fine-grained Holocene alluvium (after Black and others, 1999).*

Figure 20. *Erosion and gullying of fine-grained alluvium near Heward Creek. View to south; photo taken April 9, 2020.*

consolidated sand or silt. Bedrock units susceptible to piping and erosion (HR) contain abundant fine-grained, poorly consolidated siltstone, mudstone, or claystone, and include the Crystal Creek Member, middle unit of the Paria River Member, and Winsor Member of the Carmel Formation; Cannonville Member of the Entrada Formation; Naturita Formation; Tropic Shale; Smoky Hollow Member of the Straight Cliffs Formation; Wahweap Formation; Kaiparowits Formation; and the middle mudstone, siltstone, and sandstone unit of the white member of the Claron Formation. Bedrock units with alternating resistant and nonresistant strata include the John Henry Member of the Straight Cliffs Formation, the pink member of the Claron Formation, and the lower part of the Conglomerate at Boat Mesa (Tbml); I included these units in the HR category although site-specific investigations are necessary to properly characterize erodibility. The lower limestone unit of the white member of the Claron Formation is included in the susceptible-rock category north of the latitude of the visitor center, reflecting a prominent facies change there from relatively durable limestone to the south to a slope-forming clastic facies to the north (Knudsen et al., in preparation). Because piping occurs only where susceptible soil and rock exist in the presence of a free face and percolating groundwater, the presence of these units in and of themselves does not create a piping hazard. Conversely, a change in conditions brought about either naturally or through human activity can create the conditions necessary for piping to occur. Although susceptible to erosion, these units are generally stable in their natural, undisturbed state, but can quickly erode if disturbed or if drainage conditions change in an uncontrolled manner.

The mapped piping-and-erosion-susceptibility categories are approximate and mapped boundaries are gradational. Localized areas of soil with higher or lower piping and erosion susceptibility may 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

Unless stabilized by natural vegetation or by artificial means, loose sand will move in response to high-velocity wind. Wind transport (e.g., saltation) (deBlij and Muller, 1996) winnows the sand, producing a well-sorted (poorly graded) deposit that typically consists of subrounded to rounded sand grains with diameters ranging from very fine to coarse (0.1 to 1.0 mm [0.04–0.004 in]; Neuendorf et al., 2011). The fines content (silt and clay fraction) in wind-blown sand is generally less than 10%. Depending on topography, wind characteristics, and sand availability, blowing sand may accumulate in dunes or sand sheets, both of which may cover large areas. If development encroaches into areas with predominantly sandy soil and disturbs the natural vegetative cover and/or desert pavement, sand may migrate across roads and bury structures (Mulvey, 1992; Hayden, 2004; Lund et al., 2008b), and wind erosion may expose foundations and underground utilities. High winds can move fines by suspension and produce sand and dust storms that reduce visibility to near zero and sandblast vehicles and structures. Even a few inches of sand on a road can be dangerous (Stipho, 1992).

To evaluate wind-blown-sand susceptibility in the study area, three main sources of data were used to identify areas where geologic conditions may contribute to a wind-blown-sand hazard: (1) UGS 1:24,000-scale geologic mapping of the Bryce Canyon study area (Knudsen et al., in preparation), (2) NRCS *Soil Survey of Panguitch Area, Utah, Parts of Garfield, Iron, Kane, and Piute Counties* (Swenson and Bayer, 1990) and *Soil Survey of Grand Staircase-Escalante National Monument Area, Parts of Kane and Garfield Counties, Utah* (Sutcliffe, 2005), which report relative wind-erodibility values, and (3) a limited number of unpublished, site-specific geotechnical reports completed for projects in the Bryce Canyon study area. Based on the dominant transport mechanism, wind-blown sand deposits and mixed-unit geologic deposits containing a wind-blown sand component are grouped into high (H), moderate (M), and low (L) susceptibility categories on the wind-blown-sand-susceptibility map (Plate 9).

Utah Geological Survey geologic maps and NRCS soils maps show that loose, wind-blown sand deposits are relatively scarce in the Bryce Canyon study area. Within BCNP, some areas of low-wind-blown-sand-susceptibility deposits are mapped in drainages and minor swales, but the deposits likely lack sufficient volume to be a hazard. Areas of moderate to high wind-blown-sand susceptibility are limited to the southeast part of the map area, coincident with exposures of the Navajo Sandstone. Weathering of the Navajo Sandstone exposed in Bullrush Gorge, Tank Canyon, and Deer Range Canyon is the principal source of wind-blown sand in that area. Prevailing winds transport the sand out of those canyons and deposit the sand on adjacent benches where it is partially reworked by alluvial processes (mixed geologic map unit Qea). Mixed-unit sand deposits remain largely stable in their natural state but may become susceptible to wind transport when disturbed.

The wind-blown-sand susceptibility categories shown on Plate 9 are approximate and mapped boundaries are gradational. Localized areas of higher or lower wind-blown sand susceptibility may 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.

Soluble Rock

Soluble rock is subject to dissolution and reduced strength, which can cause considerable damage to structures, foundations, and infrastructure. Geologic units containing salt, gypsum ($CaSO_4 \cdot 2H_2O$), and limestone are susceptible to dissolution, which is associated with karst, caves, disappearing streams, sinkholes, and subsidence. Where the amount of gypsum is ≥ 10 percent, dissolution can result in localized land subsidence and sinkhole formation (Mulvey, 1992; Muckel, 2004; Santi, 2005; Johnson, 2008). Gypsum dissolution has resulted in sinkhole formation and has damaged infrastructure near Hurricane and St. George in southwestern Utah (Gourley, 1992; Everitt and Einert, 1994; Lund, 1997; Lund et al., 2008b). In September 2015, hazardous sinkholes attributed to gypsum dissolution were discovered in a Moab, Utah, subdivision (UGS, internal documents). Gypsum dissolution can be greatly accelerated by application of water from sources such as reservoirs; wastewater drain fields; street, roof, or parking lot runoff; and irrigation (Martinez et al., 1998; Cooper and Gutiérrez, 2013). Care should be taken in areas of gypsiferous materials to avoid surface-flow- and groundwater-regime changes. Gypsum is a weak material that has low bearing strength and is not suitable for subgrade or foundation soil. Surface flow should be directed to areas where it will not percolate into the gypsum-bearing units. Landscape irrigation is discouraged, and storm drain infrastructure should be regularly maintained to prevent leaks and sealed pipes should be considered.

Limestone units composed of mostly calcium carbonate ($CaCO_3$) are moderately susceptible to dissolution, and karst terrain is common in areas of limestone bedrock. Climate, water, and human activity are factors in chemical weathering resulting in limestone dissolution. The arid climate of southwestern Utah contributes to slow rates of limestone dissolution. However, changing surface-flow and groundwater regimes and/or increased precipitation could accelerate dissolution of limestone-bearing rocks in the Bryce Canyon study area.

The evaluation of soluble-rock susceptibility in the study area used three main sources of data: (1) UGS 1:24,000-scale geologic mapping of the Bryce Canyon study area (Knudsen et al., in preparation), (2) NRCS *Soil Survey of Panguitch Area, Utah, Parts of Garfield, Iron, Kane, and Piute Counties* (Swenson and Bayer, 1990) and *Soil Survey of Grand Staircase-Escalante National Monument Area, Parts of Kane and Garfield Counties, Utah* (Sutcliffe, 2005), and (3) a limited number of unpublished, site-specific geotechnical reports completed for projects in the Bryce Canyon study area. I classified geologic units into four susceptibility categories on the soluble-rock-susceptibility map (Plate 10) based on their composition and potential for dissolution: highly soluble gypsiferous bedrock that contains massive gypsum horizons (G1), gypsiferous bedrock units that lack massive gypsum but contain thin beds and veins of gypsum interspersed with other rock types (G2), limestone bedrock units (L), and bedrock units that contain significant amounts of both limestone and gypsum (LG).

Dissolution and sinkhole formation associated with limestone- or gypsum-rich geologic units have historically not been problematic in the developed parts of the Bryce Canyon study area. Despite the wide distribution of limestone-rich Claron Formation throughout large parts of the study area, there are few known karst features. A cave or sinkhole formed in the white member of the Claron Formation that caps Whiteman Bench was filled in by the NPS for safety concerns in the 1970s (unpublished NPS data). The clastic facies of the lower white member north of the BRCA Visitor Center lacks thick limestone beds and is therefore not included on the soluble-rock-susceptibility map (Plate 10). Knudsen et al. (in preparation) mapped probable sinkholes formed in the pink member of the Claron Formation near the head of Ingram Hollow and near Bristlecone Point; these are shown on Plate 10. They also mapped a linear depression formed on Claron limestone on the south end of Whiteman Bench that has likely been enhanced by dissolution. South of Willis Creek and east of the Paunsaugunt fault, extensive outcrops of the informally named gypsiferous unit of the Paria River Member of the Jurassic Carmel Formation (geologic map unit Jcpg) are present and typically consists of a 15- to 30-foot-thick (5–9 m) alabaster gypsum bed (Figure 21).

The mapped soluble-rock hazard categories on Plate 10 are approximate and mapped boundaries are gradational. Localized areas of higher or lower soluble rock hazard may 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 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 corrodes concrete and metals in areas where the amount of soil gypsum is ≥ 1% (Muckel, 2004). Sulfate-induced corrosion of unprotected concrete slabs, walls, masonry blocks, and buried infrastructure is widespread in parts of southern Utah, and damage can become severe after just a few years of exposure

Figure 21. *Alabaster gypsum bed of the Paria River Member of the Carmel Formation in Bull Valley. View to east; photo taken April 9, 2020.*

(Lund et al., 2008b; Knudsen and Lund, 2013). Corrosion of steel (metals) results from an electrochemical process that occurs from contact between steel (metals) and soluble chloride salts found in soil or water (White et al., 2008).

The evaluation of corrosive soil and rock in the study area used three main sources of data: (1) UGS 1:24,000-scale geologic mapping of the Bryce Canyon study area (Knudsen et al., in preparation), (2) NRCS S*oil Survey of Panguitch Area, Utah, Parts of Garfield, Iron, Kane, and Piute Counties* (Swenson and Bayer, 1990) and *Soil Survey of Grand Staircase-Escalante National Monument Area, Parts of Kane and Garfield Counties, Utah* (Sutcliffe, 2005), and (3) a limited number of unpublished, site-specific geotechnical reports completed for projects in the Bryce Canyon study area. Soil and rock units in the study area are grouped into four susceptibility categories on the corrosive-soil-and-rock-susceptibility map (Plate 11) based on their potential for corrosion of concrete and metals: highly corrosive rock (HR), moderately corrosive rock (MR), highly corrosive soil (HS), and moderately corrosive soil (MS).

Available geologic maps and NRCS soils maps indicate that moderate to highly corrosive soil and rock are widespread throughout much of the map area, particularly east of the Paunsaugunt Plateau (Plate 11), therefore, testing for sulfate and gypsum is advised prior to development in those areas. Units assigned to the highly corrosive rock category (HR) either contain thick gypsum beds or abundant veins or pods of gypsum and include: the Co-Op Creek Member, the Crystal Creek Member, the gypsiferous subunit of the Paria River Member; and the Winsor Member of the Jurassic Carmel Formation. Units assigned to the moderately corrosive rock category (MR) contain lesser amounts of gypsum than the HR category but can still cause corrosion if not properly identified. Units assigned to the MR category are the middle subunit of the Paria River Member and the Cannonville Member of the Entrada Formation; the Cretaceous Naturita Formation and Tropic Shale; and the Smoky Hollow and John Henry Members of the Cretaceous Straight Cliffs Formation. Highly (HS) and moderately corrosive soils (MS) are locally derived from, and mapped adjacent to, their highly and moderately corrosive parent rock units. Some moderately corrosive rock and soil is also present in Emery Valley where the John Henry Member and soils derived from it are locally present.

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. 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 mapped corrosive-soil-and-rock-susceptibility categories (Plate 11) are approximate and mapped boundaries are gradational. Localized areas of soil having higher or lower corrosive potential may 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.

Expansive Soil and Rock

Expansive soil and rock swell as they get wet and shrink as they dry out. These changes in volume can cause cracked foundations and other structural damage to buildings, structures, and underground utilities, heaving and cracking of canals and road surfaces, and failure of wastewater disposal systems. Expansive soil and rock are among the costliest natural disasters in the United States (Jones and Holtz, 1973; Chen, 1988; Nelson and Miller, 1992). Expansive soil and rock contain 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%, the expansive nature of the clay dominates, and the soil is subject to swell. Some sodium-montmorillonite clay can swell as much as 2000% upon wetting (Costa and Baker, 1981). The resulting expansion forces can be greater than 20,000 pounds per square foot (Shelton and Prouty, 1979) and can easily exceed the loads imposed by many structures (Figure 22). 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.

The evaluation of expansive soil and rock susceptibility in the study area used four main sources of data: (1) UGS 1:24,000-scale geologic mapping of the Bryce Canyon study area (Knudsen et al., in preparation), (2) NRCS *Soil Survey of Panguitch Area, Utah, Parts of Garfield, Iron, Kane, and Piute Counties* (Swenson and Bayer, 1990) and *Soil Survey of Grand Staircase-Escalante National Monument Area, Parts of Kane and Garfield Counties, Utah* (Sutcliffe, 2005), (3) a limited number of unpublished, site-specific geotechnical reports completed for projects in the Bryce Canyon study area, and (4) an analysis of expansive soil and rock in Kane County by Doelling and Davis (1989). Based on their potential for volumetric change, soil and rock units in the study area are classified into high, moderate, or low susceptibility categories on the expansive-soil-and-rock-susceptibility map (Plate 12).

Because relevant geotechnical data such as liquid limit (LL), plasticity index (PI), and swell-collapse tests (SCT) are scarce in the Bryce Canyon study area, swell potential for soils is based primarily on NRCS soils data. The NRCS soils maps that cover the Bryce Canyon study area estimated shrink-swell potential based on several factors including moist bulk density, amount and kind of clay, and linear extensibility. Linear extensibility is an expression of volume change that

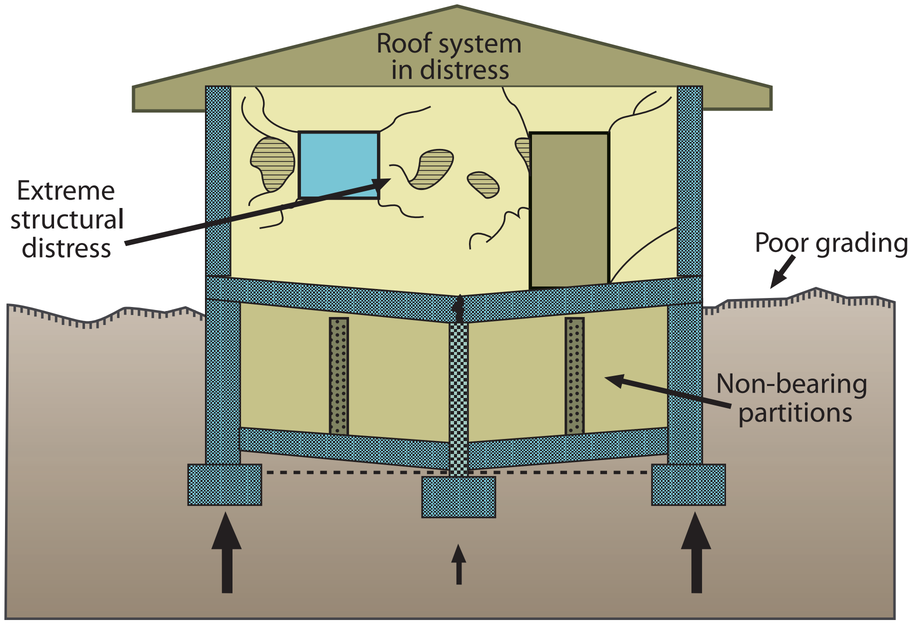

Figure 22. *Typical structural damage to a building from expansive soil (modified from Black et al., 1999).*

represents the change in length of an unconfined clod as moisture content is decreased from a moist to a dry state (Sutcliffe, 2005). The NRCS considered a soil with a linear extensibility of less than 3% to have a low (LS) shrink-swell potential, moderate (MS) if 3% to 6%, and high (HS) if greater than 6%.

I grouped bedrock units into three shrink/swell-susceptibility categories based on relative abundance of expansive clay minerals, abundance and thickness of clay-rich strata in mixed bedrock units, and experience with expansive rock units in southwestern Utah (Lund et al., 2008b, 2010; Knudsen and Lund, 2013). Bedrock units with the highest potential for volumetric change in the study area (susceptibility-map unit HR) are the Tropic Shale, Naturita Formation, Smoky Hollow and John Henry Members of the Straight Cliffs Formation, Wahweap Formation, and Kaiparowits Formation. Bedrock formations possessing little or no potential for volumetric change are not classified. Bedrock units with moderate (MR) to low (LR) susceptibility for shrink/swell have correspondingly less clay content.

The expansive-soil-and-rock susceptibility map (Plate 12) also shows locations where highly expansive bedrock may be concealed in the shallow subsurface (≤ 20 feet [≤ 6 m] deep), with little or no evidence of such materials at the ground surface (hazard-map unit HC). Experience in southern Utah has shown that when wetted, highly expansive soil or rock can cause damaging differential displacements at the ground surface even when overlain by as much as 20 feet (6 m) of non-expansive material (Lund et al., 2008b).

I observed localized areas of ground cracking and gullying resulting from repeated shrink-swell cycles in the study area. Soil and rock expansion may produce shrinkage cracks or fissures at the surface, as well as underground voids where further erosion can increase void volume and piping (Figure 23). Over time, a shrink-swell cycle can cause the erosion of potentially large subsurface caverns that may later collapse (Dunne, 1990). Ground cracks and subsurface voids are locally common on the Tropic Shale and adjacent soils derived from that rock unit. I observed several potentially hazardous gullies and sinkholes, partially obscured by vegetation, and as deep as 6 feet (2 m) south of Henderson Creek in the NW1/4 of section 33, T. 36 S., R. 2 W. (Figure 24; Plate 12).

Due to map scale, individual sites within any susceptibility category (high, moderate, low) may exhibit a high percentage of swell; therefore, site-specific geotechnical/geologic-hazard investigations should be performed at all locations to resolve inherent uncertainties.

Shallow Bedrock

Bedrock formations that are not significantly fractured provide relatively incompressible foundations that have high shear strengths, making mechanical compaction of these materials generally ineffective and unnecessary (Christenson and Deen, 1983). The principal problem related to shallow bedrock is difficulty of excavation, particularly in highly resistant bedrock units, which often require blasting. Shallow bedrock makes excavations for basements, foundations, underground utilities, and road cuts difficult, can cause areas of perched groundwater, and can create problems for wastewater disposal. Not accounting for shallow bedrock in project design may lead to excessive, unaccounted construction cost, contract change orders, and project delays.

The evaluation of shallow bedrock potential for the study area used three main sources of data: (1) UGS 1:24,000-scale geologic mapping of the Bryce Canyon study area (Knudsen

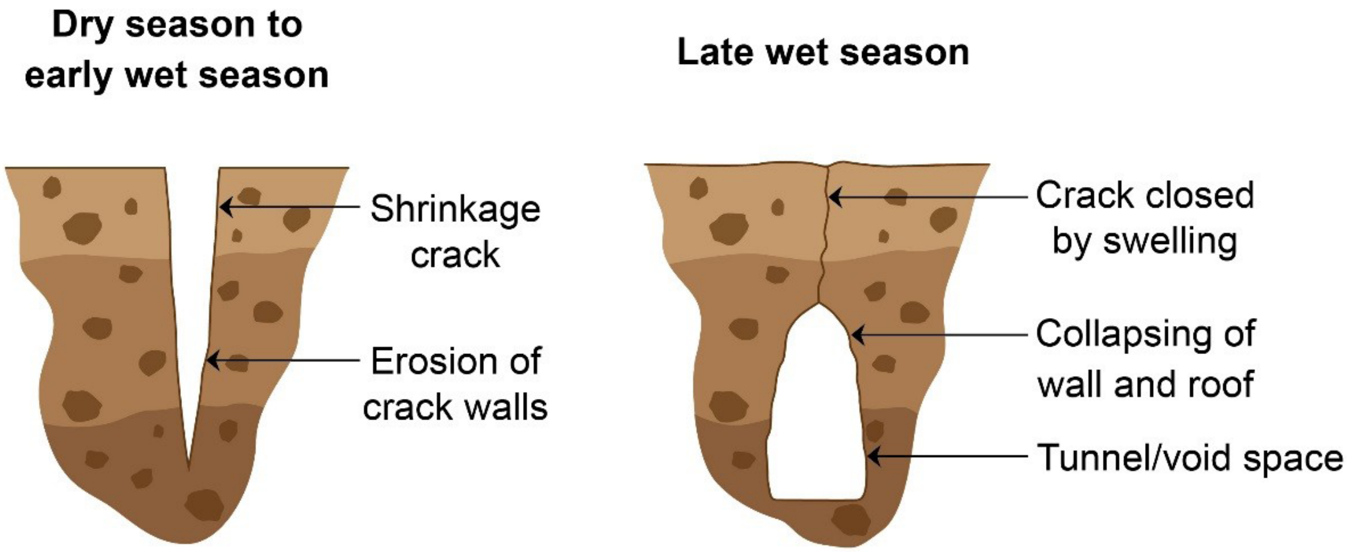

Figure 23. *Subsurface void formation due to shrink-swell of soils having a high clay content. Voids may continue to enlarge in the subsurface and propagate to the surface, creating a sinkhole hazard (modified from Dunne, 1990).*

Figure 24. *Approximate 6-foot-long (2 m) and 3-foot-deep (1 m) sinkhole formed on clay-rich expansive soils derived from the Tropic Shale near Henderson Creek. Photo taken October 2, 2019.*

et al., in preparation), (2) NRCS *Soil Survey of Panguitch Area, Utah, Parts of Garfield, Iron, Kane, and Piute Counties* (Swenson and Bayer, 1990) and *Soil Survey of Grand Staircase-Escalante National Monument Area, Parts of Kane and Garfield Counties, Utah* (Sutcliffe, 2005), and (3) a limited number of unpublished, site-specific geotechnical reports completed for projects in the Bryce Canyon study area.

Utah Geological Survey geologic maps identify areas where bedrock crops out at the ground surface. Bedrock units shown on the shallow-bedrock-potential map (Plate 13) are qualitatively classified as hard (H) or soft (S) based on geologic unit descriptions. After classifying the bedrock units, I used NRCS soils data, available geotechnical data, field reconnaissance, and outcrop patterns to classify hard bedrock that is likely buried (B) less than 10 feet (< 3 m) below the ground surface. Correlations between geologic mapping, geotechnical data, and NRCS information are generally good, but some local discrepancies may exist. Finally, several older (Pleistocene or older) alluvial units may locally contain caliche horizons (C) near the ground surface that could be difficult to excavate and greatly reduce soil permeability. Caliche forms progressively over time, and therefore is typically better developed in older unconsolidated deposits. Because caliche forms in the subsurface, its presence can be difficult to recognize in the absence of test-pit or borehole information.

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

Radon

Radon is an odorless, tasteless, and colorless radioactive gas that is highly mobile and can enter buildings through small foundation cracks and other openings, such as utility pipes. The most common type of radon is naturally occurring and results from the radioactive decay of uranium, which is found in small concentrations in nearly all soil and rock. Air movement and open space dissipate radon gas outdoors, but indoor radon concentration may reach hazardous levels because of confinement and poor air circulation in buildings. Breathing any level of radon over time increases the risk of lung cancer. 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. Most radon-induced lung cancers are caused by low and moderate radon concentrations, rather than by high radon concentrations, because fewer people are exposed to high indoor radon concentrations (World Health Organization [WHO], 2009). The U.S. Environmental Protection Agency (EPA) (U.S. EPA, 2025) recommends that action be taken to reduce indoor radon levels that are ≥ 4 picocuries per liter of air (pCi/L), and that action should be considered for indoor radon levels between 2 pCi/L and 4 pCi/L. The WHO (2009) recommends that action be taken at levels ≥ 100 Becquerel per meter (Bq/m3; ≥ 2.7 pCi/L). As there is no certain threshold concentration below which radon exposure presents no risk (WHO, 2009), radon mitigation should be seriously considered whenever radon is detected or where there is a potential geologic source of radon. As a result, the UGS strongly recommends that radon mitigation be performed where indoor radon levels are ≥ 2.7 pCi/L (Lund et al., 2020b).

Indoor radon levels are affected by several geologic factors including uranium content in soil and rock/soil permeability, and groundwater. Most soil and rock contain small amounts of uranium (1–3 ppm [parts per million]). Granitic rocks, metamorphic rocks, some volcanic rocks, black shale, and soils derived from these rocks are often associated with elevated uranium content (as much as 100 ppm; Otton, 1992). The higher the uranium content, the greater the probability that buildings built on a site will develop elevated 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. In bedrock, faults, joints, and fractures, along with the rock's primary porosity and permeability, influence the rate of radon migration. If the source of radon is below the groundwater table and the overlying sediment is not derived from a uranium-bearing bedrock unit, saturation of soil by groundwater may inhibit radon gas movement by dissolving radon in the water, reducing its ability to migrate upward through the soil. However, if groundwater is used as a source of culinary water, radon may enter a building and escape into indoor air as people use water for showering, washing dishes and clothes, and other uses (Otton, 1992; Lund et al., 2020b). Groundwater with high levels of radon is typically found where underlying geologic units have high uranium concentrations (Otton, 1992). In many areas of Utah, groundwater may not inhibit the movement of radon gas because the source of the radon gas is commonly not below the groundwater table but within or above it (Castleton et al., 2018).

Along with geologic factors, many non-geologic factors also influence radon levels in a building. Although the influence of geologic factors can be estimated, the influence of non-geologic factors, such as occupant lifestyle and home construction, are highly variable. As a result, indoor radon levels may fluctuate over time and can vary in different structures built on the same geologic unit; therefore, the radon level must be measured in each building to determine if a problem exists. Testing is easy, inexpensive, and may often be conducted by the building occupant, but professional assistance is available (for more information, visit https://radon.utah.gov). *Guidelines for Evaluation of Geologic Radon Hazard in Utah* (Lund et al., 2020b) recommends minimum standards for performing radon-hazard investigations in Utah. Evaluation of actual indoor radon levels in the Bryce Canyon study area was beyond the scope of this investigation.

The evaluation of radon susceptibility in the study area used four main sources of data to identify where underlying geologic conditions may contribute to elevated radon levels: (1) UGS 1:24,000-scale geologic mapping of the Bryce Canyon study area (Knudsen et al., in preparation), (2) soil permeability data—reported as the downward rate of movement of water in saturated soils (saturated hydraulic conductivity) in inches per hour—from the NRCS *Soil Survey of Panguitch Area, Utah, Parts of Garfield, Iron, Kane, and Piute Counties* (Swenson and Bayer, 1990) and the *Soil Survey of Grand Staircase-Escalante National Monument Area, Parts of Kane and Garfield Counties, Utah* (Sutcliffe, 2005), (3) USGS National Uranium Resource Evaluation Program (NURE) data including the Hydrogeochemical and Stream Sediment Reconnaissance dataset (HSSR) (USGS, 2004) and the airborne radiometric map of the U.S. (Duval et al., 1989; USGS, 2009), and (4) shallow-groundwater mapping (this study; Plate 4).

Using the geologic factors of uranium content (estimated using NURE data and rock type), soil permeability, and depth to groundwater, soil and rock units in the study area are classified using a three-point system (Table 5) into high (3 points; H), moderate (2 points; M), and low (1 point; L) radon-susceptibility categories on the geologic-radon-susceptibility map (Plate 14; after Black and Solomon, 1996). These categories are based on a soil or rock unit's susceptibility to generate radon gas and the ability of the gas to migrate upward through the overlying soil and rock. I assigned points based on shallow groundwater mapping (Plate 4), permeability, and relative uranium content of mapped rock units in the study area. The Smoky Hollow Member of the Straight Cliffs Formation and the Naturita Formation (formerly Dakota Formation) contain abundant carbonaceous shale and coal that are associated with elevated uranium content elsewhere on the Colorado Plateau (e.g., Averitt, 1962; Doelling and Davis, 1989). Additionally, Tertiary basin-fill deposits (Taf) of Knudsen et al. (in preparation) contain abundant material derived from volcanic rocks that may also be rich in uranium.

Saturation of soil by shallow groundwater (less than approximately 30 feet [< 10 m]) inhibits radon movement by dissolving radon in the water and reducing its ability to migrate upward through subgrade and foundation soil (Black, 1993). Groundwater mapping focused on the principal aquifer where it is shallow, and on locally unconfined or perched aquifers 30 feet or less (≤ 10 m) 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 a higher point value is assigned to the shallow groundwater factor.

The map of geologic-radon susceptibility (Plate 14) is intended to provide an estimate of the underlying geologic conditions that may contribute to radon hazard. The map is not intended to indicate absolute indoor radon levels in specific buildings and the UGS recommends testing in all existing structures. If professional assistance is required to test for radon or reduce the indoor radon hazard, a qualified contractor should be selected. The EPA provides guidelines for choosing a contractor and a listing of state radon offices in their *Consumer's Guide to Radon Reduction* (U.S. EPA, 2025).

The UGS recommends that a radon-control system be installed for new construction intended for human occupancy and for modified IBC Risk Category II(a), II(b), III, and IV facilities (ICC, 2020a) in areas mapped by the UGS as having moderate or high radon susceptibility, or where a site-specific, predevelopment, geologic investigation determined that a radon source is present at a site (Lund et al., 2020b). In areas mapped by the UGS as having low radon susceptibility, the UGS recommends that consideration be given to incorporating a radon-control system in all new construction as above. Appendix AF of the ICC's 2021 IRC (ICC, 2020b) addresses radon-resistant new construction techniques. While not currently adopted by Utah Code, adopting Appendix AF would significantly help reduce the hazard and risk from radon gas, Utah's most deadly geologic hazard (Lund et al., 2020b), by sealing foundations and venting the building foundation subgrade soils, allowing the upward-flowing radon gas to be dissipated into the air above the building. EPA Publication

Table 5. *Radon-hazard-potential classifications based on geologic factors affecting the ability of radon gas to migrate upward through the overlying soil and rock.*

Geologic Factors	Radon Hazard Category[1]		
	Low	Moderate	High
Uranium (ppm)	< 2	2–3	> 3
Soil permeability[2]	Impermeable (hydraulic conductivity < 0.6 in/hr)	Moderately permeable (0.6–6 in/hr)	Highly permeable (> 6 in/hr)
Depth to groundwater	< 10 feet	10–30 feet	> 30 feet

[1]After Black and Solomon (1996)

[2]Swenson and Bayer (1990) and Sutcliffe (2005)

EPA/402-K-01-002 (EPA, 2001), *Building Radon Out—A Step by Step Guide on How to Build Radon Resistant Homes*, provides specific guidance on how to incorporate radon-prevention systems in new construction. EPA Publication EPA 402-95-012 (EPA, 1995), *Passive Radon Control System for New Construction*, provides architectural drawings (CAD format) intended for architects, home builders, designers, radon mitigators, and others interested in the installation of passive radon-control systems in one and two-family dwellings. The typical cost to implement a radon-control system in a newly constructed home is about $500, whereas active radon mitigation systems installed in existing homes typically range from $1,200 to $1,700 (Lund et al., 2020b).

The radon-susceptibility categories shown on Plate 14 are approximate and mapped boundaries are gradational. Localized areas of higher or lower radon potential may 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.

ACKNOWLEDGMENTS

This study was performed under a cooperative agreement between the Bryce Canyon Natural History Association (now the Bryce Canyon Association) and the Utah Department of Natural Resources, Utah Geological Survey. Gayle Pollock (Bryce Canyon Association), Linda Mazzu (BCNP, retired), and Amanda McCutcheon (formerly BCNP, currently at Pipe Springs National Monument) facilitated support and funding for this study. Tyra Olstad (BCNP) collected useful unpublished NPS reports that informed this study. Bill Loughlin (Loughlin Water Associates) shared his knowledge and unpublished reports concerning springs near Tropic. Reviews by Bill Lund (UGS, retired), Steve Bowman, Sofia Agopian, and Adam McKean from the UGS, greatly improved this study.

REFERENCES

Anderson, P.B., Willis, G.C., Chidsey, J.C., Jr., and Sprinkel, D.A., 2024, Geology of Glen Canyon National Recreation Area, Utah-Arizona, *in* Sprinkel, D.A., Chidsey, T.C., Jr., Anderson, P.B., and Willis, G.C., editors, Geology of Utah's parks and monuments, fourth edition: Bryce Canyon Association and Utah Geological Association Publication 28, p. 391–434.

Arabasz, W.J., Pechmann, J.C., and Brown, E.D., 1992, Observational seismology and the evaluation of earthquake hazards and risk in the Wasatch Front area, Utah, *in* Gori, P.L., and Hays, W.W., editors, Assessment of regional earthquake hazards and risk along the Wasatch Front, Utah: U.S. Geological Survey Professional Paper 1500-D, 36 p, https://doi.org/10.3133/pp1500AJ.

Ashland, F.X., 2003, The feasibility of collecting accurate landslide-loss data in Utah: Utah Geological Survey Open-File Report 410, 25 p., https://doi.org/10.34191/OFR-410.

Ashland, F.X., Giraud, R.E., and McDonald, G.N., 2005, Ground-water-level fluctuations in Wasatch Front landslides and adjacent slopes, northern Utah: Utah Geological Survey Open-File Report 448, 22 p., https://doi.org/10.34191/OFR-448.

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

Associated Press, 2015, Minor quake rattles parts of southern Utah, KSL.com, July 4, 2015: https://www.ksl.com/article/35358355/minor-quake-shakes-parts-of-southern-utah, accessed July 22, 2022.

Averitt, P., 1962, Geology and coal resources of the Cedar Mountain quadrangle, Iron County, Utah: U.S. Geological Survey Professional Paper 389, 71 p., 3 plates, scale 1:24,000, https://doi.org/10.3133/pp389.

Baril, L., Struthers, K., and Valentine-Darby, P., 2018, Bryce Canyon National Park natural resource condition assessment: National Park Service, Natural Resource Stewardship and Science Office Report NPS/NCPN/NRR-2018/1690, Fort Collins, Colorado, 252 p.

Beukelman, G.S., and Hylland, M.D., 2020, Guidelines for evaluating landslide hazards in Utah, *in* Bowman, S.D., and Lund, W.R., editors, Guidelines for investigating geologic hazards and preparing engineering-geology reports, with a suggested approach to geologic-hazard ordinances in Utah, second edition: Utah Geological Survey Circular 128, p. 59–73, https://doi.org/10.34191/C-128.

Biek, R.F., Rowley, P.D., Anderson, J.J., Maldonado, F., Moore, D.W., Hacker, D.B., Eaton, J.G., Hereford, R., Filkorn, H., and Matyjasik, B., 2015, Geologic map of the Panguitch 30' x 60' quadrangle, Garfield, Iron, and Kane Counties, Utah: Utah Geological Survey Map 270DM, 162 p., 3 plates, scale 1:62,500, https://doi.org/10.34191/M-270dm.

Bilderback, E., 2015, Navajo Loop Trail rockfall risk assessment, Bryce Canyon National Park: National Park Service Geologic Resources Division, unpublished report, Denver, Colorado.

Black, B.D., 1993, Radon-potential-hazard map of Utah: Utah Geological Survey Map 149, 12 p., 1 plate, scale 1:100,000, https://doi.org/10.34191/M-149.

Black, B.D., Mulvey, W.E., Lowe, M., and Solomon, B.J., 1995, Geologic effects, *in* Christenson, G.E., editor, The September 2, 1992 ML 5.8 St. George earthquake, Washington County, Utah: Utah Geological Survey Circular 88, p. 2–11, https://doi.org/10.34191/C-88.

Black, B.D., and Solomon, B.J., 1996, Radon-hazard potential of the lower Weber River area, Tooele Valley, and southeastern Cache Valley, Cache, Davis, Tooele, and Weber Counties, Utah: Utah Geological Survey Special Study 90, 56 p., 1 plate, scales 1:50,000 and 1:100,000, https://doi.org/10.34191/SS-90.

Black, B.D., Solomon, B.J., and Harty, K.M., 1999, Geology and geologic hazards of Tooele Valley and the West Desert Hazardous Industry Area, Tooele County, Utah: Utah Geological Survey Special Study 96, 65 p., https://doi.org/10.34191/SS-96.

Bowers, W.E., 1991, Geologic map of Bryce Canyon National Park and vicinity, southwestern Utah: U.S. Geological Survey Miscellaneous Investigations Series Map I-2108, 15 p., 1 plate, scale 1:24,000, https://doi.org/10.3133/i2108.

Bowman, S.D., and Arabasz, W.J., 2017, Utah earthquakes (1850–2016) and Quaternary faults: Utah Geological Survey Map 277, scale 1:500,000, https://doi.org/10.34191/M-277.

Bowman, S.D., and Lund, W.R., editors, 2020, Guidelines for investigating geologic hazards and preparing engineering-geology reports, with a suggested approach to geologic-hazard ordinances in Utah, second edition: Utah Geological Survey Circular 128, 170 p., 5 appendices, https://doi.org/10.34191/C-128.

Brune, J. N., 1993, Distribution of precariously balanced rocks in Nevada and California - correlation with probability maps for strong ground motion: Eos, v. 73, no. 43, p. 351.

Brune, J. N., 1994, Constraints on ground motion from great earthquakes provided by groups of precarious rocks: Seismological Research Letters, v. 65, no. 1, p. 64.

Brune, J. N., and Whitney, J. W., 2000, Precarious rocks and seismic shaking at Yucca Mountain, Nevada: U.S. Geological Survey Digital Data Series 058, p. 1–19.

Bryant, W.A., and Hart, E.W., 2007, Fault-rupture hazard zones in California—Alquist-Priolo Earthquake Fault Zoning Act with index to earthquake fault zone maps: California Geological Survey Special Publication 42 [Interim Revision 2018], 83 p., https://www.conservation.ca.gov/cgs/documents/publications/special-publications/SP_042-a11y.pdf.

Butler, E., and Marsell, R.E., 1972, Developing a state water plan, cloudburst floods in Utah, 1939–69: Utah Department of Natural Resources, Division of Water Resources Cooperative-Investigations Report Number 11, 103 p., 1 plate.

California Geological Survey, 2008, Guidelines for evaluating and mitigating seismic hazards in California: California Geological Survey Special Publication 117A, 98 p.

Carpenter, C.H., Robinson, G.V., and Bjorklund, L.J., 1967; Ground-water conditions and geologic reconnaissance of the upper Sevier River basin, Utah: U.S. Geological Survey Water-Supply Paper 1836, 91 p., 3 plates, https://doi.org/10.3133/wsp1836.

Case, W.F., 1988, Geologic effects of the 14 and 18 August, 1988 earthquakes in Emery County, Utah: Utah Geological and Mineral Survey, Survey Notes, v. 22, p. 8–15, https://doi.org/10.34191/SNT-22-1-2.

Case, W.F., 2000, Notable Utah rock falls in the 1990s and 1980s: Utah Geological Survey Open-File Report 373, 11 p., https://doi.org/10.34191/OFR-373.

Castleton, J.J., 2009, Rock-fall hazards in Utah: Utah Geological Survey Public Information Series 94, 3 p., https://doi.org/10.34191/PI-94.

Castleton, J.J., Erickson, B.A., and Kleber, E.J., 2018, Geologic radon hazard susceptibility map of eastern Davis County, Utah: Utah Geological Survey Open-File Report 655, 1 plate, scale 1:62,500, https://doi.org/10.34191/OFR-655.

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

Christenson, G.E., and Deen, R.D., 1983, Engineering geology of the St. George area, Washington County, Utah: Utah Geological and Mineral Survey Special Study 58, 32 p., 2 plates, https://doi.org/10.34191/SS-58.

Coe, J.A., Cannon, S.H., and Santi, P.M., 2008, Introduction to the special issue on debris flows initiated by runoff, erosion, and sediment entrainment in western North America: Geomorphology, v. 96, p. 247–249.

Cohen, K.M., and Gibbard, P.L., 2019, Global chronostratigraphical correlation table for the last 2.7 million years, version 2019 QI-500: Quaternary International, v. 500, p. 20–31, https://doi.org/10.1016/j.quaint.2019.03.009.

Collins, B.D., and Stock, G.M., 2016, Rockfall triggering by cyclic thermal stressing of exfoliation fractures: Nature Geoscience, v. 9, p. 395–401, http://dx.doi.org/10.1038/ngeo2686.

Cooke, R.U., and Warren, A., 1973, Geomorphology in deserts: Berkeley and Los Angeles, University of California Press, 374 p.

Cooper, A.H., and Gutiérrez, F., 2013, Dealing with gypsum karst problems—hazards, environmental issues, and planning, *in* Shroder, J.F., editor, Treatise on Geomorphology, v. 6, p. 451–462, https://doi.org/10.1016/B978-0-12-374739-6.00106-8.

Costa, J.E., 1988, Rheologic, morphologic, and sedimentologic differentiation of water floods, hyperconcentrated flows, and debris flows, *in* Baker, V.E., Kochel, C.R., and Patton, P.C., editors, Flood geomorphology: New York, John Wiley and Sons, p. 113–122.

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

Costa, J.E., and Wieczorek, G.F., editors, 1987, Debris flows/avalanches—process, recognition, and mitigation: Geological Society of America, Reviews in Engineering Geology-Volume II, 239 p.

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

Davidson, L., 2017, Landslide near Bryce Canyon limiting SR-12 to single lane: The Salt Lake Tribune, March 19, 2017, https://www.sltrib.com/news/politics/2017/03/19/landslide-near-bryce-canyon-limiting-sr-12-to-single-lane/, accessed May 3, 2022.

Davis, G.H., 1999, Structural geology of the Colorado Plateau region of southern Utah, with special emphasis on deformation bands: Geological Society of America Special Paper 342, 157 p.

Davis, G.H., and Pollock, G.L., 2024, Geology of Bryce Canyon National Park, *in* Sprinkel, D.A., Chidsey, T.C., Jr., Anderson, P.B., and Willis, G.C., editors, Geology of Utah's parks and monuments, fourth edition: Bryce Canyon Association and Utah Geological Association Publication 28, p. 29–56.

Davis, G.H., and Rowley, P.D., 1993, Miocene thrusting, gravity sliding, and near-surface batholithic emplacement, Marysvale volcanic field, southwestern Utah [abs.]: Eos (Transactions, American Geophysical Union), v. 74, no. 43, p. 647.

deBlij, H.J., and Muller, P.O., 1996, Physical geography of the global environment (2nd edition): New York, John Wiley & Sons, 599 p.

DeCourten, F., 1994, Shadows of time—The geology of Bryce Canyon National Park: Bryce Canyon Natural History Association, Bryce Canyon, Utah, 128 p.

dePolo, C.M., and Slemmons, D.B., 1998, Age criteria for active faults in the Basin and Range Province, *in* Lund, W.R., editor, Proceedings volume, Basin and Range Province Seismic-Hazards Summit: Utah Geological Survey Miscellaneous Publication 98-2, p. 74–83, https://doi.org/10.34191/MP-98-2.

Doelling, H.H., 2008, Geologic map of the Kanab 30' x 60' quadrangle, Kane and Washington Counties, Utah, and Coconino and Mohave Counties, Arizona: Utah Geological Survey Miscellaneous Publication MP-08-2DM, scale 1:100,000, https://doi.org/10.34191/MP-08-2dm.

Doelling, H.H., and Davis, F.D., 1989, The geology of Kane County, Utah—geology, mineral resources, geologic hazards: Utah Geological and Mineral Survey Bulletin 124, 192 p., 10 plates, scale 1:100,000, https://doi.org/10.34191/B-124.

Doremus, L., and Kreamer, D., 1999, Bryce Canyon water resource study report: unpublished consultants' report for the National Park Service, 50 p.

Dunne, T., 1990, Chapter 1—Hydrology, mechanics, and geomorphic implications of erosion by subsurface flow: Geological Society of America Special Paper 252, p. 1–28.

Duval, J.S., Jones, W.J., Riggle, F.R., and Pitkin, J.A., 1989, Equivalent uranium map of the conterminous United States: U.S. Geological Survey Open-File Report 89-478: 12 p., https://doi.org/10.3133/ofr89478.

Evans, S.G., and Hungr, O., 1993, The assessment of rock fall hazard at the base of talus slopes: Canadian Geotechnical Journal, v. 30, p. 620–636.

Everitt, B., and Einert, M., 1994, The 1985 slug test of Pah Tempe springs, Washington County, Utah, *in* Blackett, R.E., and Moore, J.N., editors, Cenozoic geology and geothermal systems of southwestern Utah: Utah Geological Association Publication 23, p. 189–194.

Garcia-Ruiz, J., Beguería, S., Lana-Renault, N., Nadal-Romero, E., and Cerdà, A., 2017, Ongoing and emerging questions in water erosion studies: Land Degradation & Development, v. 28, no. 1, p. 5–21, https://doi.org/10.1002/ldr.2641.

Gartner, J.E., Cannon, S.H., Bigio, E.R., Davis, N.K., Parrett, C., Pierce, K.L., Rupert, M.G., Thurston, B.L., Trebish, M.J., Garcia, S.P., and Rea, A.H., 2005, Compilation of data relating to the erosive response of 606 recently-burned basins in the Western U.S.: U.S. Geological Survey Open-File Report 2005-1218: https://pubs.usgs.gov/of/2005/1218/Report.html, accessed June, 2019.

Giraud, R.E., 2020, Guidelines for the geologic investigation of debris-flow hazards on alluvial fans in Utah, *in* Bowman, S.D., and Lund, W.R., editors, Guidelines for investigating geologic hazards and preparing engineering-geology reports, with a suggested approach to geologic-hazard ordinances in Utah, second edition: Utah Geological Survey Circular 128, p. 75–91, https://doi.org/10.34191/C-128.

Giraud, R.E., and Shaw, L.M., 2007, Landslide susceptibility map of Utah: Utah Geological Survey Map 228DM, 11 p., 1 plate, scale 1:500,000, https://doi.org/10.34191/M-228dm.

Gonder, K., 2010, Memorandum to employees and visitors, Bryce Canyon National Park, 26 July 2010, Subject: Wall Street Trail closures: National Park Service, Bryce Canyon National Park, Utah.

Gourley, C., 1992, Geologic aspects of the Quail Creek dike failure, *in* Harty, K.M., editor, Engineering and environmental geology of southwestern Utah: Utah Geological Association Publication 21, p. 17–38.

Greco, D., 2005, Evaluation of geotechnical alternatives to the Navajo Loop Trail, Bryce Canyon National Park, Utah: National Park Service Geologic Resources Division, Denver, Colorado, 12 p.

Gregory, H.E., 1951, The geology and geography of the Paunsaugunt region: U.S. Geological Survey Professional Paper 226, 116 p., 4 plates, scale 1:62,500, https://doi.org/10.3133/pp226.

Haddad, D.E., and Arrowsmith, J.R., 2011, Geologic and geomorphic characterization of precariously balanced rocks: Arizona Geological Survey Contributed Report CR-11-B, 199 p.

Harp, E.L., and Greco, D., 2010, Assessment of rock-fall hazard within Navajo Loop Trail, Bryce Canyon National Park, Utah: U.S. Geological Survey, Golden, Colorado, and National Park Service Geologic Resources Division, Denver, Colorado.

Hayden, J.M., 2004, Geologic map of The Divide quadrangle, Washington County, Utah: Utah Geological Survey Map 197, 32 p. pamphlet, scale 1:24,000, https://doi.org/10.34191/M-197.

Hays, W.W., and King, K.W., 1982, Zoning of earthquake shaking hazards along the Wasatch fault zone, Utah: Third International Earthquake Microzonation Conference, Seattle, Washington, v. 3, p. 1307–1318.

Highland, L.M., and Bobrowsky, P., 2008, The landslide handbook—a guide to understanding landslides: U.S. Geological Survey Circular 1325, 129 p.

Hunt, C.B., 1956, Cenozoic geology of the Colorado Plateau: U.S. Geological Survey Professional Paper 279, 99 p.

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

International Code Council, 2020a, 2021 International building code: Country Club Hills, Illinois, 832 p.

International Code Council, 2020b, 2021 International residential code—for one- and two-family dwellings: Country Club Hills, Illinois, 1109 p.

Johnson, K.S., 2008, Evaporite-karst problems and studies in the USA: Environmental Geology, v. 53, p. 937–943, https://doi.org/10.1007/s00254-007-0716-8.

Jones, D.E., and Holtz, W.G., 1973, Expansive soils—the hidden disaster: Civil Engineering, American Society of Civil Engineers, v. 43, no. 8, p. 49–51.

Kaliser, B.N., 1978, Ground surface subsidence in Cedar Valley, Utah: Utah Geological and Mineral Survey Report of Investigation 124, 22 p., 1 plate, scale 1:24,000, https://doi.org/10.34191/RI-124.

Karlstrom, K.E., Lee, J.P., Kelley, S.A., Crow, R.S., Crossey, L.J., Young, R.A., Lazear, G., Beard, L.S., Ricketts, J.W., Fox, M., and Shuster, D.L., 2014, Formation of the Grand Canyon 5 to 6 million years ago through integration of older paleocanyons: Nature Geoscience, v. 7, p. 239–244.

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

Keefer, D.K., 1984, Landslides caused by earthquakes: Geological Society of America Bulletin, v. 95, p. 402–421.

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

Keller, E.A., and DeVecchio, D.E., 2019, Natural hazards—Earth's processes as hazards, disasters, and catastrophes, fifth edition: New York, Routledge, 642 p.

Knudsen, T.R., Biek, R.F., and Eaton, J.G., in preparation, Geologic map of Bryce Canyon National Park and vicinity: Utah Geological Survey Map Series, 2 plates, scale 1:24,000.

Knudsen, T.R., Hiscock, A.I., Ben-Horin, J., and Pearthree, P.A, 2021, Detailed mapping of the Washington, Hurricane, and Sevier/Toroweap fault zones, Utah and Arizona, using new high-resolution lidar data to reduce earthquake risk: Utah Geological Survey and Arizona Geological Survey, Final Technical Report to the U.S. Geological Survey National Earthquake Hazard Reduction Program, award nos. G20AP0007 and G20AP0008, 45 p.

Knudsen, T.R., and Lund, W.R., 2013, Geologic hazards of the State Route 9 corridor, La Verkin City to Town of Springdale, Washington County, Utah: Utah Geological Survey Special Study 148, 13 p., 9 plates, scale 1:24,000, https://doi.org/10.34191/SS-148.

Kromer, R., Lato, M., Hutchinson, D.J., Gauthier, D., and Edwards, T., 2015, Identifying rock slope failure precursors using LiDAR for transportation corridor hazard management: Engineering Geology, v. 95, p. 93–103, https://doi.org/10.1016/j.enggeo.2015.05.012.

Leavitt, R.E., May, S.B., and MacLean, J.S., 2011, Preliminary field investigation into the relationship between hoodoo formation and footwall shearing of the Ruby's Inn thrust fault, Bryce Canyon, Utah [abs.]: Geological Society of America Abstracts with Programs, v. 43, no. 5, p. 296.

Lefu, N. and Nokwe, V., 2020, Use of laser scanner technology as part of the slope stability risk management strategy at Letseng diamond mine, *in* Dight, P., editor, Proceedings of the 2020 International Symposium on Slope Stability in Open Pit Mining and Civil Engineering: Australian Centre for Geomechanics, University of Western Australia, Perth, p. 241–254, https://doi.org/10.36487/ACG_repo/2025_11.

Lindquist, R.C., 1980, Slope processes and forms at Bryce Canyon National Park: Salt Lake City, The University of Utah, Ph.D. dissertation, 60 p.

Loew, S., Hantz, D., and Gerber, W., 2022, Rockfall causes and transport mechanisms – a review, *in* Shroder, J., editor, Treatise on geomorphology (second edition), Academic Press, v. 5, p. 137–168, https://doi.org/10.1016/B978-0-12-818234-5.00066-3.

Love, D.W., 2001, What decision makers should know about collapsible soils in New Mexico, *in* Johnson, P.S., editor, Water, watersheds, and land use in New Mexico, New Mexico Decision-Makers Field Guide No. 1: Albuquerque, University of New Mexico Printing Services, p. 61–62.

Lucchitta, I., 1979, Late Cenozoic uplift of the southwestern Colorado Plateau and adjacent Colorado River region: Tectonophysics, v. 61, p. 63–95.

Lund, W.R., 1997, La Verkin Creek sinkhole geologic investigation, Washington County, Utah, *in* Mayes, B.H., compiler, Technical Reports for 1996, Applied Geology Program: Utah Geological Survey Report of Investigation 231, p. 25–41, https://doi.org/10.34191/RI-231.

Lund, W.R., Christenson, G.E., Batatian, L.D., and Nelson, C.V., 2020a, Guidelines for evaluating surface-fault-rupture hazards in Utah, *in* Bowman, S.D., and Lund, W.R., editors, Guidelines for investigating geologic hazards and preparing engineering-geology reports, with a suggested approach to geologic-hazard ordinances in Utah, second edition: Utah Geological Survey Circular 128, p. 31–58, https://doi.org/10.34191/C-128.

Lund, W.R., Castleton, J.J., and Bowman, S.D., 2020b, Guidelines for site-specific evaluation of geologic radon hazard in Utah, *in* Bowman, S.D., and Lund, W.R., editors, Guidelines for investigating geologic hazards and preparing engineering-geology reports, with a suggested approach to geologic-hazard ordinances in Utah, second edition: Utah Geological Survey Circular 128, p. 125–136, https://doi.org/10.34191/C-128.

Lund, W.R., and Knudsen, T.R., 2020, Guidelines for evaluating rockfall hazards in Utah, *in* Bowman, S.D., and Lund, W.R., editors, Guidelines for investigating geologic hazards and preparing engineering-geology reports, with a suggested approach to geologic-hazard ordinances in Utah, second edition: Utah Geological Survey Circular 128, p. 111–123, https://doi.org/10.34191/C-128.

Lund, W.R., Knudsen, T.R., and Sharrow, D.L., 2010, Geologic hazards of the Zion National Park geologic-hazard study area, Washington and Kane Counties, Utah: Utah Geological Survey Special Study 133, 97 p., 12 plates, scale 1:24,000, https://doi.org/10.34191/SS-133.

Lund, W.R., Knudsen, T.R., and Vice, G.S., 2008a, Paleoseismic reconnaissance of the Sevier fault, Kane and Garfield Counties, Utah—Paleoseismology of Utah, Volume 16: Utah Geological Survey Special Study 122, 37 p., https://doi.org/10.34191/SS-122.

Lund, W.R., Knudsen, T.R., Vice, G.S., and Shaw, L.M., 2008b, Geologic hazards and adverse construction conditions—St. George-Hurricane metropolitan area, Washington County, Utah: Utah Geological Survey Special Study 127, 105 p., 14 plates, scale 1:24,000, https://doi.org/10.34191/SS-127.

Lundin, E.R., 1989, Thrusting of the Claron Formation, the Bryce Canyon region, Utah: Geological Society of America Bulletin, v. 101, p. 1038–1050.

Marine, W., 1963, Ground-water resources of the Bryce Canyon National Park area, Utah: U.S. Geologic Survey Water-Supply Paper 1475-M, p. 441–486, 3 plates, https://doi.org/10.3133/wsp1475M.

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

Martinez, J.D., Johnson, K.S., and Neal, J.T., 1998, Sinkholes in evaporite rocks: American Scientist, v. 86, p. 38–51.

May, S.B., Leavitt, R.E., and MacLean, J.S., 2011, Extent of footwall shear adjacent to the Ruby's Inn thrust fault, southern Utah [abs.]: Geological Society of America Abstracts with Programs, v. 43, no. 5, p. 116.

McCalpin, J.P., 2009, editor, Paleoseismology (second edition): Burlington, Massachusetts, Academic Press (Elsevier), 613 p.

McColl, S.T., 2022, Chapter 2 – Landslide causes and triggers, *in* Davies, T., Rosser, N., and Shroder, J.F., editors, Landslide hazards, risks, and disasters, second edition: Elsevier, p. 13–41, https://doi.org/10.1016/B978-0-12-818464-6.00011-1.

Merle, O.R., Davis, G.H., Nickelsen, R.P., and Gourlay, P.A., 1993, Relation of thin-skinned thrusting of Colorado Plateau strata in southwestern Utah to Cenozoic magmatism: Geological Society of America Bulletin, v. 105, p. 387–398.

Moore, J.R., 2015, Navajo Loop Trail, Bryce Canyon National Park—Preliminary rockfall hazard evaluation: unpublished report to the National Park Service, 14 p.

Muckel, G.B., 2004, Gypsum in excess, *in* Muckel, G.B., editor, Understanding soil risks and hazards—using soil survey to identify areas with risks and hazards to human life and property: Lincoln, Nebraska, Natural Resources Conservation Service, National Survey Center, p. 58–59.

Mulvey, W.E., 1992, Soil and rock causing engineering geologic problems in Utah: Utah Geological Survey Special Study 80, 23 p., 2 plates, scale 1:500,000, https://doi.org/10.34191/SS-80.

Murphey, L.M., and Cloud, W.K., 1984, United States earthquakes, 1953: U.S. Geological Survey Open-File Report 84-953, 51 p., https://doi.org/10.3133/ofr84953.

National Park Service (NPS), 2024, National Park Service visitor use statistics for Bryce Canyon National Park: https://irma.nps.gov/Stats/Reports/Park/BRCA, accessed July 2024.

Neary, D.G., Ryan, K.C., and DeBano, L.F., editors, 2005, Wildland fire in ecosystems—effects of fire on soils and water: Ogden, Utah, U.S. Department of Agriculture, Forest Service Rocky Mountain Research Station General Technical Report RMRS-GTR-42, v. 4, 250 p.

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

Neuendorf, K.K.E., Mehl, J.P., Jr., and Jackson, J.A., editors, 2011, Glossary of geology (fifth edition, revised): Alexandria, Virginia, American Geosciences Institute, 800 p.

Nickelsen, R.P., Merle, O., and Davis, G.H., 1992, Structures of the mid-Tertiary radial compression in the High Plateaus of southern Utah in relation to Sevier, Laramide, and Basin and Range deformation [abs.]: Geological Society of America Abstracts with Programs, v. 24, no. 6, p. 55.

Ott, A., 1996, Natural spring inventory, Bryce Canyon National Park: National Park Service Resource Management Division, 42 p.

Otton, J.K., 1992, Geology of radon: U.S. Geological Survey, general interest publication, 29 p., https://doi.org/10.3133/7000018.

Owens, R.L., and Rollins, K.M., 1990, Collapsible soil hazard map for the southern Wasatch Front, Utah: Utah Geological and Mineral Survey Miscellaneous Publication 90-1, 38 p., https://doi.org/10.34191/MP-90-1.

Parker, G.G., 1963, Piping, a geomorphic agent in landform development of the drylands: International Association of Scientific Hydrology Publication 65, p. 103–113.

Reed, T., 2020, Hazard analysis of a segment of Highway SR-12 through Bryce Canyon National Park, Southern Utah: Logan, Utah State University, M.S. thesis, 213 p., https://digitalcommons.usu.edu/gradreports/1511.

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

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

Rollins, K.M., Williams, T., Bleazard, R., and Owens, R.L., 1992, Identification, characterization, and mapping of collapsible soils in southwestern Utah, *in* Harty, K.M., editor, Engineering and environmental geology of southwestern Utah: Utah Geological Association Publication 21, p. 145–158.

Santi, P., 2005, Recognition of collapsible soils based on geology, climate, laboratory tests, and structural crack patterns [abs.]: Geological Society of America Abstracts with Programs, v. 37, no. 7, p. 326.

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

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

Smith, K., and Petley, D.N., 2009, Environmental hazards—assessing risk and reducing disaster (fifth edition): New York, Routledge, 383 p.

Smith, R.B., and Arabasz, W.J., 1991, Seismicity of the Intermountain Seismic Belt, *in* Slemmons, D.B., Engdahl, E.R., Zoback, M.D., and Blackwell, D.D., editors, Neotectonics of North America: Boulder, Colorado, Geological Society of America, Decade Map Volume 1, p. 185–228.

Smith, R.B., and Sbar, M.L., 1974, Contemporary tectonics and seismicity of the western United States with emphasis on the Intermountain Seismic Belt: Geological Society of America Bulletin, v. 85, no. 8, p. 1205–1218.

Smith, T.D., and Deal, C.E., 1988, Cracking studies at the Sand H basin by the finite element method, *in* Proceedings 2nd International Conference on Case Histories in Geotechnical Engineering, St. Louis, Missouri: University of Missouri at Rolla, p. 451–455.

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

Stewart, J.H., 1978, Basin-range structure in western North America—a review, *in* Smith, R.B., and Eaton, G.P., editors, Cenozoic tectonics and regional geophysics of the Western Cordillera, Geological Society of America Memoir 152, p. 1–31.

Stipho, A.S., 1992, Aeolian sand hazards and engineering design for desert regions: Quarterly Journal of Engineering Geology and Hydrogeology, v. 25, p. 83–92, https://doi.org/10.1144/GSL.QJEG.1992.025.02.02.

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

Sutcliffe, K., 2005, Soil survey of Grand Staircase-Escalante National Monument area, parts of Kane and Garfield Counties, Utah, UT 686: U.S. Department of Agriculture, Natural Resources Conservation Service, 577 p., https://geodata.geology.utah.gov/pages/view.php?ref=83033.

Swenson, H.K., and Bayer, J., 1990, Soil survey of Panguitch area, Utah, parts of Garfield, Iron, Kane, and Piute Counties: U.S. Department of Agriculture, Soil Conservation Service, 196 p., https://geodata.geology.utah.gov/pages/view.php?ref=57446.

Thiros, S.A., and Brothers, W.C., 1993, Ground-water hydrology of the upper Sevier River Basin, south-central Utah, and simulation of ground-water flow in the valley-fill aquifer in Panguitch Valley: Department of Natural Resources Technical Publication 102, 121 p.

Thornberry-Ehrlich, T., 2005, Bryce Canyon National Park Geologic Resource Evaluation Report, Natural Resource Report NPS/NRPC/GRD/NRR—2005/002: National Park Service, Denver, Colorado.

University of Utah Seismograph Stations (UUSS), 2022a, Utah earthquake map catalog (1850–2016): https://quake.utah.edu/earthquake-information-products/earthquake-catalogs/utah-earthquake-map-catalog, accessed June 20, 2022.

University of Utah Seismograph Stations (UUSS), 2022b, Felt earthquakes in the Utah region-2012: https://quake.utah.edu/earthquake-information-products/earthquake-catalogs/felt-earthquakes-in-the-utah-region#2012, accessed June 4, 2022.

U.S. Environmental Protection Agency (EPA), 1995, Passive radon control system for new construction: EPA 402-95012, 4 p.

U.S. Environmental Protection Agency (EPA), 2001, Building radon out—A step-by-step guide on how to build radon-resistant homes: EPA 402-K-01-002, 84 p.

U.S. Environmental Protection Agency (EPA), 2025, Consumer's guide to radon reduction—How to fix your home: EPA 402/K-10/005, 18 p. https://www.epa.gov/sites/default/files/2016-12/documents/2016_consumers_guide_to_radon_reduction.pdf.

U.S. Geological Survey (USGS), 1997, Debris-flow hazards in the United States: U.S. Geological Survey Fact Sheet 1176-97, 4 p.

U.S. Geological Survey (USGS), 2004, National Uranium Resource Evaluation (NURE) hydrogeochemical and stream sediment reconnaissance data: https://mrdata.usgs.gov/nure/sediment/, accessed June 22, 2021.

U.S. Geological Survey (USGS), 2009, National Uranium Resource Evaluation (NURE) aeroradiometric grids for North America: https://mrdata.usgs.gov/radiometric/, accessed June 25, 2021.

Utah Department of Public Safety, 2024, 2024 Utah enhanced state hazard mitigation plan: Utah Division of Emergency Management, Salt Lake City, 770 p.

Utah Division of Comprehensive Emergency Management, 1981, History of Utah floods—1847 to 1981: Floodplain management status report to Federal Emergency Management Agency, contract no. EMW-R-0223, 46 p.

Utah Division of Homeland Security, 2008, Utah natural hazards handbook: Utah Division of Homeland Security, 128 p.

Utah Division of Water Rights, 2021, Well log information page, Online: https://www.waterrights.utah.gov/wellInfo/wellInfo.asp, accessed December 2021.

Utah Geological Survey, 2022, Utah geologic hazards portal, earthquake hazards, hazardous (Quaternary age) faults layer: https://geology.utah.gov/apps/hazards/, accessed July 6, 2022.

Utah Geospatial Resource Center, 2018, Southern Utah lidar elevation data: Utah Geospatial Resource Center, State Geographic Information Database, https://gis.utah.gov/data/elevation-and-terrain/2018-lidar-southern-utah/.

Utah Geospatial Resource Center, 2019, Kane County lidar elevation data: Utah Geospatial Resource Center, State Geographic Information Database, https://gis.utah.gov/data/elevation-and-terrain/2019-lidar-kane-county/.

Utah Seismic Safety Commission, 2022, Putting down roots in earthquake country—your handbook for earthquakes in Utah, second edition: Utah Seismic Safety Commission, 38 p.

Varnes, D.J., 1978, Slope movement types and processes, *in* Schuster, R.L., and Krizek, R.J., editors, Landslides—analysis and control: Washington, D.C., National Academy of Sciences, National Research Council, Transportation Research Board Special Report 176, p. 11–33.

Wallace, J., Schlossnagle, T.H., Hurlow, H., Payne, N., and Hardwick, C., 2021, Hydrogeologic study of the Bryce Canyon City area, including Johns and Emery Valleys, Garfield County, Utah: Utah Geological Survey Open-File Report 733, 55 p., 6 appendices, 2 plates, scale 1:62,500, https://doi.org/10.34191/OFR-733.

Western Regional Climate Center, 2022, Western U.S. Climatological Data Summaries, NOAA Cooperative Stations Map: https://wrcc.dri.edu/summary/Climsmut.html, accessed June, 2022.

Western States Seismic Policy Council, 2021, Policy Recommendation 21-3—Definitions of recency of surface faulting for the Basin and Range Province: Western States Seismic Policy Council, 5 p.

White, J.L., Wait, T.C., and Morgan, M.L., 2008, Geologic hazards mapping project for Montrose County, Colorado: Colorado Geological Survey,https://www.montrosecounty.net/DocumentCenter/View/119/Final_CGS_Montrose_County_geohaz_report?bidId=, accessed July 2019.

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

Wieczorek, G.F., Morrissey, M.M., Iovine, G., and Godt, J., 1998, Rock-fall hazards in the Yosemite Valley: U.S. Geological Survey Open-File Report 98-467, 7 p., 1 plate, scale 1:12,000.

Wieczorek, G.F., Wilson, R.C., and Harp, E.L., 1985, Map showing slope stability during earthquakes in San Mateo County, California: U.S. Geological Survey Miscellaneous Investigations Series Map I-1257-E, scale 1:62,500, https://doi.org/10.3133/i1257E.

Williams, T., and Rollins, K.M., 1991, Collapsible soil hazard map for Cedar City, Utah area: Utah Geological Survey

Contract Report 91-10, 44 p., https://doi.org/10.34191/CR-91-10.

Wong, I.G., and Humphrey, J.R., 1989, Contemporary seismicity, faulting, and the state of stress in the Colorado Plateau: Geological Society of America, v. 101, p. 1127–1146.

Wong, I.G., Olig, S.S., and Bott, J.D.J., 1996, Earthquake potential and seismic hazards in the Paradox basin, southeastern Utah, *in* Huffman, A.C., Lund, W.R., and Goodwin, L.H., editors, Geology and Resources of the Paradox Basin: Utah Geological Association and Four Corners Geological Society Guidebook 25, p. 241–250.

Wong, I.G., Silva, W., Olig, S., Thomas, P., Wright, D., Ashland, F., Gregor, N., Pechmann, J., Dober, M., Christenson, G., and Gerth, R., 2002, Earthquake scenario and probabilistic ground shaking maps for the Salt Lake City metropolitan area, Utah: Utah Geological Survey Miscellaneous Publication 02-05, 50 p., 9 plates, https://doi.org/10.34191/MP-02-5.

Woolley, R.R., 1946, Cloudburst floods in Utah, 1850–1938: U.S. Geological Survey Water-Supply Paper 994, 128 p., https://doi.org/10.3133/wsp994.

World Health Organization (WHO), 2009, WHO handbook on indoor radon—A public health perspective: Geneva, Switzerland, WHO Press, 94 p.

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

Youd, T.L., 1984, Geologic effects—liquefaction and associated ground failure: U.S. Geological Survey Open-File Report 84-760, p. 210–232, https://doi.org/10.3133/ofr84760.

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

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

Young, R.A., and Spamer, E.E., 2001, Colorado River origin and evolution: Grand Canyon National Park, Grand Canyon Association, 280 p.