GEOLOGIC HAZARDS OF THE ZION NATIONAL PARK GEOLOGIC-HAZARD STUDY AREA, WASHINGTON AND KANE COUNTIES, UTAH

by William R. Lund, Tyler R. Knudsen, and David L. Sharrow

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Cover Image: *Dump truck crushed by rock fall on November 23, 1947, in Zion National Park (photo courtesy of the National Park Service).*

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Chapter 1
Introduction

This chapter is part of Utah Geological Survey Special Study 133, *Geologic Hazards of the Zion National Park Geologic-Hazard Study Area, Washington and Kane Counties, Utah.*

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Chapter 1: Introduction

ABSTRACT

Zion National Park receives more than 2.5 million visitors annually, and is subject to a variety of geologic hazards that may affect park development and visitor safety. To provide the National Park Service with geologic-hazard information for future park management, the Utah Geological Survey conducted a geologic-hazard investigation of a portion of Zion National Park. The Zion National Park Geologic-Hazard Study Area is a contiguous 154-square-mile area that encompasses Zion Canyon, the Kolob Canyons and Kolob Terrace areas of the park, the Zion–Mount Carmel Highway corridor, and all currently developed and high-use areas of the park.

Results of this investigation include nine 1:24,000-scale (1"= 2000') geologic-hazard maps that cover flooding and debris flows, rock fall, landslides, surface faulting, liquefaction, collapsible soil, expansive soil and rock, gypsiferous soil and rock, and soil piping and erosion. Accompanying text documents describe the geologic hazards and provide background information on data sources, the nature and distribution of the hazards, and possible hazard-reduction measures. The text documents also include a discussion of earthquake-induced ground shaking, but data are insufficient to prepare a ground-shaking-hazard map.

The maps are intended for use in general planning to indicate where site-specific geologic-hazards investigations are necessary. We recommend a site-specific geotechnical investigation for all new construction in the study area, and a geologic assessment to identify potential geologic hazards at sites within special-study areas shown on the maps accompanying this report. Site-specific investigations can resolve uncertainties inherent in these 1:24,000-scale maps, and help increase safety by identifying the need for special construction design or hazard mitigation.

On an annual basis, the most widespread and dangerous geologic hazard in the Zion National Park Geologic-Hazard Study Area is flooding. Eight individuals lost their lives between 1950 and 2008 due to flooding, and floods and debris flows have repeatedly damaged park facilities. Rock falls have resulted in three deaths and property damage in the park. Several buildings and high-use visitor areas lie within mapped rock-fall areas. Landslides are common where clay-rich bedrock crops out on slopes. Landslides have damaged park transportation corridors, and three landslides adjacent to the park in the town of Springdale just south of the park boundary have damaged or threatened structures. Collapsible soil is the most prevalent soil-related geologic hazard, and at least one park building has sustained significant damage due to soil collapse. Large earthquakes are rare events in southwestern Utah, but faults in the region are capable of producing magnitude 6.5–7.0 earthquakes, and have the greatest potential for causing catastrophic property damage and loss of life. An earthquake in 1992 produced numerous rock falls and triggered translational and rotational landslides in and near the study area.

Because of their wide distribution, frequent occurrence, and destructive potential, we expect floods, rock falls, landslides, and collapsible soil to be the principal geologic hazards with which planners, public safety personnel, and maintenance workers in Zion National Park must contend. With the exception of the effect of a 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

The purpose of this study is to provide the National Park Service (NPS) with geographic-information-system (GIS) data on the kind and location of geologic hazards that may affect existing and future development and visitor safety in the Zion National Park Geologic-Hazard Study Area (figure 1.1). The study area boundaries are contained wholly within the boundaries of Zion National Park, and were established in consultation with the park's planning and administrative staff and the NPS Geologic Resources Division.

A geologic hazard is a naturally occurring geologic condition or phenomenon that presents a potential threat to human life, welfare, and property (modified from Neuendorf and others, 2005). Table 1.1 lists the geologic hazards considered in this study.

We compiled the data for this study at a scale of 1:24,000 (1"= 2000'). The GIS-based geologic-hazard maps accompanying this report (plates 1–9) are also at 1:24,000-scale. The maps are designed as an aid for general planning to indicate where detailed, site-specific geologic-hazards investigations are required. The maps are not intended to be enlarged for use at scales larger than the scale at which they were compiled, and are not a substitute for site-specific geotechnical investigations.

Regarding special studies, we recommend a site-specific geotechnical investigation for all new construction in the Zion National Park Geologic-Hazard Study Area, and a geologic assessment to identify potential geologic hazards at sites within special-study areas shown on the maps that accompany this report. Site-specific investigations can resolve uncertainties inherent in these 1:24,000-scale maps, and help increase safety by identifying the need for special engineering design or hazard mitigation.

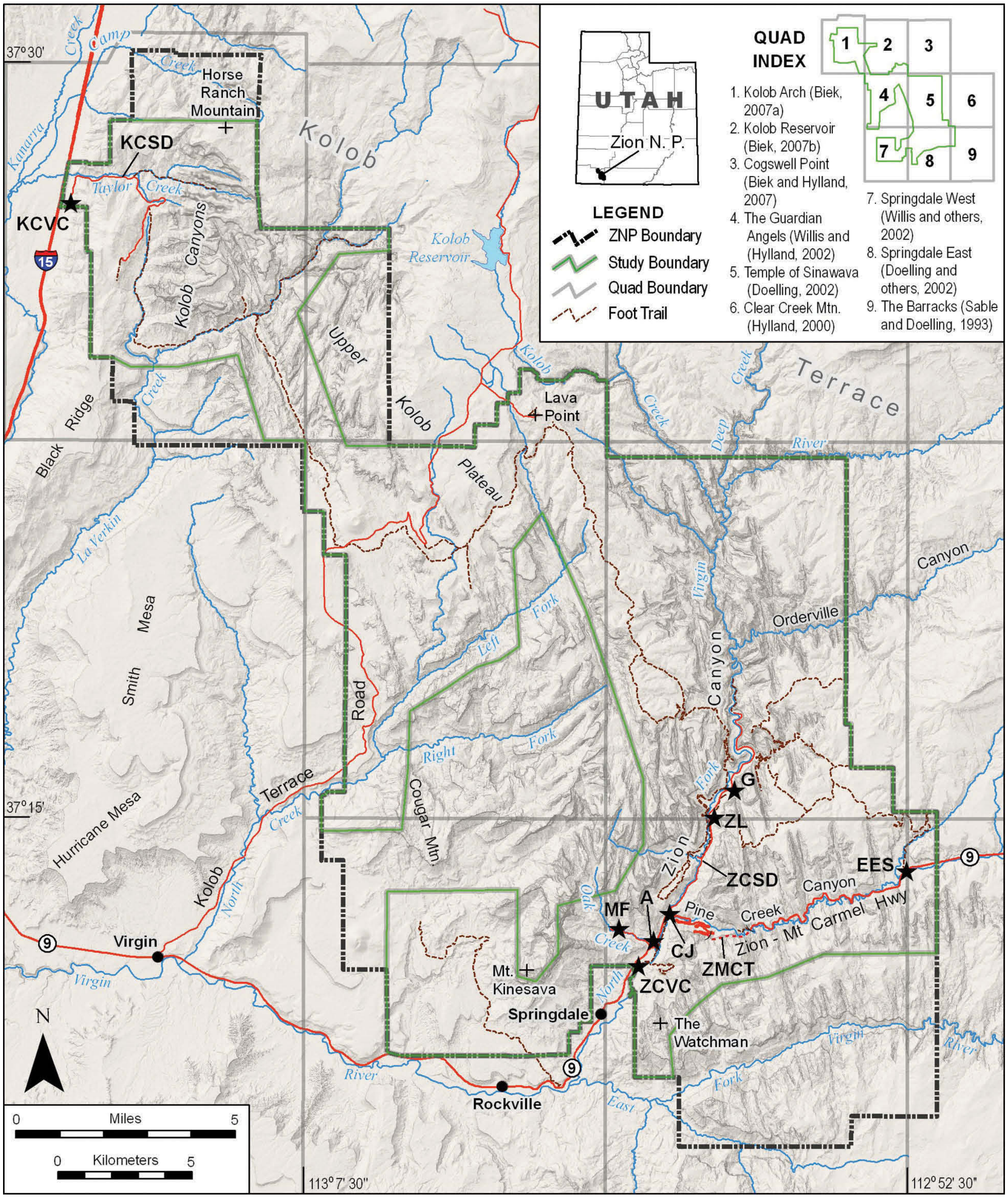

Figure 1.1. Boundaries, principal developed areas, transportation corridors, high-use trails, and index of UGS 7.5' geologic quadrangle maps (see text for references) in the Zion National Park Geologic-Hazard Study Area. Stars indicate specific locations discussed in text: A = Administration Building, CJ = Canyon Junction, EES = East Entrance Station, G = The Grotto, KCSD = Kolob Canyon Scenic Drive, KCVC = Kolob Canyon Visitor Center, MF = Maintenance Facility, ZCVC = Zion Canyon Visitor Center, ZCSD = Zion Canyon Scenic Drive, ZL = Zion Lodge, ZMCT = Zion–Mount Carmel Tunnel.

BACKGROUND

United States President William Howard Taft created Mukuntuweap National Monument in 1909 to protect the outstanding natural values of Zion Canyon. The monument was expanded and renamed Zion National Monument in 1918, and in 1919 was made a national park by the United States Congress. The Kolob section of the park was established as a second Zion National Monument in 1937 and was incorporated into the park in 1956. The original monument covered 15,840 acres (about 25 square miles), was difficult to access, and hosted a few hundred visitors per year; today, Zion National Park encompasses 147,732 acres

Table 1.1. *Geologic hazards considered in this report.*

Flooding and debris flow
Rock fall
Landslides
Surface faulting
Earthquake ground shaking[1]
Liquefaction
Collapsible soil
Expansive soil and rock
Gypsiferous soil and rock
Piping and erosion
[1]Text document only, data were insufficient to prepare a ground-shaking hazard map.

(about 231 square miles; figure 1.1), is easily reached via Utah State Route 9 from either Interstate 15 or U.S. Highway 89, and received 2,712,053 visitors in 2008 (NPS, 2009). An additional 3296 acres (about 5 square miles) of private inholdings exist in the Kolob Terrace area in the northern part of the park.

Mormon pioneers settled the Virgin River region beginning in the 1850s. In 1858, Nephi Johnson explored the upper Virgin River area in Zion Canyon, making him the first recorded visitor of European descent to enter upper Zion Canyon. Johnson returned later that year to found the town of Virgin, and additional settlers arrived in 1860 and 1861 to settle the towns of Rockville and Springdale in lower Zion Canyon (figure 1.1). Upper Zion Canyon near the site of today's Zion Lodge was settled in 1863 by Isaac Behunin, who farmed row crops and planted orchards. Additional settlers arrived within a few years bringing cattle and other domesticated animals with them. The floor of the canyon was farmed intensively until Mukuntuweap National Monument was created in 1909.

Travel to Zion Canyon prior to the area becoming a national park was limited by the area's remote location and lack of roads. A road to The Grotto (figure 1.1) was completed in 1917 and extended to the Temple of Sinawava in 1925. The NPS and later the Civilian Conservation Corps (CCC) built many of the park's trails in the 1930s and 40s, portions of which required extensive blasting to construct. Following completion of the Zion–Mount Carmel Highway in 1930, access was available to the park from the east and park visitation greatly increased. This road was constructed by the NPS expressly to improve travel connections between southern Utah parks. A principal feature of the highway is the 1.1-mile-long Zion–Mount Carmel Tunnel (figure 1.1) that provides access through sheer Navajo Sandstone cliffs from the canyon below to the plateau above.

Numerous buildings were constructed in the park for visitor use, for housing park and concessionaire employees, and to accommodate administrative and maintenance functions, and all described here remain in use. Zion Lodge (figure 1.1) was built in 1925; the main lodge burned down in 1968 and was rebuilt at the same location. The Zion Lodge complex currently includes 27 permanent structures used for guest accommodations, employee housing, and service buildings. The original ranger cabin was constructed at The Grotto in the 1920s, and the CCC built the park maintenance facility in Oak Creek Canyon in the 1930s (figure 1.1). A park administrative center has developed over the years near the south entrance to the park (figure 1.1). This area includes housing built in the 1930s through 60s on the east (Watchman) and west (Oak Creek) sides of the lower canyon and near the mouth of Pine Creek Canyon, and a visitor center constructed in the 1950s facing the Temples and Towers of the Virgin in lower Zion Canyon. A new visitor center, emergency operations center, shuttle bus maintenance facility, and greenhouse were added in the 1990s and early 2000s. The original visitor center has been converted to administrative offices and a human history museum.

SCOPE OF WORK

The scope of work performed for this study consisted of:

- Identifying and reviewing digital geologic, hydrologic, and soils information; digital elevation models; and aerial photography available for the study area.
- Digitizing and rectifying relevant nondigital geologic, hydrologic, and soils information available for the study area.
- Compiling a digital geotechnical database incorporating test pit, borehole, and laboratory data, and other information from geotechnical reports on file with the NPS and the Town of Springdale.
- Incorporating current road, trail, and land parcel information into a geographic information system (GIS) database.
- Creating GIS-based derivative geologic-hazard maps for nine principal geologic hazards affecting the study area.
- Field checking and mapping as necessary to improve the geologic-hazard maps.
- Preparing explanatory text documents to accompany the geologic-hazard maps.

The principal products of this study are nine 1:24,000-scale geologic-hazard maps for the Zion National Park Geologic-Hazard Study Area (plates 1–9) and accompanying explanatory text documents. Each map covers a different geologic hazard, and the accompanying text documents provide background information on the data sources used to create the maps, the nature and distribution of the hazards, and possible hazard-reduction measures. The text documents include a discussion of earthquake-induced ground shaking, but data are insufficient to prepare a ground-shaking-hazard map. The study includes an ArcGIS 9.3 geodatabase that contains all of the hazards information used to develop the nine maps. This geodatabase may be used directly in ArcGIS 9.3 or later versions, or in other GIS applications.

Although we compiled the data used in this study from a wide variety of sources (see individual text document chapters), the principal sources of information used to create the maps, in addition to the new databases specifically created for this project, include (1) the nine UGS 7.5-minute geologic quadrangle maps (Clear Creek Mountain [Hylland, 2000], Cogswell Point [Biek and Hylland, 2007], Kolob Arch [Biek, 2007a], Kolob Reservoir [Biek, 2007b], Springdale East [Doelling and others, 2002], Springdale West [Willis and others, 2002], Temple of Sinawava [Doelling, 2002], The Barracks [Sable and Doelling, 1993], and The Guardian Angels [Willis and Hylland, 2002]) that lie entirely within or include portions of Zion National Park (figure 1.1); (2) Natural Resources Conservation Service (formerly Soil Conservation Service) *Soil Survey of Washington County Area, Utah* (Mortensen and others, 1977), which has been digitized and made available by the Utah Automated Geographic Reference Center; (3) Utah Geological Survey Special Study 127, *Geologic Hazards and Adverse Construction Conditions, St. George–Hurricane Metropolitan Area, Washington County, Utah* (Lund and others, 2008b); (4) 29 geotechnical investigation reports from within the study area and nearby locations; and (5) unpublished memos, reports, and written communications provided by NPS personnel.

We also compared geologic units in the study area with similar geologic units characterized for a geologic-hazards study of the St. George–Hurricane metropolitan area 8 miles to the west, where geotechnical data were more abundant (Lund and others, 2008b). 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 become 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.

SETTING

The Zion National Park Geologic-Hazard Study Area is a contiguous 154-square-mile area within Zion National Park that includes all developed and high-visitation areas within the park, all major transportation corridors (Zion–Mount Carmel Highway, Zion Canyon Scenic Drive, Kolob Terrace Road, Lava Point Road, and Kolob Canyons Scenic Drive), and all trails that receive high-volume foot traffic (figure 1.1). The study area boundaries were established jointly by the UGS, the planning and administrative staff of Zion National Park, and the NPS Geologic Resources Division.

Located in Washington, Iron, and Kane Counties in southwestern Utah, Zion National Park is characterized by deep canyons, rock towers, mesas, and high plateaus. Major perennial streams within the park include the North and East Forks of the Virgin River, the Left and Right Forks of North Creek, La Verkin Creek, and Taylor Creek. The community of Springdale is adjacent to the south park entrance, St. George is 25 miles to the west, and Mount Carmel Junction and Kanab are the nearest communities to the east (figure 1.2).

Zion Canyon is the largest of the canyons within Zion National Park, and receives the majority of park visitors. Zion Canyon can be divided into upper and lower sections, with the boundary between them at Canyon Junction (figure 1.1) where the Zion–Mount Carmel Highway and Zion Canyon Scenic Drive intersect. The upper canyon is restricted at its lower end by the historically active Sentinel landslide. The canyon becomes wider above the landslide and then is characterized by an increasingly narrow canyon bottom upstream that culminates in The Narrows. In The Narrows, the North Fork of the Virgin River has carved a gorge several miles long with sandstone walls rising 2000 to 3000 feet above the stream. Lower Zion Canyon is wider (up to three-quarters of a mile wide in places), but still flanked by towering sandstone cliffs.

The southern part of the park is chiefly a desert area, with mesas bordered by rocky canyons and washes. The northern part of the park includes the Kolob Terrace and Kolob Canyons areas (figure 1.1). Kolob Terrace is forested at its higher elevations. The Kolob Canyons are incised into the western edge of the terrace at the northwest corner of the park. From the eastern portal of the Zion–Mount Carmel Tunnel to the eastern park boundary, the Zion–Mount Carmel Highway traverses sandstone plateaus and mesas. Elevations in the park vary from 8726 feet at the summit of Horse Ranch Mountain near the northern park boundary in the Kolob Canyons area, to 3635 feet at the southwestern corner of the park near the Virgin River (figure 1.1), an elevation difference of about 5100 feet.

All but the highest elevations in the study area are typified by a semiarid climate (10–20 inches of precipitation annually). Most precipitation comes in the form of intense, short-duration summer cloudburst storms and occasional longer duration, regional rainstorms generated by moisture from the Gulf of California in the summer and from the Pacific Ocean in the winter. A period of marked dryness occurs from mid-May to mid-July. There are two active weather stations in Zion National

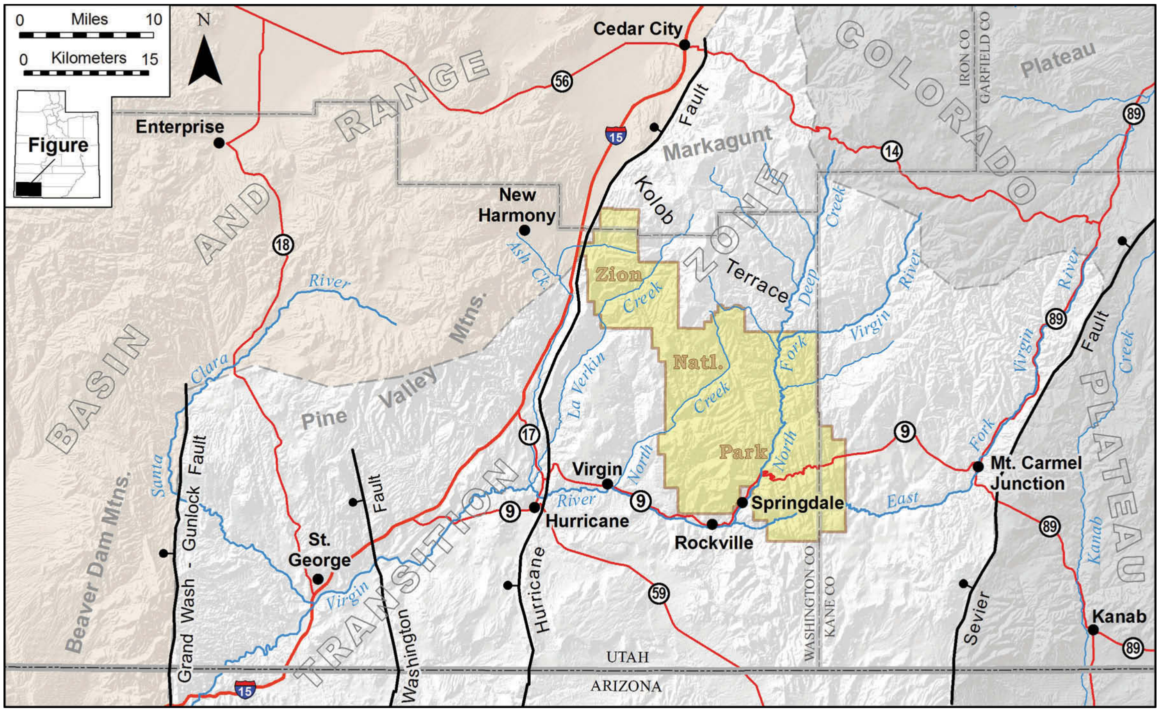

Figure 1.2. *Major transportation corridors, nearby communities, principal drainages, physiographic province boundaries, and large potentially active normal faults in the Zion National Park region.*

Park: the Zion Canyon station in lower Zion Canyon (elevation 3999 feet; period of record 1/1/1904 to present with some gaps), and the Lava Point station on the Kolob Terrace (elevation 7890 feet; period of record 7/1/1996 to present) (Western Regional Climate Center, 2008). Average annual precipitation at the Zion Canyon weather station is 15.04 inches, and the average annual maximum and minimum temperatures are 75.0 and 46.9 degrees Fahrenheit (ºF), respectively. Average high temperatures in June and July exceed 90ºF, and average low temperatures in December and January are less than 30ºF (Western Regional Climate Center, 2008). At Lava Point, average annual precipitation is 19.77 inches, and the average annual maximum and minimum temperatures are 72.03 and 16.59ºF, respectively. The average maximum temperature in July exceeds 90ºF, and the average minimum temperature in January is –1.54ºF (Western Regional Climate Center, 2008).

GEOLOGY

Numerous workers have studied the geology of Zion National Park. Biek and others (2003) provide an excellent summary of park geology that includes a reference list of geologic publications pertinent to the park. We recommend that readers interested in general information on park geology begin by consulting Biek and others (2003). We limit our discussion here to a brief description of the geologic units, structures, and conditions pertinent to geologic hazards within the Zion National Park Geologic-Hazard Study Area. The text documents that accompany the geologic-hazard maps prepared for this study contain additional information about geologic units and structures that contribute to specific geologic hazards.

Zion National Park lies within the Transition Zone between the comparatively simple geology of the high-standing Colorado Plateau to the east, and the geologically complex, lower-lying Basin and Range Province to the west (Stokes, 1977) (figure 1.2). The Transition Zone is several tens of miles wide in southwestern Utah and exhibits structural and stratigraphic characteristics of both physiographic provinces. Zion National Park lies within a structural block that is bounded by the Sevier fault on the east and the Hurricane fault on the west; both are large-displacement, down-to-the-west, normal-slip, basin-and-range-style faults (figure 1.2).

The Hurricane fault has a higher Quaternary vertical slip rate than the Sevier fault (Lund and others, 2007, 2008a), and uplift along the Hurricane fault has placed the park at an intermediate structural position and elevation between the Colorado Plateau and Basin and Range Province. Because of its comparatively high structural and topographic position relative to the Basin and Range Province and the Colorado River, to which the perennial streams in the park are tributary, erosion is the chief geomorphic process in the region. Rivers and streams incising the western edge of the structural block are actively carving the canyons of Zion National Park at the exceptionally high rate of about 1300 feet per million years (Biek and others, 2003).

Bedrock exposed in Zion National Park ranges in age from the Permian Fossil Mountain Member of the Kaibab Formation to Quaternary basalt flows and cinder cones (Biek and others, 2003) (figures 1.3 and 1.4). The rock units represent a nearly 7000-foot section of chiefly marine and continental depositional environments; rock types include limestone, mudstone, claystone, shale, sandstone, conglomerate, evaporite, and basalt. A similar, if not greater, thickness of Paleozoic and Mesozoic sedimentary rocks have been eroded from the area and crop out only at higher elevations north of the park. Some bedrock units in the park contain a high percentage of clay and are correspondingly weak and moisture sensitive, making them susceptible to landslides and volumetric change (shrink/swell). Landslides associated with weak rock units are common over large areas of the park, and frequently coalesce to form landslide complexes. More competent, cliff-forming rock formations are cut by large, through-going joint sets (figure 1.5), which make many areas of the park susceptible to rock fall. Quaternary basalt flows and cinder cones (figure 1.3) are present at several locations in the park; some flows originating in the park have been displaced hundreds to thousands of feet by normal-slip faults.

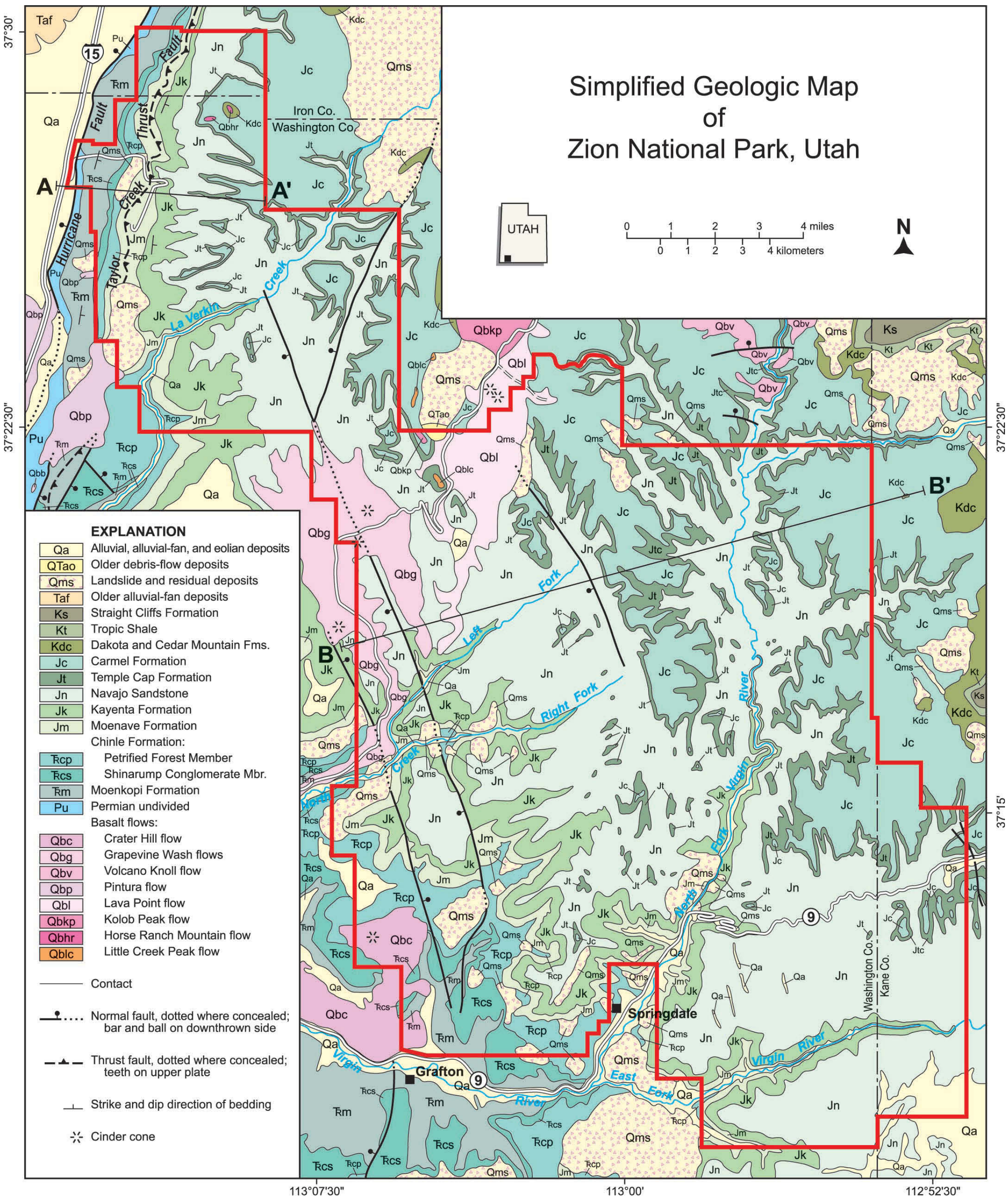

Figure 1.3. Simplified geologic map of Zion National Park (after Biek and others, 2003).

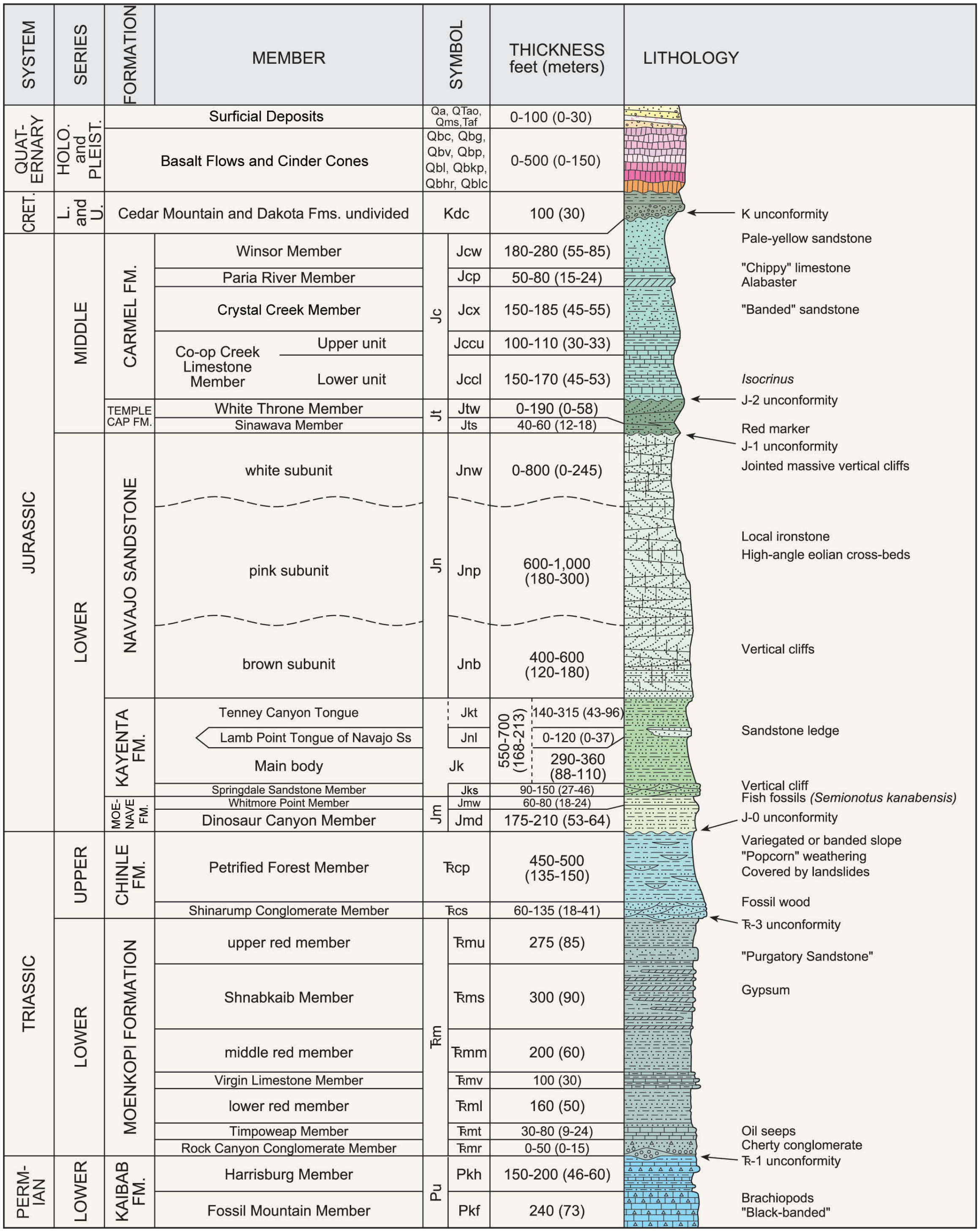

Figure 1.4. *Lithologic column of geologic units that crop out in Zion National Park (modified from Biek and others, 2003).*

Unconsolidated geologic units in the study area are generally 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, particularly the North Fork of the Virgin River in lower Zion Canyon. Alluvial fans have formed at the mouths of many tributary drainages in lower Zion Canyon and other large canyons (figure 1.6). The alluvial fans are generally small and bury stream deposits where the tributary drainages enter larger canyons. Because the debris-flood and debris-flow deposits that form the fans are typically poorly sorted and have low bulk densities, the fan deposits may be susceptible to collapse upon wetting.

Colluvium and talus deposits (figure 1.7) mantle slopes formed on the Chinle, Moenave, and Kayenta Formations, where those rock formations crop out at the base of near-vertical Navajo Sandstone cliffs. The colluvium and talus deposits contain

Figure 1.5. Jointed cliffs of Navajo Sandstone have produced numerous rock falls within the study area.

Figure 1.7. Colluvium, talus, and rock-fall deposits at the base of near-vertical Navajo Sandstone cliffs mantle underlying bedrock formations.

Figure 1.6. Small alluvial fan formed at the mouth of an ephemeral tributary to the North Fork of the Virgin River.

numerous rock-fall boulders that can be tens of feet in their longest dimension. The isolated remnants of very large rock-fall deposits are present locally in canyon bottoms far from existing cliff faces. In narrower canyons, large rock falls have blocked drainages and created temporary natural dams behind which lake deposits accumulated. Future large rock falls could create additional water impoundments with the accompanying possibility of severe flooding should a rock-fall dam breach catastrophically. In upland areas, generally thin units of mixed eolian, alluvial, and colluvial material mantle areas of shallow bedrock.

Geologic structure in Zion National Park is typified by a thick stack of sedimentary strata that dip gently (3–5 degrees) to the east (figure 1.8). However, several basin-and-range-style normal-slip faults displace rock units in the western half of the park. The largest of these is the down-to-the-west Hurricane fault, which crosses the extreme westernmost part of the park for a short distance near the Kolob Canyons Visitor Center and again at the northwest corner of the park (figures 1.2, 1.3, and 1.8). The Hurricane fault is the longest normal-slip fault in southwestern Utah. The nearly 160-mile-long fault extends from south of the Grand Canyon in Arizona to Cedar City in Utah. Net vertical displacement of the fault in the park exceeds 2000 feet (Anderson and Christenson, 1989; Lund and others, 2007). Abundant geologic evidence shows that the Hurricane fault has generated numerous large-magnitude surface-faulting earthquakes in the late Quaternary (Lund and others, 2007). Other normal-slip faults in the park have displacements that are measured in hundreds rather than thousands of feet (Biek and others, 2003). Relations with bedrock and unconsolidated deposits, chiefly volcanic basalt flows, indicate that these faults have lower vertical slip rates than the Hurricane fault, although their style and sense of movement are consistent with the region's current extensional tectonic regime.

In the northwestern part of the park, the Taylor Creek thrust fault (figure 1.3) and Kanarra anticline (figure 1.8) are older structures associated with eastward-directed thrusting during

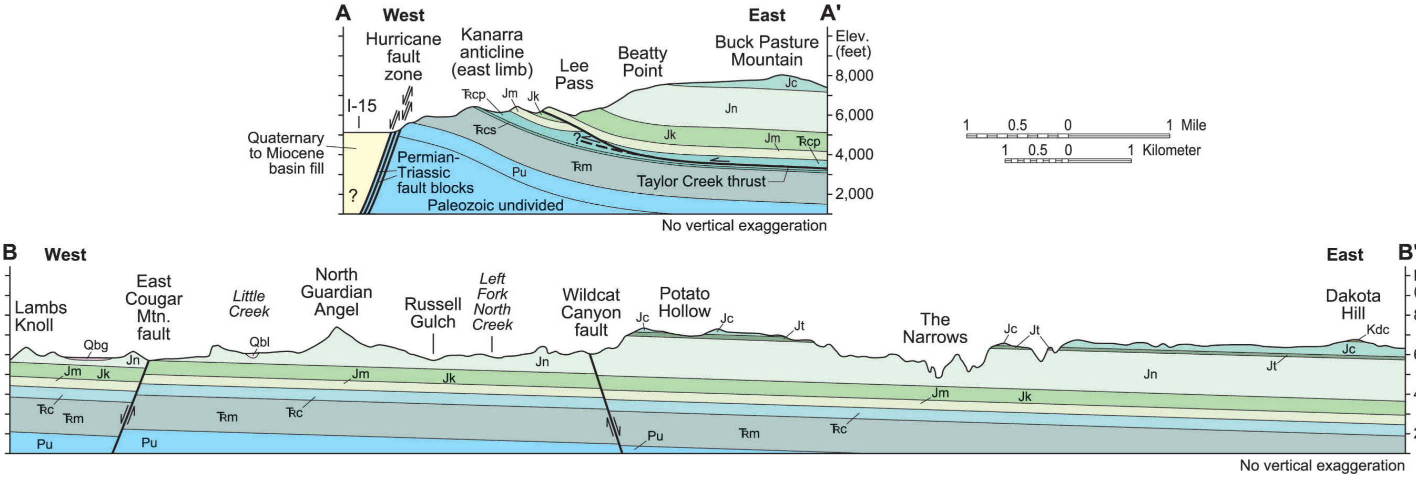

Figure 1.8. *Simplified geologic cross section of Zion National Park (after Biek and others, 2003). See figure 1.3 for explanation of geologic-unit symbols.*

the Sevier orogeny in Late Cretaceous to early Tertiary time. While no longer considered capable of producing earthquakes, these structures locally affect the strike and dip of rock units, which contributes to unstable slope conditions in some areas.

RELATIVE IMPORTANCE OF GEOLOGIC HAZARDS IN THE STUDY AREA

This report provides information on ten geologic hazards in the Zion National Park Geologic-Hazard Study Area; however, not all of the hazards are of equal concern. On an annual basis, the most widespread and potentially life threatening/damaging geologic hazard in the study area is flooding. Historic accounts of floods in Zion Canyon date back to the mid-nineteenth century (Woolley, 1946; Butler and Marsell, 1972; NPS, unpublished data) and provide ample evidence of the destructive power and life-threatening nature of flooding in the study area. Sediment-laden flash floods, debris floods, and debris flows commonly occur in response to intense summer cloudburst thunderstorms throughout the study area. Floods in larger drainages also occur in response to thunderstorms, but their large drainage areas (up to hundreds of square miles) also make them susceptible to rapid snowmelt events and prolonged regional rainstorms that linger over their headwaters. Between 1950 and 2008, eight people drowned as the result of flooding in Zion National Park (NPS, unpublished data).

Rock fall represents a significant hazard to life and property (for example, see Lund, 2002), and evidence of rock falls from cliff-forming sandstone strata (chiefly the Navajo Sandstone, Lamb Point Tongue Member of the Navajo Sandstone, Springdale Sandstone Member of the Kayenta Formation, and Shinarump Member of the Chinle Formation) is widespread in the study area. Three deaths and repeated property damage have occurred due to rock falls in Zion National Park (NPS, unpublished data). The probability of a damaging/life threatening rock fall is greatly increased where permanent facilities, transportation routes, and high-use visitor areas are located in rock-fall-hazard zones.

Landslides, especially landslides highly modified by erosion, can be difficult to recognize, but their stability remains suspect and their identification and proper accommodation in project planning and design is critical if slope-stability problems are to be avoided (Christenson, 1986; Transportation Research Board, 1996). The close correlation of landslides with weak bedrock units in the study area provides ample evidence that development on slopes underlain by landslide-susceptible geologic units must proceed with caution. Although most landslides are outside developed or high-visitation areas of the park, the Sentinel and Zion–Mount Carmel Highway Switchbacks landslides, and several landslides along the Kolob Canyons Scenic Drive, have necessitated costly repairs and demonstrate that landslides are an ongoing concern for existing and future infrastructure in the study area.

Limited geotechnical data available for facilities in the park and from nearby locations show that problem soil and rock are common in the study area, particularly in young alluvial-fan and colluvial deposits. Collapsible soils have considerable dry strength and stiffness in their dry natural state, but can settle up to 10 percent of the susceptible deposit thickness when they become wet for the first time following deposition, causing damage to property and structures. Past damage to park facilities from collapsible soil have disrupted park services. Expansive soil and rock, chiefly related to the Petrified Forest Member of the Chinle Formation, are also moisture sensitive and susceptible to rapid volumetric change (shrink/swell). Although not as widespread as collapsible soils in high-use areas of the park, expansive soil and rock are present in lower Zion Canyon adjacent to park headquarters facilities and housing. If encountered in future park development, such soil and rock must be carefully evaluated and accommodated in facility planning and design.

Large, damaging earthquakes are rare events in southwestern Utah, but some faults near Zion National Park are capable of producing earthquakes as large as magnitude 6.5-7.0 (Lund and others, 2007, 2008a). Hazards associated with large earthquakes (ground shaking, surface fault rupture, landslides, rock falls, and liquefaction) have the greatest potential for catastrophic property damage, economic disruption, and loss of life of any hazard in the study area. Because of their great destructive potential, the effects of large earthquakes must be reduced through careful land-use planning, adoption and enforcement of modern seismic building codes, engineering design, and disaster-preparedness planning and drills.

The epicenter of the September 2, 1992, magnitude 5.8 St. George earthquake on the Hurricane fault (Pechmann and others, 1995) was approximately 28 miles from Zion National Park, yet ground shaking associated with that earthquake initiated the approximately 18-million-cubic-yard Springdale landside that destroyed three homes and two water tanks, and closed State Route 9 for several days, all less than a mile from the park's south entrance (Black and others, 1995; Jibson and Harp, 1995). A magnitude 7 earthquake on the Hurricane fault would release greater than 30 times more energy than the moderate (magnitude 5.8) St. George earthquake. Seismic ground shaking and secondary hazards produced by shaking (rock falls, landslides, liquefaction, etc.) are the principal earthquake hazards in the study area. However, several potentially active faults, in particular the Hurricane fault which enters the northwestern part of the study area near the Kolob Canyons Visitor Center, make surface fault rupture a hazard in the study area. Historic stone masonry structures in the park are particularly vulnerable to strong earthquake ground shaking.

Because of their wide distribution, frequent occurrence, and destructive potential, we expect floods, rock falls, landslides, and collapsible soil to be the principal geologic hazards with which planners, public safety personnel, and maintenance workers in Zion National Park must contend on an annual basis. The remaining geologic hazards considered in this report, with the exception of the effects of a large earthquake, 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.

ADDITIONAL INFORMATION AND GUIDELINES

In addition to the references at the end of each chapter of this report, the UGS Earthquakes and Geologic Hazards Web page at http://geology.utah.gov/utahgeo/hazards/index.htm provides additional general information on geologic hazards in Utah. Additionally, the Web page for Consultants and Design Professionals (geology.utah.gov/ghp/consultants/index.htm) includes information on recommended report guidelines, UGS geologic-hazard maps and reports, geologic maps, ground-water reports, historical aerial photography, and other sources of useful information.

The UGS advises following the recommended guidelines when preparing site-specific engineering-geologic reports and conducting site-specific hazard investigations in the Zion National Park Geologic-Hazard Study Area. Typically, engineering-geologic and geologic-hazard considerations would be combined in a single report, or included as part of a geotechnical report that also addresses site foundation conditions and other engineering aspects of the project.

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Chapter 2
Flood and Debris-Flow Hazards

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Chapter 2: Flood and Debris-Flow Hazards

INTRODUCTION

Flooding is the overflow of water onto lands that are normally dry and is the most universally experienced natural hazard (Keller and Blodgett, 2006). Damaging effects from flooding include inundation of land and property, erosion, deposition of sediment and debris, and the force of the water itself, which can damage property and take lives (CH2M HILL, 1997; JE Fuller Hydrology and Geomorphology, Inc., 2005, 2007; Barjenbruch and others, 2008). Historically, flooding is the most prevalent, destructive, and deadly geologic hazard affecting Zion National Park. Several existing structures in the park, many historic, are located in flood-hazard areas because the rugged park topography leaves few alternatives. Visitors to Zion National Park frequently travel in and through flood-hazard areas.

The high flood hazard results from the complex interaction of the area's rugged topography and southwestern Utah's seasonal weather patterns. Three types of floods typically occur in the study area: (1) riverine (stream) floods, (2) flash floods/debris flows, and (3) sheetfloods. All three types of floods are associated with natural climatic fluctuations and may, under certain circumstances, occur simultaneously. Two additional types of floods may also occur within the study area—unintentional water release from water-retention structures, and flooding due to the breach of rock-fall or landslide dams—neither of which are necessarily associated with precipitation events. The risk from flooding can be significantly increased by wildfires (Neary and others, 2005) and by human activities such as placing structures and constrictions in floodplains and erosion-hazard zones, developing areas without adequate flood and erosion control, and poor watershed management practices.

SOURCES OF INFORMATION

Sources of information used to evaluate flood hazards in the Zion National Park Geologic-Hazard Study Area include (1) Federal Emergency Management Agency (FEMA) National Flood Insurance Program (NFIP) Flood Insurance Rate Map Community-Panel Number 490224 0550 B (FEMA, 1986), (2) appendix 6 "Floodplains Map" in the *Draft Development Concept Plan, Environmental Assessment, Zion Canyon Headquarters, Zion National Park* (National Park Service [NPS], 1993), (3) unpublished memos, incident reports, and written communications provided by NPS personnel, (4) *Engineering Geologic Map Folio, Springdale, Washington County, Utah* (Solomon, 1996), and (5) the distribution of young, water-deposited geologic units shown on the nine Utah Geological Survey (UGS) 1:24,000-scale geologic quadrangle maps that cover the study area (Clear Creek Mountain [Hylland, 2000], Cogswell Point [Biek and Hylland, 2007], Kolob Arch [Biek, 2007a], Kolob Reservoir [Biek, 2007b], Springdale East [Doelling and others, 2002], Springdale West [Willis and others, 2002], Temple of Sinawava [Doelling, 2002], The Barracks [Sable and Doelling, 1993], and The Guardian Angels [Willis and Hylland, 2002]) (figure 1.1).

FLOOD TYPES

Riverine Floods

Riverine flooding along major drainages in southwestern Utah is usually regional in nature, lasts for several hours or days, typically takes place on perennial streams, and usually can be predicted days to weeks in advance. Riverine floods commonly result from rapid melting of the winter snowpack or from prolonged heavy rainfall associated with major frontal storms, or from both conditions simultaneously. Large riverine floods are relatively infrequent events, as illustrated by the occurrence of only three major floods of this type on the North Fork of the Virgin River in over 80 years of stream flow records. They typically occur in watersheds of over 200 square miles that include terrain high enough to accumulate a substantial snowpack. Depending on the season, southwestern Utah receives moisture from Pacific frontal systems (late fall through early spring) and from cutoff low-pressure systems (late spring and fall) that deliver Pacific Ocean moisture, typically from dissipating tropical cyclones, including tropical storms and hurricanes (U.S. Geological Survey [USGS], 2009a). Such storms can be widespread, slow moving, and produce large amounts of precipitation as sustained, high-volume rainstorms. These two weather systems generate most of the winter snowpack that accumulates in high elevations in and surrounding the Zion National Park Geologic-Hazard Study Area. Where uncontrolled, riverine floods can inundate large areas along floodplains and cause extensive erosion and flood damage over a wide area. The historical record of riverine flood damage in the Zion National Park area goes back to the 1860s, as illustrated by this quote from a 1944 NPS report (Yeager, 1944):

> *In the winter of 1861–62, years before there was grazing or logging on the rims [of Zion Canyon], the river completely destroyed the village of Grafton, then eight miles below the present South Entrance Checking Station. Rockville, established in 1860 a few miles above Grafton, was partially destroyed that winter and was accordingly relocated. At Northrup many of the farms were washed away. Duncan's Retreat, a few miles below Grafton, was flooded in*

Figure 2.1. *Damage to homes caused by flooding on the Santa Clara River near St. George, Utah, in January 2005.*

Figure 2.2. *Small alluvial fan at the base of a steep slope north of the Watchman housing area. Drainage area of the ephemeral stream that formed the fan is less than one square mile.*

1861, and is but another village whose history records the losing struggle with flood waters of the Virgin.

Measurements or careful estimates of historical peak flows on parts of the Virgin River system date to 1909 (U.S. Army Corps of Engineers, 1973), but are not available for every year. The largest recorded flood in the study area (period of record 1925–2008) occurred in December 1966; the USGS (2009a) reported a maximum instantaneous discharge of 9150 cubic feet per second (cfs) on the North Fork of the Virgin River near Springdale. The most recent major flood on the Virgin River occurred in January 2005 and produced a maximum instantaneous discharge on the North Fork of the Virgin near Springdale of 5450 cfs (USGS, 2009a). The 2005 flood was a regional event and is the most damaging flood on record in southwestern Utah, resulting in about $85 million in private property losses (figure 2.1) and an estimated $145 million in damage to roads, bridges, parks, and utility lines (FEMA, undated; USGS, 2009b). Damage from the 1966 flood, which occurred when population densities in southwestern Utah were much lower, held the previous damage record of $14 million in 1966 dollars (U.S. Army Corps of Engineers, 1973).

Flash Floods

Flash floods are sudden, intense, localized events that occur in response to cloudburst rainfall that often accompanies convective, monsoonal thunderstorms. Because cloudburst storms result from strong convective cells produced by differential atmospheric heating, flash floods are largely a summertime phenomenon in desert regions. Flash floods in the Zion National Park Geologic-Hazard Study Area can affect both large perennial and small ephemeral drainages and alluvial fans. The North Fork of the Virgin River, its larger tributaries (Deep Creek, Kolob Creek, and Pine Creek), and North Creek are subject to periodic flash flooding, but the most intense and unpredictable floods often take place in small- to medium-sized watersheds characterized by ephemeral stream flow and normally dry stream channels.

Alluvial fans are a common geomorphic feature in the study area (figure 2.2). Alluvial fans are relatively flat to moderately sloping fan-shaped surfaces underlain by loose to weakly consolidated sediment deposited by a stream at a topographic break, such as the base of a mountain front, escarpment, or valley side (National Research Council, 1996). Because of their topographic location, alluvial fans are particularly susceptible to flash floods generated by cloudburst storms centered over their drainage basins. Flash floods on alluvial fans are characterized by great flow path uncertainty and by abrupt sediment deposition, often causing channel avulsion (a sudden change in flow path) as the stream loses its ability to carry its sediment load (National Research Council, 1996).

Debris Flows

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 debris flows. A debris flow moves as a viscous fluid capable of 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 per hour (USGS, 1997). Their greater density and high speed make debris flows particularly dangerous to life and destructive to property. Debris flows are capable of destroying buildings, roads, and bridges and of depositing thick layers of mud, rock, and other debris (figure 2.3).

Figure 2.3. *Sediment deposited by a small debris flow that discharged from an ephemeral drainage north of the Watchman housing area in 1979 (photo courtesy of NPS).*

Figure 2.4. *The 1998 Sammy's Canyon debris flow inundated the current site of the Zion National Park shuttle bus maintenance facility, visitor center, and part of the Watchman campground (photo courtesy of NPS).*

The volume and frequency of debris flows depends 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; Giraud, 2004, 2005; Coe and others, 2008). Drainage basins that have experienced a wildfire are generally more susceptible to debris flows (Gartner and others, 2005; Giraud, 2005). The sediment carried by a debris flow can be deposited anywhere on an active alluvial-fan surface. The active fan surface includes those areas where modern deposition, erosion, and alluvial-fan flooding may occur. In general, those parts of the fan surface where sediment has been deposited during the Holocene (past 11,800 years) are considered active unless proven to be otherwise. Typically, the upper part of an active alluvial fan has a higher debris-flow hazard due to greater velocities, impact pressures, burial depths, and event frequency (Giraud, 2004, 2005).

Debris flows are less common than flash floods in the Zion National Park Geologic-Hazard Study Area, but occur periodically in drainages where softer, more easily eroded bedrock crops out in the drainage headwaters. Such bedrock units include the Moenkopi, Chinle, Moenave, Kayenta, Temple Cap, and Carmel Formations, all of which weather to produce more sediment than the more-resistant Navajo Sandstone and Kaibab Formation. Debris flows occur in short, steep tributary channels, but not in the large river channels of the Virgin River and its major tributaries, because the latter do not have channel gradients steep enough to support viscous flow. The 1998 Sammy's Canyon debris flow that inundated part of the Watchman campground and the current locations of the new Zion Canyon Visitor Center and shuttle maintenance facility is a good example of a debris flow emanating from a small, ephemeral drainage with soft, sediment-producing bedrock formations in its drainage basin (Lund and Sharrow, 2005; Lund and others, 2007; figure 2.4).

Sheetfloods

Sheetflooding refers to a broad expanse of unconfined, moving storm water that spreads as a thin, continuous, relatively uniform sheet over a large area and is not concentrated into well-defined channels. The flow distance is short and duration is typically measured in minutes. Sheetflooding usually occurs before runoff is sufficient to promote channel flow, or after a period of intense rainfall. In the study area, sheetfloods occur in one of two ways: (1) as the end product of a flash flood or debris flow that has dropped its sediment load and begun to slow down and spread across the distal end (toe) of an alluvial fan, or (2) as runoff from erosion-resistant, unvegetated bedrock slopes during intense cloudburst storms. Although lacking the depth and velocity to cause serious damage to structures, sheetfloods can deposit considerable fine sediment and cause localized inundation (figure 2.5), especially where conditions allow for ponding or entrance into a basement or other below-ground facility.

Unintentional Water Release from Water-Retention Structures

An unintentional release of water due to the failure of a water-retention or conveyance structure may occur with little warning. The extent of associated flooding depends on reservoir volume and nature of the failure (Harty and Christenson, 1988; Solomon, 1996). Dams on drainages within the Zion National Park Geologic-Hazard Study Area are limited to small water-diversion structures a few feet high on the North Fork of the Virgin River that pose little threat. Two significant water

Figure 2.5. Sediment deposited by sheetflooding in the Watchman campground at the distal end of the 1998 Sammy's Canyon debris flow (photo courtesy of NPS).

retention structures are present upstream from the study area (figure 2.6): Kolob Dam on Kolob Creek (a tributary to the North Fork of the Virgin River above Zion Narrows), and Blue Springs Dam on Blue Creek (a tributary to the Left Fork of the North Fork of the Virgin River). Failure of these structures is considered a rare and unexpected event, the possibility of which is mitigated by periodic inspections by the Utah Division of Water Rights Office of Dam Safety.

Kolob Dam was constructed in 1956 and safety improvements were made in the 1990s. The dam is 81 feet high and 686 feet long. The impoundment behind the dam has a surface area of 249 acres and a storage capacity of 5586 acre-feet at the dam spillway crest (Utah Division of Water Rights, 2008a). Kolob Dam is classified as a "High Hazard" dam by the Utah Division of Water Rights Office of Dam Safety. Utah Code 73-5a-106, "Dams classified according to hazard and use," defines high-hazard dams as "those dams which, if they fail, have a high probability of causing loss of human life or extensive economic loss, including damage to critical public utilities" (Utah State Legislature, 2008).

Blue Springs Dam was constructed in 1957, and is 62 feet high and 368 feet long. The impoundment behind the dam has a surface area of 80 acres and a storage capacity of 255 acre-feet at the dam spillway crest (Utah Division of Water Rights, 2008b). Blue Springs Dam is classified as a "Moderate Hazard" dam. Utah Code 73-5a-106, "Dams classified according to hazard and use," defines moderate-hazard dams as "those dams which, if they fail, have a low probability of causing loss of human life, but would cause appreciable property damage, including damage to public utilities" (Utah State Legislature, 2008).

Emergency action plans for Kolob and Blue Springs Dams

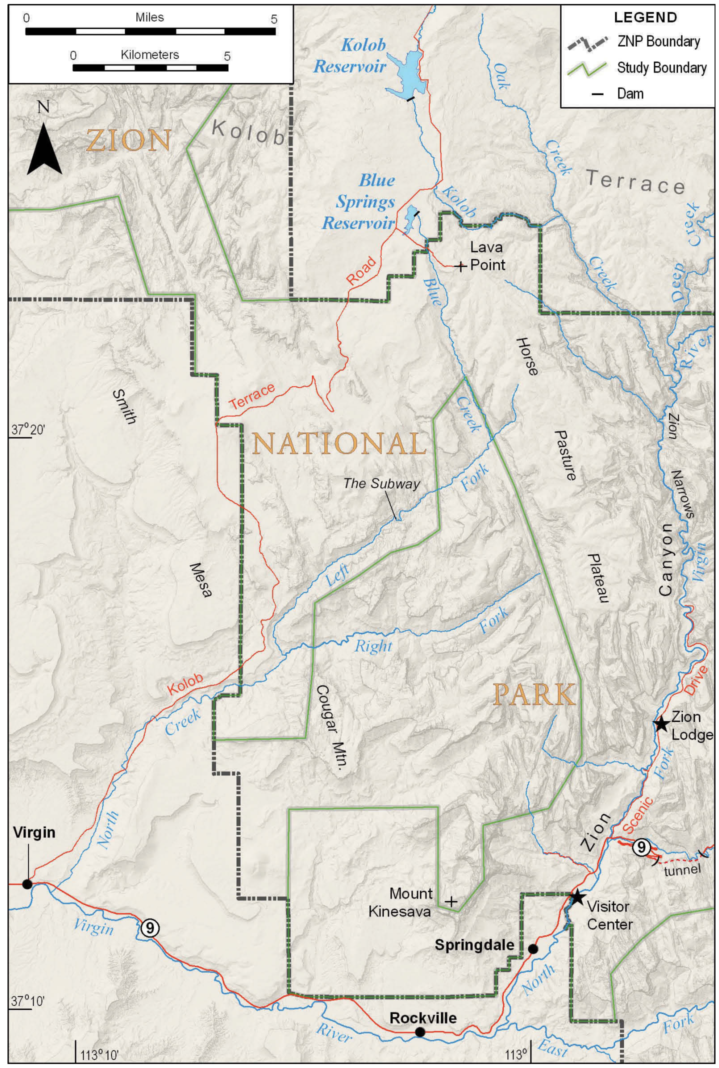

Figure 2.6. Location of Kolob and Blue Springs dams and reservoirs in the headwaters of the North Fork of the Virgin River and North Creek.

(Alpha Engineering Company, 1995; Washington County Water Conservancy District, 2007) show that failure of either dam could cause significant flooding downstream—how significant depends on the extent of the breach and the level of the reservoirs behind the dams at the time of failure. Flood inundation maps prepared for Kolob Dam (Washington County Water Conservancy District, 1991) show that the maximum flood flow would be 103,735 cubic feet per second (cfs) a short distance below the dam and 69,800 cfs at the Zion South Entrance Station several miles downstream. Maximum flood flows in Zion Narrows would exceed 90,000 cfs (Washington County Water Conservancy District, 1991). Flood inundation maps prepared for Blue Springs Dam (Alpha Engineering Company, 1995) show that the maximum flood flow would be 5611 cfs a short distance below the dam and 2045 cfs at the State Route 9 bridge across North Creek. Maximum flood flows in "The Subway" on North Creek would exceed 4000 cfs (Alpha Engineering Company, 1995).

Flooding Associated with Rock-Fall or Landslide Dams

Hamilton (1995) and Biek and others (2003) identified as many as 14 natural lakes and ephemeral ponds that formed in Zion National Park due to the impounding effects of landslides, rock falls, and lava flows. The impoundments ranged from a few acres in area and a few feet deep, up to miles long and hundreds of feet deep. The most notable were Lake Grafton and Coalpits Lake, which formed behind lava-flow dams, and Sentinel, Hop Valley, and Trail Canyon Lakes that formed behind rock-fall/landslide dams. The natural dams have been breached by erosion, and the former lakes were recognized chiefly by the fine-grained lacustrine sediments deposited behind the dams.

Future volcanic eruptions and lava flows are very low probability events; however, narrow canyons and the prevalence of rock falls and landslides in the Zion National Park Geologic-Hazard Study Area make the likelihood of future natural water impoundments a near certainty. Impoundment of a stream by a rock-fall or landslide dam can produce a potentially significant flood hazard, both from inundation upstream of the dam due to ponding and flooding downstream of the dam due to overtopping or breaching of the dam. The degree of hazard depends on the size of the impoundment, the characteristics of the impounding material, and the hydrology of the impounded drainage. If a rock fall or landslide is large enough to block a perennial stream or an ephemeral stream subject to large flash floods or high seasonal flows, and the natural dam consists chiefly of impermeable material, then upstream inundation could be extensive and overtopping and subsequent rapid erosion of the impounding mass could result in a catastrophic downstream flood. Conversely, if the rock fall/landslide is relatively small and/or consists of highly permeable material, impoundment of a large volume of water would be unlikely, and both the upstream and downstream hazard would be reduced.

The breach of a rock-fall dam on the Middle Fork of Taylor Creek (see chapter 1, figure 1.1) on March 17, 1993, provides a historical example of catastrophic flooding associated with a natural dam in the Zion National Park Geologic-Hazard Study Area. A moderate-size rock fall blocked the upper reaches of the Middle Fork of Taylor Creek on June 8, 1990. The rock-fall dam was described as consisting of "thousands of cubic yards of sand and debris" (Robinson, 1993). National Park Service personnel made periodic inspections of the rock fall and reported that "several episodes of stream down cutting into the dam and flowing past it, followed by the dam filling in again with more debris, recurred over the next several months." An inspection on March 10, 1993, seven days before the catastrophic breach, showed that the dam was about 60 feet high and had an impoundment of water approximately 60 feet wide, 500 feet long, and of unknown depth behind it. Water was flowing through rock rubble on the north side of the dam (Robinson, 1993). Details of the dam breach are unknown since there were no witnesses to the event. The ensuing flood "sent a wall of water 8-10 feet high" down Taylor Creek (Robinson, 1993). The water destroyed the Taylor Creek trail and eventually overtopped Interstate 15 just outside the park boundary. The flood resulted in four vehicle accidents and injuries to the occupants of two of the vehicles (Robinson, 1993).

FLOOD DISCHARGE AND FREQUENCY ESTIMATES

Estimates of flood discharge and frequency have been made for selected drainages in the Zion National Park Geologic-Hazard Study Area by the NPS. Martin (NPS, internal report, 1996) made a floodplain analysis for the North Fork of the Virgin River in the vicinity of Zion Lodge and determined the following discharge values: 100-year discharge = 9150 cfs, 500-year discharge = 13,500 cfs, probable maximum flood = 100,000 cfs. A floodplain analysis by Smillie (NPS, internal report, 1988) determined the following flood discharge values for Oak Creek: 100-year discharge = 3200 cfs, 500-year discharge = 5500 cfs, probable maximum flood = 24,000 cfs. Sharrow (NPS, internal report, 2008) reported a 100-year discharge estimate for Sammy's Canyon of about 2000 cfs. Table 2.1 summarizes adjusted flood frequency and discharge data compiled by the NPS, Water Resources Division for the North Fork of the Virgin River at Springdale and near Zion Lodge (NPS, internal report, 1998). It is worth noting that the maximum flood discharge on the North Fork of the Virgin River at Zion Lodge projected for a failure of Kolob Dam (see Unintentional Water Release from Water-Retention Structures section above) is several times larger than the flow estimated for a 500-year flood due to natural causes.

FLOOD-PRONE-AREA CLASSIFICATION

Several sources of floodplain mapping and evaluations of relative flood hazard exist for small parts of the Zion National Park Geologic-Hazard Study Area; however, because these maps/evaluations are site-specific or imprecise, none provided a substantial basis for our mapping analysis. As an alternative, we used the presence of young water-deposited geologic units and landforms as indicators of flood hazard.

National Flood Insurance Program 100-Year Flood Map

The Federal Emergency Management Agency (FEMA), through its National Flood Insurance Program (NFIP), has prepared Flood Insurance Rate Maps (FIRMs) for selected areas in unincorporated Washington County, Utah. FIRMs

Table 2.1. Adjusted flood discharge and frequency data, North Fork of the Virgin River at Springdale and Zion Lodge (after NPS, Water Resources Division, internal report, 1998).

Frequency[1]	Return Period (years)	Adjusted Discharge (cfs)	
		North Fork Virgin River at Springdale gage	North Fork Virgin River in vicinity of Zion Lodge[2]
0.9900	–	352	337
0.9800	–	422	404
0.9500	–	555	531
0.9000	–	709	679
0.8000	1.25	956	915
0.5000	2.0[3]	1710	1640
0.2000	5	3090	2960
0.1000	10	4230	4050
0.0500	20	5490	5250
0.0400	25	5930	5680
0.0200	50	7390	7070
0.0100	100	9020	8630
0.0050	200	10,800	10,300
0.0020	500	13,500	12,900

[1]Based on 70 years of record between 1913 and 1993 (no record for 1915 to 1925).
[2]Adjusted from a watershed area of 344 mi^2 to 308 mi^2 by multiplying by 0.957 to account for the location of Zion Lodge upstream from Springdale.
[3]Bank-full flow typically has a return period of 1.5 and 2 years.

show expected boundaries for the 100-year and in some cases the 500-year floods (floods having a 1 percent and 0.2 percent annual chance, respectively, of occurring in any given year) along selected drainages in the county. The NFIP uses FIRMs to make federally subsidized flood insurance available in flood-prone areas once required flood-proofing design features are incorporated into building construction.

FIRM Community-Panel Number 490224 0550 B (FEMA, 1986) shows the expected 100-year-flood boundaries along portions of the North and East Forks of the Virgin River, and Shunes, Oak, and Pine Creeks in Zion National Park. However, the map lacks topographic contours, does not show buildings, and has few recognizable landmarks, thus making it difficult to determine which park facilities are within the 100-year floodplain. Due to a lack of common registration points between the FIRM and the 1:24,000-scale topographic quadrangles used as the base maps for this study, we could not accurately plot the NFIP 100-year-flood boundaries on the Flood and Debris-Flow Hazards map (plate 1) accompanying this report. For information purposes only, the Flood and Debris-Flow Hazard map shows the stream reaches within the study area covered by the FIRM 100-year-flood-boundary mapping; the original FIRM should be consulted for the official FEMA flood zone designation.

National Park Service "Floodplain" Map

The NPS prepared a "Floodplain Map" for lower Zion Canyon as part of the *Draft Development Concept Plan Environmental Assessment, Zion Canyon Headquarters, Zion National Park* (NPS, 1993). The map extends from the southern Zion National Park boundary at the town of Springdale to near the intersection of the Zion-Mount Carmel Highway with the Zion Canyon Scenic Drive. The map shows both the pre- and post-levee construction 100-year and 500-year flood boundaries along the North Fork of the Virgin River and Oak Creek. Based on our literature review and discussions with NPS personnel, we believe the 1993 floodplain map is the most detailed map of this type available for the Zion National Park Geologic-Hazard Study Area, and that similar maps depicting anticipated boundaries of natural floods are not available elsewhere in the park.

Due to scale differences and insufficient common registration points between maps, it was not possible to accurately plot the 100-year and 500-year flood boundaries on the accompanying Flood and Debris-Flow Hazard map (plate 1). Those wishing to consult the NPS floodplain map for lower Zion Canyon are referred to appendix 6 of the *Draft Development Concept Plan Environmental Assessment, Zion Canyon Headquarters, Zion National Park* (NPS, 1993).

Summary of Flood Hazard to Existing National Park Service Facilities in Zion Canyon

Sharrow (NPS, internal report, 2008) used the flood discharge and frequency data presented above, the 100-year and 500-year flood boundaries for lower Zion Canyon (NPS, 1993), and site-specific qualitative analyses to summarize the flood hazard to individual NPS facilities in Zion Canyon (table 2.2). This evaluation is the best flood-hazard assessment currently available for individual facilities in Zion National Park. However, those data are limited to three drainages (North Fork Virgin River, Oak Creek, and Sammy's Canyon), and Sharrow noted that "all portions of Zion Canyon [and by inference the remainder of the Zion National Park Geologic-Hazard Study Area] are subject to sheet flow and small to moderate sized debris flows [and flash floods] coming down tributary drainages."

Other Flood-Prone Areas

As noted by Sharrow (NPS, internal report, 2008), Zion National Park contains numerous ephemeral streams, alluvial

Table 2.2. *Summary of flood hazard to NPS facilities in Zion Canyon (after Sharrow, NPS, internal report, 2008).*

NORTH FORK VIRGIN RIVER FLOOD				
Facility[1,2]	**100 yr**	**500 yr**	**PMF[3]**	**Comment**
Lodge foundation	No	No	Yes	–
Lodge grounds	No	Yes	Yes	–
Road in the vicinity of lodge	No	Yes	Yes	–
Parking area west of road, and mule saddle-up corral	Probably Yes	Yes	Yes	Not modeled
Tank, corrals, etc. at Birch Creek	No	No	Yes	–
Watchman housing	No	No	Yes (west half)	–
South Campground	No	Yes (minimal)	Yes (east half)	–
Watchman Campground	Yes (minimal)	Yes (SW portion)	Yes	–
Visitor Center	Yes (minimal)	Yes	Yes	–
OAK CREEK FLOOD				
Facility[1,2]	**100 yr**	**500 yr**	**PMF[3]**	**Comment**
Administration building	No	No	Yes	–
Administration building parking lot [4]	Yes (minimal)	Yes	Yes	–
RM Offices [4]	Yes	Yes	Yes	–
Emergency Operations Center	No	No	Probably Yes	Not modeled
Bridges and road crossings on Oak Creek	Yes	Yes	Yes	–
Oak Creek housing[4]	Yes (minimal)	Yes	Yes	–
SAMMY'S CANYON FLOOD				
Facility[1,2]	**100 yr**	**500 yr**	**PMF[3]**	**Comment**
Shuttle bus maintenance facility	No	No	Yes	Not modeled
Shuttle bus access road	Yes	Yes	Yes	Not modeled

[1]Source: descriptive flood hazard analyses from NPS, Water Resource Division trip reports (Smillie, NPS, internal report, 1989; Martin, NPS, internal report, 1996); and the floodplain map in the *Draft Development Concept Plan Environmental Assessment, Zion Canyon Headquarters, Zion National Park* (NPS, 1993).
[2]Hazard analysis considers effects of existing flood-control levees.
[3]PMF = Probable Maximum Flood.
[4]Bridge blockages will exacerbate flooding.

fans, and other areas subject to periodic flooding, chiefly as a result of cloudburst storms, that are not depicted on existing flood-hazard maps (i.e., FEMA, 1986; NPS, 1993). We used the distribution of geologically young alluvial deposits shown on UGS 1:24,000-scale geologic maps (see Sources of Information section) to identify flood-prone areas and their relative susceptibility to flooding throughout the Zion National Park Geologic-Hazard Study Area. Additionally, the study area contains a high concentration of narrow, steep-walled, bedrock-floored canyons that are subject to flash floods, but typically contain little or no mappable alluvium. The flash-flood hazard to hikers in slot canyons is particularly acute because the sheer canyon walls provide few avenues to escape flooding.

The probability of flooding, particularly flash flooding, at a particular location over a fixed period of time is uncertain; however, relative flood hazard can be estimated from the distribution of historical flooding in the study area and in southwestern Utah in general (Woolley, 1946; Butler and Marsell, 1972; Utah Division of Comprehensive Emergency Management, 1981; Lund, 1992). Our mapping delineates four categories of flood hazard (described below). Table 2.3 shows the geologic units associated with each category and the relative hazard based on geologic deposit genesis.

Very High: Active floodplains and low terraces along perennial streams (large drainage basins) subject to periodic riverine and flash flooding and accompanying erosion, active alluvial fans subject to flash floods and debris flows, and slot canyons containing perennial streams that are periodically inundated by flash floods and debris flows, which occur in response to distant cloudburst storms.

High: Stream channels, floodplains, and low terraces along normally dry ephemeral streams (smaller drainage basins) and slot canyons that are periodically inundated by flash floods and debris flows during cloudburst storms in their smaller drainage basins.

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

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

Flood-hazard category areas are shown on the accompanying Flood and Debris-Flow-Hazard map (plate 1). Narrow, bedrock-floored canyons subject to very high and high flood hazard, but that lack mappable alluvial deposits, are shown on the map by red and orange lines, respectively.

USING THE MAP

The Flood and Debris-Flow Hazard map (plate 1) accompanying this report shows flood-susceptible areas based upon topography and the presence of young, water-deposited geologic units as described in table 2.3 and on plate 1. The extent of drainages in the study area covered by FIRMs, and NPS-defined 100-year and 500-year floodplains in lower Zion Canyon are also shown on the map. However, those data are approximate and are depicted for information purposes only; readers requiring additional information regarding flood zone boundaries should consult the original FEMA (1986) and NPS (1993) documents.

The Flood and Debris-Flow Hazard map (plate 1) provides a basis for conducting site-specific flood and debris-flow hazard investigations. Site-specific investigations can resolve uncertainties inherent in generalized hazard mapping and help ensure safety by identifying the need for flood-resistant design. However, because intense cloudburst storms create a potential for flash floods, debris flows, and sheetfloods anywhere in the Zion National Park Geologic-Hazard Study Area, even locations outside identified flood-prone areas could be subject to periodic flooding. The map also shows where existing development lies in flood-prone areas, and therefore, where flood-resistant-design measures may be required. An evaluation of existing flood-mitigation measures and their likely effectiveness is beyond the scope of this study.

MAP LIMITATIONS

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

HAZARD REDUCTION

Early recognition and avoidance of areas subject to flooding are the most effective means of flood-hazard reduction. However, avoidance may not always be a viable or cost-effective option, especially for areas of existing development. Other techniques available to reduce potential flood damage may include, but are not limited to, source-area stabilization, engineered protective structures, flood and debris-flow warning systems, and flood-proofing. Some of these techniques can be expensive and their

Table 2.3. *Flood-hazard categories based on the genesis of geologic deposits mapped by the UGS and by canyon topography.*

Hazard Category	Geologic Units[1]	Description	Hazard Type	Comments
Very High[2]	Qal_1, Qaf, Qaf_1, Qafy, Qaly, Qath, Qat_2, Qac, Qa, Qa_1, Qa_2, Qafc	Active floodplains and low terraces along perennial streams (large drainage basins) subject to periodic riverine and flash flooding and accompanying erosion, active alluvial fans subject to flash floods and debris flows, and slot canyons containing perennial streams that are periodically inundated by flash floods and debris flows, which may occur in response to distant cloudburst storms.	Riverine flood, flash flood, debris flow	North Fork of the Virgin River, North Creek, lower Pine Creek, Deep Creek, Kolob Creek, La Verkin Creek, lower Timber Creek, Orderville Canyon Creek, Imlay Canyon Creek, Goose Creek, and active alluvial fans.
High[2]	Qafc, Qa_1,Qac, Qay, Qaes, Qas	Stream channels, floodplains, and low terraces along normally dry ephemeral streams (smaller drainage basins) and slot canyons that are periodically inundated by flash floods and debris flows during cloudburst storms in their smaller drainage basins.	Flash flood, debris flow	Normally dry streams with comparatively small drainage basins subject to flooding during cloudburst storms.
Moderate	Qaf_2, Qla, Qc, Qca, Qat_2	Active pediments and sloping depositional surfaces flanking ridges and other upland areas that are chiefly inundated by sheetfloods, but possibly by flash floods and debris flows during cloudburst storms.	Chiefly sheet-flood, possible flash flood and debris flow	Active depositional surfaces on the flanks and at the base of upland areas subject to flooding during cloudburst storms.
Low	Qaco, Qae, Qaeo, Qafo, Qea, Qafco	Valley bottoms and minor ephemeral drainages subject to possible sheetfloods and minor flash floods from adjacent upland areas during cloudburst storms.	Sheetflood, minor flash flood	Valley bottoms subject to infrequent flooding from adjacent upland areas during cloudburst storms.

[1]Refer to UGS geologic quadrangle maps (see Sources of Information and References sections) for descriptions of map units.
[2]Due to the absence of mappable alluvial deposits in many narrow canyons, areas of Very High and High flood-hazard susceptibility related to such canyons are shown on the Flood and Debris-Flow Hazard map (plate 1) by red and orange lines, respectively.

cost-versus-benefit ratio should be carefully evaluated along with effectiveness and reliability. With regard to sheetflooding, a properly sized and integrated drainage system is usually adequate to mitigate the hazard.

We recommend a flood-hazard investigation for new construction in all hazard categories listed in table 2.3. The first consideration in reducing the hazard from stream flooding and debris flows is the proper identification of hazard areas through detailed mapping, and qualitative assessment of the hazard (Giraud, 2005). The stream-flooding hazard assessment should determine the active flooding area, the frequency of past events, and the potential inundation and flow depths. The debris-flow hazard assessment should determine active depositional areas, the frequency and volume of past events, and sediment burial depths (Giraud, 2005). The level of detail for a hazard assessment depends on several factors, including (1) the type, nature, and location of the proposed development, (2) the geology and physical characteristics of the drainage basin, channel, and alluvial fan, (3) the history of previous flooding and debris-flow events, and (4) proposed risk-reduction measures.

Where development is proposed in areas identified on the Flood and Debris-Flow Hazard map (plate 1) as having a potential flood hazard, a site-specific investigation should be performed early in the project design phase. The investigation should clearly establish whether a flood and/or debris-flow hazard is present at a site and provide appropriate design recommendations. Additionally, Zion National Park visitors often enter areas that are prone to flooding. The risk to visitors is short-term, but constitutes a significant threat due to the number of visitors and the fact that most come to the park lacking a full appreciation of the nature of rainfall and flooding in this area. To mitigate this threat, the park has a coordinated program to inform visitors of flood hazards, with particular attention to those who engage in backcountry hiking and canyoneering. This program should continue with periodic review of its effectiveness.

The failure of a water-retention structure or breach of a natural dam represents a low-probability but high-hazard event in the Zion National Park Geologic-Hazard Study Area. Monitoring and periodic inspection of constructed dams and reservoirs help ensure their safety, and Emergency Action Plans that include a notification plan for downstream communities are required for each dam. Similarly, existing and future natural dams within or upstream of the study area should be evaluated for safety and receive periodic inspections. Natural dams from landslides or rock falls are considered to be particularly hazardous and should be regularly monitored to determine their vulnerability to overtopping or catastrophic breaching.

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Chapter 3
Rock-Fall Hazard

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Chapter 3: Rock-Fall Hazard

INTRODUCTION

Rock fall is a natural mass-wasting process that involves the dislodging and downslope movement of individual rocks and small rock masses (Cruden and Varnes, 1996). Rock falls pose a safety threat because a falling or rolling boulder can cause significant damage to property, roadways, and vehicles, as well as injury or even loss of life (figure 3.1) (see, for example, Hylland, 1995; Keller and Blodgett, 2006; Elliot and Giraud, 2009; Lund and others, 2009). Rock-fall hazards exist where a source of rock is present above slopes steep enough to allow rapid downslope movement of dislodged rocks by falling, rolling, and bouncing.

Figure 3.1. *Damage to the roof of the Zion National Park maintenance facility in Oak Canyon caused by a rock-fall boulder in 1946 (photo courtesy of the National Park Service).*

Rock-fall hazard is based on a number of factors including geology, topography, and climate. Rock-fall sources include bedrock outcrops or boulders on steep mountainsides or near the edges of escarpments such as cliffs, bluffs, and terraces. Talus cones and scree-covered slopes are indicators of a high rock-fall hazard, but other less obvious areas may also be vulnerable.

Rock falls are initiated by freeze/thaw action, rainfall, weathering and erosion of the rock and/or surrounding material, and root growth. Rock fall is also the most common type of mass movement caused by earthquakes. Keefer (1984) indicates that earthquakes as small as magnitude (M) 4.0 can trigger rock falls. All nine of Utah's historical earthquakes of M 5 or greater have caused rock falls. Sources of earthquake ground shaking that might produce rock falls in the Zion National Park Geologic-Hazard Study Area include a large earthquake on the Hurricane fault west of the study area, or a moderate earthquake (≤M 6.5) within the study area itself (Ivan Wong, URS Corporation, written communication, 2008).

Slope modification, such as cuts for roads and building pads or clearing of slope vegetation for development, can increase or create a local rock-fall hazard. However, in many cases a specific triggering event is not apparent. Although not well documented, rock falls in Utah appear to occur more frequently during spring and summer months. This is likely due to spring snowmelt, summer cloudburst storms, and large daily temperature variations (Castleton, 2009).

SOURCES OF INFORMATION

Sources of information used to evaluate rock-fall hazard in the Zion National Park Geologic-Hazard Study Area include (1) the nine Utah Geological Survey (UGS) 1:24,000-scale geologic quadrangle maps that cover the study area (Clear Creek Mountain [Hylland, 2000], Cogswell Point [Biek and Hylland, 2007], Kolob Arch [Biek, 2007a], Kolob Reservoir [Biek, 2007b], Springdale East [Doelling and others, 2002], Springdale West [Willis and others, 2002], Temple of Sinawava [Doelling, 2002], The Barracks [Sable and Doelling, 1993], and The Guardian Angels [Willis and Hylland, 2002]) (figure 1.1), (2) *Engineering Geology of the St. George Area, Washington County, Utah* (Christenson and Deen, 1983), (3) *Landslide Map of Utah* (Harty, 1991), (4) "Geologic Hazards of the St. George Area, Washington County, Utah" (Christenson, 1992), (5) "Landslide Distribution and Hazards in Southwestern Utah" (Harty, 1992), (6) *Engineering Geologic Map Folio, Springdale, Washington County, Utah* (Solomon, 1996), (7) *Landslide Susceptibility Map of Utah* (Giraud and Shaw, 2007), and (8) *Geologic Hazards and Adverse Construction Conditions, St. George–Hurricane Metropolitan Area, Washington County, Utah* (Lund and others, 2008).

ROCK-FALL SOURCES

Rock fall is the most common mass-movement type in the Zion National Park Geologic-Hazard Study Area. The combination of steep slopes capped by well-jointed, resistant bedrock formations provides ample opportunity to generate rock falls. Bedrock units particularly susceptible to rock fall in the study area include the Shinarump Member of the Chinle Formation; Springdale Member of the Kayenta Formation; Lamb Point Tongue Member of the Navajo Sandstone; other ledge- and cliff-forming strata in the Moenkopi, Moenave, and Kayenta

Figure 3.2. *Exposure typical of many in the study area where softer bedrock units crop out on slopes below more resistant cliff-forming formations. Erosion of the underlying softer unit undercuts the more resistant unit, producing numerous rock falls.*

Figure 3.3. *Large rock-fall boulders in a talus/cliff-retreat deposit in lower Zion Canyon.*

Formations; and the massive, pervasively jointed, cliff-forming Navajo Sandstone. Rock falls are particularly prevalent and hazardous where softer, more easily eroded bedrock units crop out on slopes below stronger, more resistant bedrock formations (figure 3.2). Erosion of the underlying soft units and subsequent undercutting of the more resistant bedrock formations triggers many rock falls.

Talus deposits blanket steep to moderate slopes throughout the study area. These deposits are derived from upslope ledges and cliffs and consist chiefly of accumulations of poorly sorted, coarse, angular blocks of various sizes. The boulders in talus deposits may exceed 30 feet in long dimension (Biek and others, 2003) (figure 3.3). The widespread distribution of talus and the direct relation of talus deposits to the rock-fall process attest to the widespread extent of the rock-fall hazard in the study area.

Most rock falls in the Zion National Park Geologic-Hazard Study Area are localized events that affect a comparatively small area close to the base of cliffs and steep slopes. However, Hamilton (1995) identified lacustrine deposits related to several rock-fall-created lakes in Zion National Park. The rock falls that formed the lakes were typically very large; for example, the 7000-year-old Sentinel landslide, which likely resulted from the collapse of a large, joint-controlled bedrock fin, involved approximately 280 million cubic yards of material that blocked the North Fork of the Virgin River (upper Zion Canyon) to a depth of about 700 feet for 1.3 miles (Hamilton, 1995; Biek and others, 2003), and formed a lake at least 4 miles long and hundreds of feet deep.

Historically, a rock fall in 1990 blocked the Middle Fork of Taylor Creek and created a 60-foot-high debris dam. When the dam catastrophically breached in 1993, the impounded water "sent a wall of water 8–10 feet high" down Taylor Creek that destroyed the Taylor Creek trail, and eventually overtopped Interstate 15 just outside the park boundary. The flood resulted in four vehicle accidents and injuries to the occupants of two of the vehicles (Robinson, 1993).

The presence of locally extensive lake deposits attests to the occurrence of periodic rock falls that are much larger than normal in Zion National Park. Based on $^{40}Ar/^{39}Ar$ ages on basalt flows in and near the park, Biek and others (2003) estimated that lower Zion Canyon is about 2 million years old and that the canyon becomes progressively younger upstream. Evidence for a comparatively small number of rock-fall-created prehistoric lakes in a canyon system ≤2 million years old, indicates that large rock falls are infrequent events when compared to the tens of thousands of smaller rock falls that occurred over the same time period.

Lower Zion Canyon is also likely subject to infrequent, low-probability, high-hazard rock falls. However, evidence for very large rock falls in lower Zion Canyon is generally lacking. The absence of evidence may be related to the fact that in lower Zion Canyon, large bedrock fins and other sources of large rock falls have been removed as the canyon widened, and because the North Fork of the Virgin River now occupies a mid-canyon position and is no longer actively eroding the base of the canyon walls and creating unstable undercutting conditions. Therefore, we conclude that while very large rock falls (likely joint controlled rather than produced by undercutting) are still possible in lower Zion Canyon, they are even more infrequent than in narrow canyon locations where the North Fork of the Virgin River is actively eroding the base of canyon walls.

During our field reconnaissance, we observed several large boulders and boulder clusters in lower Zion Canyon well beyond the limits of normal rock-fall accumulation bordering canyon

Figure 3.4. *Cluster of large rock-fall boulders in the Watchman campground far beyond the area of normal rock-fall accumulation at the base of canyon walls in lower Zion Canyon.*

walls (figure 3.4). The anomalous location of the boulders argues that they are either the remnants of talus/cliff-retreat deposits (perhaps fin-collapse deposits or large rock-avalanche deposits) left isolated by canyon widening, or that they were carried to their present position by catastrophic flooding related to the breaching of upstream rock-fall or landslide dams. The evidence for either scenario is inconclusive.

ROCK- FALL-HAZARD CLASSIFICATION

The Rock-Fall Hazard map (plate 2) shows areas in the Zion National Park Geologic-Hazard Study Area that are susceptible to rock fall. Determining the severity of rock-fall hazard requires evaluating the characteristics of three hazard components: (1) a rock source, in general defined by bedrock geologic units that exhibit relatively consistent patterns of rock-fall susceptibility throughout the study area, although talus/cliff-retreat deposits may also create a local source of rock falls, (2) an acceleration zone, where the rock-fall debris gains momentum as it travels downslope; this zone often includes a talus slope, which becomes less apparent with decreasing relative hazard and is typically absent where the hazard is low, and finally (3) a runout zone, which includes gentler slopes where boulders roll or bounce before coming to rest beyond the base of the acceleration zone (Evans and Hungr, 1993; Wieczorek and others, 1998) (figure 3.5).

We established the boundaries of areas subject to rock-fall hazard in the study area by measuring a shadow angle (Evans and Hungr, 1993; Wieczorek and others, 1998), which is 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 (figure 3.5). Shadow angles vary based on rock type,

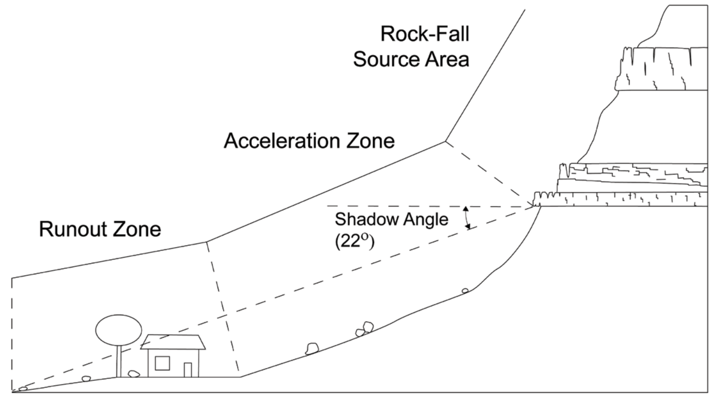

Figure 3.5. *Components of a characteristic rock-fall path profile (from Castleton, 2009).*

boulder shape, slope steepness, slope roughness, and rock source height. We measured shadow angles for 95 representative rock-fall boulders in the Zion National Park Geologic-Hazard Study Area. Our investigation showed that a shadow angle of 22º is generally applicable in the study area, and defines a hazard zone sufficiently wide to include the limits of rock-fall debris that accumulates at the base of cliffs and steep slopes.

Our investigation also showed that while most rock falls in the study area accumulate in comparatively narrow, well-defined zones at the base of steep slopes, there are several locations where large boulders are present on canyon bottoms beyond the limits of normal rock-fall accumulation. The source of most of these boulders is uncertain (as discussed above); however, based on the presence of these boulders, we conclude that some mid-canyon areas may be subject to low-probability, high-hazard rock falls.

The Rock-Fall Hazard map (plate 2) delineates four categories of rock-fall hazard. Three of the categories are associated with rock-fall accumulation areas at the base of cliffs and steep slopes. The three categories are ranked as High, Moderate, and Low depending on the combined characteristics of the three hazard components discussed above. The fourth hazard category pertains to areas where we observed a comparatively few large rock-fall boulders that extend into canyon bottoms beyond the limits of normal rock-fall accumulation. We consider rock falls in the fourth hazard category to be low-probability, high-hazard events, with recurrence intervals likely measured in thousands of years. The extent to which such large rock falls may be related to earthquake ground shaking is unknown.

We define the four rock-fall-hazard categories in the Zion National Park Geologic-Hazard Study Area as follows:

High rock-fall hazard: Areas where steep slopes below resistant cliff-forming bedrock units provide acceleration and runout zones littered with abundant rock-fall boulders ≥1.5 feet in diameter. Such large boulders can damage property and threaten lives. Rock units in high-hazard areas include the Shinarump Member of the Chinle Formation, Springdale Sandstone Member of the Kayenta Formation, Navajo Sandstone, Lamb Point Tongue Member of the Navajo Sandstone, and Quaternary basalt flows. Where jointed or fractured, these rock units can produce large (>30 feet in long dimension) angular boulders.

Moderate rock-fall hazard: Areas where (1) slopes provide sufficient relief to create an acceleration zone, but where only sparse rock-fall debris is present on slopes or in the runout zone at the base of the slope; typically bedrock units in these areas crop out in the slope instead of forming a capping unit; (2) talus/cliff-retreat deposits form steep slopes due to erosion and previous rock-fall boulders on those slopes may remobilize; or (3) resistant, cliff-forming bedrock units extend to the canyon floor with no underlying acceleration zone; rock falls in these areas tend to fall straight down and stop immediately at the base of the cliff.

Low rock-fall hazard: Areas where fine-grained, comparatively soft bedrock units such as mudstone and shale crop out on steep slopes, or where rock units typical of moderate- or high-hazard categories crop out in areas of low to moderate relief. Low rock-fall hazard areas typically contain sparse rock sources of limited extent.

Low probability, high hazard: Canyon bottoms subject to very large low-probability, high-hazard rock falls. These areas are typically bordered by towering, jointed Navajo Sandstone cliffs. The largest of these events (fin collapse/rock avalanche) may involve thousands of cubic yards of material, are typically sourced high on canyon walls, and have recurrence intervals likely measured in thousands of years. Runout zones can extend much farther than for the smaller, more frequent rock-fall events.

USING THE MAP

The Rock-Fall Hazard map (plate 2) shows areas of relative rock-fall hazard in the Zion National Park Geologic-Hazard Study Area. Site-specific, rock-fall-hazard investigations should be performed for future development in the study area as recommended in table 3.1. Existing park facilities, campgrounds, and high-use trails should be evaluated as time and funding allow, also as recommended in table 3.1. A geotechnical consultant should provide design or site-preparation recommendations as necessary to reduce the rock-fall hazard. These investigations can resolve uncertainties inherent in generalized hazard mapping and help ensure safety by identifying the need for rock-fall-resistant design or mitigation.

For some areas, site-specific assessment may only require a field geologic evaluation to determine if a rock-fall source is present. However, if a source is identified, additional work to adequately assess the hazard is needed. Rock-fall sources should be evaluated for the following parameters: rock type, joints and other fractures, bedding planes, and potential clast size. Slopes below rock sources should be evaluated for slope angle, aspect, substrate, surface roughness, and vegetation. Previous rock-fall deposits should be evaluated for distribution, clast-size range, amount of embedding, and weathering of rock-fall boulders. In addition, evaluation of the runout zone below a source can be estimated using a simple two-dimensional model, such as the Colorado Rock Fall Simulation Program (Jones and others, 2000).

The hazard presented by large rock falls in areas designated "low probability, high hazard" is high, but the likelihood of such an event at any particular location is low. These areas are considered subject only to very infrequent events. Site-specific investigations are not recommended for future development in these areas.

MAP LIMITATIONS

The map boundaries between rock-fall-hazard categories are approximate and subject to change as new information becomes available. The rock-fall hazard at any particular site may be different than shown because of geological variations within a map unit, gradational and approximate map-unit boundaries, and map scale. Small, localized areas of higher or lower rock-fall hazard may exist within any given map area, but their identification is precluded because of limitations of the map scale. This map is not intended for use at scales larger than the published scale, and is designed for use in general planning and design to indicate the need for site-specific investigations.

HAZARD REDUCTION

Early recognition and avoiding areas subject to rock fall are the most effective means of reducing rock-fall hazard. However, avoidance may not always be a viable or cost-effective option, especially for existing facilities (figure 3.6), and other tech-

Table 3.1. *Recommended requirements for site-specific investigations related to rock-fall hazards to protect life and safety.*

Hazard Potential	Occupancy Category[1]				
	I	II		III	IV
	Buildings and Other Structures That Represent a Low Hazard to Human Life in the Event of Failure	Family Dwellings and Campgrounds	All Other Buildings and Structures Except Those Listed in I, III, and IV	Buildings and Other Structures That Represent a Substantial Hazard to Human Life in the Event of Failure	Buildings and Other Structures Designated as Essential Facilities
High, Moderate	No[2]	Yes	Yes	Yes	Yes
Low	No[2]	Yes	Yes	Yes	Yes
None	No	No	No	No	No

[1]Modified from International Code Council (2009).
[2] Property damage possible, but little threat to life safety.

Figure 3.6. *Permanent park facilities in rock-fall hazard zones. A. Precariously balanced boulder on a steep slope directly above Zion Lodge. B. Large rock-fall boulders along the heavily traveled River Walk Trail.*

niques are available to reduce potential rock-fall damage. These may include, but are not limited to, rock stabilization, engineered structures, and modification of at-risk structures or facilities. Rock-stabilization methods are physical means of reducing the hazard at its source using rock bolts and anchors, steel mesh, or shotcrete on susceptible outcrops. Engineered catchment or deflection structures such as berms or benches can be placed below source areas, or at-risk structures themselves could be designed to stop, deflect, retard, or retain falling rocks. Conversely, after careful consideration of the hazard, it may be possible to conclude that the level of risk is acceptable and that no hazard-reduction measures are required.

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Chapter 4
Landslide Hazard

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Chapter 4: Landslide Hazard

INTRODUCTION

Landslide is a general term covering a wide variety of mass-movement landforms and processes involving the downslope transport, under gravitational influence, of soil and rock material en masse (Cruden and Varnes, 1996; Neuendorf and others, 2005). The term includes both deep-seated and shallow mass movements (Cruden and Varnes, 1996). The moisture content of the affected materials at the time of landsliding may range from dry to saturated.

Landslides can be both damaging and deadly. The U.S. Geological Survey (USGS) estimated that in the United States, landslides on average cause $1–2 billion in damage and more than 25 deaths annually (USGS, 2008). Harty (1993a, 1993b) compiled landslide maps of the Kanab and St. George 30′ x 60′ quadrangles. Giraud and Shaw (2007) compiled mapping of approximately 14,000 landslides statewide to create a landslide susceptibility map of Utah. Anderson and others (1984) estimated that the total direct costs of landslides in Utah in the abnormally wet spring of 1983 exceeded $250 million. The 1983 Thistle landslide, Utah's single most destructive landslide, is recognized both in terms of direct and indirect costs as the most expensive individual landslide in North American history (University of Utah, 1984; Schuster, 1996; USGS, 2008).

Rock and soil units susceptible to landsliding underlie parts of the Zion National Park Geologic-Hazard Study Area. Historical landslides have disrupted transportation routes, houses, commercial sites, and public utilities within and adjacent to the study area (figure 4.1) (Black and others, 1995; Lund and Sharrow, 2005; Lund and others, 2007).

Figure 4.1. *Home destroyed by the 1992 Springdale landslide in Springdale, Utah.*

SOURCES OF INFORMATION

Sources of information used to evaluate landslide hazards in the Zion National Park Geologic-Hazard Study Area include (1) the nine Utah Geological Survey (UGS) 1:24,000-scale geologic quadrangle maps that cover the study area (Clear Creek Mountain [Hylland, 2000], Cogswell Point [Biek and Hylland, 2007], Kolob Arch [Biek, 2007a], Kolob Reservoir [Biek, 2007b], Springdale East [Doelling and others, 2002], Springdale West [Willis and others, 2002], Temple of Sinawava [Doelling, 2002], The Barracks [Sable and Doelling, 1993], and The Guardian Angels [Willis and Hylland, 2002]) (figure 1.1), (2) *Engineering Geology of the St. George Area, Washington County, Utah* (Christenson and Deen, 1983), (3) *Landslide Maps of the Kanab and St. George 30′ x 60′ Quadrangles, Utah* (Harty, 1993a, 1993b), (4) "Geologic Hazards of the St. George Area, Washington County, Utah" (Christenson, 1992), (5) "Landslide Distribution and Hazards in Southwestern Utah" (Harty, 1992), (6) *Engineering Geologic Map Folio, Springdale, Washington County, Utah* (Solomon, 1996b), (7) *Landslide Susceptibility Map of Utah* (Giraud and Shaw, 2007), and (8) *Geologic Hazards and Adverse Construction Conditions, St. George–Hurricane Metropolitan Area, Washington County, Utah* (Lund and others, 2008).

LANDSLIDE CAUSES

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

Although one or a combination of the above causes may make a rock or soil mass susceptible to landsliding, a trigger is required for slope movement 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). Common landslide triggers in Utah include a transient snowmelt-induced rise in ground-water levels to an instability threshold (Ashland, 2003); prolonged or extreme periods of above-normal precipitation; irrigation above unstable slopes; leakage from canals, pipes, and other water conveyance structures; earthquake shaking; and erosion.

LANDSLIDE TYPES AND PROCESSES

Varnes (1978) grouped all landslides into one of five types based on their mode of movement: fall, topple, slide, spread, and flow (figure 4.2). The characteristics of the material in the landslide, the rate of movement, the state of activity, and the style of movement allow further subdivision and description of the various landslide types. Cruden and Varnes (1996) provided a detailed description of Varnes' updated nomenclature system.

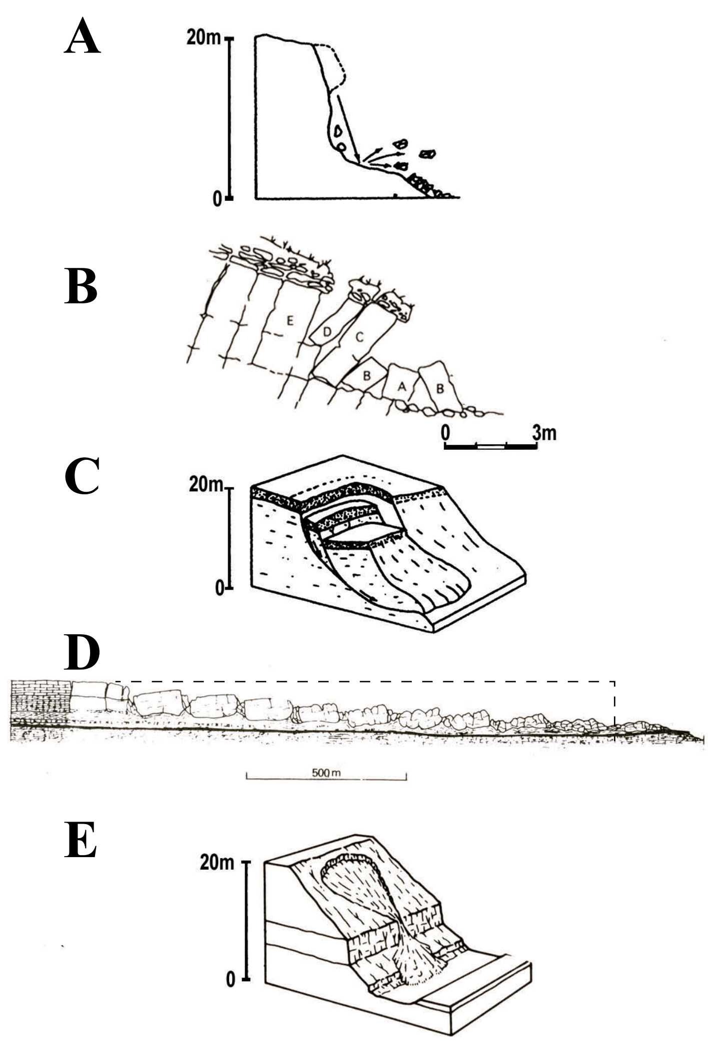

Figure 4.2. *Types of landslides: (a) fall, (b) topple, (c) slide, (d) spread, and (e) flow. Broken lines indicate original ground surfaces; arrows show portions of trajectories of individual particles of displaced mass (from Cruden and Varnes [1996], Special Report 247: Landslides—Investigation and Mitigation, figure 3-19, p. 53. Copyright, National Academy of Sciences, Washington, D.C.; reproduced with permission of the Transportation Research Board).*

All five of Varnes' (1978) landslide types are not present in the Zion National Park Geologic-Hazard Study Area. Landslides as defined for this study consist almost exclusively of "slides" as described by Varnes (1978) and Cruden and Varnes (1996) (figure 4.2c). Due to the study area's semiarid climate, spreads and slow-moving flows (figure 4.2d and 4.2e), which typically depend on a high water content to mobilize, have not been recognized in the study area and consequently are not considered further here. Debris flows are discussed in chapter 2 and rock falls in chapter 3.

A landslide is the downslope movement of a soil or rock mass occurring dominantly on surfaces of rupture or on relatively thin zones of intense shear strain (Cruden and Varnes, 1996). Slides may be rotational or translational (figure 4.3). Rotational slides have curved, concave rupture surfaces, which may be shallow or deep seated, along which the slide mass moves, sometimes with little internal disruption. Because of the curved rupture surface (figure 4.4), the head of a rotational slide commonly tilts backward toward the slide's main scarp. Rotational slide movement may be very slow to rapid and take place under dry to wet conditions, although most occur in the presence of at least some ground water.

Translational slides move along planar or gently undulating shear surfaces and typically slide out over the original ground surface (figure 4.3; Cruden and Varnes, 1996). Translational slides commonly use discontinuities such as bedding planes, joints, or faults as a rupture surface, and if the slide plane is long enough, particularly in the presence of water, may transition into a flow-type slide. Movement of translational slides ranges from very slow to rapid.

Triggering mechanisms for slides vary and in some cases may not be readily apparent (Giraud, 2002); however, periods of above-average precipitation are particularly effective in triggering landslides in Utah (Fleming and Schuster, 1985; Godfrey, 1985; Hylland and Lowe, 1997; Ashland, 2003; Christenson and Ashland, 2005). Although plentiful under static (non-earthquake) conditions, both rotational and translational slides may accompany earthquakes having Richter magnitudes greater than 4.5 (Keefer, 1984). For example, the September 2, 1992, M 5.8 St. George earthquake, which data suggest occurred on the Hurricane fault (Pechmann and others, 1995), caused a large, complex, chiefly translational landslide in the town of Springdale, 27 miles from the earthquake epicenter and only a few hundred feet from the south entrance of Zion National Park. The landslide involved approximately 18 million cubic yards (yd^3) of material, destroyed three houses (figure 4.1) and two water tanks, and closed State Route 9 (Black and others, 1995; Jibson and Harp, 1996).

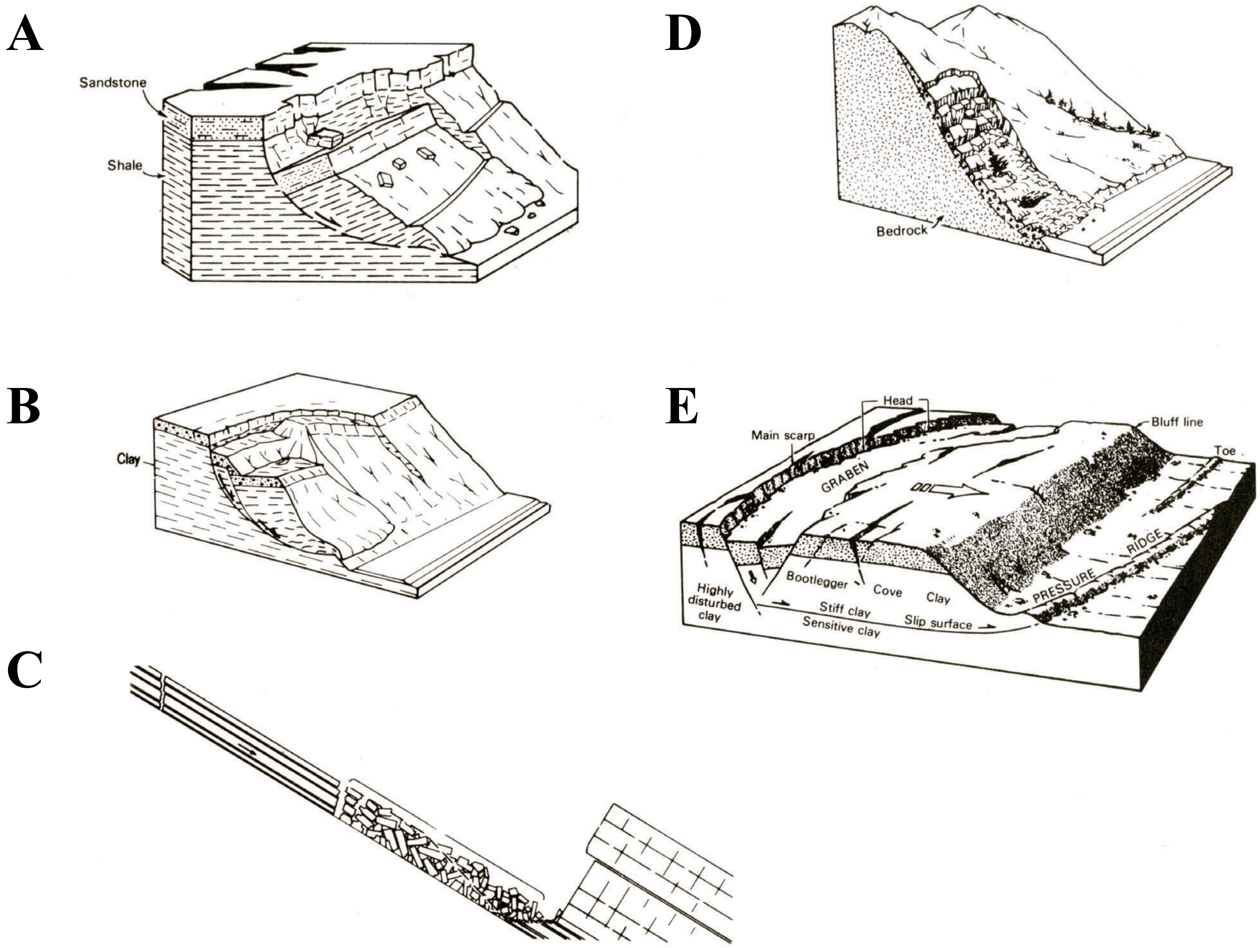

Figure 4.3. *Examples of rotational and translational landslides: (a) rotational rock slide, (b) rotational earth slide, (c) translational rock slide, (d) debris slide, and (e) translational earth slide mass (from Cruden and Varnes [1996], Special Report 247: Landslides—Investigation and Mitigation, figure 3-22, p. 57. Copyright, National Academy of Sciences, Washington, D.C.; reproduced with permission of the Transportation Research Board).*

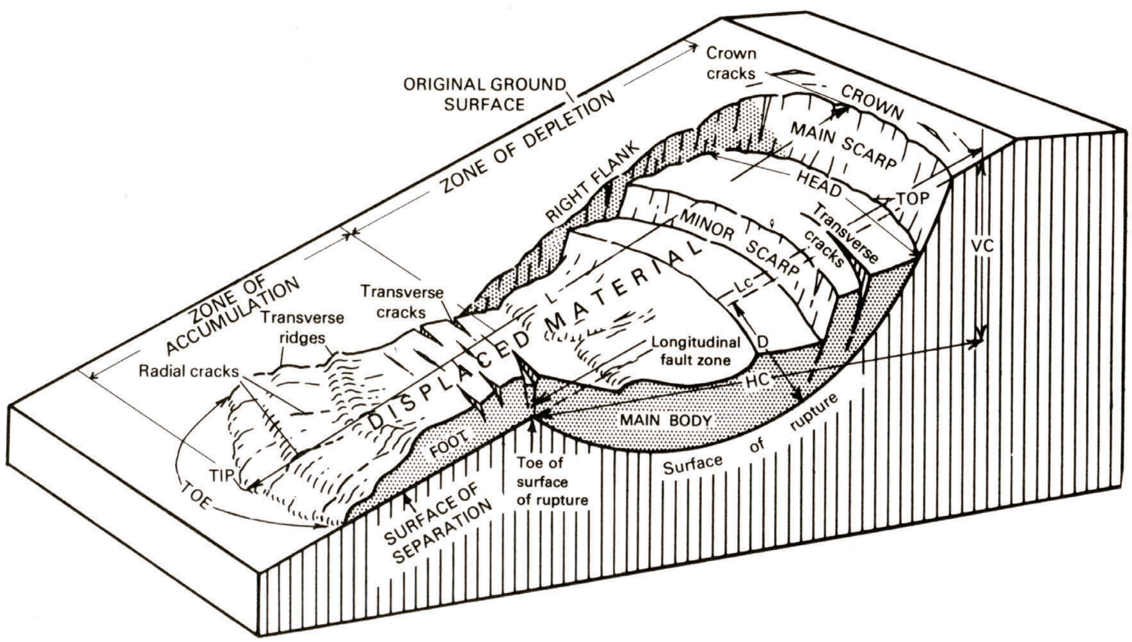

Figure 4.4. *Block diagram of an idealized complex earth slide (from Cruden and Varnes [1996], Special Report 247: Landslides—Investigation and Mitigation, figure 3-2, p. 40. Copyright, National Academy of Sciences, Washington, D.C.; reproduced with permission of the Transportation Research Board).*

LANDSLIDES IN THE ZION NATIONAL PARK GEOLOGIC-HAZARD STUDY AREA

Utah Geological Survey 1:24,000-scale geologic maps (see Sources of Information section) provide the most detailed information on landslides in the Zion National Park Geologic-Hazard Study Area. Those maps identify 142 landslides and landslide complexes in the study area. Of that total, 16 are historical landslides, 68 are mapped as "young" landslides, 28 are mapped as "old" landslides, and 30 are landslide complexes. As shown on the UGS geologic maps, the terms *young* and *old* are geomorphic descriptors that refer to the general freshness in appearance of landslide-related features. Landslides mapped as "old" typically show greater evidence of erosion and smoothing of landslide-related features (scarps, cracks, bulging toes, etc.) than do "young" landslides. Although an increasing degree of erosion and smoothing is generally an indicator of greater age, when applied to a landslide "old" does not necessarily imply greater stability or dormancy. "Old" landslides may reactivate when disturbed or when subjected to natural triggers such as a significant change in moisture conditions.

The 142 landslides/landslide complexes include both rotational and translational landslides, and some landslide complexes are as much as a square mile in area. Generally, there is a close correlation between landslides in the study area and landslide-susceptible bedrock formations. Landslides are also present in more-competent bedrock formations where the competent units are undercut by erosion or mass movement of underlying weak units. The Petrified Forest Member of the Chinle Formation, which consists chiefly of weak, highly expansive shale and claystone, is the most landslide-susceptible bedrock formation in the study area. The more-competent Moenave Formation overlies the Petrified Forest Member and also contains numerous landslides. Although the Moenave Formation is a stronger rock unit, landslides typically form where that unit has been undercut by erosion or mass movement of the Petrified Forest Member.

Three historical landslides of particular significance in the Zion National Park Geologic-Hazard Study Area are the Sentinel landslide, the Zion–Mount Carmel Highway Switchbacks landslide, and a group of small landslides along the Kolob Canyons Scenic Drive. All of these landslides have damaged roads in the study area. Three other historical landslides—the Springdale, Paradise Road, and Watchman landslides—are all within a few hundred feet or less of the park in the town of Springdale. Geologic conditions that contributed to the formation of those landslides are also present in the park administrative area near the south park entrance.

Sentinel Landslide

Approximately 7000 years ago, an estimated 280 million yd^3 of rock either (1) from the western wall of Zion Canyon (Hamilton, 1995) or (2) from a large remnant fin of Navajo Sandstone on the west side of Zion Canyon (Biek and others, 2003) collapsed and blocked the North Fork of the Virgin River. Broken and crushed rock filled the canyon to a depth of approximately 700 feet for 1.3 miles, with a small portion of the debris also spilling into the lower Pine Creek drainage. A lake formed behind the debris pile that extended at least 4 miles upstream into Zion Narrows. The river would have filled the lake in less than a year. The river eventually overtopped and cut into the landslide dam and established a new channel in the eastern part of the debris pile (Wieczorek and Schuster, 1995). Ongoing erosion of the debris by the North Fork of the Virgin River has removed about half of the original landslide material, and maintains an unstable slope on the west side of the river, which periodically produces small landslides.

In April 1995, part of the Sentinel landslide reactivated and blocked the North Fork of the Virgin River for about an hour. The river subsequently breached the landslide dam and inundated Zion Canyon Scenic Drive. The ensuing erosion destroyed about 600 feet of roadway and underground utility lines. A temporary, one-lane road was constructed in the rubble slope to the east of the highway to evacuate people from the upper canyon (figure 4.5). Similar landslides occurred at or near this location in 1924 and again in 1941 (Grater, 1945; Solomon, 1996a). Ground water appears to be a contributing factor to the landslide reactivation. An outcrop of the Springdale Sandstone Member of the Kayenta Formation at the south end of the landslide produces several seeps and small springs. During excavation to place a rock buttress at the toe of the landslide in 2000, springs were observed discharging near river level from both the upstream and downstream margins of the slide mass. Both the winters of 1941 and 1995 were exceptionally wet, with January through April precipitation being 182 percent and 235 percent of the 70-year average, respectively.

Figure 4.5. *Temporary road graded around the Sentinel landslide, April 1995 (photo credit G.F. Wieczorek, U.S. Geological Survey).*

Zion–Mount Carmel Highway Switchbacks Landslide

Beginning at the Pine Creek Bridge, the Zion–Mount Carmel Highway ascends the steep south wall of Pine Creek Canyon (north face of Bridge Mountain) via a series of six sharp switchbacks to the west portal of the Zion–Mount Carmel Tunnel. On the ascent, the roadway is underlain by bedrock, colluvium, talus, and landslide deposits (Hamilton, 1978; Doelling and others, 2002). The largest of the landslides, here referred to as the Zion–Mount Carmel Highway Switchbacks landslide (figure 4.6), occupies an area of several acres on the canyon wall and is crossed by the third and fourth switchbacks (Carl's Bend and Sandwich Rock switchbacks [Yeh and Associates, Inc., 2008]). Landslide movement has repeatedly damaged the highway in this area, and caused the Federal Highway Administration to contract with a geotechnical consulting firm to investigate the nature and cause of the landslides (Yeh and Associates, Inc., 2008).

Yeh and Associates (2008) identified three contributors to road damage in the switchbacks area: (1) small, rotational slumps along the downslope shoulder of the roadway, (2) continued consolidation of subsurface materials, partially in response to poorly compacted embankment fill dating from construction of the road in the 1920s, and in part from collapsible natural soils, and (3) a large "ancient" landslide that underlies the Carl's Bend and Sandwich Rock switchbacks. Both the slumping and embankment/soil settlement problems are attributed to poor drainage conditions where the highway crosses the large landslide. Ponding occurs along parts of the roadway, which allows water to infiltrate and cause compaction of the low-density road fill and natural soils. The ponding has been exacerbated by the plugging of some drains and culverts that are meant to convey water away from the road. The Yeh and Associates (2008) study found no visual evidence that the large landslide is presently active, but noted signs of recent movement (head scarps, hummocky landforms, disturbed ground, and tilted trees) that may date from the time of highway construction. Although not studied in detail, the large landslide is believed to be a rotational slide (Richard Andrews, Yeh and Associates, Inc., written communication, 2008).

As part of the Yeh and Associates (2008) study, several boreholes were drilled in settlement areas along the roadway, subsurface materials were sampled and tested, and inclinometers and piezometers installed to monitor future landslide movement and changes in ground-water levels. Laboratory testing indicated that fill materials in the roadway are less than 95% of maximum dry density (ASTM D 698, T 99 method A; 2002) and susceptible to compaction upon wetting. A preliminary global slope-stability analysis showed that slope stability is highly dependent on ground-water conditions. The factor of

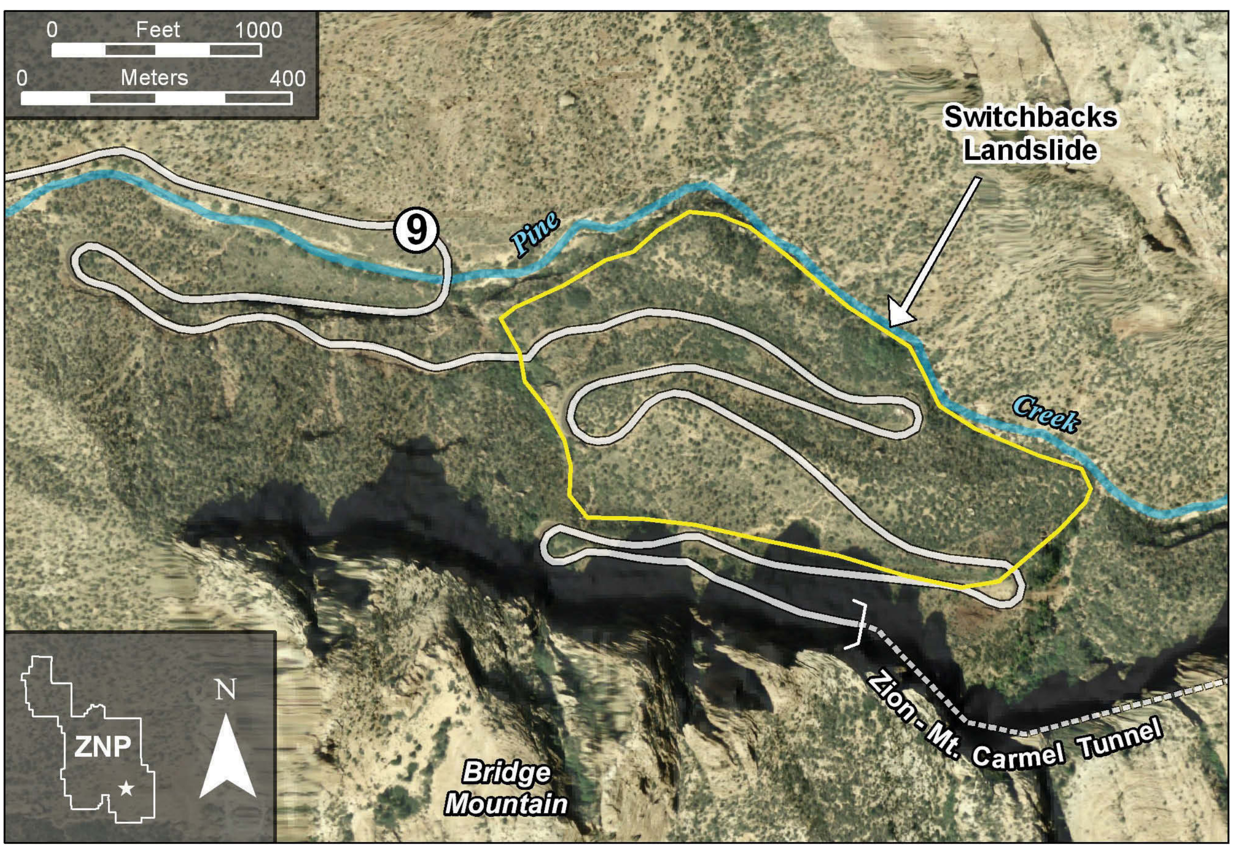

Figure 4.6. *Zion–Mount Carmel Highway Switchbacks landslide (image source 2006 National Agricultural Imagery Program).*

safety for the ancient landslide was found to be 1.56 for ground-water conditions at the time of the study (winter 2007–08), but could be as low as 0.96 for elevated ground-water conditions. For the small, rotational slope failures, the factor of safety was 1.05 for deeper ground-water conditions and 0.79 for shallow ground-water conditions. The Yeh and Associates (2008) recommendations to mitigate landslide movement included adding cross culverts, regrading and lining drainage ditches, removing debris that is currently plugging existing culverts, and adding erosion protection at culvert outlets.

Kolob Canyons Scenic Drive Landslides

Kolob Canyons Scenic Drive is in the northwestern part of the Zion National Park Geologic-Hazard Study Area. The road has experienced numerous small to moderate-sized damaging landslides that in several instances resulted in prolonged periods of road closure. The most notable landslides occurred during the late winter of 1979, when three translational/rotational slides located approximately 2.5, 3.9, and 5.0 miles from the Kolob Canyons Visitor Center displaced the roadbed and necessitated closing the road. The Federal Highway Administration investigated the landslides in June 1979, and concluded that all three originated in natural soil and rock underlying sections of embankment fill (Hanson, 1979).

Lower Landslide

Hanson (1979) did not provide precise locations for the three landsides, but based on the reported mileage from the Kolob Canyons Visitor Center, the lower landslide likely occurred in young landslide deposits and possibly soft shale units of the Chinle, Moenave, or Kayenta Formations close to the trace of the Taylor Creek thrust fault.

The lower landslide exhibited chiefly translational movement, had a semicircular main scarp, and displaced a 39-foot-wide section of the roadbed 21 feet down toward the South Fork of Taylor Creek (Hanson, 1979). A single borehole at this location penetrated a 6-foot section of rock-debris embankment fill overlying 11 feet of reddish brown, fine- to coarse-grained colluvium and talus, and 7.5 feet of reddish gray, soft shale. A slide plane is not indicated on the borehole log, so it is unclear if the rupture surface was in colluvium or shale. Hanson (1979) stated that the “direction of the slide is only 25º off the direction of the bedrock dip and that the angle of the slide plane may be close to the [bedrock] dip angle,” and concluded that “the bedrock attitude is conducive to this type of slide; however, the failure surface may not be deep enough to be controlled by the shale formation.”

Middle Landslide

The middle landslide is likewise not precisely located, but a distance of 3.9 miles from the Kolob Canyons Visitor Center places the landslide in an area mapped by Biek (2007a) as the Kayenta Formation on a steep slope above Timber Creek. The Kayenta Formation consists chiefly of interbedded reddish brown claystone, siltstone, and sandstone. The landslide’s location in a bedrock area is confirmed by a single borehole that penetrated 4 feet of rock-debris embankment fill overlying 10 feet of reddish brown sandstone with shale layers (Hanson, 1979).

The middle landslide was principally translational with slight rotational movement, and had a semicircular main scarp across which a 59-foot-long section of the roadbed was displaced 2.8 to 4.2 feet down to the east (Hanson, 1979). Strike and dip of bedrock immediately adjacent to the slide was N. 19º E., 28º E., which was within 4 and 8 degrees, respectively, of the roadway trend and embankment slope.

Upper Landslide

The upper landslide was the largest of the three landslides, and was described by Hanson (1979) as “a massive, compound slide which appears to have been primarily caused by erosion of the slope [on which the road is located] by stream action some 700 feet down slope from the roadway, well beyond the [road] fill limits.” The upper landslide was approximately 5 miles from the Kolob Canyons Visitor Center and a few hundred feet south of the parking lot at the Kolob Canyons Overlook. The landslide displaced a section of roadbed 144 feet long and as much as 12 feet wide. Diagonal tension cracks in the roadway extended beyond the immediate landslide area and showed that the distressed area encompassed the entire 200-foot-long fill section along this part of the road (Hanson, 1979).

Hanson (1979) indicated that bedrock crops out just above and on each side of the landslide. Mapping by Biek (2007a) shows that the bedrock is likely the Whitmore Point Member of the Moenave Formation, which consists chiefly of mudstone and claystone horizons interbedded with fine-grained sandstone. Three boreholes penetrated 4 to 6 feet of mostly gravelly embankment fill overlying 5 to 9 feet of reddish brown clayey silt; a fourth borehole encountered 6 feet of embankment fill over 11 feet of dark brown, moist silty clay. All four boreholes encountered bedrock at depths ranging from 9 to 17 feet. The bedrock consisted of interbedded shale, siltstone, and sandstone (Hanson, 1979). Hanson (1979) reported that bedrock adjacent to the landslide strikes N. 31º E. and dips 37º SE. in the same direction as the hill slope on which the road was constructed.

Hanson (1979) concluded that the majority of the upper landslide involved a large block of soil and rock beneath the embankment fill, and that the likely cause of the landslide was progressive undercutting of the hill slope by Timber Creek. The undercutting caused multiple episodes of progressive landsliding, which finally reached far enough upslope to affect the road. Hanson (1979) noted that at the time of his inspection a number of springs were flowing from the toe of the landslide 700 to 800 feet downslope from the road, and that debris consisting of mud, rocks, and trees extended down the stream channel for 230 feet beyond the landslide boundaries.

Other Small Landslides

We conducted a field reconnaissance along Kolob Canyons Scenic Drive and observed several additional small landslides above the road with the potential to affect the roadway. Most of the landslides were in or near road cuts, and variously involved slope colluvium, pre-existing landslide deposits, or highly weathered bedrock. For most of its length above the Hurricane Cliffs, Kolob Canyons Scenic Drive either crosses bedrock containing abundant claystone, mudstone, and siltstone horizons, or traverses pre-existing landslide deposits. The abundance of landslide deposits attests to the weak nature of the bedrock in the area; bedrock strength is likely further compromised by deformation and fracturing associated with the Taylor Creek thrust fault, which trends north-south through the area. We anticipate that small landslides will continue to be an ongoing maintenance problem along Kolob Canyons Scenic Drive, and larger landslides, similar to those that occurred in 1979, are possible in wet years, particularly if water is allowed to pond along the roadway. An area of particular concern for future translational, dip-slope landslides is the part of Kolob Canyons Scenic Drive in the vicinity of the 1979 upper landslide from Lee's Pass to the Kolob Overlook, where alternating layers of competent sandstone and weak shale of the Kayenta and Moenave Formations dip as much as 80º toward the road.

Springdale and Paradise Road Landslides

The most damaging effect of the 1992 St. George M 5.8 earthquake (Arabasz and others, 1992; Pechmann and others, 1995) was the Springdale landslide (figure 4.7), which destroyed three homes (figure 4.1), two water tanks, and several storage buildings. The landslide also blocked State Route 9 leading to Zion National Park, ruptured both buried and above-ground utility lines, and caused a condominium complex and several businesses around the periphery of the landslide to be temporarily evacuated. The earthquake also triggered the smaller Paradise Road landslide west of the Springdale landslide, which caused no damage (figure 4.7) (Black and others, 1995; Jibson and Harp, 1995, 1996).

The Springdale landslide is a complex block slide that involves both rotational and translational elements (Black, 1994). Although ground shaking initiated the movement, the landslide continued to move slowly for several hours after the earthquake. The landslide measures approximately 1600 feet from the main scarp to the toe, has a width of about 3600 feet, and a surface area of about 4.4 million square feet. The total volume of the landslide is approximately 18 million yd^3 (Black and others, 1995). The landslide has a clearly defined main scarp as well as numerous fissures and minor scarps that form broken irregular topography within the landslide mass. The spacing and orientation of the scarps and fissures indicate that the landslide likely moved as several coherent blocks (Black, 1994). Several smaller landslides also developed on the oversteepened toe of the main landslide mass.

The landslide rupture surface was in the Petrified Forest Member of the Chinle Formation, and also involved the overlying Moenave Formation and alluvium and colluvium derived from the Kayenta Formation. Prehistoric landslides in the Petrified Forest Member are common in the Springdale area (Solomon, 1996b), and this unit is involved in many deep-seated landslides throughout southwestern Utah (Harty, 1992).

The Springdale landslide is exceptional because it occurred 27 miles from the earthquake epicenter; worldwide data (Keefer, 1984) indicate that the previous maximum recorded epicentral distance for a coherent landslide of this size in a M 5.8 earthquake was only 11 miles. The Springdale landslide may be the largest historical landslide triggered by an earthquake of this magnitude (Jibson and Harp, 1995, 1996). Slope-stability analysis indicates that the static factor of safety for the landslide before the earthquake may have been as low as 1.30 (Jibson and Harp, 1995, 1996). The earthquake apparently triggered only a small amount of coseismic displacement, but enough to elevate pore-water pressure in the clays of the Petrified Forest Member in which the basal shear plane then formed. The elevated pore-water pressure probably reduced the factor of safety below 1.0, leading to large-scale slope movement (Jibson and Harp, 1995, 1996).

Watchman Landslide

In the spring of 2005, a landslide began to develop on the southeast side of the North Fork of the Virgin River in Springdale, and is herein named the Watchman landslide (figure 4.7). The landslide first became noticeable to Springdale residents in early May, and then grew quickly over a period of three to four weeks. The UGS performed a reconnaissance investigation of the landslide (Lund and Vice, 2005) at the request of Rick Wixom, Springdale Town Manager. Mr. Wixom's principal concern was that the landslide or large rock-fall boulders derived from it might block the Virgin River and cause flooding in Springdale.

The landslide lies a few hundred feet southwest of the Zion National Park boundary and formed in unconsolidated deposits that have accumulated at the base of the steep east wall of Zion Canyon. The area of the landslide is approximately 3.1 acres, and the landslide toe abuts flat-lying alluvial terrace deposits

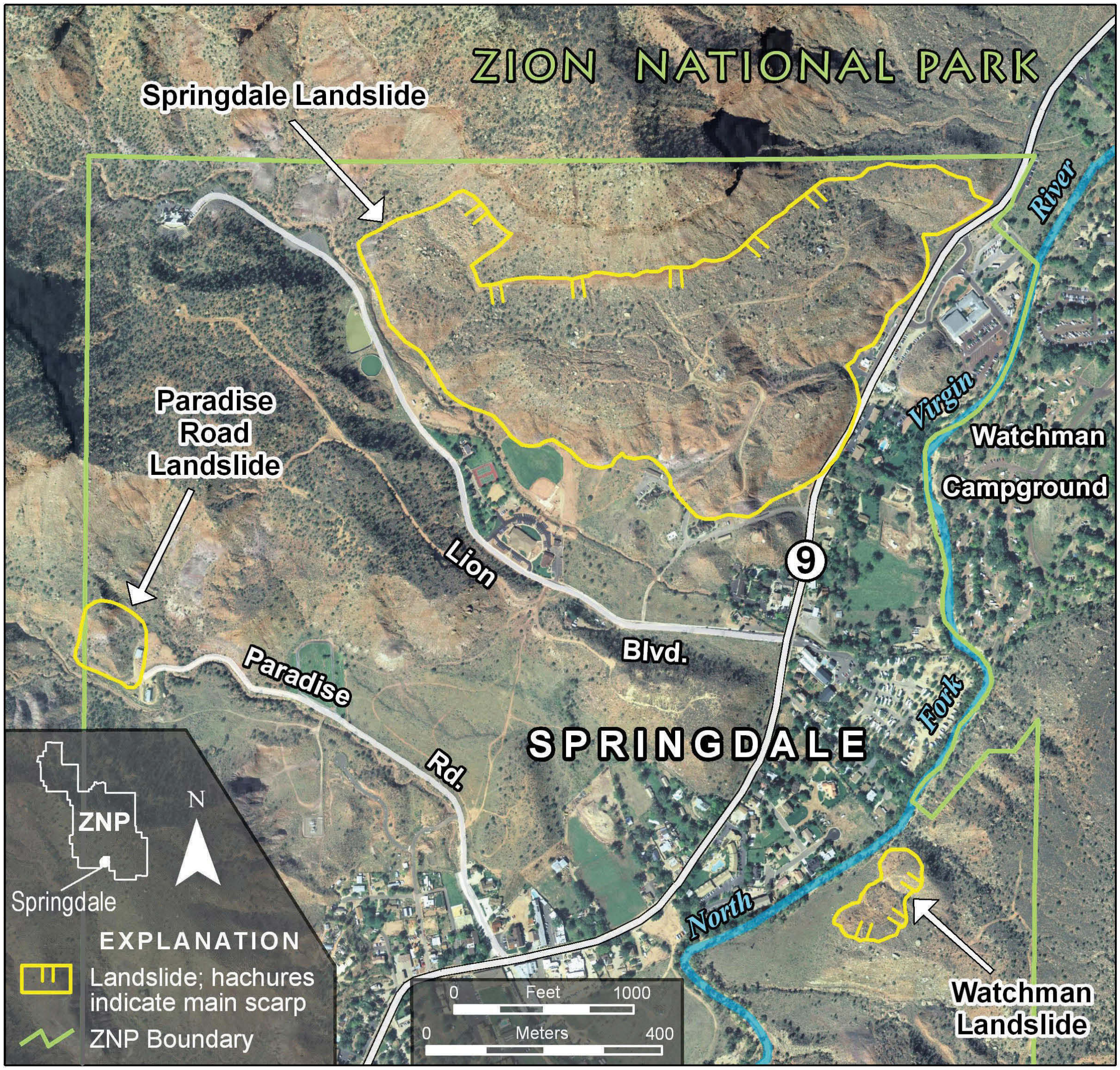

Figure 4.7. *Springdale, Paradise Road, and Watchman landslides in Springdale, Utah (image source 2006 National Agricultural Imagery Program).*

along the North Fork of the Virgin River. As of this writing, the landslide has not affected the terrace deposits.

The landslide is a rotational slump with a main scarp up to 6 feet high and numerous internal transverse scarps. The rupture surface appears to be steep, and there is no discernable location where the slide plane daylights; a pioneer rock wall at the landslide toe remains undisturbed, except where impacted by rock falls and talus shed from the landslide surface. Where exposed in scarps, the material comprising the landslide has been dry during repeated visits to the site (Lund and Vice, 2005; UGS unpublished data) and consists chiefly of brownish-red fine sand derived from the sandstone formations exposed in the walls of Zion Canyon. However, the landslide is underlain by the Petrified Forest Member of the Chinle Formation (Solomon, 1996b; Doelling and others, 2002), and the Petrified Forest Member is likely involved in the landsliding.

Over the course of several visits, we have observed no water draining from or near the landslide (Lund and Vice, 2005; UGS unpublished data). However, the Zion Canyon weather station is less than a mile from the landslide and reported 26.59 inches of precipitation at the end of May for the 2005 water year, which is 14.7 inches greater than the average for that time of year, and remains by far the wettest winter/spring season on record for Springdale. The high precipitation level was likely a contributing factor to landslide initiation. Geologic conditions similar to those at the Watchman landslide, such as cliff-derived colluvium underlain by the Petrified Forest Member of the Chinle Formation on steep slopes, are also present in the Zion National Park administrative area.

LANDSLIDE-HAZARD CLASSIFICATION

We classified landslide hazards in the Zion National Park Geologic-Hazard Study Area using a three-step procedure:

1. Geologic units on UGS geologic maps were grouped into four relative susceptibility categories based on their lithologic characteristics as they relate to material strength and stability, and on the number of landslides mapped in each unit.
2. Average ground-surface slope inclinations (% slope) of representative landslides in the study area were measured to identify the critical slope inclination above which landsliding may initiate in the various susceptibility categories.
3. The results of steps (1) and (2) were integrated to create four Landslide Susceptibility Categories.

Landslide Susceptibility

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, and basalt). We consider the number of landslides mapped in each geologic unit to be an important, but secondary, indicator of overall landslide susceptibility. Whereas the presence of landslides clearly indicates susceptibility to landsliding, the number of landslides in a geologic unit is, at least in part, a function of the unit's outcrop area. A geologic unit that contains mostly weak rock types, but crops out over a small area, may exhibit fewer total landslides than a stronger unit that crops out over a larger area. Additionally, many landslides mapped in relatively strong geologic units are the result of slope movement in an underlying weaker unit that undermined the more competent overlying rocks.

We assigned geologic units in the study area to four broad susceptibility categories ranging from most susceptible to least susceptible (A through D), based on the perceived strength characteristics and relative percentage of strong versus weak lithologies in each unit, and secondarily on the number of landslides present in each unit. Table 4.1 summarizes the susceptibility categories.

Landslide Slope Inclination

We measured average ground-surface slope inclinations for representative landslides in each of the susceptibility categories in table 4.1. Landslide slope inclination is the overall ground-surface slope of the displaced landslide mass, and is calculated by dividing the difference between the landslide head and toe elevations by the horizontal distance from the head to the toe (Hylland and Lowe, 1997), which gives the tangent of the overall slope angle. Multiplying that value by 100 gives percent slope. Hylland and Lowe (1997) considered landslide slope inclinations to represent the approximate maximum quasi-stable slope for a geologic unit under constant conditions of material strength, nature and origin of discontinuities, and ground-water conditions at a given site.

Considering the broad scale of this study and the intended use of the maps as land-use planning tools to indicate where site-specific investigations are needed, we selected the lowest measured landslide slope inclination, or lowest proxy estimate from nearby well-studied areas, for each susceptibility category as the critical slope inclination for that category. Table 4.2 shows representative landslide slope inclinations measured for geologic units comprising the different susceptibility categories in the study area, or where measuring reliable post-failure angles was not possible, angles for those same geologic units were used as determined by Lund and others (2008) in the St. George–Hurricane metropolitan area. The critical slope inclination is the minimum slope above which landsliding typically occurs in a particular susceptibility category, and serves as a conservative guide for initiating site-specific, slope-stability investigations for that susceptibility category.

Landslide-Hazard Categories

We combined the four landslide-susceptibility categories in table 4.1 with the critical slope inclinations determined for each of those categories in table 4.2 to characterize landslide hazard in the Zion National Park Geologic-Hazard Study Area. The four resulting levels of landslide hazard are described below. Due to the highly landslide-prone nature of the clay-rich Petrified Forest Member of the Chinle Formation (landslide-susceptibility category B, table 4.1), we included areas where the Petrified Forest Member crops out on slopes less than 15 percent (the critical slope for susceptibility category B) in the Moderate Hazard category (see hazard category Moderate B below) to indicate the hazard posed by this unit even in gently sloping areas.

Very High: Existing landslides (susceptibility category A).

High: Areas where the Petrified Forest Member of the Chinle Formation and the overlying Moenave Formation (susceptibility category B) crop out on slopes greater than 15 percent (8º).

Moderate C: Areas where susceptibility-category C geologic units crop out on slopes greater than 20 percent (12º).

Moderate B: Areas where the Petrified Forest

Table 4.1. Landslide susceptibility of geologic units in the Zion National Park Geologic-Hazard Study Area.

Susceptibility Category	Geologic Unit[1]	Comments
A	Existing landslides	Existing landslides are considered the most likely units in which new landslides may initiate (Ashland, 2003).
B	Petrified Forest Mbr., Chinle Fm.; Moenave Fm. where above slopes of Petrified Forest Mbr.	The Petrified Forest Member consists chiefly of bentonitic clay, which is expansive and has low shear strength. This unit includes the greatest number of landslides in the study area. Numerous landslides have also formed in the overlying Moenave Formation. where the Petrified Forest crops out on lower slopes.
C	Harrisburg Mbr., Kaibab Fm.; Shnabkaib Mbr. and red members, Moenkopi Fm.; Moenave Fm. not above slopes of Petrified Forest Mbr.; Kayenta Fm. above Springdale Sandstone Mbr.; Temple Cap Fm.; Carmel Fm.; Cedar Mountain Fm.	These bedrock 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, which often occur as landslide complexes.
D	Remaining bedrock and unconsolidated geologic units exclusive of the Navajo Sandstone. Mass wasting in the Navajo Sandstone is limited to rock falls and fin-collapse mass wasting which are discussed in the Rock-Fall Hazard section of this study.	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. Landslides identified within these units typically result from mass movement or erosion in underlying, weaker geologic units.

[1] See figure 1.4 in chapter 1 for complete geologic unit names.

Table 4.2. Representative landslide and critical slope inclinations for landslide-susceptible geologic units in the Zion National Park Geologic-Hazard Study Area.

Susceptibility Category[1]	Representative Landslide Slope Inclinations	Critical Slope Inclination
A[1]	Not applicable	Not applicable
B[2]	—	15% (8º)
C	20–80% (12º–38º)	20 % (12º)
D[3]	—	30 % (17º)

[1]Category A is not slope dependent.
[2]Landslides in category B are typically mapped as landslide complexes or mixed landslide/colluvial/alluvial deposits—it was difficult to identify discrete landslides for measurements of slope inclinations, so we adopted a critical slope inclination of 8º, which was the angle used for the same units in the St. George–Hurricane metropolitan area (Lund and others, 2008).
[3]Discrete landslides not related to undercutting by underlying weak units were not identified in category D, so we adopted a critical slope inclination of 17º, which was the angle used for low-susceptibility units in the St. George–Hurricane metropolitan area (Lund and others, 2008).

Member of the Chinle Formation crops out on slopes less than 15 percent (8º).

Low: Areas where susceptibility-category D geologic units crop out on slopes greater than 30 percent (17º).

While it is possible to classify relative landslide hazard in a general way on the basis of material characteristics and critical slope inclinations, landslides ultimately result from the effects of site-specific conditions acting together to promote mass movement. For that reason, we recommend that a site-specific investigation be conducted to evaluate the effect of development on slope stability for all development in areas of sloping terrain where modifications to natural slopes are planned, and where landscape irrigation, onsite wastewater disposal systems, or infiltration basins may cause ground-water levels to rise (see, for example, Ashland, 2003; Ashland and others, 2005, 2006; Christenson and Ashland, 2005).

USING THE MAP

The Landslide Hazard map (plate 3) shows areas of relative landslide hazard and provides a basis for requiring site-specific hazard investigations. Site-specific investigations can resolve uncertainties inherent in generalized geologic-hazard mapping and help ensure safety by identifying the need for hazard mitigation.

The Landslide Hazard map (plate 3) identifies areas, based on previous landslide history, material characteristics, and slope, where site-specific slope-stability conditions (such as material strength, orientation of bedding or fractures, ground-water conditions, erosion or undercutting) should be evaluated prior to development. The level of investigation needed at a given site depends on the relative hazard and the nature of the proposed development (structure type, size, use, and placement; required cuts and fills; and changes in ground-water conditions). A valid landslide-hazard investigation must address all pertinent conditions that could affect, or be affected by, the proposed development, including earthquake ground shaking. This can only be accomplished through the proper identification and interpretation of site-specific geologic conditions and processes (Blake and others, 2002). Nearby conditions that may affect the site must also be considered.

The analysis of natural and modified slopes for static and/or seismic stability is a challenging geotechnical problem. Blake and others (2002, p. 3) consider the following steps required for a proper static and seismic slope-stability analysis.

"Accurate characterization of:

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

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

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

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

Accordingly, landslide-hazard investigations must be interdisciplinary in nature and performed by qualified, experienced geotechnical engineers and engineering geologists working as a team. Utah Geological Survey Circular 92 *Guidelines for Evaluating Landslide Hazards in Utah* (Hylland, 1996) presents minimum standards for performing landslide-hazard evaluations. Turner and Schuster (1996) and Blake and others (2002) provide additional guidance for evaluating landslide hazards. Local jurisdictions may adopt more stringent requirements for slope-stability investigations, as they deem necessary, to meet local needs and conditions. Recommendations for site-specific investigations in each landslide-hazard category are given in table 4.3.

MAP LIMITATIONS

The Landslide Hazard map (plate 3) accompanying this report is based on 1:24,000-scale UGS geologic mapping, and the inventory of landslides obtained from that mapping and shown on the Landslide Hazard map reflects that level of mapping detail. Some smaller landslides may not have been detected during the mapping or are too small to show at that scale. Therefore, site-specific geotechnical and geologic-hazard investigations

Table 4.3. *Recommendations for landslide-hazard studies in the Zion National Park Geologic-Hazard Study Area.*

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

should be preceded by a careful field evaluation of the site to identify any landslides present. The mapped boundaries of the landslide-hazard categories are approximate and subject to change as new information becomes available. The landslide hazard at any particular site may be different than shown because of variations in the physical properties of geologic units, ground-water conditions within a map unit, gradational and approximate map-unit boundaries, and the generalized map scale. Small, localized areas of higher or lower landslide hazard may exist within any given map area, but their identification is precluded by limitations of map scale. This map is not intended for use at scales other than the published scale and is intended for use in general planning and design to indicate the need for site-specific investigations.

HAZARD REDUCTION

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

Where development is proposed in areas identified on the Landslide Hazard map (plate 3) as having a potential for landsliding, we recommend that a phased site-specific investigation be performed early in the project design phase. A site-specific investigation can establish whether the necessary conditions for landsliding are present at a site; if they are, appropriate design and construction recommendations should be provided.

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Chapter 5
Earthquake Hazards

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Chapter 5: Earthquake Hazards

INTRODUCTION

Earthquakes occur without warning and can cause injury and death, major economic loss, and social disruption (Utah Seismic Safety Commission, 1995). An earthquake is the abrupt, rapid shaking of the ground caused by sudden slippage of rocks deep beneath the Earth's surface. The rocks break and slip when the accumulated stress exceeds the rock's strength. The surface along which the rocks slip is called a fault. Seismic waves are then transmitted outward from the earthquake source, producing ground shaking. The consequences of an earthquake depend upon several factors including its magnitude, depth, and distance from population centers, and geologic and soil conditions at a particular site (Keller and Blodgett, 2006). Earthquakes cause a wide variety of geologic hazards including surface faulting, ground shaking, liquefaction, landsliding, regional subsidence, and various types of flooding (table 5.1).

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

Table 5.1. *Principal earthquake hazards, expected effects, and hazard-reduction techniques (modified from Utah Seismic Safety Commission, 1995).*

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

SOURCES OF INFORMATION

Sources of information used to evaluate earthquake hazards in the Zion National Park Geologic-Hazard Study Area include (1) the nine Utah Geological Survey (UGS) 1:24,000-scale geologic quadrangle maps that cover the study area (Clear Creek Mountain [Hylland, 2000], Cogswell Point [Biek and Hylland, 2007], Kolob Arch [Biek, 2007a], Kolob Reservoir [Biek, 2007b], Springdale East [Doelling and others, 2002], Springdale West [Willis and others, 2002], Temple of Sinawava [Doelling, 2002], The Barracks [Sable and Doelling, 1993], and The Guardian Angels [Willis and Hylland, 2002]) (figure 1.1), (2) information on historical earthquakes in southwestern Utah and northwestern Arizona, chiefly from the University of Utah Seismograph Stations earthquake catalog (University of Utah Seismograph Stations, 2009) and the Arizona Earthquake Information Center earthquake catalog (Arizona Earthquake Information Center, 2009), (3) the *Quaternary Fault and Fold Database of the United States* (U.S. Geological Survey [USGS], 2009a), which includes estimates of most recent surface faulting, (4) 29 geotechnical reports on file with the National Park Service (NPS) and the nearby Town of Springdale, and (5) the occurrence of wet, or potentially wet soils mapped by the Natural Resources Conservation Service (formerly Soil Conservation Service) (Mortensen and others, 1977). Geotechnical and ground-water data are limited in both amount and distribution; consequently, detailed information about depth to and distribution of ground water, and the physical characteristics of unconsolidated geologic deposits as they relate to liquefaction hazard is unavailable for most of the Zion National Park Geologic-Hazard Study Area.

Anderson and Christenson (1989) reviewed Quaternary faulting and folding in southwestern Utah, including the Zion National Park area, and Christenson (1995) edited a volume of papers on the 1992 St. George earthquake. Studies by Pearthree and others (1998), Stenner and others (1999), Lund and others (2001, 2002, 2007, 2008a), and Amoroso and others (2004) present paleoseismic information for the Hurricane and Sevier faults.

The principal sources of information for the earthquake-ground-shaking evaluation of the Zion National Park Geologic-Hazard Study Area were the USGS National Seismic Hazard Maps (NSHM) (2009b), *International Building Code* (IBC) (International Code Council, 2009a), and *International Residential Code for One- and Two-Family Buildings* (IRC) (International Code Council, 2009b).

EARTHQUAKES IN SOUTHWESTERN UTAH

In Utah, most earthquakes are associated with the Intermountain Seismic Belt (ISB) (Smith and Sbar, 1974; Smith and Arabasz, 1991), an approximately 100-mile-wide, north-south-trending zone of earthquake activity that extends from northern Montana to northwestern Arizona (figure 5.1). Within the ISB and adjacent areas of the Intermountain West, the threshold for surface faulting is about M 6.5. Earthquakes smaller than about M 6.5 generally leave little or no geologic evidence of their occurrence. Since 1850, there have been at least 16 earthquakes of M 6.0 or greater within the ISB (University of Utah Seismograph Stations, 2009). Included among those 16 events are Utah's two largest historical earthquakes, the 1901 Richfield earthquake with an estimated magnitude of 6.5, and the 1934 Hansel Valley M 6.6 earthquake, which produced Utah's only historical surface faulting. In an average year, Utah experiences more than 700 earthquakes, but most are too small to be felt. Moderate (M 5.5–6.5) earthquakes happen every several years on average, the most recent being the M 5.8 St. George earthquake on September 2, 1992. Large (M 6.5–7.5) earthquakes occur much less frequently in Utah, but geologic evidence shows that most areas of the state within the ISB, including the Zion National Park region, have experienced large surface-faulting earthquakes in the Holocene (past 11,800 years [Gradstein and others, 2004]).

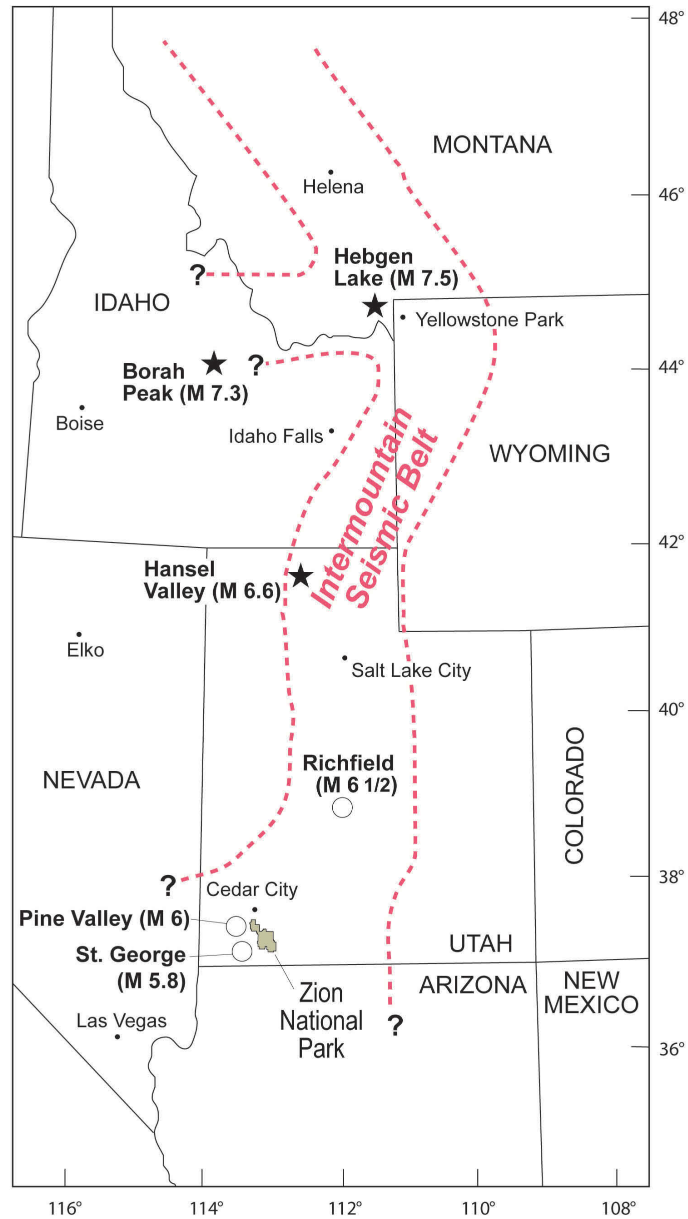

Figure 5.1. *The Intermountain Seismic Belt (ISB) and major historical ISB earthquakes (stars denote earthquakes that produced surface faulting, open circles indicate significant non-surface-faulting earthquakes).*

Fault-related surface rupture has not occurred in southwestern Utah historically, but the area does have a pronounced record of seismicity. At least 21 earthquakes greater than M 4 have occurred in southwestern Utah in historical time (Christenson and Nava, 1992; University of Utah Seismograph Stations, 2009; figure 5.2); the largest events were the estimated M 6 Pine Valley earthquake in 1902 (Williams and Tapper, 1953) and the M 5.8 St. George earthquake in 1992 (Christenson, 1995). The Pine Valley earthquake is pre-instrumental and poorly located, and therefore cannot be attributed to a known fault. However, the epicenter is west of the surface trace of the west-dipping Hurricane fault, so the earthquake may have occurred on that fault. Pechmann and others (1995) tentatively assigned the St. George earthquake to the Hurricane fault as well.

The largest historical earthquake in northwestern Arizona is the 1959 Fredonia earthquake (approximately M 5.7; DuBois and others, 1982). Since 1987, northwestern Arizona has experienced more than 40 earthquakes of M >2.5, including the 1993 M 5.4 Cataract Canyon earthquake between Flagstaff and the Grand Canyon (Pearthree and others, 1998). On the basis of limited instrumental data and extensive felt reports, three poorly documented earthquakes that occurred near and north of Flagstaff in 1906, 1910, and 1912 are thought to have been in the M 6–6.2 range (figure 5.2) (Phil Pearthree, Arizona Geological Survey, verbal communication, 2007). Despite the lack of historical surface faulting in southwestern Utah, available geologic data for faults in the region indicate a moderate rate of long-term Quaternary activity. Mid-Quaternary basalt flows are displaced more than a thousand feet at several locations, and alluvial and colluvial deposits have been displaced feet to tens of feet in late Quaternary time.

ACTIVE FAULTS IN SOUTHWESTERN UTAH

Because earthquakes result from slippage on faults, from an earthquake-hazard perspective, faults are commonly classified as (1) active, capable of generating damaging earthquakes, or (2) inactive, not capable of generating earthquakes. The term "active fault" is frequently incorporated into regulations pertaining to earthquake hazards, and over time, the term has been defined differently for different regulatory and legal purposes. In nature, faults possess a wide range of activity levels. Some, such as the San Andreas fault in California, produce large earthquakes and associated surface faulting every hundred years or so, while others, like the Wasatch fault and other faults in the Basin and Range Province, produce large earthquakes and surface faulting every few hundred to tens of thousands of years. Therefore, depending on the area of interest or the intended purpose, the definition of "active fault" may vary. The time period over which faulting activity is assessed is critical because it determines which faults are ultimately classified as hazardous, and therefore, subject to regulatory hazard mitigation (Allen, 1986).

Activity Classes

In California, the Alquist-Priolo Earthquake Fault Zoning Act (Bryant and Hart, 2007), which regulates development along known active faults, defines an "active" fault as one that has had "surface displacement within Holocene time (about the past 11,000 years)." 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 time 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 advocate a late Pleistocene age criterion, specifically 130,000 years, to define active faults in the Basin and Range Province. They base their recommendation on the observation that six to eight (>50%) of the 11 historical surface-faulting earthquakes in that region 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 08-2, 2008; first adopted in 1997 as WSSPC Policy Recommendation 97-1, and revised and re-adopted in 2002, 2005, and 2008 [WSSPC, 2008]):

> **Holocene fault –** a fault that has moved within the past 10,000 years (11,500 cal yr B.P.) and has been large enough to break the ground surface.
>
> **Late Quaternary fault –** a fault that has moved within the past 130,000 years and has been large enough to break the ground surface.
>
> **Quaternary fault –** a fault that has moved within the past 1,800,000 years and has been large enough to break the ground surface.

Christenson and Bryant (1998) and Christenson and others (2003) recommended adopting the WSSPC fault activity-class definitions in Utah, and we follow that recommendation in this study.

Evaluating Fault Activity

Because both the instrumental and historical records of seismicity in Utah are short (less than 200 years), geologists must use other means to assess fault activity levels, including evaluating the prehistoric record of surface faulting. Paleoseismology is the study of prehistoric surface-faulting earthquakes (Solonenko, 1973; Wallace, 1981; McCalpin, 2009). Paleoseismic studies can provide information on the timing of the most recent surface-faulting earthquake (MRE) and earlier events, the average recurrence interval between surface-faulting earthquakes, net displacement per event, slip rate (net displacement averaged over time), and other faulting-related parameters (Allen, 1986; McCalpin, 2009). Determining the timing of the

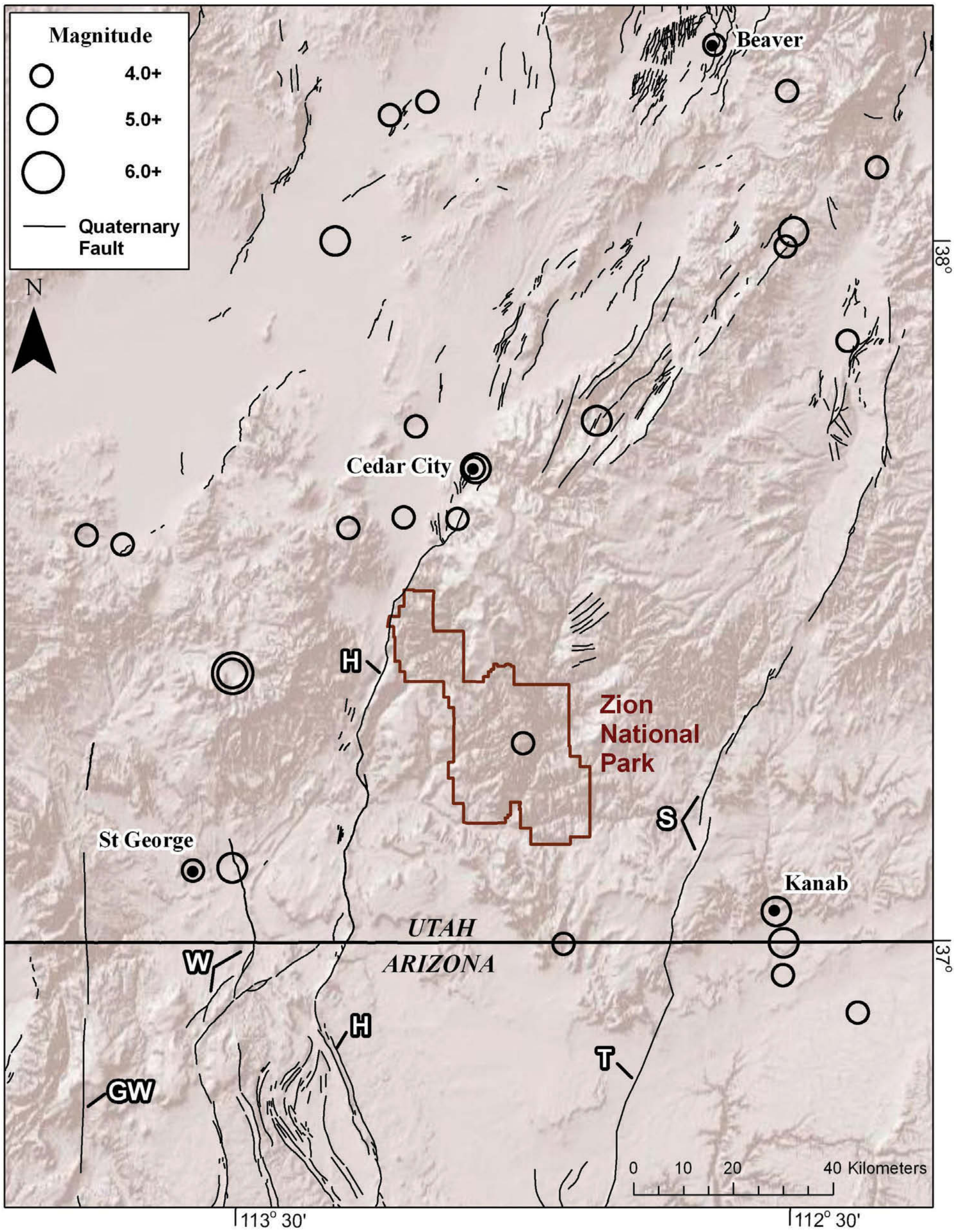

Figure 5.2. Earthquake epicenter map of southwestern Utah and northwestern Arizona and major Quaternary faults in the region: GW = Grand Wash fault; H = Hurricane fault; S = Sevier fault; T = Toroweap fault; W = Washington fault. Figure courtesy of the Arizona Geological Survey; epicenter locations from the Arizona Earthquake Information Center earthquake catalog (Arizona Earthquake Information Center, 2009) and University of Utah Seismograph Stations earthquake catalog (University of Utah Seismograph Stations, 2009).

MRE establishes the fault's activity class (see above). Paleoseismic data from multiple sites can show if a fault ruptures as a single entity, or if it is subdivided into smaller segments that are each independently capable of generating earthquakes. Importantly, paleoseismic studies can establish the relation between the elapsed time since the MRE and the average recurrence interval between surface-faulting earthquakes. Once that relation is known, the likelihood of surface faulting in a time frame of significance to most engineered structures can be estimated.

SURFACE-FAULT-RUPTURE HAZARD

Large earthquakes ($\geq$M 6.5) are commonly accompanied by surface faulting. The rupture may affect a zone tens to hundreds of feet wide and tens of miles long. Surface faulting on normal faults produces ground cracking and typically one or more "fault scarps" (figure 5.3). When originally formed, fault scarps have near-vertical slopes and, depending on the size of the earthquake, can range from a few inches to many feet high. Local ground tilting and graben formation by secondary (antithetic) faulting may accompany surface faulting, resulting in a zone of deformation along the fault trace tens to hundreds of feet wide (figure 5.3). Surface faulting, while of limited aerial extent when compared to other earthquake-related hazards such as ground shaking and liquefaction, can have serious consequences for structures or other facilities that lie along or cross the fault rupture path (Bonilla, 1970). Buildings, bridges, dams, tunnels, canals, and pipelines have all been severely damaged by surface faulting (see, for example, Lawson, 1908; Ambraseys, 1960, 1963; Duke, 1960; California Department of Water Resources, 1967; Christenson and Bryant, 1998; USGS, 2000).

The hazard due to surface faulting is directly related to the activity of the fault—that is, how often the fault ruptures the ground surface and how likely it is to rupture in the future (Christenson and Bryant, 1998). Because designing a structure to withstand surface faulting is generally considered impractical from an economic, engineering, and architectural standpoint for most structures (Christenson and others, 2003; Bryant and Hart, 2007), avoiding active fault traces is the recommended approach for mitigating surface-faulting hazards. Effectively avoiding surface faulting requires conducting a site-specific investigation to (1) identify all potentially active faults at a site, (2) assess the level of activity of the faults, and (3) establish appropriate setback distances from the fault(s).

Faults in the Zion National Park Geologic-Hazard Study Area

Fault Types

Utah Geological Survey 1:24,000-scale geologic mapping shows that two principal types of faults exist in the Zion National Park Geologic-Hazard Study Area: thrust faults and normal faults (figure 5.4). Thrust faulting occurs when the fault hanging wall (the block of rock above the fault plane) moves upward relative to the fault footwall (the block of rock below the fault plane). Thrust faults form in response to compressional (pushing together) forces, have dips less than 45 degrees (figure 5.4c), and place older rock on top of younger rock.

Normal faulting occurs when the fault hanging wall moves downward relative to the fault footwall (figure 5.4b). Normal faults form in response to tensional (pulling apart) forces, typically dip between 45 and 90 degrees, and place younger rock on older rock. Tensional forces have characterized the regional stress regime in southwestern Utah for the past several million years. Consequently, normal faults in the Zion National Park region are typically geologically young, and many, if not most, are considered capable of producing earthquakes. Conversely, thrust faults in the region are related to an older, no longer active compressional stress regime, and do not pose a serious earthquake threat. Therefore, thrust faults in the Zion National

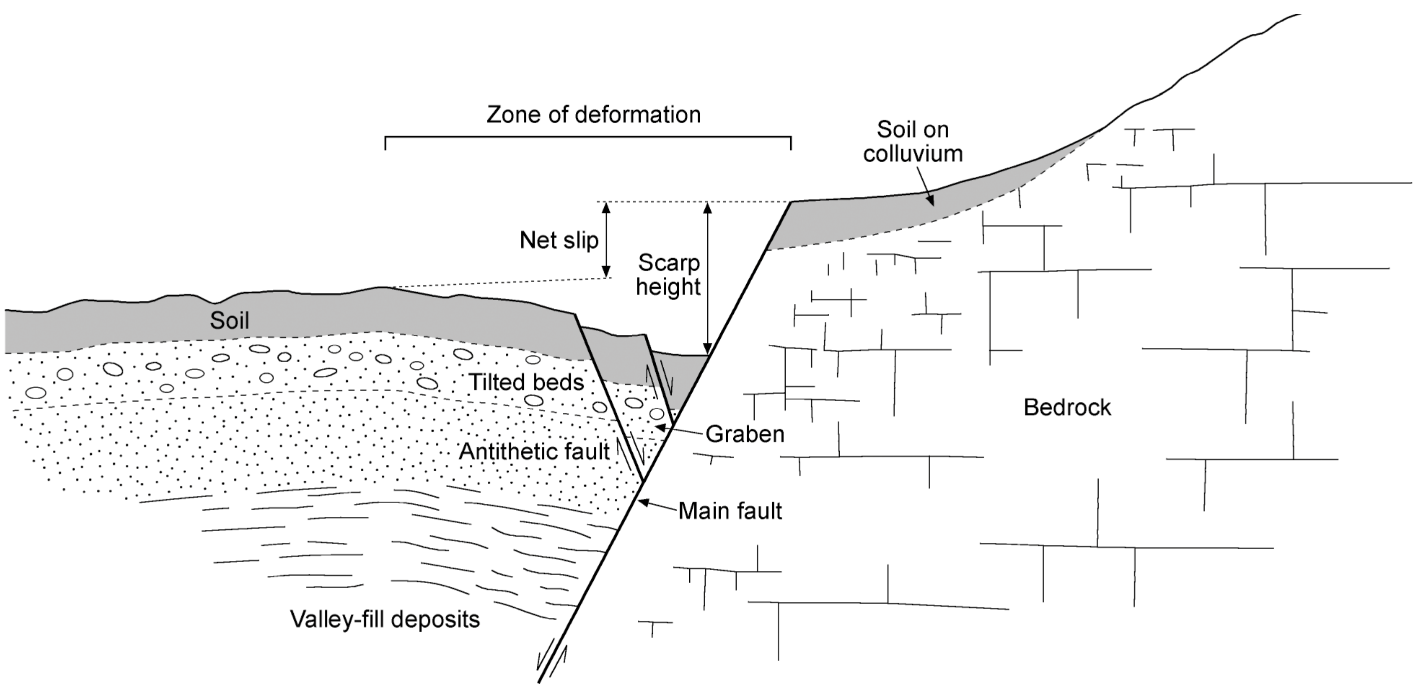

Figure 5.3. *Cross section of a typical normal fault showing scarp formation, tilted beds, and graben formation in the deformation zone associated with the fault (modified from Robison, 1993).*

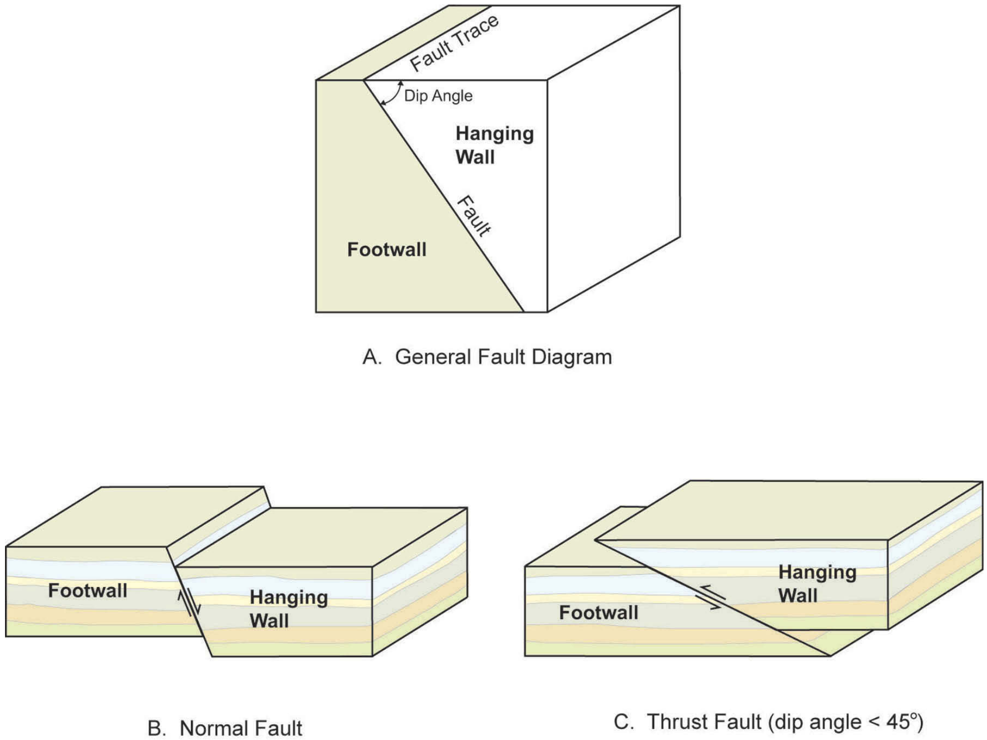

Figure 5.4. *Fault types in the Zion National Park Geologic-Hazard Study Area.*

Park Geologic-Hazard Study Area, chiefly the Taylor Creek thrust fault in the northwestern part of the study area (figure 5.5), will not be considered further.

Normal Faults

The UGS geologic maps used as the basis for this study (see Sources of Information section) show 10 normal faults in the Zion National Park Geologic-Hazard Study Area (figure 5.5). Chief among them is the Hurricane fault, a long, complex, Holocene-active fault that forms a wide zone of braided and branching fault strands that trend north-south through southwestern Utah and northwestern Arizona (figure 5.6). Other normal faults in the study area include the East and West Cougar Mountain faults, Wildcat Canyon fault, Bear Trap Canyon fault, Scoggins Wash faults, Grafton Mesa fault, and three short unnamed faults (figure 5.5). Maximum displacements are thousands of feet across the Hurricane fault and hundreds of feet or less across the other faults.

Hurricane fault: The 155-mile-long Hurricane fault (figure 5.6) is the longest normal fault in the region and shows abundant geologic evidence for down-to-the-west Quaternary surface faulting (note that fault lengths reported in this study are straight line, end-to-end measurements). Vertical displacement across the fault increases to the north, and is greatest in the oldest deposits offset by the fault; nearly flat-lying Mesozoic and Cenozoic bedrock is displaced multiple thousands of feet, early and middle Quaternary basalt flows hundreds of feet to more than a thousand feet, and late Quaternary alluvial and colluvial deposits up to tens of feet (Pearthree and others, 1998; Stenner and others, 1999; Lund and others, 2001, 2002, 2007).

The Hurricane fault has been divided into segments, each considered capable of generating its own earthquakes (USGS, 2009a). Previous workers (Stewart and Taylor, 1996; Stewart and others, 1997; Pearthree and others, 1998; Reber and others, 2001) have suggested that major convex fault bends and zones of structural complexity are likely candidates for boundaries between seismogenic fault segments. Stewart and Taylor (1996) identified a possible segment boundary at the south end of Black Ridge near Toquerville between the proposed Ash Creek segment in Utah and the Anderson Junction segment in Utah and Arizona (figure 5.6). Stewart and others (1997) and Reber and others (2001) identified another potential boundary between the Anderson Junction segment and the proposed Shivwits segment (Pearthree, 1998) to the south, about 6 miles south of the Utah-Arizona border. Lund and others (2007) proposed a Cedar City segment, which extends from Murie Creek about a mile north of Kanarraville to Cedar City.

Parts of both the Anderson Junction and Ash Creek segments parallel the western border of Zion National Park. The distance between the park boundary and the fault decreases to the north until the Ash Creek segment enters the park twice for short distances, once near the Kolob Canyons Visitor Center and again at the extreme northwestern corner of the park near the mouth of Camp Creek (figure 5.5). There has been no historical

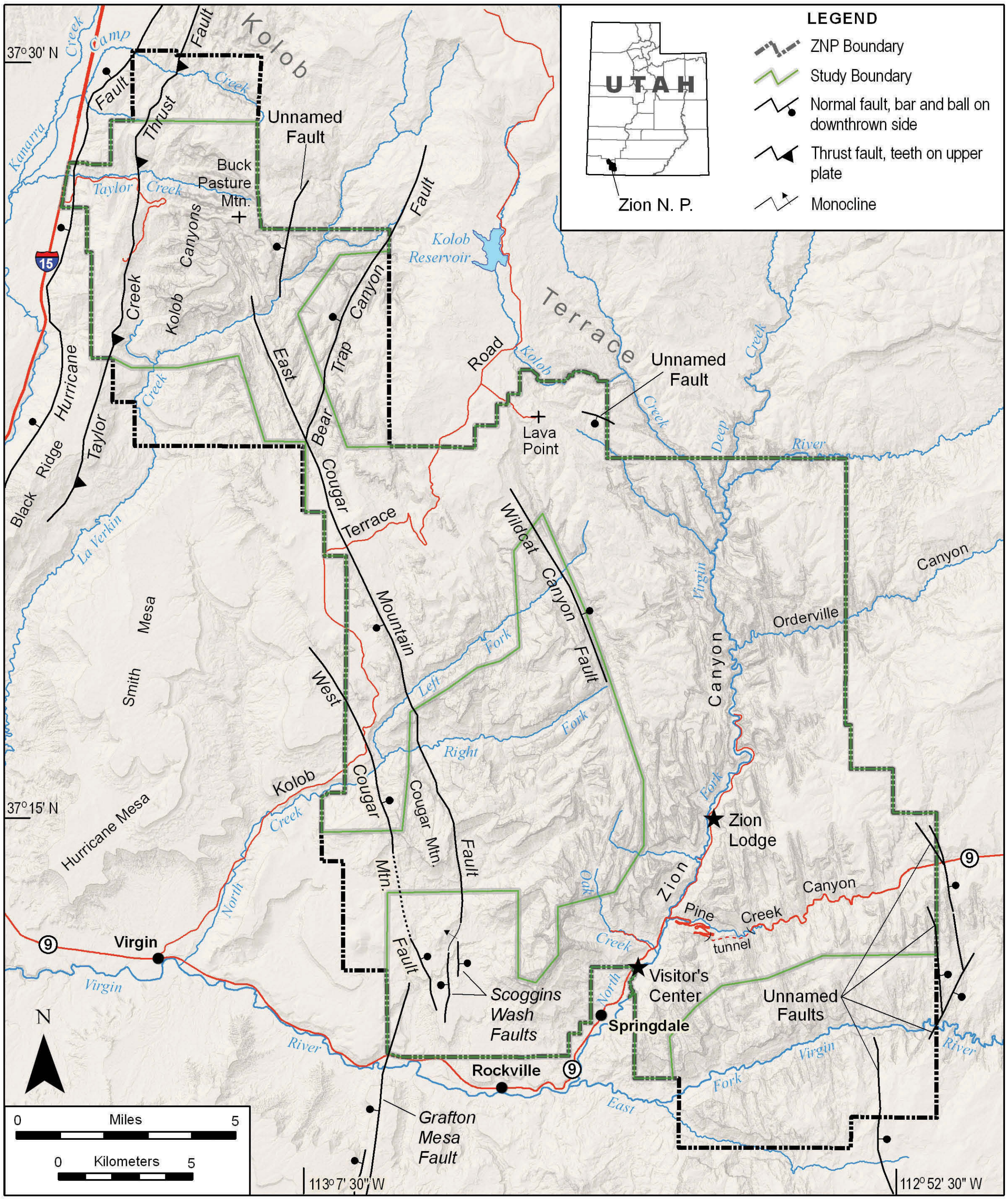

Figure 5.5. *Normal and thrust faults in the Zion National Park Geologic-Hazard Study area.*

surface faulting on the Hurricane fault, but based on available paleoseismic information, the most recent surface faulting on both the Ash Creek and Anderson Junction segments occurred during the Holocene. Stenner and others (1999) trenched the Anderson Junction segment at Cottonwood Canyon in Arizona (figure 5.6) and found evidence for an early to middle Holocene surface-faulting earthquake. Lund and others (2007) radiocarbon dated a faulted young alluvial fan at Coyote Gulch (figure 5.6) on the Ash Creek segment in Utah and obtained a late Holocene age for the MRE.

Lund and others (2007) used geochemically correlated and radiometrically dated displaced basalt flows to calculate long-term average geologic (vertical) slip rates for the Anderson Junction and Ash Creek segments of the Hurricane fault (table 5.2). These slip rates are about one-half to one-fifth of the late Pleistocene and Holocene slip rates reported for the more active Wasatch fault in northern Utah, but are large enough to show that the Hurricane fault is active and capable of generating large surface-faulting earthquakes. Lund and others (2007) estimated earthquake moment magnitudes for the Anderson Junction and Ash Creek segments, based both on estimated surface rupture

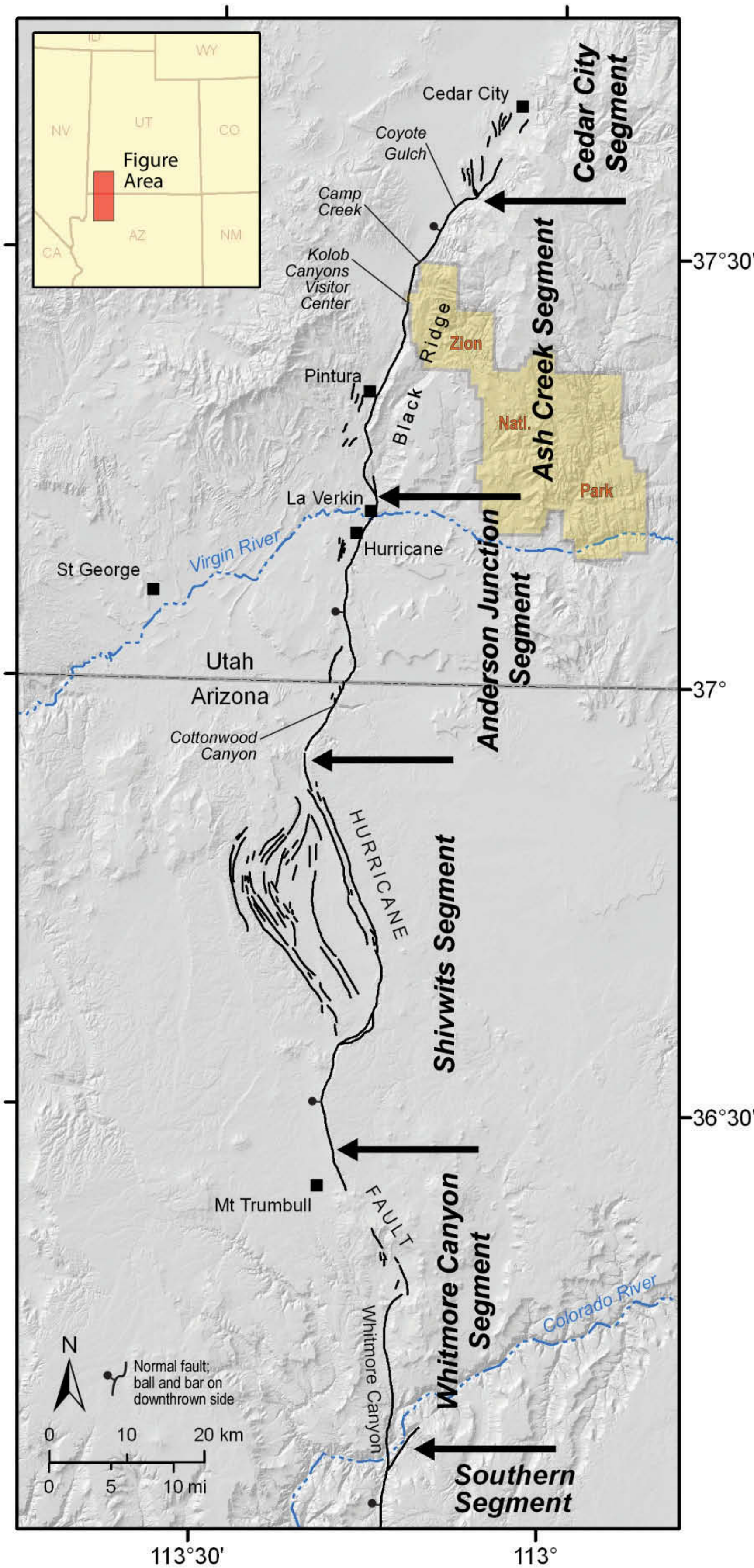

***Figure 5.6.** Proposed Hurricane fault segments (after Lund and others, 2007). Black arrows indicate proposed segment boundaries.*

length and average and maximum displacement, of 6.8 to 7.3.

East and West Cougar Mountain faults: The East and West Cougar Mountain faults are subparallel, northwest-trending, steeply dipping normal faults with opposite directions of displacement (figure 5.5) (Biek and others, 2003). The East Cougar Mountain fault is 13 miles long and dips to the west. The West Cougar Mountain fault, including a southernmost extension in the vicinity of Coalpits Wash (Robert Biek and Grant Willis, UGS, verbal communication, 2008), is approximately 12 miles long and dips to the east. Together, the two faults create a northwest-trending block of downthrown bedrock between them called a graben. Displacement on the East Cougar Mountain fault is about 750 feet near Coalpits Wash. Vertical displacement on the West Cougar Mountain fault is less than on the east fault, so the overall displacement across the two faults is down-to-the-west (Biek and others, 2003; Biek, 2007a). No paleoseismic studies have been conducted on either fault, but both faults are overlain by the 220,000- to 310,000-year-old Grapevine Wash basalt flows (Willis and Hylland, 2002; Biek and others, 2003). The flows are not faulted and demonstrate that the MREs on both the East and West Cougar Mountain faults occurred more than 310,000 years ago; how much before is not known. The long elapsed time since the MREs indicates that both faults have long earthquake recurrence intervals and represent a low earthquake hazard. However, both structures are normal faults and as such are related to the current regional extensional tectonic regime, and therefore are considered capable of producing future earthquakes.

Wildcat Canyon fault: The Wildcat Canyon fault is an east-dipping, northwest-trending normal fault (figure 5.5). The fault is about 5 miles long and displaces the Temple Cap and Carmel Formations up to 180 feet (Biek and others, 2003). No paleoseismic studies have been conducted on the Wildcat Canyon fault; however, the fault is overlain by and does not displace the one-million-year-old Lava Point basalt flow, indicating that the MRE occurred more than a million years ago. The long elapsed time since the MRE demonstrates that the Wildcat Canyon fault has a long earthquake recurrence interval and represents a low seismic hazard. However, because it is a normal fault and as such is related to the current regional extensional tectonic regime, the Wildcat Canyon fault is considered capable of producing future earthquakes.

***Table 5.2.** Geologic slip rates derived from displaced basalt flows along the Anderson Junction and Ash Creek segments of the Hurricane fault (from Lund and others, 2007).*

Location	Segment	Basalt Age (Ma)	Slip Rate (mm/yr)	Comments
Grass Valley	Anderson Junction	1.0	0.44	Near Utah-Arizona border
Pah Tempe	Anderson Junction	0.353	0.21	Youngest basalt flow
S. Black Ridge	Segment Boundary	0.81	0.45	At boundary between two segments
N. Black Ridge	Ash Creek	0.86	0.57	Near Kolob Canyons Visitor Center

Bear Trap Canyon fault: The Bear Trap Canyon fault is a high-angle, steeply west-dipping normal fault that trends northeast in the Kolob Canyons portion of the study area (figure 5.5) (Biek and others, 2003). The fault is approximately 9 miles long and places Temple Cap and Carmel Formation strata in fault contact with the Navajo Sandstone. Hamilton (1995) measured more than 900 feet of displacement on the fault. No paleoseismic studies have been conducted on the Bear Trap Canyon fault; however, mapping by Biek (2007a, 2007b) shows that unconsolidated Quaternary deposits along the fault are not displaced. There are no Quaternary basalt flows along the fault, and therefore no constraints on MRE timing.

At its south end, the Bear Trap Canyon fault intersects the East Cougar Mountain fault at Hop Valley. There is no evidence that the Bear Trap Canyon fault extends to the south beyond the intersection (Robert Biek, UGS, verbal communication, 2008). Therefore, the Bear Trap Canyon fault is likely a branch of the larger East Cougar Mountain fault and, like the East Cougar Mountain fault, has a long surface-faulting recurrence interval and represents a low earthquake hazard. However, because it is a normal fault and as such is related to the current regional extensional tectonic regime, the Bear Trap Canyon fault is considered capable of producing future earthquakes.

Scoggins Wash faults: The Scoggins Wash faults consist of a complex, 2-mile-long zone of both east- and west-dipping normal faults separated from the southern end of the East Cougar Mountain fault by an approximately 1-mile-long, west-dipping monocline (figure 5.5) (Willis and others, 2002). Vertical displacement on the Scoggins Wash faults is less than 200 feet. In many places the displacement is contained entirely within the Shinarump Conglomerate Member of the Chinle Formation (Willis and others, 2002), which in the vicinity of Zion National Park is 60 to 135 feet thick (Biek and others, 2003). In other places, the fault brings the Shinarump into fault contact with the underlying upper red member of the Moenkopi Formation. Those two rock units are normally in stratigraphic contact with each other, so minimal fault displacement is required to create a fault contact between them. No paleoseismic studies have been conducted on the Scoggins Wash faults; however, mapping by Willis and others (2002) shows that unconsolidated Quaternary deposits along the faults are not displaced. There are no Quaternary basalt flows along the fault, and therefore no constraints on MRE timing.

The close spatial relation between the East Cougar Mountain fault and the Scoggins Wash faults indicates a probable affinity between the structures. Therefore, the Scoggins Wash faults, like the East Cougar Mountain fault, likely have long surface-faulting recurrence intervals and represent a low earthquake hazard. However, because the Scoggins Wash faults are normal faults and as such are related to the current regional extensional tectonic regime, they are considered capable of producing future earthquakes, possibly coseismically with the East Cougar Mountain fault.

Grafton Mesa fault: For the purposes of this report, we name an approximately 5-mile-long, northeast-trending, west-dipping normal fault that enters Zion National Park at the southwestern corner of the park the Grafton Mesa fault (figure 5.5). Vertical displacement on the fault is likely less than 200 feet. In many places the displacement is contained entirely within the Shinarump Conglomerate Member of the Chinle Formation (Willis and others, 2002), which in the vicinity of Zion National Park is 60 to 135 feet thick (Biek and others, 2003). At its south end, the fault brings the Shinarump into fault contact with the overlying Petrified Forest Member of the Chinle Formation. Those two rock units are normally in stratigraphic contact with each other, so minimal fault displacement is required to create a fault contact between them. No paleoseismic studies have been conducted on the Grafton Mesa fault; however, mapping by Willis and others (2002) shows that unconsolidated Quaternary deposits along the fault are not displaced. The fault is overlain by and does not displace (Willis and others, 2002) the estimated 100,000-year-old Crater Hill basalt flow (Biek and others, 2003), indicating that the MRE on the Grafton Mesa fault occurred more than 100,000 years ago. However, because it is a normal fault and as such is related to the current regional extensional tectonic regime, the Grafton Mesa fault is considered capable of producing future earthquakes.

Unnamed faults: Three unnamed faults impinge on the Zion National Park Geologic-Hazard Study Area (figure 5.5): a northeast-trending, west-dipping normal fault about 2.5 miles long in the Kolob Canyons area of Zion National Park; a complex, generally northwest-trending, east-dipping zone of faults at the southeast park boundary; and a short, nearly west-trending fault near Lava Point. Vertical displacement on the fault in the Kolob Canyons area is less than 100 feet and is entirely within the Carmel Formation (Biek, 2007a). Displacements on the other faults are unknown, but are thought to be a few hundred feet or less. No paleoseismic studies have been conducted on these faults. There are no Quaternary basalt flows along the faults, and therefore no constraints on MRE timing. However, because they are normal faults, the three unnamed faults are related to the current regional extensional tectonic regime, and are considered potentially capable of producing future earthquakes.

Surface-Fault-Rupture-Hazard Classification

The Surface-Fault-Rupture Hazard map (plate 4) shows the normal faults in the Zion National Park Geologic-Hazard Study Area mapped by the UGS. Because of the prevailing regional extensional tectonic regime, we consider all normal faults in the study area as potentially active until proven otherwise.

Special-Study Areas

Based upon UGS geologic mapping, we categorized the normal faults in the Zion National Park Geologic-Hazard Study Area as either "Well Defined" or "Approximately Located or Buried," and established surface-fault-rupture-hazard special-study areas (Christenson and others, 2003; Lund and others, 2008b) for each fault category.

Well-defined faults: We consider a fault well defined if its trace is clearly detectable by a trained geologist as a physical feature at the ground surface (Bryant and Hart, 2007). We classified normal faults in the Zion National Park Geologic-Hazard Study Area 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. The surface-fault-rupture-hazard special-study areas established for well-defined faults extend for 500 feet on the downthrown side and 250 feet on the upthrown side of each fault, and are shown on the Surface-Fault-Rupture Hazard map (plate 4).

Approximately located and buried faults: The UGS mapped some normal faults in the Zion National Park Geologic-Hazard Study Area as approximately located (dashed lines) or buried (dotted lines) because the traces of those faults are not evident at the ground surface. The reasons for the lack of clear surface evidence for these faults are varied, but are chiefly related to one or more of the following causes: (1) long earthquake recurrence intervals combined with a long elapsed time since the MRE allow evidence for the faults to be obscured by subsequent erosion and deposition, (2) rapid deposition occurs in some areas that quickly obscures faults, even those with comparatively short recurrence intervals, (3) the faults generate earthquakes that produce relatively small scarps (<3 feet) that are quickly obscured, or (4) faulting occurs at or above the bedrock/alluvium contact in relatively steep terrain and is difficult to identify.

Although not evident at the surface, these faults may still represent a surface-fault-rupture hazard and should be evaluated prior to development in areas where they may rupture to the ground surface. Because their location is uncertain, the surface-fault-rupture-hazard special-study areas around these faults are broader, extending 1000 feet on each side of the suspected trace of the faults. Special-study-area boundaries around approximately located or buried faults are shown on the accompanying Surface-Fault-Rupture Hazard map (plate 4).

Fault Activity Levels

The faults on the Surface-Fault-Rupture Hazard map (plate 4) are color-coded to indicate what is presently known about their activity level. Each color-code category includes recommendations for surface-fault-rupture special investigations based on fault activity class (see Activity Classes section above) and the type of building or structure proposed. These recommendations are modified from the UGS *Guidelines for Evaluating Surface-Fault-Rupture Hazards in Utah* (Christenson and others, 2003).

Red Holocene-active or suspected Holocene-active fault: surface-fault-rupture-hazard investigation recommended for all IBC Occupancy Category II, III, and IV buildings and other structures (International Code Council, 2009a).

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

Black Suspected late-Quaternary- or Quaternary-active fault: normal fault related to the current regional extensional tectonic regime overlain by an unfaulted mid- or late-Quaternary basalt flow ≥ 100,000 years old; the most recent surface-faulting earthquake is older than the age of the overlying basalt, but how much older is unknown. Surface-fault-rupture-hazard investigation recommended for IBC Occupancy Category III and IV buildings and other structures (International Code Council, 2009a). Studies for other structures designed for human occupancy remain prudent for faults demonstrated to be late-Quaternary active (see Activity Classes section), but should be based on an assessment of whether risk-reduction measures are justified by weighing the probability of occurrence against the risk to lives and potential economic loss. Studies for other structures intended for human occupancy for faults demonstrated to be Quaternary active (see Activity Classes section) are optional because of the low likelihood of surface faulting, although surface rupture along the fault is still possible.

Using the Map

The Surface-Fault-Rupture Hazard map (plate 4) shows potentially active faults along which surface faulting may occur. A special-study area is shown around each fault, within which we recommend that a site-specific, surface-fault-rupture-hazard investigation be performed prior to construction. These investigations can resolve uncertainties inherent in generalized hazard mapping and help ensure safety by identifying the need for setbacks from the fault.

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

For well-defined faults color-coded red and black (Holocene and Suspected Quaternary, respectively), we recommend that surface-fault-rupture-hazard investigations be performed in accordance with the UGS guidelines. Because age constraints are lacking for the orange-coded faults (fault activity class unknown), we recommend that those faults be considered Holocene active until paleoseismic studies performed in accordance with the UGS guidelines demonstrate them to be otherwise.

Because approximately located and buried faults lack a clearly identifiable surface trace, they are not amenable to trenching, which is the standard surface-fault-rupture-hazard investigation technique used to study well-defined faults (Christenson and others, 2003; McCalpin, 2009). Where development is proposed in a special-study area for a buried or approximately located fault, we recommend that, at a minimum, the following tasks be performed to better define the surface-fault-rupture hazard in those areas:

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

If the results of these investigations reveal evidence of possible surface-faulting-related features, those features should be trenched in accordance with the UGS guidelines for evaluating surface-fault-rupture hazards in Utah (Christenson and others, 2003). Following the above-recommended studies, if no evidence of surface faulting is found, development at the site can proceed as planned. However, we recommend that construction excavations and cut slopes be carefully examined for evidence of faulting as development proceeds.

Map Limitations

The Surface-Fault-Rupture Hazard map (plate 4) is based on 1:24,000-scale geologic mapping, and the inventory of potentially active faults obtained from that mapping and shown on the map reflects that level of detail. Some smaller faults may not have been detected during the mapping or faults may be concealed beneath young geologic deposits. Additionally, approximately located and buried faults by definition lack a clearly identifiable surface trace, and therefore their location is less well known. Site-specific fault-trenching investigations should be preceded by a careful field evaluation of the site to identify the surface trace of the fault, other faults not evident at 1:24,000-scale, or other fault-related features at a site-specific scale.

Hazard Reduction

Because surface faulting is typically confined to relatively narrow zones along the surface trace of a fault, early recognition and avoidance are the most effective strategies for mitigating this hazard. Once the activity class of the fault is determined (see Activity Classes section above), we recommend that setbacks from the fault trace and any associated zone of deformation be established in accordance with UGS guidelines for evaluating surface-fault-rupture hazards in Utah (Christenson and others, 2003). Carefully locating all potentially active fault traces at a site, assessing their level of activity and amount of displacement, establishing an appropriate setback distance from the fault, and proper facility and site design remain the most reliable procedures for mitigating damage and injury due to surface faulting. Considering the proximity of the Kolob Entrance Station and associated buildings to the surface trace of the Hurricane fault, we recommend that a reconnaissance surface-fault-rupture-hazard investigation be conducted for those facilities. If the reconnaissance shows that a surface-rupture hazard may exist, we recommend a follow-up trenching investigation to fully assess the hazard.

In Utah, earthquake-resistant design requirements for construction are specified in the seismic provisions of the IBC (International Code Council, 2009a) and IRC (International Code Council, 2009b), which are adopted statewide. IBC Section 1803.5.11 requires that an investigation be conducted for all structures in Seismic Design Categories C, D, E, or F (see Earthquake Ground-Shaking Hazard section) to evaluate the potential for surface rupture due to faulting.

EARTHQUAKE GROUND-SHAKING HAZARD

Ground shaking is the most widespread and typically most damaging earthquake hazard (Yeats and others, 1997). Ground shaking is caused by seismic waves that originate at the source of the earthquake and radiate outward in all directions. Strong ground shaking can last from several seconds to minutes, and can be amplified or reduced depending on local soil and rock conditions (Reiter, 1990). In general, ground shaking is strongest near the earthquake epicenter and decreases away from that point. The type and quality of construction play a large role in the degree of damage caused by ground shaking. The extent of property damage and loss of life due to ground shaking depends on specific factors such as (1) the strength of the earthquake, (2) the proximity of the earthquake to an affected location, (3) the amplitude, duration, and frequency of earthquake ground motions, (4) the nature of the geologic materials through which the seismic waves travel, and (5) the design of engineered structures (Costa and Baker, 1981; Reiter, 1990).

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

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

Potential sources of strong earthquake ground shaking in the Zion National Park Geologic-Hazard Study Area include the Hurricane fault and several normal faults within the study area that have very long recurrence intervals, but which are still potentially capable of generating damaging earthquakes (figure 5.5) (see Surface-Fault-Rupture Hazard section). The potential for damaging ground motions resulting from earthquakes on the long-recurrence-interval faults in the study area is very low. However, the Hurricane fault represents a viable source of strong earthquake ground shaking that could affect the study area and induce secondary earthquake effects such as liquefaction, landslides, and rock falls.

International Code Council Seismic Design

The IBC (International Code Council, 2009a) and IRC (International Code Council, 2009b) are adopted statewide in Utah and provide design and construction requirements for resisting earthquake motions (loads) based on a structure's seismic-design category.

International Building Code

Determining an IBC seismic-design category is a multi-step process:

1. Define a site class based on the types and engineering properties of soil and rock present in the upper 100 feet beneath a proposed building site (IBC Section 1613.5.2). The IBC defines Site Classes A through F (table 1613.5.2). Site Classes A through E (hard rock to soft soil) may be defined on the basis of average shear-wave velocity, average Standard Penetration Test blow count (N value), or average undrained shear strength (table 1613.5.2). Additionally, soils may be classified as Site Class E or F depending upon other geotechnical characteristics that make them particularly vulnerable to earthquake ground shaking.
2. Determine maximum considered earthquake ground motions (mapped spectral accelerations) on rock (Site Class B) from IBC figures 1613.5(1) through 1613.5(14), or from the USGS National Seismic Hazard Maps (USGS, 2009b). Different structures are affected by different frequencies of ground motion which, when matching the natural frequency of vibration of a structure (a function of building height and construction type), may cause resonance resulting in severe damage or collapse. Therefore, the IBC and USGS provide maximum considered earthquake ground motions for two periods (0.2 sec and 1.0 sec), which together are appropriate for a wide range of building types. The 0.2 sec mapped spectral acceleration (S_s) is appropriate when evaluating the effect of short-period (high-frequency) ground motions, which typically affect short buildings (1–2 stories). The 1.0 sec mapped spectral acceleration (S_1) is appropriate when evaluating the effect of long-period (low-frequency) ground motions, which typically affect tall buildings (more than 2 stories).
3. Adjust the maximum considered earthquake ground motion for a rock site (Site Class B) for deamplification or amplification of earthquake ground motions, due to other site-specific soil and rock conditions. Accelerations are adjusted using site coefficients. The IBC provides site coefficients (F_a and F_v) for each site class for both

Table 5.3. *IBC site-class definitions (modified from 2009 IBC table 1613.5.2).*

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

short-period (F_a) and long-period (F_v) ground motions (IBC tables 1613.5.3[1] and 1613.5.3[2]). Site coefficients for the other site classes are calculated relative to the coefficient (1.0) for Site Class B. Site coefficients <1 indicate that ground motions will be less than those for Site Class B (deamplified), and site coefficients >1 indicate that ground motions will be greater than those for Site Class B (amplified). The site coefficients for both short- and long-period ground motions for Site Class A (hard rock) are 0.8, indicating that ground shaking will be deamplified. The site coefficients for Site Classes C, D, and E (very dense soil or soft rock, stiff soil, and soft soil, respectively) range from 1.2 to 3.5, indicating that ground shaking will be amplified. Amplification generally increases as the period increases and soil or rock strength decreases. Because of the unique properties of soils in Site Class F, the IBC does not provide site coefficients for that site class. Instead, the IBC requires that site-specific geotechnical investigations and dynamic site-response analyses be performed to determine appropriate values.

4. Multiply the site coefficients by the mapped spectral accelerations to produce adjusted maximum considered earthquake spectral response accelerations (S_{MS} and S_{M1}) that account for ground motion amplification or deamplification due to site-specific soil or rock conditions. The adjusted maximum considered earthquake spectral response accelerations are then multiplied by 2/3 to arrive at design spectral response accelerations (S_{DS} and S_{D1}).

5. Determine the seismic design category for the structure by comparing the design spectral response acceleration with the proposed structure's IBC Occupancy Category (IBC table 1604.5) using IBC tables 1613.5.6(1) and 1613.5.6(2) (International Code Council, 2009a). Buildings and structures are assigned the more severe seismic design category, regardless of the fundamental vibration period of the structure. The resulting seismic design category determines the applicable seismic design requirements for the structure.

This procedure is automated using the USGS Java Ground Motion Parameter Calculator available at http://earthquake.usgs.gov/research/hazmaps/design/.

International Residential Code

The IRC (International Code Council, 2009b) applies to one- and two-family dwellings and townhouses. The IRC bases its seismic design categories on soil Site Class D (Section R301.2.2.1.1) as defined in Section 1613.5.2 of the IBC. For soil conditions other than Site Class D, the short-period design spectral response acceleration (S_{DS}) for a site is determined according to Section 1613.5 of the IBC. The resulting IBC S_{DS} value is used to determine the IRC seismic design category using IRC table R301.2.2.1.1.

Zion National Park Geologic-Hazard Study Area Seismic Design Categories

Insufficient geotechnical data are available, both in terms of areal distribution and depth, to prepare an IBC site class map for the Zion National Park Geologic-Hazard Study Area. Table 5.4 shows IBC seismic design categories for all IBC site classes for the Zion Canyon Visitor Center, Zion Lodge, and Kolob Canyons Visitor Center. We obtained values of S_S, S_1, S_{MS}, S_{M1}, S_{DS}, S_{D1}, and the resulting seismic design categories using the USGS National Seismic Hazard Maps Java Ground Motion Parameter Calculator – Version 5.0.9. Table 5.4 is for informational purposes only; it is always necessary to make a site-specific site-class determination for individual projects.

Hazard Reduction

Hazards associated with earthquake ground shaking can be both widespread and costly in terms of property damage, injury, and death. 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 IBC and IRC, which are adopted statewide. We recommend that the NPS adopt current IBC and IRC codes for all new construction in the study area. Additionally, we recommend review and consideration of the Federal Emergency Management Agency (2005) document *Avoiding Earthquake Damage*, which contains recommendations for reducing the risk from falling objects, fire, and water damage during an earthquake. Fire caused by damage to gas pipelines, or failure of large water impoundment or conveyance structures also present significant earthquake-ground-shaking-related hazards.

Special investigations are required to ensure that buildings and other structures will be designed and constructed to resist the effects of earthquake ground motions. These effects may be particularly severe in areas subject to amplified ground

Table 5.4. *Seismic design categories for selected locations in the Zion National Park Geologic-Hazard Study Area by site class and IBC occupancy category; categories determined in November 2008 using USGS Java Ground Motion Parameter Calculator version 5.0.9; check the USGS Seismic Hazards Program Web site http://earthquake.usgs.gov/research/hazmaps/design/ for the most recent version of the calculator (these data are for informational purposes only; it is always necessary to make a site-specific site-class determination for individual projects).*

Site Class	Maximum Spectral Response Accelerations[1]		Site Coefficients[1]		Maximum Considered Spectral Response Accelerations[1]		Design Spectral Response Accelerations[1]		Seismic Design Category[2]				
									Occupancy Category				
									I	II		III	IV
	Short Period (S_s)	Long Period (S_l)	Short Period (F_a)	Long Period (F_v)	Short Period (S_{MS})	Long Period (S_{Ml})	Short Period (S_{DS})	Long Period (S_{Dl})	Buildings and Other Structures That Represent a Low Hazard to Human Life in the Event of Failure (IBC)	All Other Buildings and Structures Except Those Listed in Categories I, III, and IV (IBC)	One- and Two-Family Dwellings and Townhouses (IRC)	Buildings and Other Structures That Represent a Substantial Hazard to Human Life in the Event of Failure (IBC)	Buildings and Other Structures Designated as Essential Facilities (IBC)
Zion Canyon Visitor Center: Spectral response accelerations mapped at latitude 37.2001º longitude -112.9870º.													
A	0.498	0.172	0.8	0.8	0.399	0.137	0.266	0.092	B	B	B	B	C
B			1.0	1.0	0.498	0.172	0.332	0.114	B	B	B	B	C
C			1.2	1.628	0.598	0.280	0.399	0.186	C	C	C	C	D
D			1.401	2.113	0.698	0.363	0.466	0.242	D	D	D	D	D
D_{IRC}[3]		–	1.401	–	0.698	–	0.466	–	–	–	C	–	–
E		0.172	1.705	3.285	0.850	0.564	0.567	0.376	D	D	D	D	D
F			Site-specific geotechnical investigation and dynamic site-response analysis shall be performed to determine appropriate values and seismic design categories										
Zion Lodge: Spectral response accelerations mapped at latitude 37.2508º longitude -112.9564º.													
A	0.509	0.175	0.8	0.8	0.408	0.140	0.272	0.093	B	B	B	B	C
B			1.0	1.0	0.509	0.175	0.340	0.116	C	C	C	C	D
C			1.196	1.625	0.609	0.284	0.406	0.189	C	C	C	C	D
D			1.392	2.101	0.709	0.367	0.473	0.245	D	D	D	D	D
D_{IRC}[3]		–	1.392	–	0.709	–	0.473	–	–	–	C	–	–
E		0.175	1.681	3.276	0.856	0.572	0.571	0.382	D	D	D	D	D
F			Site-specific geotechnical investigation and dynamic site-response analysis shall be performed to determine appropriate values and seismic design categories										

Table 5.4. *(continued)*

Site Class	Mapped Spectral Response Accelerations[1]		Site Coefficients[1]		Maximum Considered Spectral Response Accelerations[1]		Design Spectral Response Accelerations[1]		Seismic Design Category[2]				
									Occupancy Category				
									I	II		III	IV
	Short Period (S_s)	Long Period (S_l)	Short Period (F_a)	Long Period (F_v)	Short Period (S_{MS})	Long Period (S_{Ml})	Short Period (S_{DS})	Long Period (S_{Dl})	Buildings and Other Structures That Represent a Low Hazard to Human Life in the Event of Failure (IBC)	All Other Buildings and Structures Except Those Listed in Categories I, III, and IV (IBC)	One- and Two-Family Dwellings and Townhouses (IRC)	Buildings and Other Structures That Represent a Substantial Hazard to Human Life in the Event of Failure (IBC)	Buildings and Other Structures Designated as Essential Facilities (IBC)
Kolob Canyons Visitor Center: Spectral response accelerations mapped at latitude 37.4534º longitude -113.2254º.													
A	0.652	0.206	0.8	0.8	0.522	0.165	0.348	0.110	C	C	C	C	D
B			1.0	1.0	0.652	0.206	0.435	0.138	C	C	C	C	D
C			1.139	1.594	0.743	0.329	0.495	0.219	C	C	C	C	D
D			1.278	1.987	0.833	0.410	0.556	0.273	D	D	D	D	D
D_{IRC}[3]		–	1.278	–	0.833	–	0.556	–	–	–	D_0[4]	–	–
E		0.206	1.396	3.174	0.910	0.655	0.607	0.437	D	D	D	D	D
F			Site-specific geotechnical investigation and dynamic site-response analysis shall be performed to determine appropriate values and seismic design categories										

[1] Maximum spectral response accelerations with a 2% probability of exceedance in 50 years (S_s and S_l), site coefficients (F_a and F_v), maximum considered spectral response accelerations (S_{MS} and S_{Ml}), and 0.2-sec and 1.0-sec design spectral response accelerations (S_{DS} and S_{Dl}) appropriate for the IBC obtained using Java Ground Motion Parameter Calculator – Version 5.0.9 at the USGS National Seismic Hazard Map Web site http://earthquake.usgs.gov/research/hazmaps/design/. The Ground Motion Parameter Calculator is updated periodically; **check the USGS Web site for the most recent version of the calculator.**

[2] In accordance with IBC Section 1613.5.6, the seismic design category is the most severe category specified in IBC tables 1613.5.6(1) or 1613.5.6(2), irrespective of the fundamental period of vibration of the structure.

[3] D_{IRC} values of maximum spectral response accelerations with a 2% probability of exceedance in 50 years (S_s and S_l), site coefficients (F_a and F_v), and 0.2-sec design spectral response acceleration (S_{DS}) appropriate for the IRC were obtained using Java Ground Motion Parameter Calculator – Version 5.0.9 at the USGS National Seismic Hazard Map Web site http://earthquake.usgs.gov/research/hazmaps/design/. The Ground Motion Parameter Calculator is updated periodically; **check the USGS Web site for the most recent version of the calculator.** For soil or rock conditions other than site class D, short-period design spectral response accelerations (S_{DS}) were determined in accordance with Section 1613.5 of the IBC; seismic design categories were then assigned in accordance with IRC table R301.2.2.1.1.

[4] Buildings assigned to Seismic Design Category D_0 shall conform to the requirements of Seismic Design Category C and the additional requirements of Section R301.2.2.4 of the IRC.

motions. IBC site classes should always be confirmed in the field as outlined in the IBC or IRC for all projects. In general, site class is determined by conducting a geotechnical soil-foundation investigation during the project design phase prior to construction.

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

We recommend that IBC or IRC site classes be determined on a site-specific basis for new construction in the Zion National Park Geologic-Hazard Study Area using the most currently available USGS Java Ground Motion Parameter Calculator and applicable IBC or IRC design and construction requirements for resisting earthquake motions. Additionally, historic stone masonry structures in Zion National Park are particularly vulnerable to ground shaking, and other park facilities were built prior to the general adoption of seismic design criteria. We recommend that structures in those categories be evaluated to determine their ability to withstand strong earthquake ground shaking, and where appropriate, be seismically retrofitted to improve their life safety capability.

LIQUEFACTION HAZARD

Liquefaction and liquefaction-induced ground failure are major causes of earthquake damage (Keller and Blodgett, 2006). During liquefaction, a soil loses its strength and ability to support the weight of overlying structures or sediment. Soil liquefaction is caused by strong earthquake ground shaking where saturated, cohesionless, granular soil is transformed from a solid to a nearly liquid state. Soil liquefaction generally occurs in sand, silty sand, and sandy silt soils (Youd and Idriss, 1997). All of the following conditions are required for liquefaction to occur:

- The soils must be submerged below the water table.
- 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.

Plastic or clay-rich soils having either a clay content greater than 15 percent, a liquid limit greater than 35 percent, or a moisture content less than 90 percent of the liquid limit are generally immune to liquefaction (Seed and Idriss, 1982; Youd and Gilstrap, 1999).

Four types of ground failure commonly result from liquefaction: (1) loss of bearing capacity, (2) ground oscillation and subsidence, (3) lateral spreading, and (4) flow failure (Youd, 1978, 1984; Tinsley and others, 1985; figure 5.7). The expected mode of ground failure at a given site largely depends upon the ground-surface slope. Where slope inclination is less than 0.5 percent, liquefaction may cause damage in one of two ways. The first is the loss of bearing capacity and resulting deformation of soil beneath a structure, which causes the structure to settle or tilt. Differential settlement is commonly accompanied by cracking of foundations and damage to structures. Buoyant buried structures, such as underground storage or septic tanks, may also float upward under these conditions. The second results from liquefaction at depth below soil layers that do not liquefy. Under these conditions, blocks of the surficial, non-liquefied soil detach and oscillate back and forth on the liquefied layer. Damage to structures is caused by subsidence of the blocks, opening and closing of fissures between and within the blocks, and formation of sand blows as liquefied sand is ejected through the fissures from the underlying pressurized liquefied layer.

Lateral spreading may occur where the ground surface slopes from 0.5 to 5 percent, particularly near a “free face” such as a stream bank or cut slope. Lateral spreads are characterized by surficial soil blocks that are displaced laterally downslope as a result of liquefaction in a subsurface layer. Lateral spreading can cause significant damage to structures and may be particularly destructive to pipelines, utilities, bridges, roadways, and structures with shallow foundations.

Flow failures may occur where the ground surface slopes more than about 5 percent. Flow failures are composed chiefly of liquefied soil or blocks of intact material riding on a liquefied layer. Flow failures can cause soil masses to be displaced several miles and are the most catastrophic mode of liquefaction-induced ground failure.

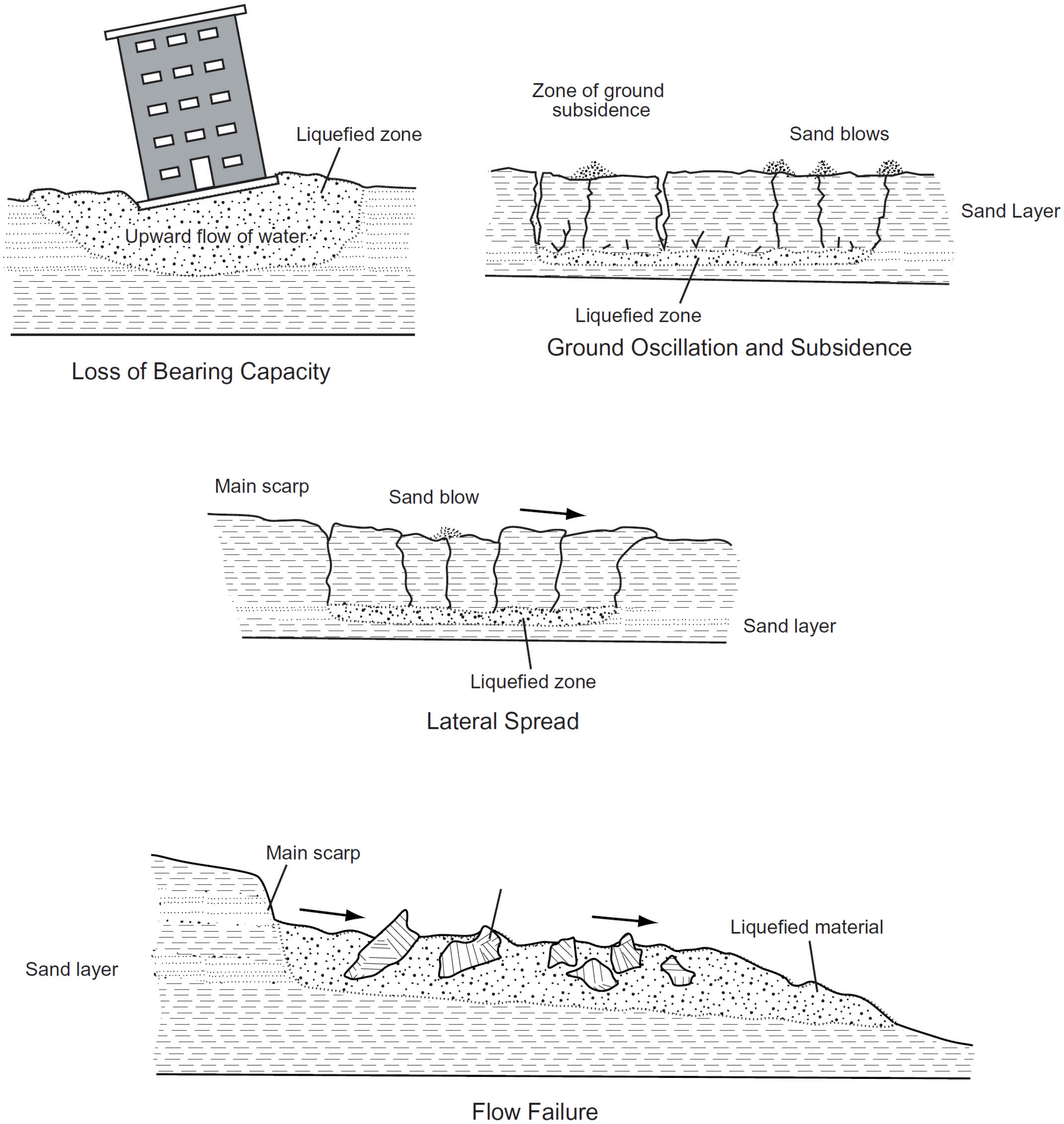

Figure 5.7. *Four principal types of liquefaction-induced ground failure; arrows indicate direction of movement (modified from Youd, 1984; Harty and Lowe, 2003).*

Historical Liquefaction in Southwestern Utah

The September 2, 1992, M 5.8 St. George earthquake produced liquefaction in saturated sand deposits along the Virgin River (Black and others, 1995). The earthquake's epicenter was in Washington Fields east of St. George, and the earthquake likely was the result of movement on the Hurricane fault (Pechmann and others, 1995). Liquefaction occurred along the river from approximately 1 mile south of Bloomington to approximately 4 miles west of Hurricane (Black and others, 1995). The affected geologic deposits consisted of well-sorted, modern channel sands covered by thin layers of silt and clay from overbank flooding. Observed liquefaction features included lateral spreads (figure 5.8), caved stream banks, and sand blows (figure 5.9). Lateral spreads were the most common feature (17 recorded); the largest was 200 feet long and 66 feet wide, and had total lateral movement of about 19 inches (Black and others, 1995). The greatest distance reported by Black and others (1995) between a recognizable liquefaction feature and the earthquake epicenter was 10.6 miles. No facility damage due to liquefaction was documented from the St. George earthquake.

Sources of Earthquake Ground Shaking

A saturated, cohesionless soil must be subjected to intense cyclic ground shaking to induce liquefaction. For liquefaction hazard analyses, earthquake ground shaking is typically

Figure 5.8. *Lateral-spread cracking from liquefaction along the Virgin River resulting from the September 2, 1992, M 5.8 St. George earthquake. Folding shovel for scale (photo credit W.E. Mulvey).*

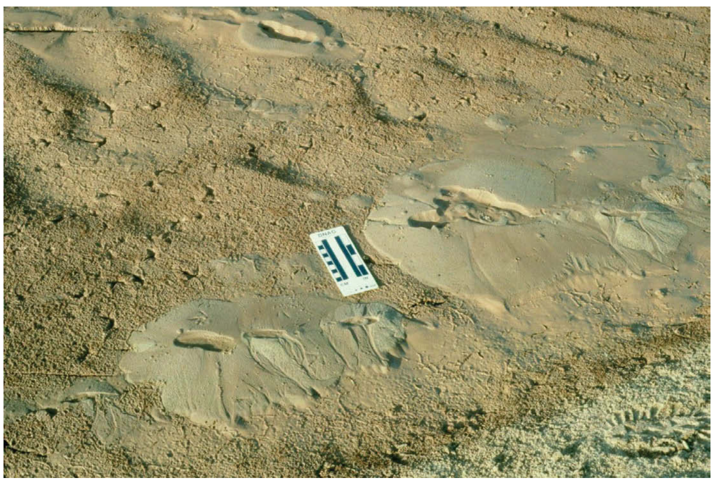

Figure 5.9. *Sand blows from liquefaction along the Virgin River resulting from the September 2, 1992, M 5.8 St. George earthquake. Scale card shows centimeters (left) and inches (right) (photo credit W.E. Mulvey).*

expressed as Peak Horizontal Ground Acceleration (PGA) reported as a fraction of the acceleration of gravity (*g*). The level of ground shaking required to produce liquefaction depends chiefly on the physical characteristics (grain size and sorting) of the saturated soil, but generally a minimum PGA of 0.2 *g* is required for liquefaction to occur (Martin and Lew, 1999). Large earthquakes typically produce stronger ground shaking over greater distances than smaller earthquakes; therefore, large earthquakes can produce more liquefaction and at greater distances than small earthquakes, all other factors being equal.

Potential sources of earthquake ground shaking in the Zion National Park Geologic-Hazard Study Area include (1) the Hurricane fault and several other comparatively short normal faults with very long recurrence intervals within the study area (see Surface-Fault-Rupture Hazard section), (2) the Sevier fault about 15 miles east of the study area (Lund and others, 2008a), and (3) a random background earthquake with a magnitude below that required to produce surface rupture (~M 6.5) that occurs either within or near the study area on an unrecognized fault. While all of these sources could potentially produce ground shaking, the shorter normal faults within the study area and the Sevier fault have very long recurrence intervals for moderate to large earthquakes, and are unlikely to produce ground shaking strong enough to cause liquefaction in a planning time frame of interest (a few decades) to park administrators.

The Hurricane fault shows evidence for large, surface-faulting earthquakes during the Holocene (Lund and others, 2007). An earthquake ≥M 7 on the Hurricane fault near Zion National Park within the next several decades cannot be discounted. Zion National Park is on the upthrown block (footwall) of the Hurricane fault, an area dominated by shallow bedrock and thin unconsolidated deposits. Bedrock attenuates (dampens) earthquake ground shaking, so the severity of shaking in the Zion National Park Geologic-Hazard Study Area from a Hurricane fault earthquake would be less than that produced on the downthrown (hanging wall) block of the fault, where thicker deposits of unconsolidated sediment are present. However, a large earthquake on the Hurricane fault or a moderate-magnitude (M 5.0–6.5) background earthquake in or near the study area would likely liquefy loose, saturated unconsolidated deposits along perennial streams and in wet areas near springs.

The USGS National Seismic Hazard Maps (USGS, 2009b) interactive deaggregation tool determines PGA for different mean return times (*x* percent probability in *y* years) at a designated point. Table 5.5 shows PGAs predicted by the deaggregation tool for different mean return times at the Zion Canyon Visitor Center. PGA values would vary for other locations closer to or farther from potential earthquake sources. A PGA greater than 0.2 *g*, the minimum required to produce liquefaction, has a mean return time at the Visitor Center of about 2400 years (table 5.5), indicating that the liquefaction hazard in the Zion National Park Geologic-Hazard Study Area is low. However, it is not known how much time has elapsed since the last earthquake that was large enough to produce that level of ground shaking in the study area.

Table 5.5. *Earthquake mean return times and predicted PGA at the Zion Canyon Visitor Center (lat. 37.2001 N, long. 112.9870 W).*

Mean Return Time	Predicted PGA[1]
108 years (50% in 75 years)	0.04246 *g*
225 years (20% in 50 years)	0.06328 *g*
475 years (10% in 50 years)	0.09507 *g*
975 years (5% in 50 years)	0.13649 *g*
2475 years (2% in 50 years)	0.2067 *g*

[1]PGA values from USGS Java Ground Motion Parameter Calculator available at http://earthquake.usgs.gov/research/hazmaps/design/.

Liquefaction Hazard Classification

The texture (grain size and sorting) and cementation of unconsolidated geologic deposits, the presence of shallow (≤50 feet) ground water, and the liquefaction response of unconsolidated deposits in past earthquakes are largely unknown within the Zion National Park Geologic-Hazard Study Area. The limited geotechnical data available for the study area come chiefly from lower Zion Canyon in the park administrative area and from the nearby town of Springdale. Review of these data showed that unconsolidated deposits (chiefly alluvium and colluvium) in valley-bottom areas typically consist of silty sand, clayey sand, sandy silt, sandy clay, and silty clay with occasional lenses of cleaner sand, gravel, cobbles, and boulders. Laboratory consolidation test results show that some sand, silt, and clay deposits have low densities and are subject to collapse (see chapter 6—Problem Soil and Rock Hazards). Standard Penetration Test blow-count (*N* value) data confirm the low density of many deposits. *N* values of <10 blows per foot were not uncommon. An *N* value <15 in sandy soil is an indicator of liquefaction susceptibility, with well-sorted, cohesionless sands generally being more susceptible to liquefaction than silty sands and sandy silts.

Given the general lack of geotechnical data, delineating areas of liquefaction hazard required making assumptions regarding two conditions necessary to produce liquefaction in the study area. The first assumption is that unconsolidated Quaternary geologic units not specifically identified as consisting chiefly of clay, silt, cobbles, boulders, or other material not typically subject to liquefaction are potentially liquefiable. The second assumption is that any unconsolidated geologic deposit ≤50 feet above an adjacent perennial stream could be, at least in part, saturated by shallow ground water. Limited information from monitoring and culinary/irrigation wells in the study area supports that assumption (NPS, unpublished data; Utah Division of Water Rights, 2008).

Due to the lack of geotechnical data, the system used to classify liquefaction hazard in the Zion National Park Geologic-Hazard Study Area employs a relative susceptibility ranking as opposed to a hazard-severity ranking. Combining the assumptions regarding geologic deposit texture and presence of shallow ground water, we defined a “Liquefaction-Susceptibility Zone” (plate 5). This zone delineates areas where deposit texture and ground-water conditions may be suitable for liquefaction to occur. Table 5.6 summarizes potentially liquefiable geologic deposits in the study area. Determining whether liquefaction is in fact possible at any given location requires additional site-specific information about the texture and density of the deposits, ground-water conditions, and anticipated earthquake ground motions. Note that liquefaction susceptibility differs from liquefaction *potential*, which combines susceptibility with consideration of the probability of a sufficiently high PGA occurring within some specified time interval.

Table 5.6. *Unconsolidated geologic deposits in the Zion National Park Geologic-Hazard Study Area that may be susceptible to liquefaction if saturated.*

Stream and Terrace Alluvium	Alluvial Deposits	Eolian Deposits	Colluvial Deposits	Lacustrine Deposits
Qaly, Qath, Qat_2	Qaso, Qae, Qa, Qa_1, Qa_2, Qac, Qay, Qaec, Qaf, Qaf_1, Qaf_2, Qafy, Qafc, Qage, Qao, Qaeo	Qes, Qea, Qre, Qer, Qed	Qc, Qce, Qces	Qla, Qlbc, Qls

[1]Refer to UGS 1:24,000-scale geologic maps (see Sources of Information section) for a description of map units.

The Liquefaction-Susceptibility Zone shown on plate 5 is characterized as follows:

> **Liquefaction-Susceptibility Zone –** Areas where potentially liquefiable unconsolidated geologic units may also be saturated. Determining if a liquefaction hazard exists at a particular location requires acquiring site-specific information about soil texture and density, ground-water conditions, and the frequency and intensity of anticipated ground shaking.

Unclassified areas on the Liquefaction Susceptibility map (plate 5) include areas of exposed or shallow (≤5 feet) bedrock, unconsolidated geologic deposits with textural or cementation characteristics that generally preclude liquefaction, and areas where depth to ground water is estimated to be >50 feet. Unclassified areas are considered to have no liquefaction hazard; 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, particularly near springs and seeps.

Using the Map

The Liquefaction Susceptibility map (plate 5) shows areas where liquefaction may be possible in the Zion National Park Geologic-Hazard Study Area. The map is based on limited information about the textural characteristics of unconsolidated geologic units and the distribution and depth of ground water in the study area. The map does not integrate earthquake ground motions with material characteristics and depth to ground water, 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.

The Liquefaction Susceptibility map (plate 5) is intended for general planning and design purposes to indicate where liquefaction hazards may exist and to assist in liquefaction-hazard investigations. In Utah, soil-test requirements are specified in chapter 18 (Soils and Foundations) of the IBC (International Code Council, 2009a) and chapter 4 (Foundations) of the IRC (International Code Council, 2009b), which are adopted statewide. 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 through F (see Earthquake-Ground-Shaking Hazard section). In general, seismic design categories in the Zion National Park Geologic-Hazard Study Area for structures built on unconsolidated materials fall into Seismic Design Categories C and D (see table 5.4), 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 occupancy category of the proposed structure (see Earthquake Ground-Shaking Hazard section). Because the risk to human life and the requirement that certain essential structures remain functional during natural or other disasters varies by occupancy category, we recommend the following levels of liquefaction-hazard investigation for the different IBC occupancy categories (table 5.7) in areas identified on the Liquefaction Susceptibility map (plate 5) as potentially liquefiable. Detailed (quantitative) subsurface investigations should be performed for Occupancy Category II, III, and IV structures, and reconnaissance (screening) investigations for Occupancy Category I structures. Additionally, a reconnaissance investigation should be performed for Occupancy Category II, 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 Occupancy Category I structures in nonsusceptible areas. Martin and Lew (1999) provide guidelines for conducting both reconnaissance and detailed liquefaction investigations.

Map Limitations

The Liquefaction Susceptibility map (plate 5) is based on limited geological, geotechnical, and hydrological data; a site-specific investigation is required to produce more detailed information. The map also depends on the quality of those data, which varies throughout the study area. The mapped boundaries of the Liquefaction-Susceptibility Zone are approximate and subject to change as new information becomes available. Liquefaction susceptibility at any particular site may be different than shown because of geologic and hydrologic variations within a map unit, gradational and approximate map-unit boundaries, and the map scale. Small, localized areas of liquefaction susceptibility may exist anywhere within the study area, but their identification is precluded because of limitations of either data or map scale. Seasonal and long-term fluctuations in ground-water levels can affect liquefaction hazard at a site. The map is not intended for use at scales other than the published scale, and is designed for use in general planning and design to indicate the need for site-specific studies.

Table 5.7. *Recommended requirements for liquefaction-hazard investigations.*

Liquefaction Hazard	IBC Occupancy Category			
	I	II	III	IV
	Buildings and Other Structures That Represent a Low Hazard to Human Life in the Event of Failure (IBC)	All Other Buildings and Structures Except Those Listed in Categories I, III, and IV (Includes One- and Two-Family Dwellings and Townhouses) (IRC) (IBC)	Buildings and Other Structures That Represent a Substantial Hazard to Human Life in the Event of Failure (IBC)	Buildings and Other Structures Designated as Essential Facilities (IBC)
Susceptible	Reconnaissance	Detailed[1]	Detailed[1]	Detailed[1]
Not Susceptible	None	Reconnaissance[2]	Reconnaissance[2]	Reconnaissance[2]

[1]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.
[2]A reconnaissance investigation should be followed by a detailed investigation if a liquefaction hazard is determined to be present.

Hazard Reduction

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

Liquefaction damage may be reduced either by using ground improvement methods to lower the liquefaction hazard (for example, compacting or replacing soil; installing drains or pumps to dissipate or lower the water table) or by designing structures to withstand liquefaction effects (using deep foundations or structural reinforcement). Existing structures threatened by liquefaction may be retrofitted to reduce the potential for damage. Because the cost of reducing liquefaction hazards for existing structures may be high relative to their value, and because liquefaction is generally not a life-threatening hazard, we consider it prudent, although not essential, to reduce liquefaction hazards for existing structures, unless significant ground deformation (lateral spreading) is anticipated and the structures fall into IBC Occupancy Categories III or IV, in which case retrofitting is recommended.

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Chapter 6
Problem Soil and Rock Hazards

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Chapter 6: Problem Soil and Rock Hazards

INTRODUCTION

Soil and rock having characteristics that make them susceptible to collapse, shrink/swell, subsidence, or other engineering-geologic problems are classified as problem soil and rock (Mulvey, 1992). Geologic parent material, climate, and depositional processes largely determine the type and extent of problem soil and rock. Geologic materials and conditions in the Zion National Park Geologic-Hazard Study Area are highly variable; as a result, various categories of problem soil and rock exist both locally and over broad segments of the study area. Problem soil and rock can be costly factors in facility construction and maintenance if not recognized and taken into consideration in the planning and design process (Shelton and Prouty, 1979). However, problem soil and rock rarely, if ever, cause rapid catastrophic property damage or present a threat to life safety. This study addresses four principal types of problem soil and rock: (1) collapsible (hydrocompactible) soil, (2) expansive soil and rock, (3) gypsiferous soil and rock, and (4) soil susceptible to piping and erosion.

The definitions of soil and rock used in this study generally conform to those in general use by engineers and engineering geologists (Sowers and Sowers, 1970; U.S. Bureau of Reclamation, 1998a, 1998b). We define soil as any generally nonindurated accumulation of solid particles produced by the physical and/or chemical disintegration of bedrock, with gases or liquids between the particles and which may or may not contain organic matter. Rock is defined as lithified or indurated crystalline or noncrystalline materials in which primary features of the rock mass, such as bedding, joints, or crystalline structure are still recognizable. By this definition, rock weathered in place, even though it can be excavated without blasting or ripping, would be considered rock and not a residual soil if primary features of the rock unit are still recognizable and can influence the engineering properties of the material.

SOURCES OF INFORMATION

Sources of information used to evaluate problem soil and rock in the Zion National Park Geologic-Hazard Study Area include (1) 29 geotechnical reports on file with the National Park Service (NPS) and the Town of Springdale, (2) Natural Resources Conservation Service (NRCS) (formerly Soil Conservation Service) *Soil Survey of Washington County Area, Utah* (Mortensen and others, 1977), (3) the nine Utah Geological Survey (UGS) 1:24,000-scale geologic quadrangle maps covering the study area (Clear Creek Mountain [Hylland, 2000], Cogswell Point [Biek and Hylland, 2007], Kolob Arch [Biek, 2007a], Kolob Reservoir [Biek, 2007b], Springdale East [Doelling and others, 2002], Springdale West [Willis and others, 2002], Temple of Sinawava [Doelling, 2002], The Barracks [Sable and Doelling, 1993], and The Guardian Angels [Willis and Hylland, 2002]) (figure 1.1), (4) *Engineering Geology of the St. George Area, Washington County, Utah* (Christenson and Deen, 1983), (5) "Geologic Hazards of the St. George Area, Washington County, Utah" (Christenson, 1992), (6) *Engineering Geologic Map Folio, Springdale, Washington County, Utah* (Solomon, 1996), and (7) *Geologic Hazards and Adverse Construction Conditions, St. George–Hurricane Metropolitan Area, Washington County, Utah* (Lund and others, 2008).

Only limited geotechnical data were available for this study. Those data were unevenly distributed within the study area and locations adjacent to Zion National Park, chiefly in the Town of Springdale. We compiled the data into a geotechnical database to characterize geologic and soil units. Some units had no geotechnical data available for them; in those cases we estimated unit properties by comparing them with similar geologic and soil units in the St. George–Hurricane metropolitan area where geotechnical data are more abundant (Lund and others, 2008).

COLLAPSIBLE SOIL

Collapsible (hydrocompactible) soils have considerable dry strength and stiffness in their dry natural state, but can settle up to 10 percent of the susceptible deposit thickness when they become wet for the first time following deposition (Costa and Baker, 1981; Rollins and Rogers, 1994) causing damage to property and structures. Collapsible soils are common throughout the arid southwestern United States and are typically geologically young materials, chiefly debris-flow deposits in Holocene-age alluvial fans, and some wind-blown, lacustrine, and colluvial deposits (Owens and Rollins, 1990; Mulvey, 1992; Santi, 2005).

Collapsible soils typically have a high void ratio and corresponding low unit weight (<80 to 90 lb/ft^3; Costa and Baker, 1981; Walter Jones, consulting engineer, written communication, 2007) and a relatively low moisture content (<15%; Owens and Rollins, 1990), all characteristics that result from the initial rapid deposition and drying of the sediments. Intergranular bonds form between the larger grains (sand and gravel) of a collapsible soil; these bonds develop through capillary tension or a binding agent such as silt, clay, or salt. Later wetting of the soil results in a loss of capillary tension or the softening, weakening, or dissolving of the bonding agent, allowing the larger particles to slip past one another into a denser structure (Williams and Rollins, 1991).

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

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

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

Naturally occurring deep percolation of water into collapsible deposits is uncommon after deposition due to the arid conditions in which the deposits typically form, and the steep gradient of many alluvial-fan and colluvial surfaces. Therefore, soil collapse is usually triggered by human activity such as irrigation, urbanization, and/or wastewater disposal. Kaliser (1978) reported serious damage (estimated $3 million) to public and private structures in Cedar City, Utah, from collapsible soils. Rollins and others (1994) documented more than $20 million in required remedial measures to a cement plant near Leamington, Utah, and Smith and Deal (1988) reported damage to a large flood-control structure near Monroe, Utah. In 2001, collapsible soils damaged the Zion National Park greenhouse soon after it was constructed, as soils below and around the building were wetted by excess irrigation water. Park employees later reported that a wastewater treatment plant that had once been located nearby had also had a history of damage from ground subsidence. Damage due to collapse of wind-blown deposits is not as well documented in Utah as damage associated with collapsible alluvial and colluvial deposits; this may be due in part to the relatively lesser abundance of loess deposits in the state.

Description

Geologic Characteristics

Review of geotechnical reports prepared for projects in and near the Zion National Park Geologic-Hazard Study Area showed that collapsible soils are common in areas underlain by geologically young alluvial-fan and colluvial deposits. However, the geotechnical data are limited to a few newer buildings in the Zion National Park administrative area, to shuttle bus stops in Zion Canyon, and to the Town of Springdale just outside the study area boundary (see chapter 1 – Introduction, figure 1.1). To estimate the collapse potential of soils where geotechnical data were not available, it was necessary to extrapolate based on the geologic unit characteristics shown on UGS geologic maps (see Sources of Information section) and make comparisons with similar units in the St. George area, where geotechnical data are more abundant (Lund and others, 2008). The NRCS *Soil Survey of Washington County Area, Utah* (Mortensen and others, 1977) does not contain information on soil-collapse potential. However, park staff reported that a new soil survey is scheduled to begin in the next 2–3 years. We recommended that this survey include an evaluation for soil-collapse potential and other soil-related hazards.

Utah Geological Survey geologic mapping classifies the unconsolidated deposits in the study area into 48 geologic units. Swell/collapse test (SCT) data are available for only a few of those units. Seven units have reported collapse values of $\geq$3 percent, the level at which collapse generally becomes a significant engineering concern given a sufficient thickness of susceptible soil (Jennings and Knight, 1975). As discussed above, soil collapse is closely associated with soil texture. A variation of a few percent in clay content can be the difference between a deposit that will collapse and one that will swell when wetted. The unconsolidated geologic units on UGS geologic maps are defined by geomorphology (landform), genesis, and to a lesser extent texture. Therefore, some unconsolidated geologic units show considerable textural variation. For example, geologic unit Qafc, which denotes mixed alluvial-fan and colluvial deposits, is reported, depending on location, to have SCT values in excess of both 3 percent collapse and 3 percent swell. Therefore, while geology can be used as an indicator of collapse potential, it is not an infallible guide, and site-specific soil testing is always required.

Geotechnical Data Evaluation

The geotechnical database compiled for this study contains 82 SCT soil/rock sample test results. The results for 50 of the samples (63%) indicate collapse potential. Of the 50 collapsible samples, 25 have SCT values ≥3 percent, and therefore are problematic from an engineering standpoint. Table 6.1 shows the relation between ASTM Unified Soil Classification System (USCS) soil types and collapse values ≥3 percent in the Zion National Park Geologic-Hazard Study Area and vicinity. As expected, most collapsible soils consist of silty or clayey sand and silts. The silts (ML) tested show a higher percentage of collapsible samples than do clayey sands (SC). The silts are likely loess deposits of eolian origin. Clay-rich soils (CL and CH) and poorly graded (well sorted) sands (SP) show the lowest potential for collapse, but nevertheless, more than 9 percent of CL clays tested show significant collapse potential.

Hazard Classification

We grouped unconsolidated geologic units that may be prone to collapse into three susceptibility categories (table 6.2 and plate 6). The categories are based on the type of geotechnical data available, and if the deposit genesis or texture is permissive of collapse. Due to the lack of geotechnical data over much of the study area, the classification system presented below employs a relative susceptibility ranking as opposed to a hazard-severity ranking. The soils in all three categories could exhibit ≥3 percent collapse, and therefore be regarded as having significant collapse potential.

The collapsible-soil-susceptibility categories shown in table 6.2 and on plate 6 are characterized as follows:

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

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

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

Using the Map

The Collapsible-Soil Susceptibility map (plate 6) shows the location of known and suspected collapsible-soil conditions in the Zion National Park Geologic-Hazard Study Area. The map is intended for general planning and design purposes to indicate where collapsible-soil conditions may exist and special investigations should be required. 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.

Table 6.1. *Relation of high collapse test values (≥3%) to USCS soil types in the geotechnical database.*

USCS Soil Type	Total Samples in Database	Samples Tested (number)	Samples Tested (percent)	Samples Having Collapse ≥3%	Samples Having Collapse ≥3% (percent)
SM	188	30	16	15	50
SC	30	5	17	3	60
SM/SP	30	4	13	2	50
SP	18	1	6	0	0
CH	10	4	40	0	0
ML	25	3	12	2	67
CL	180	32	18	3	9
Bedrock	19	3	16	0	0
Total	500	82	16	25	30

Table 6.2. *Geologic deposits known or likely to have a significant potential for soil collapse.*

Type of Deposit	Geologic Map Units[1]	Collapsible Soil Category
Stream and Terrace Alluvium	Qa_1, Qal_1, Qat_2, Qat_3, Qath	CS_A
	Qa, Qaly, Qay, Qa_2, Qat_4, Qat_5, Qat_6, Qas, Qaso	CS_B
	Qato, Qav	CS_C
Fan Alluvium	Qafc, Qafco, Qmsc (alluvial parts)	CS_A
	Qae, Qac, Qaes, Qaeo, Qaf, Qaf_1, Qaf_2, Qafy, Qao, Qafo, Qage, $Qmcp_1$, $Qmcp_2$	CS_B
	Qaco, Qaec, Qap_2, $Qmcp_3$	CS_C
Eolian Deposits	Qea, Qer, Qes, Qed, Qre	CS_B
Colluvial Deposits	Qc, Qmt, Qmts, Qce, Qces	CS_B
	Qco	CS_C
Lacustrine Deposits	Qla, Qls	CS_B
	Qlbc	CS_C

[1]Refer to UGS geologic quadrangle maps (see Sources of Information section) for a description of map units.

Map Limitations

The Collapsible-Soil Susceptibility map (plate 6) is based on limited geologic and geotechnical data; site-specific investigations are required to produce more detailed geotechnical information. The map also depends on the quality of those data, which may vary throughout the study area. The mapped boundaries between susceptibility categories are approximate and subject to change as new information becomes available. The susceptibility may be different than shown at any particular site because of variations in the physical properties of geologic deposits within a map unit, gradational and approximate map-unit boundaries, and the small map scale. The map is not intended for use at scales other than the published scale, and is designed for use in general planning and design to indicate the need for site-specific investigations.

Hazard Reduction

Although potentially costly when not recognized and properly accommodated in project design and construction, problems associated with collapsible soil rarely are life threatening. As with most geologic hazards, early recognition and avoidance are the most effective ways to mitigate potential problems. However, collapsible soil is widespread in the study area, and avoidance may not always be a viable or cost-effective option.

In Utah, soil-test requirements are specified in chapter 18 (Soils and Foundations) of the 2009 International Building Code (IBC) (International Code Council, 2009a) and chapter 4 (Foundations) of the 2009 International Residential Code for One- and Two-Family Dwellings (IRC) (International Code Council, 2009b), which are adopted statewide. IBC Section 1803.3 contains requirements for soil investigations in areas where questionable soil (soil classification, strength, or compressibility) is present. IRC Section R401.4 states that the building official shall determine whether to require a soil test to determine the soil's characteristics in areas likely to have expansive, compressible, shifting, or other unknown soil characteristics. IBC table 1613.5.2 identifies collapse-prone soils as Site Class F. Site Class F soils require a site-specific investigation to determine the proper seismic design category and parameters for a proposed facility (see chapter 5 – Earthquake Hazards).

Where the presence of collapsible soil is confirmed, possible mitigation techniques include soil removal and replacement with noncohesive, compacted backfill; use of special foundation designs such as drilled pier deep foundations, grade beam foundations, or stiffened slab-on-grade construction; moisture barriers; and careful site landscape and drainage design to keep moisture away from buildings and collapse-prone soils (Nelson and Miller, 1992; Pawlak, 1998; Keller and Blodgett, 2006).

EXPANSIVE SOIL AND ROCK

Expansive soil and rock increase in volume (swell) as they get wet, and decrease in volume (shrink) as they dry out. Expansive soil and rock contain a significant percentage of clay minerals that can absorb water directly into their crystal structure when wetted. Some sodium-montmorillonite clay can swell as much as 2000 percent upon wetting (Costa and Baker, 1981). The resulting expansion forces can be greater than 20,000 pounds per square foot (Shelton and Prouty, 1979), and can easily exceed the loads imposed by most structures, resulting in

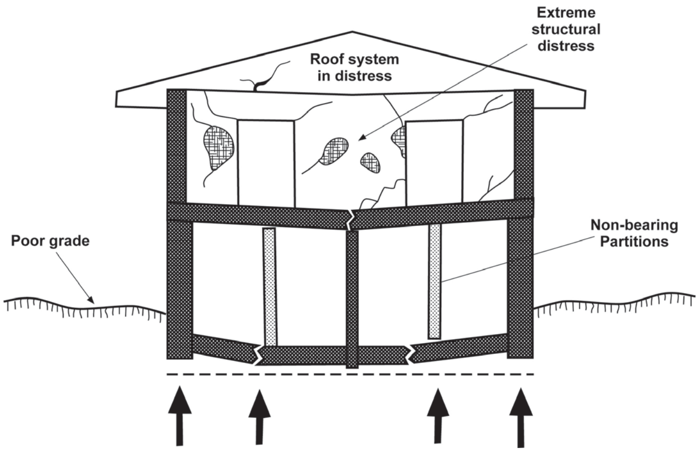

Figure 6.1. *Typical structural damage to a building from expansive soil (modified from Black and others, 1999).*

Figure 6.2. *Home in southwestern Utah damaged by expansive soil/rock.*

cracked foundations and pavement, structural damage, and other building distress (figure 6.1).

Description

Geologic Characteristics

Several bedrock formations in the Zion National Park Geologic-Hazard Study Area consist in whole or part of shale, claystone, or mudstone containing expansive clay minerals. These rock units and the expansive soils derived from them are capable of significant expansion and contraction when wetted and dried, causing structural damage to buildings (figure 6.2); cracked roads and driveways; damage to curbs, gutters, and sidewalks; and heaving of roads and canals. Expansive soils are chiefly derived from the weathering of clay-bearing rock formations (figure 6.3) 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 may play important roles locally.

Figure 6.3. *Outcrop of the clay-rich Petrified Forest Member of the Chinle Formation in southwestern Utah.*

Table 6.3. *Correlation of soil swelling potential with plasticity index (from Chen, 1988).*

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

Geotechnical Data Evaluation

Data on expansive soils in the Zion National Park Geologic-Hazard Study Area are limited. The geotechnical database compiled for this study includes laboratory test data for soil samples collected from test pits and exploratory boreholes in and near the study area. The database includes 55 samples with liquid limit (LL) and plasticity index (PI) data, and 82 samples with SCT data. Swell/collapse test results are the most reliable indicator of a soil's capacity to shrink or swell. An SCT value of ≥3 percent swell is generally considered problematic from an engineering standpoint (Russell Owens, Alpha Engineering, verbal communication, 2000, in Lund and others, 2008). Plasticity index, LL, and expansion index data are commonly used as qualitative indicators of shrink/swell potential (table 6.3) (Chen, 1988; International Code Council, 2009a) either in the absence of SCT data or to assist in selecting samples for swell/collapse testing. The IBC states (Section 1803.5.3; International Code Council, 2009a) that a soil meeting the following four provisions shall be considered expansive: (1) PI ≥15, determined in accordance with ASTM D 4318 (2) >10 percent of soil particles pass the No. 200 sieve (0.075 mm), determined in accordance with ASTM D 422, (3) >10 percent of the soil particles are less than 5 micrometers (0.005 mm) in size, determined in accordance with ASTM D 422, and (4) expansion index >20 determined in accordance with ASTM D 4829.

Table 6.4 shows the relation between USCS soil types and SCT test results in the geotechnical database. Of the 82 SCT values in the database, 8 (10%) exhibited ≥3 percent swell and therefore fall into the problematic-swell category. Problematic-swell values are associated with three types of material: CH soil (high-plasticity inorganic clays), CL soil (low- to medium-plasticity inorganic clays), and clay-rich bedrock. Seventy-five percent of the CH clays and 67 percent of fine-grained bedrock samples tested reported values ≥3 percent swell, while a much smaller percentage of CL clays (10%) showed ≥3 percent swell. Note that for all three material types, a relatively small number of the total available samples were tested: 40 percent of CH clays, 18 percent of CL clays, and 16 percent of fine-grained bedrock.

Hazard Classification

Soil

We grouped soils into three shrink/swell-hazard categories on the Expansive-Soil-and-Rock Hazards map (plate 7) on the basis of their expansive characteristics and potential for volumetric change. The principal sources of information regarding expansive soil characteristics in the study area are the "Estimated Soil Properties of Significance to Engineering" and "Interpretation of Engineering Test Data" tables in the NRCS *Soil Survey of Washington County Area, Utah* (Mortensen and others, 1977). We compared the ratings and data presented in those tables with the limited laboratory test results in our geotechnical database. The correlation between the NRCS information and the geotechnical test data are generally good, with a few local discrepancies. The discrepancies are not unexpected given the generalized nature of the NRCS information and the susceptibility of soil characteristics to local influences, such as adjacent or underlying bedrock, depositional process and history, effects of soil-forming processes, and limited depth of characterization (upper 60 inches of the soil column) of the NRCS data.

Details of our geotechnical data analysis are presented in the Geotechnical Data Evaluation section. Information from UGS geologic maps (see Sources of Information section) was used to estimate shrink/swell hazard beyond the boundaries of the NRCS mapping and geotechnical database coverage.

The expansive-soil-hazard categories shown on plate 7 are characterized as follows:

High Hazard – Soils classified by the NRCS as having high hazard for volumetric change. These soils are typically clay rich and have a LL ≥35, PI ≥15, and/or SCT value of ≥3 percent swell (Mortensen and others, 1977; Chen, 1988; Nelson and Miller, 1992). Soils having these characteristics are of limited aerial extent in the study area, and are typically associated with the Petrified Forest Member of the Chinle Formation, other clay-rich bedrock units, and some weathered basalt flows.

Moderate Hazard – Soils classified by the NRCS as having moderate hazard for volumetric change (LL 25–55, PI 5–35). The LL and PI values in this category overlap at their upper ends with soils in the high hazard category. Chen (1988) recognized that while PI is an indicator of expansive potential, other factors also exert an influence, and therefore reported a range of PI values when categorizing a soil's capacity to shrink or swell.

Table 6.4. *Relation of high swell test values (≥3%) to USCS soil types and fine-grained bedrock in the geotechnical database.*

USCS Soil Type	Total Samples in Database	Samples Tested (number)	Samples Tested (percent)	Samples Having Collapse ≥3%	Samples Having Collapse ≥3% (percent)
SM	188	30	16	0	0
SC	30	5	17	0	0
SM/SP	30	4	13	0	0
SP	18	1	6	0	0
CH	10	4	40	3	75
ML	25	3	12	0	0
CL	180	32	18	3	10
Bedrock	19	3	16	2	67
Total	500	82	16	8	10

Low Hazard – Soils classified by the NRCS as having low hazard for volumetric change (LL 0–40, PI from nonplastic to 15). The LL and PI values in this category overlap at their upper ends with soils in the moderate hazard category. However, the low hazard category includes soils with highly variable potential for volumetric change that do not fit easily into the moderate or high categories.

No Data – Unconsolidated alluvial deposits in areas of upper Zion Canyon, Hop Valley, and LaVerkin Creek that may contain some clay-rich horizons subject to volumetric change, but a lack of information about the physical characteristics of the deposits precludes hazard categorization. These deposits are not included in the geotechnical database, and are mapped by the NRCS as chiefly Rock Outcrop (NRCS soils-map unit RT) or Fluvaquents and Torrifluvents (NRCS soils-map unit FA) for which soil property estimations and engineering tests were not performed. Due to the variable nature of these deposits and a general lack of geotechnical data for them, we recommend site-specific testing for expansive soil for all proposed construction within map areas having no data.

Rock

We also grouped bedrock units in the study area into three shrink/swell-hazard categories on the Expansive-Soil-and-Rock Hazards map (plate 7) on the basis of relative abundance of expansive clay minerals, abundance and thickness of fine-grained strata in mixed bedrock units, and past experience with expansive rock units in southwestern Utah (Lund and others, 2008). We did not classify bedrock formations possessing little or no potential for volumetric change.

The expansive-rock-hazard categories shown on plate 7 are characterized as follows:

High Hazard – Bedrock units with high shrink/swell hazard, which include claystone horizons in the Virgin Limestone Member of the Moenkopi Formation, the Petrified Forest Member of the Chinle Formation, and the lower red beds of the Dinosaur Canyon Member and the Whitmore Point Member of the Moenave Formation. We include landslides mapped within these rock units in the high-hazard category because the landslides contain debris from high-hazard bedrock units. These bedrock units contain an abundance of expansive clay minerals and are commonly associated with expansive rock problems throughout southwestern Utah.

Moderate Hazard – Bedrock units with moderate shrink/swell hazard, which include the Shnabkaib and lower, middle, and upper red members of the Moenkopi Formation; the Sinawava Member of the Temple Cap Formation; and the lower unit of the Co-op Creek Member and the Crystal Creek Member of the Carmel Formation. These rock units are chiefly fine grained and contain alternating strata of shale, claystone, mudstone, siltstone, sandstone, and limestone. Not all or even the majority of these strata contain expansive clay minerals; however, past experience in southwestern Utah has shown that a sufficiently high percentage of strata do contain expansive clay that shrink/swell problems are often associated with these bedrock units. We include landslides mapped within moderate-hazard rock units in this category.

Low Hazard – Bedrock units with low shrink/swell hazard, which include the Timpoweap Member of the Moenkopi Formation, the Kayenta Formation, and the Winsor Member of the Carmel Formation. We consider these units to have a lower hazard than the bedrock units identified above; however, low-hazard units contain some fine-grained, clay-rich strata that may cause shrink/swell problems locally.

Areas of Concealed Highly Expansive Soil or Rock

The Expansive-Soil-and-Rock Hazards map (plate 7) shows several locations chiefly in the southern and southwestern part of the study area where highly expansive soil or rock may be present in the shallow subsurface (≤20 feet), with little or no evidence of such materials at the ground surface. The likely presence of highly expansive materials in the shallow subsurface is based on the outcrop pattern of the Petrified Forest Member of the Chinle Formation, which indicates that the Petrified Forest Member likely underlies thin unconsolidated deposits in those areas. The Petrified Forest Member typically contains highly expansive shale and claystone, and past experience in southwestern 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 of nonexpansive material (Lund and others, 2008). Therefore, we consider areas where the Petrified Forest Member may be present in the shallow subsurface to have a potential for highly expansive soil and rock problems despite the lack of surface evidence of such materials.

The areas of concealed highly expansive soil or rock shown on plate 7 are characterized as follows:

Concealed – Area suspected of having highly expansive soil or rock (≥3 percent swell) in the shallow subsurface (≤20 feet), with little or no evidence of such material at the ground surface.

Using the Map

The Expansive-Soil-and-Rock Hazard map (plate 7) shows the location of known or suspected expansive soil and rock in the Zion National Park Geologic-Hazard Study Area. The map is intended for general planning and design purposes to indicate where expansive soil and rock may exist and special investigations should be required. Site-specific investigations can resolve uncertainties inherent in generalized mapping and help identify the need for special foundation designs, site grading and soil placement, or mitigation techniques. The presence and severity of expansive soil and rock, along with other geologic hazards should be addressed in these investigations. If expansive soil or rock is present at a site, appropriate design and construction recommendations should be provided.

Map Limitations

The Expansive-Soil-and-Rock Hazards map (plate 7) is based on limited geologic and geotechnical data; site-specific investigations are required to produce more detailed geotechnical information. The map also depends on the quality of those data, which may vary throughout the study area. The mapped boundaries between hazard categories are approximate and subject to change as new information becomes available. The hazard from expansive soil and rock may be different than shown at any particular site because of variations in the physical properties of geologic deposits within a map unit, gradational and approximate map-unit boundaries, and the small map scale. The map is not intended for use at scales other than the published scale, and is designed for use in general planning and design to indicate the need for site-specific investigations.

Hazard Reduction

Although potentially costly when not recognized and properly accommodated in project design and construction, problems associated with expansive soil and rock rarely are life threatening. As with most geologic hazards, early recognition and avoidance are the most effective ways to mitigate potential problems. However, expansive soil and rock are present in some of the most heavily developed parts of the study area, and avoidance may not always be a viable or cost-effective option.

In Utah, soil-test requirements are specified in chapter 18 (Soils and Foundations) of the 2009 IBC (International Code Council, 2009a) and chapter 4 (Foundations) of the 2009 IRC (International Code Council, 2009b), which are adopted statewide. IBC Section 1803.3 and IRC Section R401.4 contain requirements for soil investigations in areas where expansive soil may be present. Where the presence of expansive soil or rock is confirmed, possible mitigation techniques include soil removal and replacement with noncohesive, compacted backfill; use of special foundation designs such as drilled pier deep foundations, grade beam foundations, or stiffened slab-on-grade construction; moisture barriers; chemical stabilization of expansive clays; and careful site landscape and drainage design to keep moisture away from buildings and expansive soils (Nelson and Miller, 1992; Keller and Blodgett, 2006).

Figure 6.4. *Gypsum-rich Shnabkaib Member (white unit in middle distance) of the Moenkopi Formation in southwestern Utah.*

GYPSIFEROUS SOIL AND ROCK

Gypsum-bearing soil and rock are subject to dissolution of the gypsum ($CaSO_4 \cdot 2H_2O$), which causes a loss of internal structure and volume. Where the amount of gypsum is ≥10 percent, dissolution can result in localized land subsidence and sinkhole formation (Mulvey, 1992; Muckel, 2004; Santi, 2005). Dissolution of gypsum may lead to foundation problems and may affect roads, dikes, underground utilities, and other infrastructure. Gypsum dissolution can be greatly accelerated by application of water, such as that provided by reservoirs; septic-tank drain fields; street, roof, or parking lot runoff; and irrigation (Martinez and others, 1998). Gypsum is also a weak material with low bearing strength and is not well suited as a foundation material. Additionally, when gypsum weathers it forms dilute sulfuric acid and sulfate, which can corrode and weaken unprotected concrete and metals. Type V or other sulfate-resistant cement is typically required in such areas, as is corrosion protection for metals.

Description

In the Zion National Park Geologic-Hazard Study Area, gypsum is an important component of the Shnabkaib Member of the Moenkopi Formation (figure 6.4) and the Paria River Member of the Carmel Formation. Gypsum is present in lesser

Figure 6.5. *Quail Creek dike failure, January 1, 1989, in southwestern Utah was due in part to gypsum dissolution in the underlying Shnabkaib Member of the Moenkopi Formation (photo credit Ben Everitt).*

amounts in the lower red, middle red, and upper red members of the Moenkopi Formation, and the Crystal Creek Member of the Carmel Formation. Additionally, residual and colluvial soils derived from these bedrock units may contain locally significant pedogenic gypsum. However, because gypsum is typically concentrated in subsurface horizons by soil-forming processes, problem soils may be difficult to recognize in the absence of subsurface exploration.

Gypsum Dissolution

Gypsum dissolution in bedrock is common in southwestern Utah. Dissolution of gypsum (Shnabkaib Member of the Moenkopi Formation) was an important factor in the January 1, 1989, failure of the Quail Creek dike near Hurricane, Utah (figure 6.5; Gourley, 1992). Elsewhere in the region, gypsum solution caverns as much as several feet in diameter have formed in susceptible bedrock units. The entire flows of the Virgin River and La Verkin Creek have been captured by sinkholes that opened in their streambeds (Harrisburg Member of the Kaibab Formation) (Everitt and Einert, 1994; Lund, 1997). In St. George, a bulldozer broke through the roof of a cavern and was suspended by its front blade and back ripper (J and J Construction Company, personal communication, 1995, as reported in Higgins and Willis, 1995). David Black (Black, Miller, and Associates, personal communication, 1995, as reported in Higgins and Willis, 1995) reported honeycomb pedogenic gypsum with solution cavities as much as 2 feet wide in an excavation for a swimming pool in central St. George.

Corrosive Soil and Rock

Gypsum is the most common sulfate mineral in soils in the western United States (Muckel, 2004). Gypsum is soluble and along with associated sulfates, such as sodium sulfate and magnesium sulfate, can dissolve in water to form a weak

Figure 6.6. *Corrosion of masonry block walls in southwestern Utah due to the reaction of the non-Type V cement used in the masonry blocks with high-sulfate soils (photo credit David Black, Rosenberg Associates).*

acid solution that is corrosive to concrete and metals in areas where the amount of soil gypsum is one percent or greater (Muckel, 2004). The ions within the acid react chemically with the cement (a base) in the concrete. Gypsum-induced corrosion of unprotected concrete slabs, walls, and masonry blocks is widespread in southwestern Utah (figure 6.6), and damage can become severe after just a few years of exposure (David Black, Rosenberg Associates, written communication, 2007). Precipitation of excess sulfate in soils can also cause foundation slabs to lift and crack (David Black, Rosenberg Associates, written communication, 2007). We did not observe evidence of corrosive soils in currently developed parts of the study area, and believe that this is due to the absence of gypsum-bearing bedrock units in those areas. Gypsum is abundant elsewhere in the study area, and if future development occurs in those areas, the corrosive nature of gypsiferous soil and rock should be taken into account.

Hazard Classification

Soil

Information on gypsiferous soil in the study area is limited. Mortensen and others (1977) mapped and described the soils in Zion National Park, and did not report the presence of pedogenic gypsum in their soil profiles. The absence of gypsum in the soil is likely due to the higher average annual precipitation in the study area (10–20 inches; see chapter 1 – Introduction) than in the more arid St. George area where average annual precipitation is 8.25 inches and pedogenic gypsum is common (Lund and others, 2008). Because of limited information, no areas of gypsiferous soil are shown on the Gypsum Susceptibility map (plate 8). Although unmapped in the study area, we anticipate that locally high concentrations of pedogenic gypsum are present in residual soils formed on gypsum-rich bedrock and in colluvial soils derived from gypsum-bearing rock units.

Rock

We grouped gypsum-bearing bedrock units (table 6.5) into two susceptibility categories (GR_A and GR_B) on the Gypsum Susceptibility map (plate 8) based on the relative amount of gypsum present in the bedrock units that constitute each category. While there is a general decrease in the amount of gypsum present from GR_A to GR_B, both hazard categories may contain abundant gypsum locally, and have a significant potential for dissolution and collapse. Therefore, the classification system presented below employs a relative susceptibility ranking as opposed to a hazard-severity ranking.

The gypsiferous-rock-susceptibility categories shown in table 6.5 and on plate 8 are characterized as follows:

GR_A Bedrock units that contain abundant gypsum, often in laterally continuous horizons as much as several feet thick. These units and the soils derived from them are commonly associated with dissolution and collapse features. This category includes the Shnabkaib Member of the Moenkopi Formation and the Paria River Member of the Carmel Formation.

GR_B Bedrock units that lack massive gypsum horizons, but contain thin to medium beds and veins of gypsum interspersed with other rock types. These units and the soils derived from them may contain sufficient gypsum locally to cause foundation or other problems. This category includes the lower red, middle red, and upper red members of the Moenkopi Formation; the Moenkopi Formation undivided; and the Crystal Creek Member of the Carmel Formation.

Table 6.5. *Geologic units known or likely to contain abundant gypsum.*

Bedrock Units[1]	Geologic Map Symbols	Gypsiferous Rock Category
Shnabkaib Member, Moenkopi Formation, Paria River Member, Carmel Formation	TRms, Jcp	GR_A
lower red, middle red, and upper red members, Moenkopi Formation; Moenkopi Formation undivided; Crystal Creek Member, Carmel Formation	TRml, TRmm, TRmu, TRm, Jcx	GR_B

[1]See figure 1.4 in chapter 1 for complete geologic unit names.

Using the Map

The Gypsum Susceptibility map (plate 8) shows the location of known and suspected gypsiferous rock in the Zion National Park Geologic-Hazard Study Area. The map is intended for general planning and design purposes to indicate where gypsiferous rock conditions may exist and special investigations, including sodium sulfate testing to determine the presence of corrosive soil or rock, should be required. Site-specific investigations can resolve uncertainties inherent in generalized mapping and help identify the need for special design or mitigation techniques. The presence and severity of gypsiferous rock units and gypsum-rich soils derived from them, along with other geologic hazards, should be addressed in these investigations. If gypsiferous soil or rock is present at a site, appropriate design and construction recommendations should be provided.

Map Limitations

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

Hazard Reduction

Although potentially costly when not recognized and properly accommodated in project design and construction, problems associated with gypsiferous soil and rock rarely are life threatening. As with most geologic hazards, early recognition and avoidance are the most effective ways to mitigate potential problems. However, avoidance may not always be a viable or cost-effective option.

In Utah, soil-test requirements are specified in chapter 18 (Soils and Foundations) of the 2009 IBC (International Code Council, 2009a) and chapter 4 (Foundations) of the 20096 IRC (International Code Council, 2009b), which are adopted statewide. IBC Section 1803.3 contains requirements for soil investigations in areas where questionable soil (soil classification, strength, or compressibility is in doubt) is present. IRC Section R401.4 states that the building official shall determine whether to require a soil test to determine the soil's characteristics in areas likely to have expansive, compressible, shifting, or other unknown soil characteristics. Where the presence of gypsiferous soil or rock is confirmed, possible hazard-reduction techniques include use of Type V or other sulfate-resistant cement for concrete; corrosion protection for metals; soil removal and replacement with noncohesive, compacted backfill; careful site landscape and drainage design to keep moisture away from concrete and gypsum-bearing deposits; and the use of a vapor barrier beneath concrete slabs to prevent sulfate migration (Keller and Blodgett, 2006). Where gypsum problems are particularly acute, design recommendations should be provided by a qualified corrosion engineer.

PIPING AND EROSION

Piping refers to the subsurface erosion of permeable, fine-grained, unconsolidated or poorly consolidated deposits by percolating ground water (Cooke and Warren, 1973; Costa and Baker, 1981; figure 6.7). 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 ground-water flow. Piping eventually leads to caving and collapse of the overlying surficial materials (figure 6.8), and is an important process in the headward extension of gullies in the arid southwestern United States (Costa and Baker, 1981).

For piping to take place, the following conditions are required: (1) fine-grained, noncohesive or poorly consolidated, porous materials, such as 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 ground water to percolate through

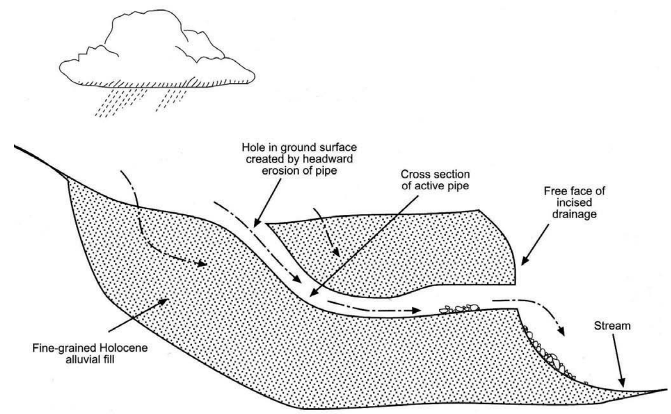

Figure 6.7. *Cross section of a pipe in fine-grained Holocene alluvium (after Black and others, 1999).*

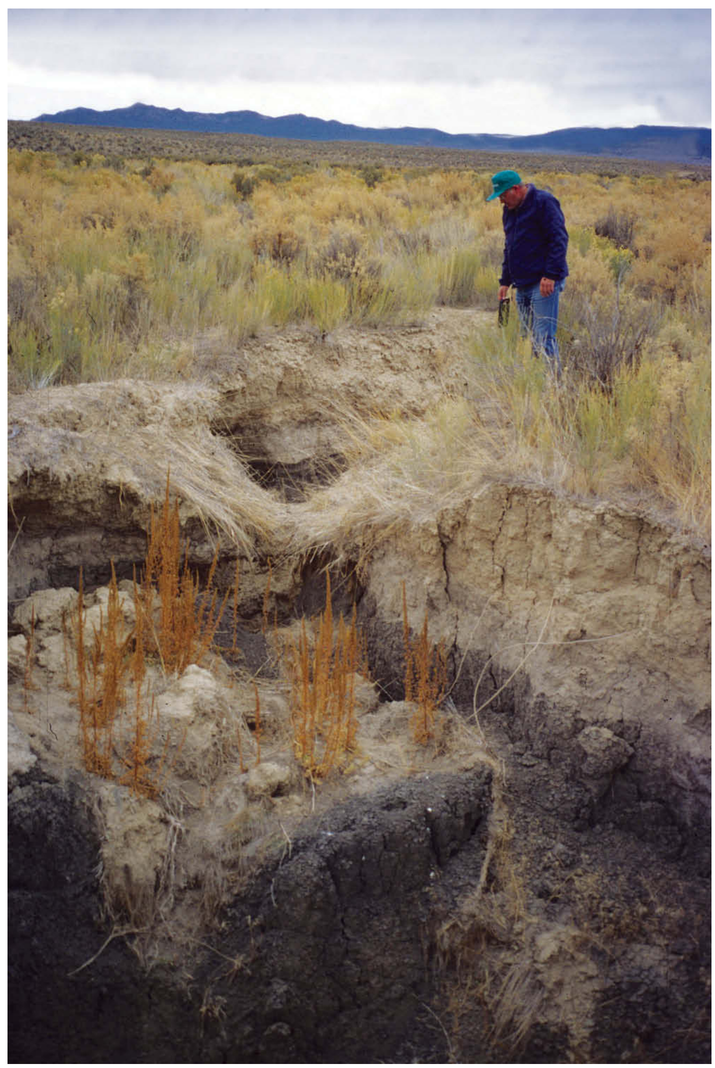

Figure 6.8. *Collapsed pipe in fine-grained floodplain alluvium in southwestern Utah.*

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. 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 induce piping. Parker and Jenne (1967, in Costa and Baker, 1981) describe extensive damage to U.S. Highway 140 where it traverses dissected and extensively piped valley fill along Aztec Wash in southwestern Colorado. Christenson and Deen (1983) reported piping at several locations in the St. George area.

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 southern Utah, most erosion occurs during cloudburst storms 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 is removed.

Description

Utah Geological Survey geologic maps (see Sources of Information section) show that fine-grained, noncohesive, loose sand and silt deposits are present in many areas of the Zion National Park Geologic-Hazard Study Area. They include eolian, alluvial, and lacustrine deposits, and mixed-unit geologic deposits that contain a high percentage of wind-blown sand derived from the weathering and erosion of sandstone bedrock that crops out in the study area. Poorly consolidated, often highly weathered, fine-grained bedrock units also crop out over portions of the study area.

Hazard Classification

The Piping-and-Erosion Susceptibility map (plate 9) shows the location of highly erodible soil and bedrock deposits susceptible to piping. Because piping only occurs where susceptible soil and rock exist in the presence of a free face and percolating ground water, 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. While 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.

We grouped geologic deposits in the Zion National Park Geologic-Hazard Study Area considered potentially susceptible to piping and erosion (table 6.6) into two susceptibility categories, one for unconsolidated deposits (soil) and the other for bedrock. The piping-and-erosion-susceptibility categories shown in table 6.6 and on plate 9 are characterized as follows:

Soil – Typically fine-grained, noncohesive, loose to poorly consolidated sand, silt, and landslide deposits consisting of similar material.

Rock – Typically fine-grained, poorly consolidated siltstone, mudstone, claystone, and landslide deposits consisting of such rock types.

Using the Map

The Piping-and-Erosion Susceptibility map (plate 9) shows the location of geologic units in the Zion National Park Geologic-Hazard Study Area that are potentially susceptible to piping and erosion. The map is intended for general planning and design purposes to indicate where susceptible soil and rock exist and where special investigations should be required. Site-specific investigations can resolve uncertainties inherent in generalized mapping and help identify the need for special design or mitigation techniques. The presence of soil or rock susceptible to piping and erosion along with other geologic hazards should be addressed in these investigations. If a potential for piping and erosion is present at a site, appropriate design and construction recommendations should be provided.

Map Limitations

The Piping-and-Erosion Susceptibility map (plate 9) is based on limited geologic and geotechnical data; site-specific investigations are required to produce more detailed geotechnical information. The map also depends on the quality of those data, which may vary throughout the study area. The boundaries of the areas shown as susceptible to piping and erosion are approximate and subject to change as new information becomes available. The susceptibility may be different than shown at any particular site because of variations in the physical properties of geologic deposits within a map unit, gradational and approximate map-unit boundaries, and the small map scale. Localized areas of piping and erosion susceptibility may exist throughout the study area, but their identification is precluded because of limitations of map scale. The map is not intended for use at scales other than the published scale, and is designed for use in general planning and design to indicate the need for site-specific investigations.

Hazard Reduction

Although potentially costly when not recognized and properly accommodated in project design and construction, problems associated with piping and erosion rarely are life threatening. As with most geologic hazards, early recognition and avoidance are the most effective ways to mitigate potential problems.

Table 6.6. *Geologic deposits susceptible to piping and erosion.*

Type of Deposit	Geologic Map Units[1]	Piping and Erosion Category
Stream Alluvium	Qa_1, Qa_2, Qal_1, Qa, Qaly	Soil
Alluvial/TerraceDeposits	Qas, Qaso, Qay, Qae, Qac, Qat_2, Qatm, Qath, Qaec, Qaes	Soil
Eolian/Colluvial Sand Deposits	Qes, Qed, Qces, Qer, Qre, Qea, Qce,Qmts	Soil
Lacustrine Deposits	Qlbc, Qls, Qla	Soil
Poorly Consolidated Bedrock	Petrified Forest Mbr., Chinle Fm.; Shnabkaib Mbr. and red mbrs., Moenkopi Fm.; Moenkopi Fm. Undivided; Whitmore Point and Dinosaur Canyon Mbrs., Moenave Fm.; Crystal Creek Mbr., Carmel Fm.	Rock
Landslide Deposits	Qmsy, Qmsh, Qmsc, Qmso	Fine-grained Soil or Rock

[1]Refer to UGS geologic quadrangle maps (see Sources of Information section) for a description of map units.

However, geologic units susceptible to piping and erosion are widespread in the study area, and avoidance may not always be a viable or cost-effective option.

In Utah, soil-test requirements are specified in chapter 18 (Soils and Foundations) of the 2009 IBC (International Code Council, 2009a) and chapter 4 (Foundations) of the 2009 IRC (International Code Council, 2009b), which are adopted statewide. IBC Section 1803.3 contains requirements for soil investigations in areas where questionable soil (soil classification, strength, or compressibility in doubt) is present. IRC Section R401.4 states that the building official shall determine whether to require a soil test to determine the soil's characteristics in areas likely to have expansive, compressible, shifting, or other unknown soil characteristics. Where the presence of soil or rock susceptible to piping or rapid erosion is confirmed, possible mitigation techniques include minimizing disturbance of vegetated areas, controlling the flow of shallow ground water, and managing surface drainage onsite in a controlled manner.

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