GUIDELINES FOR INVESTIGATING GEOLOGIC HAZARDS AND PREPARING ENGINEERING-GEOLOGY REPORTS, WITH A SUGGESTED APPROACH TO GEOLOGIC-HAZARD ORDINANCES IN UTAH

Steve D. Bowman and William R. Lund, editors

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Cover photo: *August 2014 Parkway Drive landslide, North Salt Lake. The landslide damaged the Eagle Ridge Tennis and Swim Club (white tent structure), severely damaged a house (directly above the tent structure), and removed part of the backyard of a second home. This landslide illustrates the significant impact geologic hazards can have on individuals, property owners, local governments, and the community.*
Photo credit: Gregg Beukelman, August 14, 2014.

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CONTENTS

FIGURES

TABLES

PREFACE

The purpose of these guidelines for investigating geologic hazards and preparing engineering-geology reports, is to provide recommendations for appropriate, minimum investigative techniques, standards, and report content to ensure adequate geologic site characterization and geologic-hazard investigations to protect public safety and facilitate risk reduction. Such investigations provide important information on site geologic conditions that may affect or be affected by development, as well as the type and severity of geologic hazards at a site, and recommend solutions to mitigate the effects and the cost of the hazards, both at the time of construction and over the life of the development. The accompanying suggested approach to geologic-hazard ordinances and school-site investigation guidelines are intended as an aid for land-use planning and regulation by local Utah jurisdictions and school districts, respectively. Geologic hazards that are not accounted for in project planning and design often result in additional unforeseen construction and/or future maintenance costs, and possible injury or death.

These guidelines are chiefly intended for engineering geologists performing geologic site investigations and for preparing engineering-geology reports on behalf of owners/developers seeking approval for site-specific development projects. The guidelines also provide a technical (scientific) basis for geologic-hazard ordinances and land-use regulations implemented by local jurisdictions. The guidelines and accompanying investigation checklists (appendix A) will be helpful to regulatory-authority engineering geologists conducting technical reviews of engineering-geology/geologic-hazard reports in support of the planning and development permit process.

Chapters 2, 3, 4, 5, 8, and 9 update and revise the following Utah Geological Survey (UGS) guidelines, which were previously individually published as:

- *Guidelines for Evaluating Landslide Hazards in Utah* (1996), Utah Geological Survey Circular 92
- *Guidelines for Evaluating Surface-Fault-Rupture Hazards in Utah* (2003), Utah Geological Survey Miscellaneous Publication 03-6
- *Guidelines for Preparing Geologic Reports in Utah* (1986), Utah Geological and Mineral Survey Miscellaneous Publication M
- *Guidelines for the Geologic Evaluation of Debris-Flow Hazards on Alluvial Fans in Utah* (2005), Utah Geological Survey Miscellaneous Publication 05-06
- *Suggested Approaches to Geologic Hazards Ordinances in Utah* (1987), Utah Geological Survey Circular 79
- Utah State Office of Education – Geologic-Hazard Report Guidelines and Review Checklist for New Utah Public School Buildings (2012), http://geology.utah.gov/ghp/school-site_review/pdf/ssr_checklist.pdf

Chapters 6 and 7 provide new guidelines for investigating land-subsidence and earth-fissure hazards, and rockfall hazards, respectively. We combined all of the UGS geologic-hazard-related guidelines into one volume to ensure users have easy and convenient access to all of the guidelines in one document, and to facilitate future updates. As the UGS develops additional geologic-hazard investigation guidelines, this publication will be updated as necessary. Users should refer to the UGS web page for the most current information and guidelines: http://geology.utah.gov/about-us/geologic-programs/geologic-hazards-program/for-consultants-and-design-professionals/recommended-report-guidelines/

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CHAPTER 1
INTRODUCTION

by
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Dump truck crushed by rockfall on November 23, 1947, in Zion National Park (photo courtesy of the National Park Service).

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CHAPTER 1: INTRODUCTION

by Steve D. Bowman, Ph.D., P.E., P.G.

OVERVIEW

Geologic hazards affect Utah, negatively impacting life safety, health, property, and the state's economy. While many geologic hazards are not life threatening, they are often costly when not recognized and properly accommodated in project planning and design, and may result in additional, significant construction and/or future maintenance costs and injury or death. To ensure that future development within Utah is protected from geologic hazards, the Utah Geological Survey (UGS) recommends that a comprehensive engineering-geology investigation be performed for all development subject to local permitting. Such investigations provide valuable information on site geologic conditions that may affect or be affected by development, as well as the type and severity of geologic hazards at a site, and recommend solutions to mitigate the effects and the cost of the hazards, both at the time of construction and over the life of the development. Engineering-geology investigations and accompanying geologic-hazard evaluations may be performed independently, or be included as part of a more broadly based geotechnical investigation before project engineering design.

The guidelines presented herein provide recommendations for appropriate, minimum investigative techniques, standards, and report content to ensure adequate geologic site characterization and geologic-hazard investigations to protect public safety and facilitate risk reduction. Chapter 2 presents guidelines for conducting engineering-geology investigations and preparing engineering-geology reports; chapters 3 through 7 provide guidance for evaluating surface-fault-rupture, landslide, debris-flow, land-subsidence and earth-fissure, and rockfall hazards. These guidelines are intended to ensure effective site investigations and geologic-hazard recognition and mitigation at the municipal or county level. Chapter 8 provides a suggested approach to geologic-hazard ordinances and effective review of engineering-geology reports in Utah. Chapter 9 provides guidance on reviewing Utah school-site engineering-geology reports and the UGS review of these reports.

Geologic hazards are defined in Utah Code as a "geologic condition that presents a risk to life, of substantial loss of real property, or of substantial damage to real property" (Title 17, Chapter 27a, Section 103, http://le.utah.gov/xcode/Title17/Chapter27A/17-27a-S103.html?v=C17-27a-S103_2015051220150512). Geologic hazards commonly encountered in Utah include, but are not limited to:

- Landslide Hazards, including
  - Landslides
  - Rockfall
  - Debris flows
  - Snow avalanches
- Earthquake Hazards, including
  - Ground shaking
  - Surface fault rupture
  - Liquefaction
  - Tectonic deformation
- Flooding Hazards, including
  - River, lake, or sheet flooding
  - Debris flows
  - Dam and water conveyance structure failure
  - Seiches
  - Tsunamis
- Problem Soil and Rock Hazards, including
  - Collapsible soils
  - Expansive soil and rock
  - Shallow bedrock
  - Corrosive soil and rock
  - Wind-blown sand
  - Breccia pipes and karst
  - Piping and erosion
  - Land subsidence and earth fissures
  - Caliche
  - Gypsiferous soil and rock
  - Radon gas
- Shallow Groundwater
- Volcanic Hazards, including
  - Volcanic eruption
  - Lava flows

COSTS OF GEOLOGIC HAZARDS

Geologic hazards that are not accounted for in project planning and design often result in additional unforeseen construction and/or future maintenance costs, and possible injury or death. There is only limited information on the direct and indirect economic costs of geologic hazards in the United States, including Utah; however, some information is available for large landslide events. For example, landslides in the United States cause between $1.6 and $3.2 billion (2013 dollars) in damages each year (Committee on Ground Failure Hazards, 1985).

Since 1847, approximately 5797 fatalities from geologic hazards have been documented in Utah (table 1), as well as a significantly larger, but undetermined number of injuries. Radon gas exposure (lung cancer) has been Utah's most deadly geologic hazard, with over 5372 fatalities (data only available from 1973 to 2012), followed by landslide hazards with 337 documented fatalities, and then flooding hazards with 101 documented fatalities. As debris flows are both a landslide and flooding hazard, fatalities are listed in both hazard categories. Using the economic value of a statistical life of $11.6 million (2016 dollars; U.S. Department of Transportation, 2014), the 5797 fatalities are valued at $67.2 trillion. The estimated economic value of human life is not considered in the hazard economic costs given below.

In almost all cases, it is more cost effective to perform a comprehensive engineering-geology investigation to identify and characterize geologic hazards and implement appropriate mitigation in project design and construction, rather than relying on additional maintenance over the life of the project or to incur costly change orders during construction.

Table 1. *Summary of known geologic-hazard fatalities in Utah.*

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

[1] Because of uncertainty in event initiation, three fatalities are listed in both the "Landslides" and "Dam and Water Conveyance Structure Failure" categories.
[2] Debris flows are both a landslide and flooding hazard.
[3] The majority of post-1950 snow avalanche fatalities are in the backcountry from human-induced avalanches; however, many have occurred near or in developed areas where appropriate mitigation measures should be used.
[4] Limited data are available and contain various assumptions; exact number of fatalities is unknown.
[5] Based on World Health Organization general estimate that 14% of lung cancer cases are attributable to radon gas (Sasha Zaharoff, Utah Department of Health, written communication, 2015) and data from http://epht.health.utah.gov/epht-view/query/result/ucr/UCRCntyICDO2/Count.html.
[6] Utah Environmental Public Health Tracking Network (2015).

Landslide Hazards

Landslide hazards have resulted in at least 337 fatalities in Utah since 1850, with 89.8% of deaths from snow avalanches and 10.2% of deaths from landslides (rock and soil), rockfall, and debris flows (table 2). While nearly all the recorded snow avalanche deaths since 1950 have been caused by human-triggered avalanches, many of these events have occurred at or near developed areas where appropriate mitigation measures should be employed.

Landslides

The 1983 Thistle landslide, Utah's largest natural (non-mining related) historical landslide, resulted in direct costs of $200 million, including $81 million in lost revenue by the Denver and Rio Grande Western Railroad (now Union Pacific Railroad; University of Utah, 1984). The Utah Department of Transportation estimates that repairs from damage to Utah State Highway 14 from a major 2011 landslide cost between $13 and $15 million (Dave Fadling, Utah Department of Transportation, verbal communication, 2012). The 2014 Parkway Drive landslide in North Salt Lake severely damaged a house and tennis and swim club, and threatens other houses and nearby regional natural gas pipelines (figure 1; Bowman, 2015); remediation is expected to cost $2 million (KSL, 2015), not including emergency response or homeowner relocation costs.

The Springhill landslide in North Salt Lake resulted in demolition of 18 homes since movement began around the late 1990s. Due to ongoing movement and subsequent public safety hazards, the City of North Salt Lake applied for a Federal Emergency Management Agency grant in 2011, to mitigate landslide hazards by purchasing 11 affected homes and demolishing them at a cost of $2.5 million (City of North Salt Lake, 2011). Figure 2 shows one of the affected homes.

Rockfall

Rockfall has caused significant damage to structures and property and resulted in at least 15 deaths in Utah since 1850 (table 3). Many of these fatalities were recreation related, and there-

Table 2. *Utah landslide fatalities since 1850, based on newspaper, report, and scientific descriptions of events.*

Date	Location	Fatalities	Notes	References[1]
3/12/2005	Kanab Creek, Kanab	1	Stream bank collapse	UGS RI 269, p. 17–24
7/11/2009	Logan Bluffs, Logan	3	Canal/landslide failure, home destroyed with three occupants[2]	UGS, Survey Notes, 2009, v. 41, no. 3, p. 10
	Total:	4		

[1] RI (Report of Investigation), UGS (Utah Geological Survey).
[2] It is unknown if a landslide initially caused the canal failure or if the canal failure caused the landslide; therefore, the three fatalities are included in both the "Landslides" and "Dam and Water Conveyance Structure Failure" categories.

Figure 1. *August 2014 Parkway Drive landslide, North Salt Lake. The landslide damaged the Eagle Ridge Tennis and Swim Club (white tent structure), severely damaged a house (directly above the tent structure), and removed part of the backyard of a second home. Photo credit: Gregg Beukelman, August, 14, 2014.*

fore, the hazard outside of developed areas should not be discounted. Utah's most recent rockfall-related fatalities are from the December 12, 2013, rockfall in Rockville, Utah (Lund and others, 2014), where two people died when numerous large rockfall boulders struck their home (figure 3), completely destroying two buildings. Seven major rockfalls have been documented in Rockville since 1976 (Knudsen, 2011).

Debris Flows

Debris flows have caused significant damage to structures and property and resulted in at least 15 deaths in Utah since 1847 (table 4). Damage to 29 homes and two businesses from the September 12, 2002, Santaquin, Utah, fire-related debris flow (figure 4) totaled about $500,000 (Brad Bartholomew, Utah Division of Emergency Management, verbal communication, 2012). As debris flows are both a landslide and flooding hazard, fatalities are listed in both hazard categories.

Figure 2. *House on Springhill Drive, North Salt Lake City, Utah, severely damaged by the Springhill landslide. This home had been "red tagged" by the city building official as unsafe to enter. Photo credit: Gregg Beukelman, February 29, 2012.*

Table 3. Utah rockfall fatalities since 1850, based on newspaper, report, and scientific descriptions of events.

Date	Location	Fatalities	Notes	References[1]
4/25/1874	Hyrum Canyon, Hyrum	2	Broken ledge	UGS OFR 514
10/20/1892	Ogden Canyon, near Kilns	1	–	UGS OFR 514
5/5/1895	Weber Canyon	1	Railroad engineer	UGS OFR 514
2/7/1909	Ruby-Westwater	1	Railroad worker, possibly in Colorado	UGS OFR 514
7/29/1937	Price	2	Occurred after rain storm	UGS OFR 514
1960s–1970s?	Timpanogos Cave National Monument	?	–	NPS communication
7/25/1994	Hanging Rock Picnic Area, American Fork Canyon	1	–	USGS OFR 1229
1/14/1995	Big Cottonwood Canyon	1	–	UGS RI 228
7/29/1995	Hanging Rock Picnic Area, American Fork Canyon	1	–	UGS OFR 373, USGS OFR 1229
8/2/1999	Lake Powell, Goosenecks of San Juan Arm, Glen Canyon National Recreation Area	1	Camper struck on head, boulder rolled onto tent	UGS OFR 373, PI 94; NPS Geologic Hazard Events
10/1/2007	Lake Powell, Lake Canyon, Glen Canyon National Recreation Area	2	Rock slab collapse onto boat from overhanging alcove roof	NPS Geologic Hazard Events; http://www.ksl.com/?nid=148&sid=1897666
12/12/2013	368 West Main Street, Rockville	2	Home destroyed	UGS RI 273
	Total:	15		

[1] NPS (National Park Service), OFR (Open-File Report), PI (Public Information series), RI (Report of Investigation), UGS (Utah Geological Survey), USGS (U.S. Geological Survey).

***Figure 3.** House in Rockville, Utah, destroyed by a rockfall on December 12, 2013, that resulted in the death of the two house occupants. Photo credit: Tyler Knudsen, December 13, 2013.*

Snow Avalanches

Snow avalanches have resulted in at least 303 fatalities in Utah since 1847, with 193 from avalanches in developed areas and 110 from winter sports-related avalanches (table 5). Whereas most of the winter sports-related fatalities were caused by human-triggered avalanches, many occurred at or near developed areas, where appropriate mitigation measures should be employed to protect from avalanches triggered within or adjacent to developed areas.

Earthquake Hazards

Although only two fatalities (ground shaking related) from earthquakes have occurred in Utah since 1847 (table 6), scenario modeling predicts 2000 to 2500 fatalities, 7400 to 9300 life-threatening injuries, 55,400 buildings completely damaged, 21 billion tons of debris, and $33.2 billion in estimated short-term, direct economic losses from a major (magnitude [M] 7.0) earthquake on the Salt Lake City segment of the Wasatch fault zone (Earthquake Engineering Research Institute [EERI], 2015). About 90,200 unreinforced masonry buildings (URM), or over 61% of the total number of buildings in the 12-county area, will be moderately damaged or totally destroyed (EERI, 2015). Such an event will likely take decades to recover from and will be the single-most costly geologic hazard event to affect Utah.

Damage from the 2008 Wells (population 1657), Nevada, earthquake (M 6.0), the most recent damaging earthquake near Utah, totaled approximately $10.6 million, with nearly half of the approximately 80 non-residential buildings damaged and 10 severely damaged (dePolo, 2011). The Wells earthquake is an important analog for rural Utah towns and cities, with similar URM building stock and fragile economic conditions.

Flooding Hazards

Flooding hazards have caused significant damage to structures and property and resulted in at least 101 fatalities in Utah since 1847, with 80.1% of deaths from floods and flash floods,

Table 4. *Utah debris-flow fatalities since 1847, based on newspaper, report, and scientific descriptions of events.*

Date	Location	Fatalities	Notes	References[1]
8/13/1923	Farmington Creek, Farmington	6	Campers	UGS files
6/11/1965	Sheep Creek, Flaming Gorge National Recreation Area	7	Campers	UGA Publication 28
5/13/1984	Clear Creek, Carbon County	1	Slope above house	UGS files
5/14/1984	Middle Fork Canyon, Carr Fork mine, Tooele County	1	Dozer operator	UGS files, Brough and others (1987)
	Total:	15		

[1] UGA (Utah Geological Association), UGS (Utah Geological Survey).

Figure 4. *September 12, 2002, Santaquin, Utah, fire-related debris flow. This debris flow moved and partially buried several vehicles, broke through a house wall, and entered other houses through broken basement windows and doors. Photo taken September 12, 2002.*

14.9% from debris flows, and 5.0% from dam and water conveyance structure failures. Sixteen major flood events since 1923 have caused over $1.3 trillion in damage (Utah Division of Emergency Management, 2014), and to date, flooding is Utah's most economically costly geologic hazard. As debris flows are both a landslide and flood hazard, fatalities are listed in both hazard categories.

Floods and Flash Floods

Floods and flash floods have caused significant damage to structures and property and resulted in at least 81 fatalities in Utah since 1847 (table 7). Flash floods produced Utah's most deadly, single-event geologic hazard (20 fatalities), when on September 14, 2015, seven canyoneers in Keyhole Canyon in Zion National Park and 13 people in two vehicles in Hildale drowned in flash flooding resulting from a single summer thunderstorm.

Debris Flows

See debris-flow hazards in the Landslide Hazards section above.

Dam and Water Conveyance Structure Failure

Dam and water conveyance structure failures have caused significant damage to structures and property and resulted in five

Table 5. Utah snow avalanche fatalities since 1847, based on newspaper, report, and scientific descriptions of events.

Date	Location[1]	Fatalities		Notes	References[2]
		Sports	Other		
1847–1949	Various[3]	118		–	Brough
2/13/1885	Emma mine, Alta	–	16	Covered 3/4th of town	Brough
1/1903	Near Park City	–	3	Miners	Brough
1/31/1911	Alta	–	4	Miners	Brough
3/1920	Canyons around Salt Lake Valley	–	9	Also first few days of April	Brough
2/17/1926	Bingham Canyon	–	39[4]	Homes destroyed	Deseret News
1950–1957	Various	1			Brough
3/9/1958	Snowbasin	2	–	Rescuers	NWS/UAC
3/29/1964	Snowbasin	–	1	Worker	NWS/UAC
2/12/1967	Pharaohs Glen	2	–	Climbers	NWS/UAC
2/19/1968	Rock Canyon	1	–	Hiker	NWS/UAC
1/29/1970	Alta	1	–	In-bounds skier	NWS/UAC
1/29/1970	Park West	1	–	In-bounds skier	NWS/UAC
1/6/1976	Alta	1	–	Out-of-bounds skier	NWS/UAC
3/3/1976	Snowbird	1	–	In-bounds skier	NWS/UAC
1/19/1979	Helper	–	1	Worker	NWS/UAC
4/2/1979	Lake Desolation	1	–	Backcountry skier	NWS/UAC
1/11/1980	Evergreen Ridge	1	–	Out-of-bounds skier	NWS/UAC
2/1/1981	Cardiff	1	–	Hiker	NWS/UAC
3/1/1981	Millcreek	1	–	Backcountry skier	NWS/UAC
3/22/1982	Near Park West	1	–	Backcountry skier	NWS/UAC
1/2/1984	Superior Peak	1	–	Backcountry skier	NWS/UAC
2/22/1985	Powder Mountain	1	–	Backcountry skier	NWS/UAC
3/19/1985	Park City	1	–	In-bounds wet slide	NWS/UAC
11/13/1985	Sunset Peak	2	–	Backcountry skiers	NWS/UAC
1/6/1986	Provo Canyon	1	–	Backcountry skier	NWS/UAC
2/17/1986	BCC	1	–	Backcountry snowboarder	NWS/UAC
2/19/1986	Alta	1	–	In-bounds skier	NWS/UAC
11/20/1986	Sugarloaf, Alta	1	–	Hiker, unopened area	NWS/UAC
2/15/1987	Twin Lakes Reservoir	1	–	Backcountry skier	NWS/UAC
11/25/1989	Tony Grove Lake	1	–	Backcountry skier	NWS/UAC
2/12/1992	Gold Basin, La Sal Mountains	4	–	Backcountry skiers	NWS/UAC
4/1/1992	Mineral Basin, Snowbird	1	–	Backcountry skier	NWS/UAC
1/16/1993	Sundance	1	–	Backcountry skier, closed area	NWS/UAC
2/25/1993	Pinecrest, Emigration Canyon	1	–	Backcountry skier	NWS/UAC
4/3/1993	Wolverine Cirque	1	–	Backcountry skier	NWS/UAC
2/18/1994	10,420′ Peak, BCC	1	–	Backcountry skier	NWS/UAC
11/7/1994	Snowbird	1	–	Backcountry skier, pre-season	NWS/UAC
1/14/1995	Ben Lomond Peak	2	–	Snowmobilers	NWS/UAC
1/23/1995	Midway	–	1	Resident in roof slide.	NWS/UAC
2/12/1995	Gobblers Knob, BCC	1	–	Backcountry skier	NWS/UAC
2/2/1996	Solitude	1	–	Patroller	NWS/UAC
3/27/1996	Maybird Gulch, LCC	1	–	Backcountry skier	NWS/UAC
12/7/1996	Bountiful Peak	1	–	Snowmobiler	NWS/UAC
12/26/1996	Flagstaff Peak	1	–	Snowmobiler	NWS/UAC

Table 5. *Continued*

Date	Location[1]	Fatalities		Notes	References[2]
		Sports	Other		
1/11/1997	Logan Peak	3	–	Campers	NWS/UAC
1/25/1997	Provo Canyon	1	–	Climber	NWS/UAC
1/17/1998	Near Coalville	1	–	Snowmobiler	NWS/UAC
1/18/1998	Sanpete County	1	–	Snowmobiler	NWS/UAC
2/26/1998	Near Weber State	1	–	Hiker (possible suicide)	NWS/UAC
11/7/1998	Snowbird	1	–	Snowboarder, pre-season	NWS/UAC
1/2/1999	Wasatch Plateau	2	–	Snowboarders	NWS/UAC
1/29/1999	Mt. Nebo	1	–	Snowmobiler	NWS/UAC
2/6/1999	Little Willow Canyon	1	–	Hiker	NWS/UAC
1/11/2000	Squaretop, Canyons	2	–	Out-of-bounds skiers	NWS/UAC
2/27/2001	Near Canyons	1	–	Out-of-bounds skier	NWS/UAC
3/10/2001	Oakley, Uinta Mountains	2	–	Snowmobilers	NWS/UAC
4/28/2001	Stairs Gulch, BCC	2	–	Climbers	NWS/UAC
12/14/2001	Willard Basin	1	–	Snowmobiler	NWS/UAC
1/31/2002	Windy Ridge, Uinta Mountains	1	–	Backcountry skier	NWS/UAC
3/16/2002	Pioneer Ridge, Brighton	2	–	Out-of-bounds snowboarders	NWS/UAC
2/15/2003	Gobblers Knob, BCC	1	–	Backcountry skier	NWS/UAC
12/26/2003	Aspen Grove, Timpanogos	3	–	Backcountry snowboarders	NWS/UAC
2/26/2004	Empire Canyon, Park City	1	–	Snowshoer	NWS/UAC
12/10/2004	Twin Lakes Pass, SLC	1	–	Backcountry skier	NWS/UAC
12/11/2004	Trout Creek, Strawberry	1	–	Snowmobiler	NWS/UAC
	Mineral Fork, SLC	2	–	Snowshoers	NWS/UAC
1/8/2005	Choke Cherry, Mt. Pleasant	1	–	Snowmobiler	NWS/UAC
	Ephraim Canyon	1	–	Snowboarder	NWS/UAC
1/14/2005	Dutch Draw, Park City	1	–	Snowboarder	NWS/UAC
3/31/2005	Whiskey Hill	1	–	Snowboarder	NWS/UAC
12/31/2005	Emerald Lake, Timpanogos	1	–	Snowshoer	NWS/UAC
3/11/2006	Taylor Canyon, Ogden	1	–	Snowboarder	NWS/UAC
4/3/2006	Pioneer Ridge, Brighton	1	–	Out-of-bounds snowboarder	NWS/UAC
2/17/2007	Signal Peak	1	–	Snowmobiler	NWS/UAC
	Tower Mountain	1	–	Snowmobiler	NWS/UAC
2/18/2007	Hells Canyon, Snowbasin	1	–	Out-of-bounds skier	NWS/UAC
2/21/2007	Gobblers Knob, BCC	1	–	Backcountry skier	NWS/UAC
12/23/2007	Canyons	1	–	Skier	NWS/UAC
12/25/2007	Thousand Peaks	1	–	Snowmobiler	NWS/UAC
12/31/2007	Co-op Creek	1	–	Snowmobiler	NWS/UAC
12/14/2008	Mt. Baldy, Snowbird	1	–	In-bounds skier	NWS/UAC
12/24/2008	Providence Canyon	2	–	Snowmobilers	NWS/UAC
12/29/2008	Windy Ridge-Moffit Basin	1	–	Snowmobiler	NWS/UAC
1/24/2010	Hells Canyon, Snowbasin	1	–	Out-of-bounds skier	NWS/UAC
1/27/2010	Silver Fork, BCC	1	–	Out-of-bounds skier	NWS/UAC
1/29/2010	Grandview Peak	1	–	Snowmobiler	NWS/UAC
4/4/2010	Francis Peak	1	–	Snowmobiler	NWS/UAC
3/26/2011	Big Horseshoe Bowl	1	–	Backcountry skier	NWS/UAC
11/13/2011	Gad Valley, Snowbird	1	–	Skier, pre-season	NWS/UAC

Table 5. *Continued*

Date	Location[1]	Fatalities		Notes	References[2]
		Sports	Other		
1/28/2012	Kesler Ridge	1	–	Backcountry snowboarder	NWS/UAC
2/5/2012	Fish Lake	1	–	Snowmobiler	NWS/UAC
2/23/2012	Dutch Canyon, Canyons	1	–	Out-of-bounds snowboarder	NWS/UAC
3/3/2012	Beaver Basin	1	–	Snowmobiler	NWS/UAC
2/8/2014	Tibble Fork Reservoir	1	–	Snowshoer	NWS/UAC
2/9/2014	Huntington Reservoir	1	–	Snowmobiler	NWS/UAC
3/7/2014	Whitney Reservoir	1	–	Snowmobiler	NWS/UAC
1/21/2015	Gobblers Knob	1	–	Backcountry skier	http://www.sltrib.com/news/3446097-155/1-person-rescued-from-utah-avalanche
1/31/2016	Shale Shot, Summit County	1	–	Backcountry skier	http://www.ksl.com/?sid=38367916
	Totals:	108	192		
		300			

[1] BCC (Big Cottonwood Canyon), LCC (Little Cottonwood Canyon), SLC (Salt Lake City).
[2] Brough (Brough and others, 1987), Deseret News (1986); NWS (National Weather Service, Salt Lake City Weather Forecast Office, 2015a), UAC (Utah Avalanche Center, 2015).
[3] Most of these fatalities occurred in the early mining days of Utah.
[4] Brough and others (1987) indicate 36 fatalities.

Table 6. *Utah earthquake fatalities since 1847, based on newspaper, report, and scientific descriptions of events.*

Date	Location	Fatalities	Notes	References[1]
3/12/1934	Hansel Valley fault zone (M6.6)	2	Trench collapse (1) and death of sick woman (1)	UUSS
	Total:	2		

[1] UUSS (University of Utah Seismograph Stations).

fatalities in Utah since 1847 (table 8). The failure of Quail Creek dam on December 31, 1988, resulted in approximately $12 million in damage and cost $8 million to rebuild (UDEM, 2014). Most Utah dam and canal failures have resulted from piping, erosion, and other soil or rock problems.

Problem Soil and Rock Hazards

Problem soils, such as expansive, compressible, and/or collapsible soils, can cause extensive damage to structures and foundations. Problem soils may also damage pavements after construction, resulting in high maintenance and/or replacement costs, along with increased legal and financial liability from pavement separation and/or gaps causing tripping hazards. In addition, future maintenance may disrupt business activities, resulting in increased costs and/or lost revenue. While no deaths have been reported in Utah from problem soil hazards, they have caused an undetermined, but very significant, amount of infrastructure damage and resulting economic impact.

Land Subsidence and Earth Fissures

Land subsidence and earth fissures due to groundwater mining have caused significant damage in Utah, including in the Escalante (Lund and others, 2005), Cedar (Kaliser, 1978; Knudsen and others, 2014), and Parowan (DuRoss and Kirby, 2004) Valleys. While damage cost estimates for Utah are not available, between 1990 and 2000, the federal government and the State of Nevada spent over $7.5 million to move residents from and demolish the Windsor Park Subdivision in North Las Vegas due to earth fissures from groundwater withdrawal in the Las Vegas Valley (Harris, 2001).

Radon Gas

Between 1973 and 2012, there were approximately 5372 fatalities in Utah attributable to lung cancer caused by radon gas, having an estimated total first-year treatment cost of $2.7 to $3.6 million (based on World Health Organization general estimate that 14% of lung cancer cases are attributable to radon gas [Sasha Zaharoff, Utah Department of Health, written communi-

Table 7. *Utah flood fatalities since 1847, based on newspaper, report, and scientific descriptions of events.*

Date	Location	Fatalities[1]	Notes	References[2]
7/17/1863	Pine Creek, Iron County	4	Cloudbursts flood Pine Creek to a level of 20 feet.	NWS
7/23/1878	Skull Valley	2	A cloudburst at Johnson's settlement.	NWS
8/16/1889	Wood Canyon, Mayfield	1	Flash flood	NWS
7/14/1896	Eureka	3	Torrential rain flooded town.	NWS, Brough
7/28/1896	Eureka	4	Raging torrent down Main Street.	NWS
8/22/1896	Clear Creek Canyon, Joseph	1	Wagonload of laborers caught in a flooded stream.	NWS
10/7/1896	Mill Creek, Moab	1	Man drowned attempting to cross.	NWS
10/16/1889	Mayfield	1	Boy drowned in flash flood.	Brough
8/4/1900	Orangeville	1	Creek flooded by heavy rain.	NWS
8/4/1901	Coyote (La Sal)	1	Girl drowned in flood.	Brough
8/5/1901	Gorge 15 miles below Escalante	1	Boy drowned swimming when freshet came down gully.	NWS
8/6/1901	Winter Quarters, Scofield	2	–	NWS
8/10/1903	Dry Creek, Toquerville	1	Man trapped in flash flood.	NWS
9/1/1909	Ashley River, Vernal	1	Man drowned in flash flood while driving a wagon across.	NWS
6/19/1918	Pleasant Creek, Mount Pleasant	1	Intense cloudburst causing extensive flooding.	NWS
8/2/1922	Magna	1	Boy drowned in flood.	NWS
8/13/1923	Willard	2	Fatalities in home damaged by flood.	Brough
7/4/1925	Five Mile Creek, Vernal	1	Child drowned when swept from auto mobile by a flood.	NWS
8/16/1928	Nine Mile Canyon, Price	1	Man drowned from heavy flooding that covered his automobile.	NWS
8/13/1930	Mona	1	Mud on highway, boy killed.	Brough
8/1931	Cisco	1	Woman swept to death.	Brough
7/21/1934	Lost Creek, Salina	1	Boy drowned in a sudden flood.	NWS
7/29/1936	Ferron	1	Woman drowned in cloudburst flood down a dry wash.	NWS
7/30/1936	Minersville	1	Cloudburst flood.	NWS
7/29/1937	Price	1	Flood rolled boulders into a home.	Brough
8/31/1939	Diamond Creek, Book Cliffs	1	Woman swept to death by flood waters.	NWS
8/5/1948	Sunnyside	1	Body in debris after flash flood.	NWS
8/26/1952	Buckhorn Wash Proving Ground, Castle Dale	1	Man drowned in tunnel when cloudburst flooded the tunnel.	NWS
9/17/1961	Virgin River Narrows, Zion NP	5	Party of 26 caught in flash flood, 14 foot flood crest in some locations.	NWS
	Wahweap Creek, Glen Canyon City	1	Girl drowned in flash flood.	NWS
9/5/1970	Four Corners area	2	Drove car off washed-out bridge.	NWS
2/18/1980	Kolob Creek, Virgin	1	Car driving across creek carried down stream, drowning.	NWS
2/18/1986	Box Elder County	1	Boy drowned in rain-swollen canal.	NWS
9/14/1996	White Canyon, Blanding	1	Hiking party of 13 caught in flash flood.	NWS
7/27/1998	Virgin River Narrows, Zion NP	2	Flash flood.	NWS
9/5/1998	Ice Cream Canyon, Glen Canyon NRA	1	Girl swept away from flash flood, canyon wall gave away.	NWS
5/13/2001	Washington County	1	Boy swept off cliff by flash flood.	NWS

Table 7. Continued

Date	Location	Fatalities[1]	Notes	References[2]
1/10/2005	Red Cliff Recreation Area	1	Party of 2 caught in dry wash flood in their vehicle	NWS
7/30/2006	Garleys Wash, Carbon County	2	Family offroading vehicle was hit with flash flood	NWS
9/10/2008	Slot Canyon in Garfield County	2	Party of 8 caught in slot canyon flash flood.	NWS
10/1/2012	La Verkin Creek, Washington County	1	Girl playing in backyard swept away by flash flood	NWS
9/27/2014	Virgin River Narrows, Zion NP	1	Man killed from flash flood	NWS
9/14/2015	Keyhole Canyon, Zion NP	7	Hiking party of 7 caught in flash flood	UGS files, http://www.ksl.com/?sid=36545005&nid=148
	Short Creek, Hildale	13	Sixteen individuals in two vehicles caught in flash flood	UGS files, http://www.ksl.com/?sid=36545005&nid=148
	Total:	81		

[1] Not including vehicular fatalities (crashes, skidding, etc.) caused by flooding.
[2] Brough (Brough and others, 1987), NWS (National Weather Service, Salt Lake City Weather Forecast Office, 2015b), UGS (Utah Geological Survey).

Table 8. *Utah dam and water conveyance structure failure fatalities since 1847, based on newspaper, report, and scientific descriptions of events.*

Date	Location	Fatalities	Notes	References[1]
5/16/1963	Little Deer Creek Dam, Uinta Mountains	1	Dam failure, four year old boy died	UDEM
6/24/1983	DMAD Dam, Delta	1	Dam failure, man drowned from flash flood	NWS, UDEM
7/11/2009	Logan Bluffs, Logan	3	Canal/landslide failure, home destroyed with three occupants[2]	UGS, Survey Notes, 2009, v. 41, no. 3, p. 10
	Total:	5		

[1] NWS (National Weather Service, Salt Lake City Weather Forecast Office, 2015b), UDEM (Utah Division of Emergency Management, 2014), UGS (Utah Geological Survey).
[2] It is unknown if a landslide initially caused the canal failure or if the canal failure caused the landslide; therefore, the three fatalities are included in both the "Landslides" and "Dam and Water Conveyance Structure Failure" categories.

cation, 2015], data from http://epht.health.utah.gov/epht-view/query/result/ucr/UCRCntyICDO2/Count.html, and Utah Environmental Public Health Tracking Network, 2015). Thousands of fatalities before 1973 from radon gas are likely. To date, lung cancer fatalities caused by radon gas are Utah's most deadly geologic hazard. Geologic conditions directly affect indoor radon gas concentrations; however, indoor radon gas concentrations are highly dependent on building construction methods; see chapter 2, section on International Building/Residential Code and Local Requirements for more information.

UGS GEOLOGIC-HAZARD GUIDELINES BACKGROUND

Recognizing Utah's susceptibility to geologic hazards, as evidenced by damage to infrastructure and injury or death to Utah citizens, the UGS began developing and/or collaborating on guidelines starting in the 1980s and continuing into the 2000s for (1) conducting engineering-geology investigations and preparing engineering-geology reports, (2) evaluating landslide, surface-fault-rupture, and debris-flow hazards, and (3) developing geologic-hazard ordinances. Full citations for those documents are presented below; this publication updates and supersedes these guidelines:

- Engineering Geology Reports – Association of Engineering Geologists (Utah Section), 1986, Guidelines for preparing engineering geologic reports in Utah: Utah Geological and Mineral Survey Miscellaneous Publication M, 2 p.
- Geologic Hazard Ordinances – Christenson, G.E., 1987, Suggested approach to geologic hazards ordinances in Utah: Utah Geological and Mineral Survey Circular 79, 16 p.

- Landslides – Hylland, M.D., 1996, Guidelines for evaluating landslide hazards in Utah: Utah Geological Survey Circular 92, 16 p.
- Surface Fault Rupture – Christenson, G.E., Batatian, L.D., and Nelson, C.V., 2003, Guidelines for evaluating surface-fault-rupture hazards in Utah: Utah Geological Survey Miscellaneous Publication 03-6, 14 p.
- Debris Flows – Giraud, R.E., 2005, Guidelines for the geologic evaluation of debris-flow hazards on alluvial fans in Utah: Utah Geological Survey Miscellaneous Publication 05-6, 16 p.
- Utah School-Site Reports – Bowman, S.D., Giraud, R.E., and Lund, W.R., 2012, Utah State Office of Education—geologic-hazard report guidelines and review checklist for new Utah public school buildings: Utah Geological Survey, online, http://geology.utah.gov/ghp/school-site_review/pdf/ssr_checklist.pdf.

CURRENT UGS GEOLOGIC-HAZARD GUIDELINES

This publication provides revised and updated guidelines for conducting engineering-geology investigations and preparing engineering-geology reports (chapter 2); for investigating surface-fault-rupture (chapter 3), landslide (chapter 4), and debris-flow (chapter 5) hazards; for implementing geologic-hazard ordinances (chapter 8); and for preparing and reviewing engineering-geology reports for school sites (chapter 9). Additionally, the UGS has prepared new investigation guidelines for evaluating land-subsidence and earth-fissure hazards (chapter 6) and rockfall hazards (chapter 7). All of the current guidelines are now combined into one publication to reduce duplication of topics, form a more complete reference, and facilitate easier updates and additions to the guidelines in the future.

These guidelines represent the recommended minimum acceptable level of effort for conducting geologic-hazard investigations and preparing engineering-geology reports in Utah. These guidelines identify important issues and general methods for investigating geologic hazards; they do not discuss all methods and are not a step-by-step primer for hazard investigations. The level of detail appropriate for a particular investigation depends on several factors, including the type, nature, and location of proposed development; the geology and physical characteristics of the site; and the level of risk acceptable to property owners, users, and land-use regulators.

The state-of-practice of geologic-hazard investigations continues to evolve as new or improved techniques become available and are incorporated into hazard investigations. The methods outlined in these guidelines are considered to be practical and reasonable methods for obtaining planning, design, and risk-reduction information, but these methods may not apply in all cases. The engineering geologist in charge of a geologic-hazard investigation is responsible for understanding the appropriateness of the various methods and where they apply.

As the UGS revises existing or develops new geologic-hazard guidelines, this publication will be updated as appropriate. Users should refer to the UGS web page for the most current information and guidelines: http://geology.utah.gov/about-us/geologic-programs/geologic-hazards-program/for-consultants-and-design-professionals/recommended-report-guidelines/.

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CHAPTER 2
GUIDELINES FOR CONDUCTING ENGINEERING-GEOLOGY INVESTIGATIONS AND PREPARING ENGINEERING-GEOLOGY REPORTS IN UTAH

by
Steve D. Bowman, Ph.D., P.E., P.G., and William R. Lund, P.G.

Excavation of a test pit for a geotechnical investigation in Utah.

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CHAPTER 2: GUIDELINES FOR CONDUCTING ENGINEERING-GEOLOGY INVESTIGATIONS AND PREPARING ENGINEERING-GEOLOGY REPORTS IN UTAH

by Steve D. Bowman, Ph.D., P.E., P.G., and William R. Lund, P.G.

INTRODUCTION

The Utah Geological Survey (UGS) recommends that for all development subject to local permitting, a comprehensive engineering-geology investigation be performed to ensure that site geologic conditions are adequately characterized and accommodated in project design, and that the project is protected from geologic hazards. Investigation results should be presented in an engineering-geology report, which depending on project type and scope, may be a stand-alone document, or if conducted concurrently with a geotechnical-engineering investigation, may be part of a more comprehensive geotechnical report. In many, if not most, instances, engineering-geology investigations focus on geologic hazards, and the investigations and subsequent reports are often termed "geologic-hazard" investigations and reports. Engineering-geology investigations provide valuable information on site geologic conditions and the nature of geologic hazards present, and provide recommendations for accommodating geologic conditions in project design and for solutions to mitigate geologic hazards, both at the time of construction and over the life of the development.

Chapter 1 of this publication identifies the numerous geologic hazards in Utah that may affect present and future development. Engineering-geology investigations should be comprehensive and address all geologic hazards at a site. As the UGS continues to develop guidance for investigating other geologic hazards, those guidelines will be available on the UGS website (see chapter 1), and this publication will be periodically updated. The UGS website contains links to other guidance documents for investigating geologic hazards not currently covered by UGS guidelines; those guidance documents should be consulted as necessary by geologists conducting geologic-hazard investigations (http://geology.utah.gov/about-us/geologic-programs/geologic-hazards-program/for-consultants-and-design-professionals/useful-websites/).

The UGS Geologic Hazards Program developed these engineering-geology investigation and report preparation guidelines based on current engineering-geology state-of-practice, and previous guidelines prepared by the Utah Section of the Association of Engineering Geologists (1986; see chapter 1) published by the UGS. The 1986 guidelines were based on a series of guidelines developed in California since 1973, by the California Division of Mines and Geology (CDMG, now California Geological Survey) (CDMG, 1973, 1975a, 1975b, 1975c, 2011a; Slosson, 1984). Those guidelines were subsequently updated and modified by the California Board for Geologists and Geophysicists (CBGG, now California Board for Professional Engineers, Land Surveyors, and Geologists) (CBGG, 1998a, 1998b, 1998c, 1998d).

ENGINEERING-GEOLOGY INVESTIGATIONS

The engineering-geology investigation required for a development depends on site geologic conditions, geologic hazards present, and the nature of the proposed development (structure type, size, placement, and occupancy; required cuts, fills, and other grading; groundwater conditions; and the specific purpose and use of the development). An engineering-geology investigation must address all pertinent geologic conditions that could affect, or be affected by, the proposed development. This can only be accomplished through proper identification and interpretation of site-specific geologic conditions and processes, and nearby features that may affect the site and/or development.

The scope of investigation and specific investigation methods will vary depending on project requirements and the regulatory agency that reviews and approves the project. However, the UGS considers these engineering-geology investigation guidelines and the geologic-hazard investigation guidelines in later chapters to represent the minimum acceptable level of effort in conducting engineering-geology/geologic-hazard investigations in Utah. Additionally, while withdrawn, ASTM International (ASTM) Standard D420 *Standard Guide to Site Characterization for Engineering Design and Construction Purposes* (ASTM, 2003) contains valuable information about performing geotechnical investigations. If soil and/or rock testing is part of the investigation, the organization performing the testing should meet the requirements of ASTM Standard D3740 *Standard Practice for Agencies Engaged in the Testing and/or Inspection of Soil and Rock as Used in En-*

gineering Design and Construction (ASTM, 2012a) and the Laboratory Testing section below. These standards are not meant to be inflexible descriptions of requirements and do not address all concerns.

When Geologic-Hazard Special Study Maps Are Not Available

Where geologic-hazard special study maps are not available, the first step in a geologic-hazard investigation is to determine if the site is near mapped or otherwise known geologic hazards. If so, larger scale maps (if available) should be examined, aerial photograph and other remote sensing imagery interpreted, and a field investigation performed to produce a detailed geologic map (see below) to determine if a geologic hazard(s) is present that will affect the site. If evidence for a hazard(s) is found, the UGS recommends that a site investigation be performed in accordance with the guidelines presented in this chapter and chapters 3 through 7 as applicable.

International Building/Residential Code and Local Requirements

The 2015 International Building and Residential Codes (IBC/IRC; International Code Council, 2014a, 2014b), adopted statewide in Utah after July 1, 2016 (Title 15A, http://le.utah.gov/xcode/Title15A/15A.html), specify requirements for geotechnical investigations that also include evaluation of some geologic hazards. Local governments (Utah cities, counties, and special service districts) may also adopt ordinances related to geologic hazards that must be followed for development projects. These ordinances may include hillside development regulations. Existing ordinances vary significantly throughout the state, and it is the responsibility of the investigator to know the requirements and ordinances that apply to a site. A comprehensive geologic-hazard investigation will almost always exceed IBC/IRC and local minimum requirements.

The 2015 IBC/IRC specify seismic provisions for earthquake hazards. Section 1613.1 of the IBC states, "Every structure, and portion thereof…shall be designed and constructed to resist the effects of earthquake motions…" and Section R301.1 of the IRC states, "Buildings and structures, and all parts thereof, shall be constructed to safely support all loads, including…seismic loads as prescribed by this code." Both the IBC and IRC assign structures, with some exceptions, to a Seismic Design Category (IBC Section 1613.3.5 and IRC Section R301.2.2.1). Engineering-geology and geotechnical investigations are often needed to properly determine the seismic design parameters required to implement the code requirements. Seismic provisions of the IBC and IRC are intended to minimize injury and loss of life by ensuring the structural integrity of a building, but do not ensure that a structure or its contents will not be damaged during an earthquake.

Specifically, the 2015 IBC (Section 1803.5.11) requires an investigation for all structures in Seismic Design Categories C, D, E, or F to include an evaluation of slope instability, liquefaction, differential settlement, and surface displacement due to faulting or lateral spreading. Although the 2015 IRC does not specifically mention liquefaction and other seismic hazards, IRC Section R401.4 leaves the need for soil tests up to the local building official in areas likely to have expansive, compressive, shifting, or other questionable soil characteristics; however, investigators conducting engineering-geology or geotechnical investigations should always provide an evaluation of these hazards, and if present, provide recommendations to mitigate the hazard and/or risk.

For flooding, the 2015 IBC (Section 1612.1) and IRC (Section R301.1) state that construction of new buildings and structures and additions to existing buildings and structures must be designed and constructed to resist the effects of flood hazards and flood loads. These requirements apply to construction in flood-hazard areas (Zone A and other zones identified by the local jurisdiction) identified on Flood Insurance Rate Maps by the Federal Emergency Management Agency.

The 2015 IBC/IRC addresses issues related to problem soil and rock in Chapter 18, Soils and Foundations, and Chapter 4, Foundations, respectively. IBC Section 1803.5.3 and IRC Section R401.4 contain requirements for soil investigations in areas where expansive soil may be present.

For shallow groundwater, the 2015 IBC Section 1805 and IRC Section R406 contain dampproofing and waterproofing requirements for structures built in wet areas. IBC Section 1803.5.4 contains requirements for soil investigations in areas of shallow groundwater.

The 2015 IBC does not address radon hazards; however, investigators should always evaluate radon potential, and if present, provide recommendations to mitigate the risk from radon exposure. Appendix F, Radon Control Methods of the 2015 IRC and ASTM Standard E1465-08a *Standard Practice for Radon Control Options for the Design and Construction of New Low-Rise Residential Buildings* (ASTM, 2009) describe radon-resistant construction techniques. The adoption of 2015 IRC appendix F and implementation of its construction techniques is at the discretion of local jurisdictions, but radon hazard should be evaluated during a comprehensive engineering-geology investigation regardless.

For tsunami-generated flood hazards, the 2015 IBC appendix M contains brief tsunami regulatory criteria. No tsunami hazard maps have been developed for Utah (Great Salt Lake or Utah Lake, where sub-lacustrine faults exist). The adoption of 2015 IBC appendix M is at the discretion of local jurisdictions, but tsunami hazard should be evaluated during a comprehensive engineering-geology investigation regardless for areas near Great Salt Lake and Utah Lake. The potential for ground-shaking-related seiche waves on these lakes and on Bear Lake should also be evaluated as appropriate.

Investigator Qualifications

Engineering-geology investigations and accompanying geologic-hazard evaluations often are interdisciplinary in nature, and in Utah, must be performed by qualified, experienced, Utah licensed Professional Geologists (PG, specializing in engineering geology) and Professional Engineers (PE, specializing in geological and/or geotechnical engineering) often working as a team. The Utah Division of Occupational and Professional Licensing (DOPL, http://dopl.utah.gov/) defines a Professional Geologist as a person licensed to engage in the practice of geology before the public, but does not define or license geologic specialists, such as engineering geologists. The DOPL issues Professional Geologist (http://dopl.utah.gov/licensing/geology.html) and Professional Engineer (http://dopl.utah.gov/licensing/engineer_land_surveying.html) licenses in Utah, based on approved education and experience criteria, and also performs enforcement actions against licensees and others as necessary to protect Utah citizens and organizations.

Accordingly, engineering-geology investigations shall be performed by or under the direct supervision of a Utah licensed Professional Geologist, who must stamp and sign the final report. The evaluation of geologic hazards is a specialized area within the practice of engineering geology, requiring technical expertise and knowledge of techniques not commonly used in other geologic disciplines. In addition to meeting the qualifications for geologist licensure in Utah, minimum recommended qualifications of the engineering geologist in charge of a geologic-hazards investigation include five full years of experience in a responsible position directly in the field of engineering geology. This experience should include familiarity with local geology and hydrology, and knowledge of appropriate techniques for evaluating and mitigating geologic hazards.

Geologists performing engineering-geology investigations are ethically bound first and foremost to protect public safety and property, and as such must adhere to the highest ethical and professional standards in their investigations. Conclusions, drawn from information gained during the investigation, should be consistent, objective, and unbiased. Relevant information gained during an investigation may not be withheld. Differences in opinion regarding conclusions and recommendations and perceived levels of acceptable risk may arise between geologists performing investigations and regulatory-authority geologists working as reviewers for a public agency. Adherence to these minimum guidelines should reduce differences of opinion and simplify the review process.

Literature Searches and Information Resources

A thorough literature search is an important part of engineering-geology investigations and subsequent reports. The search should be performed soon after the initiation of an investigation to collect geologic and other data to develop an appropriate investigation scope and to discover geologic conditions and other hazards that may impact a site.

Published and unpublished geologic and engineering literature, maps, and other records (such as aerial photography and other remote sensing imagery) relevant to the site and the site region's geology, geologic hazards, soils, hydrology, and land use should be reviewed as part of the engineering-geology investigation. These materials are available from a wide variety of sources (table 9), including the UGS; UGS Library (http://geology.utah.gov/library/); U.S. Geological Survey; U.S. Bureau of Reclamation; city, county, state, and university libraries; Natural Resources Conservation Service; Federal Emergency Management Agency; and city and county governments (typically planning and community development departments). Additional information on seismic hazards and risk is available from the Utah Seismic Safety Commission at https://ussc.utah.gov.

Available UGS Information

The UGS Geologic Hazards Program has a web page for consultants and design professionals (http://geology.utah.gov/about-us/geologic-programs/geologic-hazards-program/for-consultants-and-design-professionals/). In addition to the recommended guidelines in this document, the page includes geologic-hazard reports relevant to surface-fault-rupture, landslide, debris-flow, land-subsidence and earth-fissure, and rockfall hazards in Utah; published UGS geologic-hazard maps, reports, and site-specific studies; geologic maps; hydrogeology publications; historical aerial photography; groundwater data; relevant non-UGS publications; and links to external geologic-hazard-related websites.

The UGS Geologic Hazards Program Geologic Hazards Mapping Initiative develops modern, comprehensive geologic-hazard map sets on U.S. Geological Survey (USGS) 1:24,000-scale quadrangles in urban areas of Utah (Bowman and others, 2009; Castleton and McKean, 2012) as PDFs and full GIS products. These map sets typically include 10 or more individual geologic-hazard maps (liquefaction, surface-fault rupture, flooding, landslides, rockfall, debris flow, radon, collapsible soils, expansive soil and rock, shallow bedrock, and shallow groundwater). Some quadrangles may have more maps if additional geologic hazards are identified within the mapped area. The Magna and Copperton quadrangle map sets (Castleton and others, 2011, 2014) within Salt Lake Valley have been published, with mapping continuing in Salt Lake and Utah Valleys. Similar UGS geologic-hazard map sets are available for the St. George–Hurricane metropolitan area (Lund and others, 2008), high-visitation areas in Zion National Park (Lund and others, 2010), and the State Route 9 corridor between La Verkin and Springdale (Knudsen and Lund, 2013). Detailed surface-fault-rupture-hazard maps have been published for the southern half

Table 9. *Potential information sources for engineering-geology investigations in Utah.*

	Maps				Publications and Reports							
Source	**Topographic**	**Geologic**	**Geologic Hazard**	**Flooding**	**Geology**	**Soils**	**Seismology**	**Geotechnical**	**Geologic-Hazard and Geotechnical Investigations**	**Hydrology and Groundwater**	**Aerial Photography**	**Lidar**
Utah Geological Survey[1]	x	x	x		x		x		x	x	x	x
City or county planning and community development departments			x	x					x		x	x
City, county, and university libraries	x	x	x		x	x		x		x	x	
Federal Emergency Management Agency[2]				x								
Natural Resources Conservation Service[3]						x				x		
U.S. Geological Survey (USGS)[4]	x	x	x		x		x			x		x
University of Utah Seismograph Stations[5]							x					
USDA Aerial Photography Field Office[6]											x	
USGS EROS Data Center[7]											x	x
Utah Automated Geographic Reference Center[8]	x	x		x							x	x
Utah Division of Water Rights – Dam Safety Program[9]				x								
OpenTopography[10]												x

[1] http://geology.utah.gov/
[2] http://msc.fema.gov/
[3] http://soils.usda.gov/survey/printed_surveys/state.asp?state=Utah&abbr=UT
[4] http://www.usgs.gov/
[5] http://www.seis.utah.edu/
[6] http://www.apfo.usda.gov/
[7] http://eros.usgs.gov/
[8] http://gis.utah.gov/
[9] http://waterrights.utah.gov/daminfo/default.asp
[10] http://opentopography.org/

of the Collinston, and the Levan, and Fayette segments of the Wasatch fault zone (Harty and McKean, 2015; Hiscock and Hylland, 2015). The UGS routinely partners with local governments to expedite the publication of geologic-hazard special study maps in critical areas.

The UGS GeoData Archive System (http://geodata.geology.utah.gov) contains unpublished Utah geology-related scanned documents, photographs (except aerial), and other digital materials from our files and from other agencies or organizations in one easy-to-use web-based system. Resources available to the public are in the public domain/record and may contain reports (such as geologic-hazard and geotechnical reports) submitted to state and local governments as part of their permit review process. Reports for nearby developments can provide valuable insight into local geologic conditions and help develop appropriate and adequate investigations. Metadata describing each resource are searchable, along with spatial searching for resources that are local in nature. Reports within the system may be downloaded as text-searchable PDF files. Not all resources are available to all users due to end-user, copyright, and/or distribution restrictions. Users are also encouraged to search the UGS Library (http://geology.utah.gov/library/) for books and similar materials.

While the UGS website provides a source of much current, published information on Utah's geology and geologic hazards, it is not a complete source for all available geologic-hazard information, and investigators should search and review other relevant literature and data as necessary.

Aerial Photography

Aerial photography can provide an important historical view of a site to determine geomorphic activity, such as landslides and debris flows; document past land use and land cover; and provide a means to map in urbanized areas with significant to complete contemporary land-surface disturbance (as shown in Bowman, 2008). In Utah, the earliest known aerial photography dates from 1935, covering the Navajo Indian Reservation. The earliest known aerial photography along the Wasatch Front dates from 1936, and much subsequent aerial photography was acquired by the U.S. Department of Agriculture (USDA) Agricultural Adjustment Administration (now the Farm Service Agency) for use in national programs in conservation, land-use planning, and ensuring compliance with farm output (Monmonier, 2002). An extensive collection of public-domain aerial photography of Utah is available from the UGS (as of August 2016, over 96,000 images are available at http://geology.utah.gov/map-pub/publications/aerial-photographs/, and described in Bowman, 2012) and the USDA Aerial Photography Field Office (http://www.apfo.usda.gov) in Salt Lake City, Utah. Avery and Berlin (1992) discuss the acquisition, analysis, and interpretation of aerial photography in detail.

Low-sun-angle aerial photography, pioneered by Slemmons (1969), can be a valuable tool to identify geomorphic features related to geologic hazards, including fault scarps, earth fissures, landslide scarps, and other features. The UGS recently published two compilations of low-sun-angle aerial photography obtained by others in the 1970s and 1980s—one along the Wasatch fault zone and West and East Cache fault zones in northern Utah and southern Idaho (Bowman and others, 2015b), and the other along the Hurricane and Washington fault zones in southern Utah (Bowman and others, 2011).

Lidar Data

Light detection and ranging (lidar) is a technique of transmitting laser pulses and measuring the reflected returns to measure the distance to an object or surface. Lidar is commonly used to determine ground surface elevations to create highly accurate, bare-earth digital elevation models of the ground surface where the effects of vegetation have been removed. A lidar instrument can send pulses at a rapid rate, making a high point-spacing density (for example, several returns per square meter) possible, much denser than would be possible by traditional surveying methods. Lidar can measure the ground surface with accuracies of a few inches horizontally and a few tenths of an inch vertically (Carter and others, 2001). Landslides, fault scarps, and other features that are difficult to detect visually because of vegetation, access, or other issues, are often clearly visible in lidar data (figures 5 and 6). First developed in the 1960s with early laser components (Miller, 1965; Shepherd, 1965), lidar has evolved from simple electronic distance measurement systems used in surveying (Shan and Toth, 2009) into a sophisticated surface mapping technique on multiple platforms including airplanes, helicopters, ground vehicles, stationary tripods, etc.

In 2011, the UGS acquired approximately 1902 square miles of 1-meter (ground cell size) lidar data including parts of Cedar and Parowan Valleys, Great Salt Lake shoreline/wetland areas, the Hurricane fault zone, the Lowry Water area, Ogden Valley, and North Ogden, Utah, and in 2013, acquired approximately 1352 square miles of 0.5-meter lidar data for all of the Wasatch fault zone (Utah and Idaho) and Salt Lake and Utah Valleys, Utah. The UGS data are available at http://geology.utah.gov/resources/data-databases/lidar-elevation-data/. Public domain lidar data in Utah are also available from the Utah Automated Geographic Reference Center (http://gis.utah.gov/elevation), OpenTopography (http://opentopography.org/), and may also be available from city and county governments. Additional information on lidar, including background, acquisition, processing, and analysis is presented in appendix C and in Bowman and others (2015a).

Excavation Safety

Excavation safety is of utmost importance when digging test pits and trenches, and performing other subsurface exploration. Two workers are killed every month in the United States from trench collapses (Occupational Safety and Health Administration [OSHA], 2011). Proper excavation methods, including following allowable minimum trench widths and maximum vertical slope heights, are necessary for all excavations. Excavations are regulated under federal code (29 CFR 1926 Subpart P – Excavations; https://www.osha.gov/pls/oshaweb/owasrch.search_form?p_doc_type=STANDARDS&p_toc_level=1&p_keyvalue=1926). More information on excavation safety is available online from OSHA (https://www.osha.gov/SLTC/trenchingexcavation/index.html) and the State of Utah Labor Commission (http://www.laborcommission.utah.gov/divisions/UOSH/OutreachMaterials.html).

Site Characterization

The Utah Department of Transportation (2011), Federal Highway Administration (2003), National Highway Institute (2002), U.S. Department of Defense (2004), U.S. Bureau of Reclamation (1998a, 1998b, 2001), and the guidelines contained in this publication provide information regarding site characterization methods and techniques.

As part of site characterization, an adequate number, spacing, and location of subsurface exploration and subsequent laboratory testing are necessary, and will depend upon the specific project and local ordinances and requirements. Table 10 contains recommended minimum spacing and depth of subsurface exploration for a variety of constructed features. Often, engineering-geology investigations will require additional subsurface exploration (including increased depths) due to complex structural configurations; complex and/or variable geologic conditions; complex or large structural, seismic, or other loading; and other conditions. It is imperative that subsurface exploration extends to sufficient depths to adequately characterize geologic conditions and provide input data to engineering analysis, design, and mitigation of geologic hazards.

Extensive professional engineering geology and geotechnical experience and judgement are required to design an appropriate engineering-geologic site investigation. Reliance on input values from other projects, published general ranges or values, and data not directly acquired from the site should not be used for final reports and design. Review and acceptance of engineering-geology investigation proposals should strongly consider the frequency, spacing, and depth of subsurface exploration to ensure the proposed investigation will adequately characterize the site; cost should not be a significant proposal selection factor. Proposals submitted to local governments

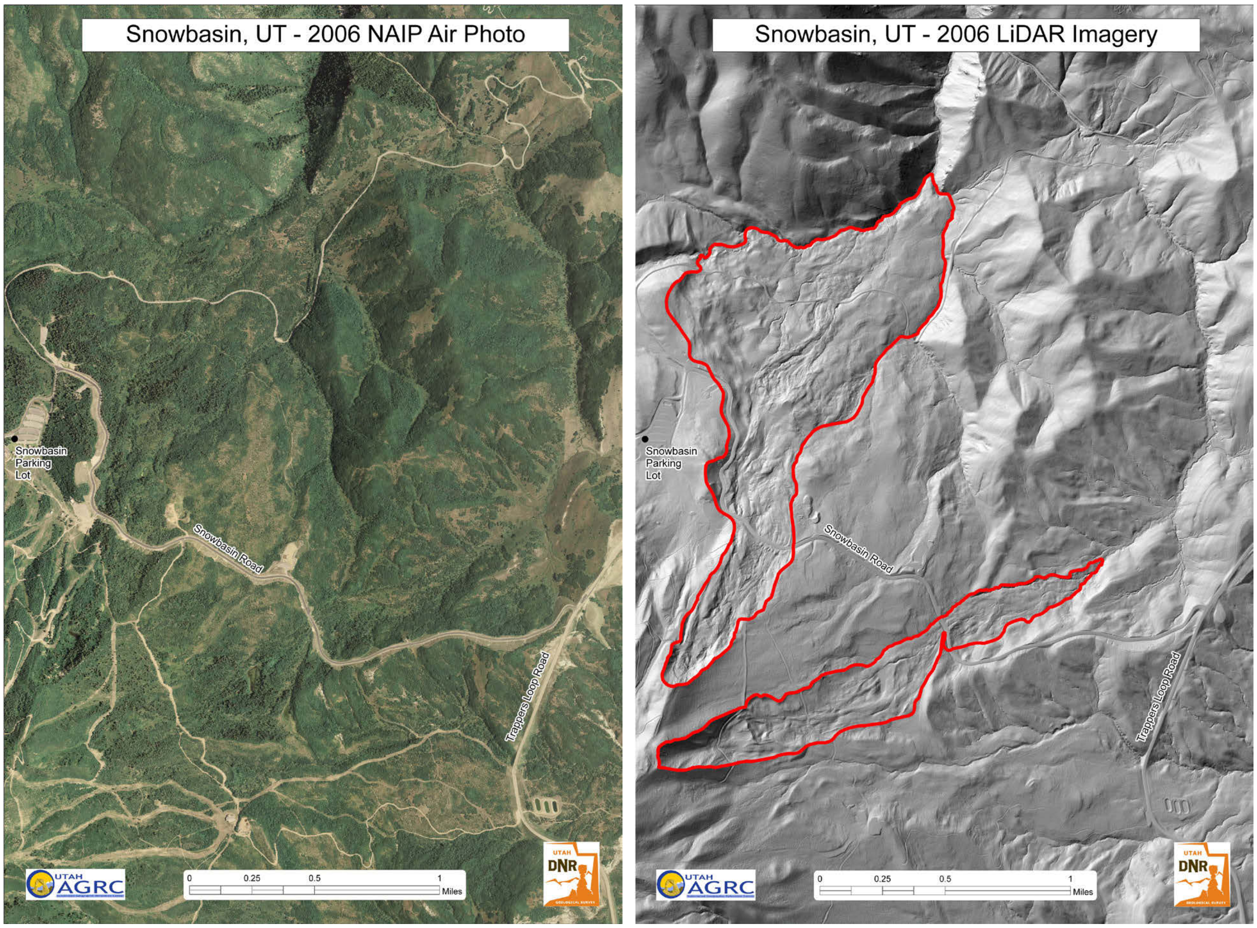

Figure 5. *Comparison of 2006 National Agriculture Imagery Program (NAIP) 1-meter color orthophoto imagery (left) and 2006 2-meter airborne LiDAR imagery (right) in the Snowbasin area, Weber County, Utah. Red lines outline the Green Pond and Bear Wallow landslides that are clearly visible in the lidar imagery, but barely visible to undetectable in the NAIP imagery. Data from the Utah Automated Geographic Reference Center (2006a, 2006b).*

Figure 6. *Comparison of 2009 High-Resolution Orthophotography (HRO) 1-foot color imagery (left) and 2011 1-meter airborne lidar imagery (middle and right) in the International Center area, Salt Lake City, Utah. Fault scarps indicated by red lines show traces of the Granger fault, West Valley fault zone, that are clearly visible in the lidar imagery, but barely visible to undetectable in the HRO imagery. Salt Lake International Airport visible to the right on each image. Data from Utah Automated Geographic Reference Center (2009, 2011).*

Table 10. *Recommended minimum subsurface exploration frequency and depth for constructed features (modified from Utah Department of Transportation, 2011, 2014; American Association of State Highway and Transportation Officials, 2014).*

Constructed Feature[1]		Frequency and Location[2]	Minimum Depth[2]
Pavements	Roadway Pavements	200 to 1000 feet	≥10 feet below pavement bottom elevation
Slopes	Cut Slopes	Every 200 to 600 feet, minimum of one for every cut ≥15 feet in depth	≥15 feet below base of cut and into competent soil or rock
	Embankments	Every 200 to 600 feet	≥2x embankment height
Structures	Buried Structures	One or more at each location	≥15 feet below foundation bottom elevation
	Shallow Foundations	Maximum 70 foot spacing	≥10 feet below foundation bottom or fully penetrating unsuitable soils, whichever is deeper
	Retaining Walls	100 to 200 feet with locations alternating in front of and behind the wall; for anchored walls, additional locations in the anchorage zone; and for soil-nail walls, additional locations behind at a distance 1–1.5x the height of the wall, all 100 to 200 foot spaced.	To a depth below wall bottom where stress increase is < 10 percent of existing overburden stress and between 1 to 2x the wall height, or fully penetrating unsuitable soils, whichever is deeper
	Sound and Other Freestanding Walls	Every 250 to 500 feet	≥10 feet below foundation bottom elevation

[1] See chapter 3 for surface-fault-rupture, chapter 4 for landslide, chapter 5 for debris-flow, chapter 6 for land-subsidence and earth-fissure, and chapter 7 for rockfall hazard investigation subsurface exploration recommendations.
[2] Additional subsurface exploration (borings, test pits, etc.) and/or increased depths will often be needed, due to complex and/or variable geology; structural, seismic, and other loads; and/or other conditions. Extensive professional engineering geology and geotechnical experience and judgement is needed.

should be reviewed by the regulatory-authority engineering geologist as defined below in the Field Review and Report Review sections. Poorly developed engineering-geology investigations will result in inadequate input data for subsequent engineering analysis, design, and mitigation of geologic hazards; may result in cost overruns/change orders, decreased project performance, and increased maintenance costs; and may increase potential costs to local governments, and ultimately, the taxpayer.

Geologic Mapping

Site geologic mapping should be performed in sufficient detail to define the geologic conditions present at and adjacent to the site. For most purposes, published geologic maps lack the necessary detail to provide a basis for understanding site-specific geologic conditions, and new, larger scale, independent geologic mapping is required. If suitable geologic maps are available, they must be updated to reflect topographic and geologic changes that have occurred since map publication. Extending mapping into adjacent areas will likely be necessary to define geologic conditions impacting the project area. Often, geologic mapping will be more useful to the project if performed with the intent of creating an engineering-geologic map that specifically focuses on site geologic conditions and geologic hazards as they affect the proposed development.

Mapping should be performed on a suitable topographic base map at an appropriate scale and accuracy applicable to the project. The type, date, and source of the base map should be indicated on each map. Mapping for most projects should be at a scale of 1:10,000 or larger to show pertinent features with sufficient detail. In certain cases where detailed topographic base maps at scales larger than 1:24,000 (U.S. Geological Survey (USGS) 7-1/2 minute quadrangles) are not available, geologic mapping may be performed on aerial photography of suitable scale to document pertinent features. On small-scale maps, one inch commonly equals 2000 feet (1:24,000) or more, whereas on large-scale maps, one inch commonly equals 500 feet (1:6000) or less. The base map should also include locations of proposed structures, pavements, and utilities.

The geologist performing the geologic mapping and preparing the final map should pay particular attention to the nature of bedrock and surficial materials, structural features and relations, three-dimensional distribution of earth materials exposed and inferred in and adjacent to the site shown on a cross section(s), and potential geologic hazards (such as landslides, rock-fall and debris-flow deposits, springs/seeps, aligned vegetation possibly indicative of a fault, and problem soil and rock). A clear distinction should be made between observed and inferred features and relations. Doelling and Willis (1995) provide guidelines for geologic maps submitted to the UGS for publication that may also be applied to mapping for engineering-geology/geologic-hazard investigations.

Engineering-geology mapping may be performed using the Genesis-Lithology-Qualifier (GLQ) system, which promotes communication of geologic information to non-geologists (Keaton, 1984). The GLQ system incorporates the Unified Soil Classification System (USCS; ASTM, 2002), which has been used for many years in geotechnical and civil engineering, rather than the conventional time-rock system employed on most geologic maps. An import aspect when mapping for engineering-geology purposes is to map units having distinctive engineering-geology/geologic-hazard characteristics. The USDA system of soil classification for agriculture is generally inappropriate for engineering-geology mapping and delineating geologic hazards. The Unified Rock Classification System (Williamson, 1984) provides a systematic and reproducible method of describing rock weathering, strength, discontinuities, and density in a manner directly usable by engineering geologists and engineers. The Geological Strength Index (GSI) provides a system to describe rock mass characteristics and estimate strength (Marinos and Hoek, 2000; Marinos and others, 2005; Hoek and others, 2013). For altered materials, Watters and Delahaut (1995) provide a system for classification that can be incorporated into overall rock classification.

Laboratory Testing

An appropriate suite of samples should be tested to determine site soil and/or rock properties that match the scope and requirements of the project. Too often soil classification testing is incomplete in that testing is performed on one sample for moisture content, another for plasticity index (PI), and perhaps a third sample for fines content (-#200 mesh percent). An accurate soil classification cannot be determined from these tests performed independently of each other. An adequate number of samples should be tested to determine the laboratory-based soil classification (PI and gradation) as a check on field-derived (visual-manual) soil classification to reduce error.

Laboratory testing of geologic samples collected as part of an engineering-geology investigation should conform to current ASTM and/or American Association of State Highway and Transportation Officials (AASHTO) standards, as appropriate to the specific project. In addition, testing laboratories should be accredited by the AASHTO Materials Reference Laboratory (AMRL, http://www.amrl.net/AmrlSitefinity/default/aap.aspx) and may also be validated by the U.S. Army Corps of Engineers Materials Testing Center (http://www.erdc.usace.army.mil/Media/FactSheets/FactSheetArticleView/tabid/9254/Article/476661/materials-testing-center.aspx) to ensure compliance with current laboratory testing standards and quality control procedures. Most ASTM engineering-geology-related test standards are contained in Volumes 4.08 and 4.09 (Soil and Rock).

Complete laboratory test results should be placed in an appendix with a summary of results in the report text as needed. Test results should clearly state the laboratory identification, sample identification and location, test method standard used, date of testing, equipment identification (if applicable), laboratory technician performing the test, test data, and note any irregularity or changes from the standardized test method.

Geochronology

Evaluating geologic hazards frequently requires determining the timing (age), rate, and recurrence of past (paleo) geologic-hazard events. This is particularly true for characterizing earthquake hazards, which includes the investigation of surface-fault-rupture hazard (chapter 3). However, determining the timing and rate at which other geologic hazards occur is also useful for many kinds of geologic-hazard investigations. Therefore, engineering geologists conducting geologic-hazard investigations in Utah should have a good working knowledge of the more useful and commonly applied geochronologic methods.

When applying geochronologic methods to geologic-hazard investigations, investigators should keep certain conventions of terminology in mind. By definition, a "date" is a specific point in time, whereas an "age" is an interval of time measured backward from the present. It is generally accepted to use the word "date" as a verb to describe the process of producing age estimates (e.g., dating organic sediments using ^{14}C). However, when used as a noun, "date" carries the implication of calendar years and a high degree of accuracy that is generally not appropriate (Colman and Pierce, 2000). Most "dates" are more accurately described as "age estimates" or "ages," exceptions being dates derived from the historical record, and some dates derived from tree rings, glacial varves, or coral growth bands (Colman and Pierce, 2000). The North American Stratigraphic Code (NASC) (North American Commission on Stratigraphic Nomenclature, 2005) makes a distinction between ages determined by chronologic methods and intervals of time. The NASC recommends that the International System of Units (SI [metric system]) symbols ka and Ma (kilo-annum and mega-annum, or thousands and millions of years ago, respectively, measured from the present) be used for ages, and informal abbreviations such as kyr and myr be used for time intervals (e.g., 1.9 ± 0.3 ka for the age of an earthquake, but 1.9 kyr to describe the interval of elapsed time since that earthquake). Radiocarbon ages are typically reported with the abbreviation yr B.P. (years before present; by convention radiocarbon ages are measured from A.D. 1950). Because radiocarbon ages depart from true calendar ages due to variations in atmospheric production of radiocarbon, radiocarbon ages must be calibrated to account for the variation. When calendar-calibrated radiocarbon ages are reported, the designation "cal" is included (e.g., 9560 ± 450 cal yr B.P.). By convention, the abbreviations yr B.P. and cal yr B.P. are restricted to radiocarbon ages (Colman and Pierce, 2000).

Many geochronologic methods are available to engineering geologists conducting engineering-geology investigations. The methods typically fall into one of two general categories: well established and experimental (Noller and others, 2000). Well-established methods are widely accepted and applied by the geologic community, and importantly, are usually commercially available. Experimental methods are new, usually still under development, not fully tested, and not widely accepted or applied. Experimental methods commonly are in the "research phase" of development, and as such are not usually available for most engineering-geology investigations. Colman and Pierce (2000) classified geochronologic methods according to their shared assumptions, mechanisms, or applications as follows.

1. Sidereal (calendar or annual) methods, which determine calendar dates or count annual events.
2. Isotopic methods, which measure changes in isotopic composition due to radioactive decay and/or growth.
3. Radiogenic methods, which measure cumulative effects of radioactive decay, such as crystal damage and electron energy traps.
4. Chemical and biological methods, which measure the results of time-dependent chemical or biological processes.
5. Geomorphic methods, which measure the cumulative results of complex, interrelated, physical, chemical, and biological processes on the landscape.
6. Correlation methods, which establish age equivalence using time-independent properties.

Geochronologic methods may also be categorized by the results they produce. Colman and Pierce (2000) further identified four general result-based categories: numerical-age, calibrated-age, correlated-age, and relative-age methods. The methods are described here in order of decreasing precision.

1. Numerical-age methods produce quantitative estimates of age and uncertainty and are sometimes called “absolute ages,” but are more appropriately referred to as “numerical” ages.
2. Calibrated-age methods provide approximate numerical ages, and are based on systematic changes that depend on environmental variables such as temperature or lithology and must be calibrated using independent numerical ages (McCalpin and Nelson, 2009). These methods should not be confused with “calibrated” radiocarbon ages.
3. Correlated-age methods do not directly measure age and produce age estimates by demonstrating equivalence to independently dated deposits or events.
4. Relative-age methods provide an ordinal ranking (first, second, third, etc.) of an age sequence, and may provide an estimate of the magnitude of the age difference between members of the sequence.

Table 11 is modified from Colman and Pierce (2000) and McCalpin and Nelson (2009), and classifies the more commonly applied geochronologic methods by result and method. All of the methods in table 10 are potentially applicable to engineering-geology investigations. Methods shown in italic type are known to have been used in Utah; methods shown in bold italic type are commonly employed in Utah. Geologists conducting engineering-geology investigations in Utah should develop a working knowledge of those commonly applied techniques, both for potential use on future projects, and to develop an understanding of the nature and limitations of the different kinds of age estimates reported in the literature.

Evaluating uncertainty associated with an age, numerical or otherwise, is critical to constraining the timing and recurrence of past geologic-hazard events. Many numerical ages are reported with a laboratory estimate of the precision (analytical reproducibility) of the age, commonly expressed as one or two standard deviations (σ or 2σ) around a mean. Frequently the largest source of error in paleoevent dating is sample context error, or the error involved in inferring the time of an event from the age of an accurately dated (how closely a reported age corresponds to the actual age) sample (McCalpin and Nelson, 2009). Sample context error is often much larger than the 2σ deviation laboratory precision estimate, and must be carefully evaluated and explicitly acknowledged when calculating paleo-hazard event timing and recurrence. Where accurate information on earthquake timing and recurrence are of critical importance (e.g., where development is proposed directly across an active fault trace), it is recommended that timing and recurrence be modeled using OxCal ^{14}C calibration and analysis software (Bronk Ramsey, 1995, 2001, 2010), which probabilistically models the time distributions of undated events by incorporating stratigraphic ordering information for numerical (e.g., ^{14}C and luminescence) ages (Bronk Ramsey, 2008, 2009). See Lienkaemper and Bronk Ramsey (2009) and DuRoss and others (2011) for additional discussions on the use of OxCal in paleoseismic investigations.

Evaluating paleo-hazard event timing and recurrence from available age estimates, which may be limited by a lack of datable material or by time or budget constraints, is often a difficult task. However, given the often critical nature of determining geologic-hazard activity, the engineering geologist conducting a geologic-hazard investigation is responsible for evaluating the geologic conditions at the site, and for selecting the dating methods best suited to constrain paleo-hazard timing and associated uncertainty. Rarely can a single analysis of a single sample by any dating method provide a definitive age for a paleo-hazard event (McCalpin and Nelson, 2009). Multiple samples evaluated by multiple techniques provide an improved basis for determining paleo-hazard timing and recurrence, and in instances where such data are critical to hazard evaluation and project design, the analysis will benefit from retaining an expert in the application and interpretation of geochronologic methodologies.

Critical, but often overlooked, aspects of geochronologic dating, particularly numerical dating, are proper sample collection and handling prior to delivery to the laboratory. Most commercial dating laboratories post sample collection and handling instructions on their websites (e.g., Beta Analytic Radiocarbon Dating, 2014; Utah State University Luminescence Laboratory, 2014). Improper sample collection and handling may result in incorrect ages, ages that are difficult to interpret, or no useful age information at all. Where samples are collected from trenches that are then closed, or from other ephemeral or hard-to-access sample locations, it may not be possible to resample if the original samples are compromised by bad sampling and handling techniques.

Table 11. *Classification of geochronologic methods potentially applicable to geologic-hazard investigations (after Colman and Pierce [2000] and McCalpin and Nelson [2009]).*

TYPE OF RESULT[1]					
Numerical Age		**Calibrated Age**		**Correlated Age**	**Relative Age**
TYPE OF METHOD[2]					
Calendar Year	**Isotopic**	**Radiogenic**	**Chemical/ Biological**	**Correlation**	**Geomorphic**
Historical records	***Radiocarbon (^{14}C)***	Fission track	*Amino-acid racemization*	***Stratigraphy***	***Soil-profile development***
Dendrochronology	***K-Ar and $^{40}Ar/^{39}Ar$***	*Thermoluminescence*	Obsidian and tephra hydration	*Paleomagnetism*	*Rock and mineral weathering*
Varve chronology	Uranium series	***Optically stimulated luminescence***	Lichenometry	*Tephrochronology*	***Scarp morphology and other progressive landform modification***
	Cosmogenic isotopes other than ^{14}C; e.g., ^{26}Al, ^{36}Cl, ^{10}Be, ^{3}He	Infrared stimulated luminescence	Soil chemistry	*Paleontology*	Rate of deposition
	U-Pb, Th-Pb	Electron-spin resonance	Rock varnish chemistry	*Archeology*	Rate of deformation
				Stable isotopes	***Relative geomorphic position***
					Stone coatings ($CaCO_3$)
					Precariously balanced rocks

[1] Boundaries between "Type of Result" categories are dashed to show that results produced by geochronologic methods in one category may in some instances contribute to results typical of another category; i.e., boundaries between the categories are not sharply defined.
[2] Geochronologic methods shown in italic type are known to have been applied to geologic-hazard investigations in Utah. Methods shown in bold italic type are commonly employed for geologic-hazard investigations in Utah.

ENGINEERING-GEOLOGY REPORTS

Engineering-geology reports will be prepared for projects at sites where geologic conditions range from relatively simple to complex; with some, many, or no geologic hazards present; and with varying types of development (structures, pavements, underground facilities, site grading, landscaping, etc.) and uses. As a result, the format and scope of an engineering-geology report should reflect project and regulatory requirements, and succinctly and clearly inform the reader of the geologic conditions present at and adjacent to the project site, and procedures and recommendations to mitigate geologic hazards Reports should include a discussion of geologic conditions and hazards present that were not investigated, and why they were not investigated (e.g., limited scope and/or budget), and provide recommendations for future, more comprehensive investigation if necessary. All reports, addenda, and related materials should be dated and properly referenced or numbered, so that any revisions and a report timeline may be clearly determined.

The type and nature of the report should be clear to the end-user and reviewer so the report will be used for its intended purpose. Three types of engineering-geology reports are in general use: reconnaissance, preliminary investigation, and final investigation/design.

- Reconnaissance Reports – Present summary geologic information on a particular project based on a limited literature review and site visit, but without subsurface exploration. Often used for real-estate due-diligence activities and in preparation for in-depth investigations and subsequent final design reports. These reports should present only general conclusions, recommend additional investigation as necessary, and users should be clearly informed about report limitations. These reports should not be used for final design or construction.
- Preliminary Investigation Reports – Present incomplete geologic information during an investigation, including preliminary results of subsurface exploration, laboratory testing, and other activities. Often used during a project to inform other project professionals (such as engineers and architects) of geologic issues and preliminary conclusions and recommendations prior to the completion of a final investigation report. Users should be clearly informed about report limitations. These reports should not be used for final design or construction.

- Final Investigation/Design Reports – Present the results of a completed geologic investigation of a project, including literature review results, aerial photograph and other remote sensing interpretation, subsurface exploration, laboratory testing, geologic analysis, cross sections, and final geologic conclusions and recommendations. These reports are suitable for permit review and approval, final project design, and decision making related to the project.

General Information

Each report should include sufficient background information to inform the reader (client, reviewing agency, etc.) of the general site setting, proposed land use, and the purpose, scope, and limitations of the geologic investigation. Reports should address:

- Location and size of the project site, and its general setting with respect to major or regional geologic and geomorphic features, including a detailed location map indicating the site.
- Purpose and scope of the geologic investigation and report.
- Name(s) of geologist(s) who performed the geologic investigation, developed interpretations and conclusions, and wrote the report. In addition, the name(s) of others who were involved with recording field observations and/or performing laboratory testing should be clearly stated on all results.
- Topography and drainage conditions within and adjacent to the project site.
- General nature, distribution, and abundance of soil and rock within the project site.
- Basis of interpretations and conclusions regarding the project site geology. Nature and source of available subsurface information and geologic publications, reports, and maps. Suitable explanations of the available data should provide a regulatory-authority reviewer with the means of evaluating the reliability and accuracy of the data. Reference to cited publications and field observations must be made to substantiate opinions and conclusions.
- Building setbacks and areas designated to avoid geologic hazards.
- Disclosure of known or suspected geologic hazards affecting the project site, including information on past performance of existing facilities (such as buildings, utilities, pavements, etc.) in the immediate vicinity of the site.

Descriptions of Geologic Materials, Features, and Conditions

Engineering-geology reports should contain detailed descriptions of geologic materials (soil, intermediate geomaterials, and rock), structural features, and hydrologic conditions within and adjacent to the project site. The following is a general list; however, it is not a complete guide to geologic descriptions and additional information may be necessary.

- Soils (unconsolidated alluvial, colluvial, eolian, glacial, lacustrine, marine, residual, mass movement, volcanic, or fill [uncontrolled or engineered] deposits).
    - Identification of material, relative age, and degree of activity of originating process.
    - Distribution, dimensional characteristics, thickness and variations, degree of pedogenic soil development, and surface expression.
    - Physical characteristics (color, grain size, lithology, particle angularity and shape, density or consistency, moisture condition, cementation, strength).
    - Special physical or chemical features (indications of shrink/swell, gypsum, corrosive soils, etc.).
    - Special engineering characteristics or concerns.
- Rock
    - Identification of rock type/lithology.
    - Relative age and formation.
    - Surface expression, areal distribution, and thickness.
    - Physical characteristics (color, grain size, stratification, strength, variability).
    - Special physical or chemical features (voids, gypsum, corrosive nature, etc.).
    - Distribution and extent of weathering and/or alteration.
    - Special engineering characteristics or concerns.
- Structural Features (faults, fractures, folds, and discontinuities)
    - Occurrence, distribution, dimensions, orientation, and variability; include projections into the project area or site.
    - Relative ages, where applicable.
    - Special features of faults (topographic expression, zones of gouge and breccia, nature of offsets, movement timing, youngest and oldest faulted units).
    - Special engineering characteristics or concerns.
- Hydrologic Conditions
    - Distribution, occurrence, and variations of drainage courses (rivers, streams, ephemeral and dry drainages), ponds, lakes, swamps, springs, and seeps.
    - Identification and characterization of aquifers, depth to groundwater, and seasonal fluctuations.
    - Relations to topographic and geologic features and units.
    - Evidence for earlier occurrence of water at locations now dry (vegetation changes, peat deposits, mineral deposits, historical records, etc.).
    - Special engineering characteristics or concerns (such as a fluctuating water table).

- Seismic Conditions
  - Description of the seismotectonic setting of the project area or site (earthquake size, frequency, and location of significant historical earthquakes).
  - Current IBC/IRC seismic design parameters.

Assessment of Geologic Hazards and Project Suitability

The evaluation of geologic hazards in relation to a proposed development is a major focus of most engineering-geology investigations. This involves (1) the effects of the geologic features and hazards on the proposed development (grading; construction of buildings, utilities, etc.; and land use), and (2) the effects of the proposed development on future geologic processes within and adjacent to the site (such as constructed cut slopes causing slope instability and/or erosion problems). A clear understanding of all geologic hazards that may affect the construction, use, and maintenance of a proposed development is required to ensure development proceeds in a cost-effective and safe manner for the design professional, owner, contractor, user, community, and environment.

Identification and Extent of Geologic Hazards

Common geologic hazards encountered in Utah and that should be addressed in a comprehensive geologic-hazards investigation are listed below, along with specific guidelines contained in this publication as separate chapters or available elsewhere as short references.

- Earthquake Hazards, including
  - Surface-fault-rupture – chapter 3
  - Ground shaking – see 2015 IBC Section 1613.1 and IRC Section R301.1
  - Liquefaction
  - Lateral spreading
  - Tectonic deformation
- Landslide Hazards, including
  - Landslides – chapter 4
  - Debris flows – chapter 5
  - Rockfall – chapter 7
  - Snow avalanches – see Mears (1992) for guidance
  - Earthquake-induced landslides – chapter 4
- Flooding Hazards, including
  - River, lake, or sheet flooding – see 2015 IBC appendix G, and commonly addressed in locally adopted FEMA regulations
  - Debris flows – chapter 5
  - Dam and water conveyance structure failure
  - Seiches
  - Tsunamis – see 2015 IBC appendix M
- Problem Soil and Rock, including
  - Collapsible soils
  - Expansive soil and rock
  - Shallow bedrock
  - Corrosive soil and rock
  - Wind-blown sand
  - Breccia pipes and karst
  - Piping and erosion
  - Ground subsidence and earth fissures – chapter 6
  - Caliche
  - Gypsiferous soil and rock
  - Radon – see 2015 IRC appendix F, Radon Control Methods and ASTM Standard E1465-08a
- Shallow Groundwater – see 2015 IBC Section 1805 and IRC Section R406
- Volcanic Hazards, including
  - Volcanic eruption and ash clouds
  - Lava flows

Suitability of Proposed Development in Relation to Geologic Conditions and Hazards

Once the geologic conditions and hazards at a site have been identified and investigated, the suitability of a proposed development in relation to these conditions and hazards must be determined. A proposed development may be found to be incompatible with one or more geologic conditions and/or hazards, resulting in development design changes. If these changes can be made early in the design process, significant cost savings may be realized.

Report Structure and Content

Engineering-geology reports should generally follow the recommended report format presented below; however, the content and scope of these reports should reflect applicable project and regulatory requirements, and may be combined with geotechnical investigation reports as appropriate. Relevant and well-drafted figures and/or tables should be included in the report as needed. Subcontractor reports, such as geophysical reports, should be included as an appendix and referenced in the text.

1. Introduction
   - Description of project and location
   - Investigation purpose
   - Investigation scope

2. Geology
    - Description of regional geologic setting
    - Description of site-specific geology, including cross section(s)
3. Geologic Investigation
    - Results of literature reviews and prior work
    - Description of aerial photography and other imagery analysis
    - Description of geologic mapping and surface investigation
    - Description of geophysical investigation
    - Description of subsurface investigation
        - Test pits
        - Trenches
        - Drilling
    - Description of laboratory testing
    - Description of other work or investigation
4. Investigation Results and Interpretations
    - Geologic hazards
    - Geologic conditions that could affect the site and/or development.
    - Avoidance and/or mitigation options
5. Conclusions and Recommendations
    - Conclusions and recommendations should be clear and concise, and be supported by investigation-derived observations, data, and external references.
    - Limitations of the investigation and data.
    - Recommendations for future investigation, if needed.
6. References
    - Reports must provide complete references for all cited literature and data not collected as part of the investigation.
    - For aerial photography and other imagery, report project code, project name, acquisition date, scale, and frame identification for all frames used.
7. Appendices
    - Supporting laboratory test results and data, separated as necessary into individual appendices or sections.
8. Plates
    - Oversize maps, drawings, or other figures related to the report and properly named, numbered, and referenced within the report.

Figures and plates should use clear, high-quality graphics and commonly accepted scale values so users may make measurements with commercially available engineering scales. Figures and plates should rarely be drawn not-to-scale, and this method should never be used with site maps and drawings in locating site features and proposed development. Appropriate explanation information, including symbol definitions and north arrow, should be used as appropriate. Figure sizes should not exceed one page, preferably tabloid (11 x 17 inches) maximum page size. Plate sizes should generally not exceed 24 x 36 inches (Architectural D size) for ease of use and printing on commonly available large-format printers.

Summaries of data and/or condensed conclusions at the front of reports should be used with caution, as results are often used by readers without understanding the background information necessary to effectively interpret the data and/or recommendations.

Engineering-geology reports must be stamped, signed, and dated by the engineering geologist who conducted the investigation. In addition, any oversize plates should also be stamped, signed, and dated. The geologist must be licensed to practice geology in Utah. If a geotechnical report or other engineering analysis and/or recommendations are included with the engineering-geology report, an engineer licensed to practice in Utah must also stamp, sign, and date the report or pertinent sections.

FIELD REVIEW

Once an engineering-geology site investigation is complete, the UGS strongly recommends a technical field review of the site by the regulatory-authority engineering geologist. Field reviews are critical to ensuring that site geologic conditions are adequately characterized and that geologic hazards are identified and evaluated. The field review should take place after trenches or test pits are logged, but before they are closed so subsurface site conditions can be directly observed and evaluated. In general, adequate site characterization is seldom possible by opening, logging, reviewing, and closing trenches or test pits in one day; however, the UGS recognizes that for safety or other reasons, it may be necessary in some instances to open and close such excavations in a single day.

Although not required, the UGS appreciates being afforded the opportunity to participate in field reviews of proposed development sites. The UGS is particularly interested in obtaining earthquake timing, recurrence, and displacement data for Utah Quaternary faults, and information on land subsidence and earth fissures associated with groundwater mining. Contact the UGS Geologic Hazards Program in Salt Lake City at 801-537-3300, or the UGS Southern Regional Office in Cedar City at 435-865-9036.

REPORT REVIEW

The UGS recommends regulatory review of all reports by a Utah licensed Professional Geologist experienced in engineering-geology investigations (see Investigator Qualifications section) and acting on behalf of local governments to protect public health, safety, and welfare, and to reduce risks to future property owners (Larson, 1992, 2015). The reviewer should evaluate the technical content, conclusions, and recommendations presented in a report, in relation to the geology of the site, the proposed development, and the recommended hazard mitigation method(s). The reviewer should always participate in the field review of the site, and should advise the local government regarding the need for additional work, if warranted.

DISCLOSURE

The UGS recommends disclosure during real-estate transactions whenever an engineering-geology investigation has been performed for a property to ensure that prospective property owners are made aware of geologic hazards present on the property, and can make their own informed decision regarding risk. Disclosure should include a Disclosure and Acknowledgment Form provided by the jurisdiction, which indicates an engineering-geology report was prepared and is available for public inspection.

Additionally, prior to approval of any development, subdivision, or parcel, the UGS recommends that the regulating jurisdiction require the owner to record a restrictive covenant with the land identifying any geologic hazard(s) present. Where geologic hazards are identified on a property, the UGS recommends that the jurisdiction require the owner to delineate the hazards on the development plat prior to receiving final plat approval.

ACKNOWLEDGMENTS

The Intermountain Section of the Association of Environmental and Engineering Geologists, the Utah Section of the American Society of Civil Engineers, Robert Tepel, and Gregg Beukelman, Rich Giraud, and Adam McKean (Utah Geological Survey) provided insightful comments and additional data that substantially improved the utility of these guidelines.

CHAPTER 3
GUIDELINES FOR EVALUATING SURFACE-FAULT-RUPTURE HAZARDS IN UTAH

by
William R. Lund, P.G., Gary E. Christenson, P.G. (UGS, retired), L. Darlene Batatian, P.G. (Terracon, Inc.), and Craig V. Nelson, P.G. (Western Geologic, LLC)

Airport East paleoseismic trench on the Taylorsville fault, West Valley fault zone, Salt Lake County, Utah, on September 4, 2015. Photo credit: Adam Hiscock.

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

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INTRODUCTION

These guidelines update and revise Utah Geological Survey Miscellaneous Publication 03-6—*Guidelines for Evaluating Surface-Fault-Rupture Hazards in Utah* (Christenson and others, 2003). The intent of these guidelines is to provide engineering geologists with standardized minimum recommended criteria for performing surface-faulting investigations for new buildings for human occupancy and for International Building Code (IBC) Risk Category II, III, and IV facilities (International Code Council [ICC], 2014a) to reduce risk from future surface faulting. However, performing a surface-faulting investigation and adherence to the investigation recommendations in these guidelines does not guarantee safety. Significant uncertainty often remains due to limited paleoseismic data related to the practical limitations of conducting such investigations (epistemic uncertainty), and natural variability in the location, recurrence, and displacement of successive surface-faulting earthquakes (aleatory variability). Aleatory variability in fault behavior cannot be reduced; therefore, predicting exactly when, where, and how much ground rupture will occur during future surface-faulting earthquakes is not possible. New faults may form, existing faults may propagate beyond their present lengths, elapsed time between individual surface-faulting earthquakes can vary by hundreds or thousands of years and be affected by clustering, triggering, and multi- or partial-segment ruptures. For those reasons, developing property in the vicinity of hazardous faults will always involve a level of irreducible, inherent risk.

These guidelines outline (1) appropriate investigation methods, (2) report content, (3) map, trench log, and illustration criteria and scales, (4) mitigation recommendations, (5) minimum criteria for review of reports, and (6) recommendations for geologic-hazard disclosure. However, these guidelines do not include systematic descriptions of all available investigative techniques or topics, nor does the UGS suggest that all techniques or topics are appropriate for every hazard investigation.

Considering the complexity of evaluating surface and near-surface faults, additional effort beyond the minimum criteria recommended in these guidelines may be required at some sites to adequately address surface-faulting hazard. The information presented in these guidelines does not relieve engineering geologists of their duty to perform additional geologic investigations necessary to fully assess the surface-faulting hazard at a site. As required by Utah state law (Utah Code, 2011), surface-faulting investigation reports and supporting documents must be signed and stamped by the licensed Utah Professional Geologist in responsible charge of the investigation.

Purpose

A surface-faulting investigation uses the characteristics of past surface faulting at a site as a scientific basis for providing recommendations to reduce the risk for damage, injury, or death from future, presumably similar, surface faulting. The purpose of these guidelines is to provide appropriate minimum surface-faulting investigation and report criteria to:

- protect the health, safety, and welfare of the public by minimizing the potentially adverse effects of surface faulting;
- assist local governments in regulating land use in hazardous areas and provide standards for ordinances;
- assist property owners and developers in conducting reasonable and adequate surface-faulting investigations;
- provide engineering geologists with a common basis for preparing proposals, conducting investigations, and recommending surface-faulting risk-mitigation strategies; and
- provide an objective framework for preparation and review of surface-faulting reports.

These guidelines pertain only to new buildings for human occupancy and high-risk-category facilities. These guidelines are not intended for siting linear lifelines (highways, utilities, pipelines), which commonly must cross faults; large water impoundments (dams, dikes, lagoons); hazardous waste facilities; or nuclear power generation or repository facilities. Surface-faulting investigation methods are similar for these facilities (e.g., Hanson and others, 1999; American National Standards Institute/American Nuclear Society, 2008), but due to their potential for catastrophic failure, hazard investigations, including surface-faulting hazard, are typically controlled by regulations promulgated by a regulating/permitting authority (e.g., U.S. Nuclear Regulatory Commission, 2011).

These guidelines only address surface-fault rupture, which is displacement of the ground surface along a tectonic fault during an earthquake (figure 7). These guidelines do not ad-

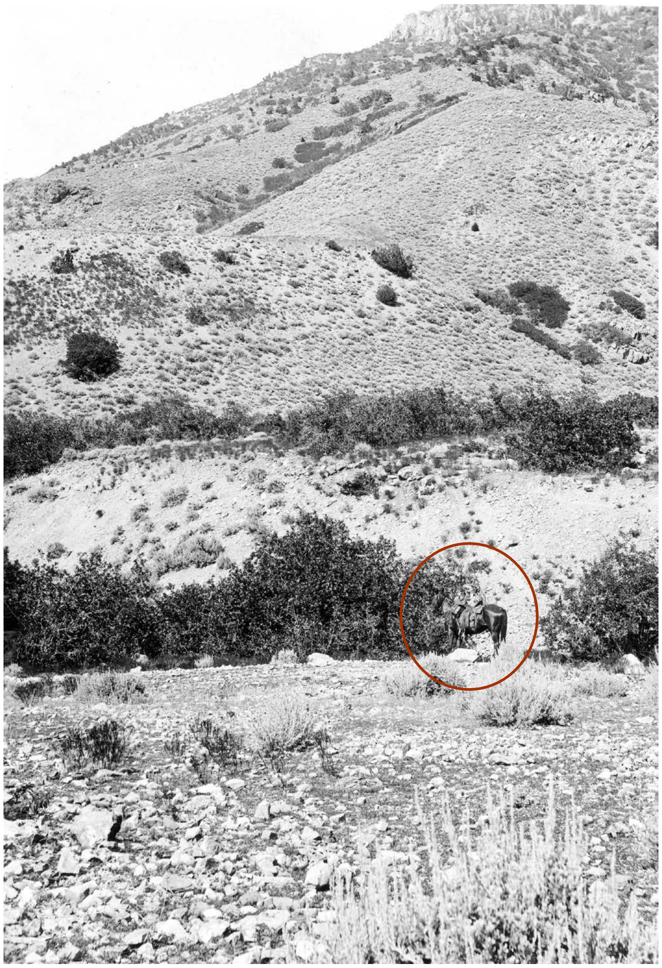

Figure 7. *Scarp caused by surface faulting on the Nephi segment of the Wasatch fault zone (photo credit F.B. Weeks, USGS). Note man sitting on horse for scale.*

dress (1) ground-surface displacements caused by non-tectonic faults as defined by Hanson and others (1999), including those resulting from landsliding (described in chapter 4), (2) non-tectonic fault creep or post-seismic slip, (3) earth fissures caused by land subsidence due to groundwater mining (Knudsen and others, 2014; chapter 6), or (4) other earthquake hazards and non-earthquake geologic hazards that displace the ground surface, which should be addressed as part of a comprehensive geologic-hazards site investigation (see chapters 1 and 2).

These guidelines do not supersede pre-existing state or federal regulations or local geologic-hazard ordinances, but provide useful information to supplement adopted ordinances/regulations, and assist in preparation of new ordinances. The UGS believes adherence to these guidelines will help ensure adequate, cost-effective investigations and minimize report review time.

Background

Earthquakes produce a variety of hazards, including strong ground shaking, liquefaction, and landslides, as well as surface faulting (e.g., Smith and Petley, 2009). In Utah, faults capable of causing surface faulting are chiefly normal faults along which fault displacement at the ground surface is primarily vertical, with one side dropping down relative to the other along a fault plane dipping beneath the downthrown fault block (figure 8). Surface faulting commonly recurs along existing fault traces (Bonilla, 1970; McCalpin, 1987, 2009; Kerr and others, 2003) for earthquakes ≥ M 6.75 (Working Group on Utah Earthquake Probabilities [WGUEP], 2016). Past major earthquakes on the central five most active segments of the Wasatch fault zone have generated average displacements for individual surface-faulting earthquakes of about 6.6 feet (DuRoss, 2008; DuRoss and Hylland, 2015). However, single-event displacements more than twice that large have been documented on the Weber (14.8 feet; Nelson and others, 2006) and Provo (15.4 feet; Olig, 2011 [compiled in Bowman and Lund, 2013]) segments.

Displacements during surface-faulting earthquakes on other Utah normal faults are less well documented, but limited available data indicate that for comparable rupture lengths, displacements are similar to the central Wasatch fault zone segments. Consequently, if a normal fault were to displace the ground surface beneath a building or critical structure (e.g., large water or petroleum storage tanks, telecommunications tower, electrical switching station), significant structural damage or collapse may occur (figure 9), possibly causing injuries and loss of life. Therefore, site-specific investigations are required to accurately locate faults that present a potential surface-faulting hazard, determine their level of activity and displacement characteristics, and implement appropriate risk-reduction measures prior to development.

Consideration of surface faulting in land-use planning and regulation in Utah began in earnest in the early 1970s when Cluff and others (1970, 1973, 1974; compiled in Bowman and others, 2015b) completed their investigations and maps of major faults along the Wasatch Front in northern Utah. These aerial-photograph-based maps presented the first comprehensive compilation of fault locations available to local governments, and increased awareness of the hazard posed by the Wasatch, East Cache, and West Cache fault zones. Early paleoseismic trenching investigations (Swan and others, 1980, 1981a, 1981b; compiled in Bowman and Lund, 2013) further highlighted the hazard by documenting multiple, large, geologically recent surface-faulting earthquakes on the central part of the Wasatch fault zone.

In subsequent years, maps designating special-study areas within which surface-faulting investigations are recommended, have been prepared by or with the assistance of the Utah Geological Survey (UGS) at varying levels of detail for Cache, Davis, Iron, Salt Lake, eastern Tooele, Utah, western Wasatch, and Weber Counties (adopted by and on file with the respective county planning departments). More recently, the UGS has prepared similar maps for the St. George-Hurricane metropolitan area (figure 10; Lund and others, 2008), high-visitation areas of Zion National Park (Lund and others, 2010), and

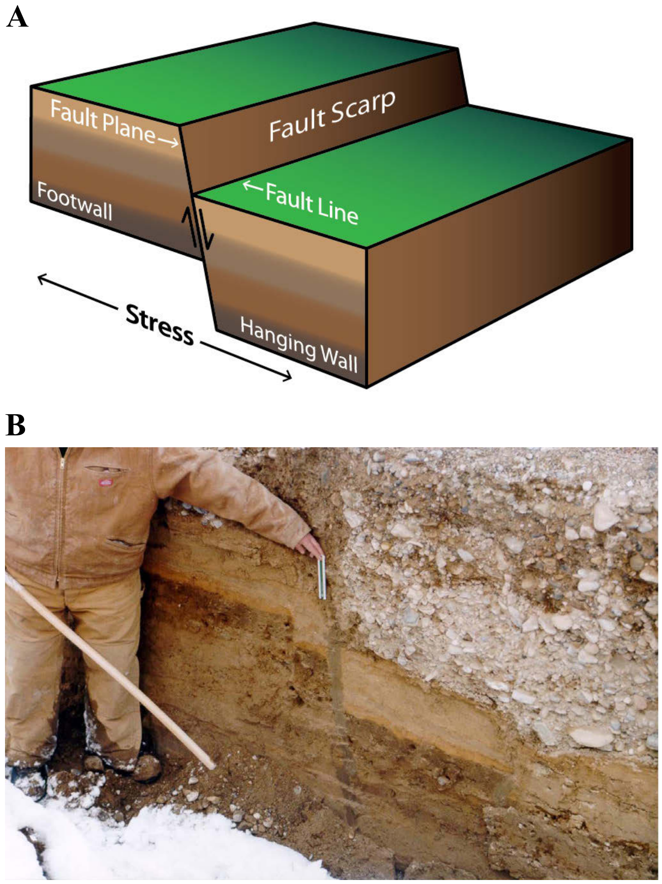

Figure 8. *Normal fault: (A) schematic diagram, (B) exposed in an excavation (photo courtesy of David Simon).*

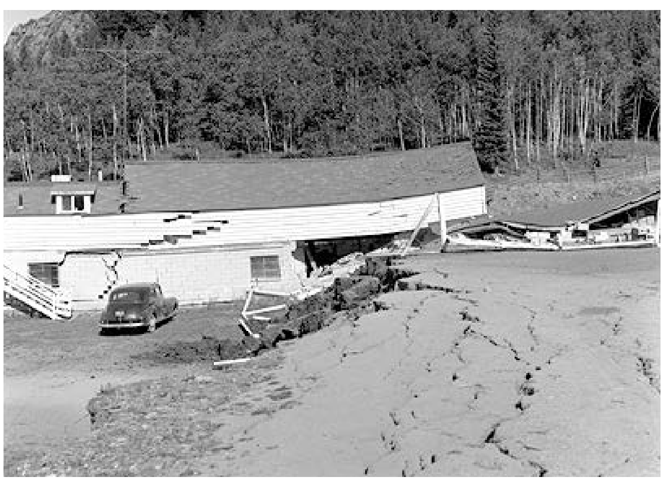

Figure 9. *Normal fault surface-faulting damage to a building, 1959 Hebgen Lake, Montana, M 7.3 earthquake. (Photograph by I.J. Witkind, USGS.)*

the State Route 9 corridor between La Verkin and Springdale (Knudsen and Lund, 2013) in Washington County. Additionally, the UGS is preparing geologic-hazard-map sets for select 7.5-minute quadrangles in Utah (see http://geology.utah.gov/maps/geohazmap/index.htm). Where Quaternary faults are present in the quadrangles, the hazard-map sets contain a surface-faulting-hazard map (e.g., Castleton and others, 2011).

Recognizing the risk from earthquakes, some local governments began adopting rudimentary ordinances requiring fault and other geologic-hazard investigations prior to development in the 1970s. Guided by publication of UGS Circular 79, *Suggested Approach to Geologic Hazard Ordinances in Utah* (Christenson, 1987) and U.S. Geological Survey (USGS) Professional Paper 1519, *Applications of Research from the U.S. Geological Survey Program, Assessment of Regional Earthquake Hazards and Risk Along the Wasatch Front, Utah* (Gori, 1993), some Wasatch Front counties and municipalities had adopted and were enforcing modern hazard ordinances by the mid-1990s. Local government staff relied heavily on developers' consultants as professional experts responsible for evaluating the hazards and recommending risk-reduction measures for proposed developments. Consultants' reports would sometimes be sent to the UGS for review, but in general, technical regulatory reviews were not systematically performed prior to 1985.

This informal review process lasted until June 1985, when the UGS initiated the Wasatch Front County Hazards Geologist Program, funded through the USGS National Earthquake Hazards Reduction Program (Christenson, 1993). Geologists hired by Weber, Davis, Salt Lake, Utah, and Juab Counties began preparing surface-faulting and other geologic-hazard maps and assisting city and county planning departments in requiring and reviewing site-specific hazard investigations. This program directly resulted in or spurred development of various published guidelines for surface-faulting investigations in Utah including those of the Association of Engineering Geologists, Utah Section (1987); Nelson and Christenson (1992); Robison (1993); Christenson and Bryant (1998); Batatian and Nelson (1999); Salt Lake County (2002b); and Christenson and others (2003). The county geologist program came to an end in Weber, Davis, Utah, and Juab Counties in the late 1980s after USGS funding expired. The county geologist program in Salt Lake County persisted with local funding until 2006.

Most Wasatch Front and other urban counties and municipalities now have hazard ordinances that require geologic-hazards investigations prior to approving new development. Several of these ordinances adopt surface-faulting-hazard special-study maps (Christenson and Shaw, 2008), which define areas where site-specific investigations are required prior to approval of new development to protect life, safety, and welfare from surface faulting (figure 10). Most geologic-hazard ordinances in Utah mitigate surface faulting by prohibiting construction of habitable structures and high-risk-category facilities across "active" faults (hazard avoidance). The ordinances typically define "active" (hazardous) faults as faults having evidence for displacement during the Holocene Epoch (the period of time extending from the present back to about 10,000 radiocarbon years before present [^{14}C yr B.P.], or about 11,700 calibrated years before present [cal yr B.P.]). Presently, a few municipalities and counties with geologic-hazard ordinances retain consultants to

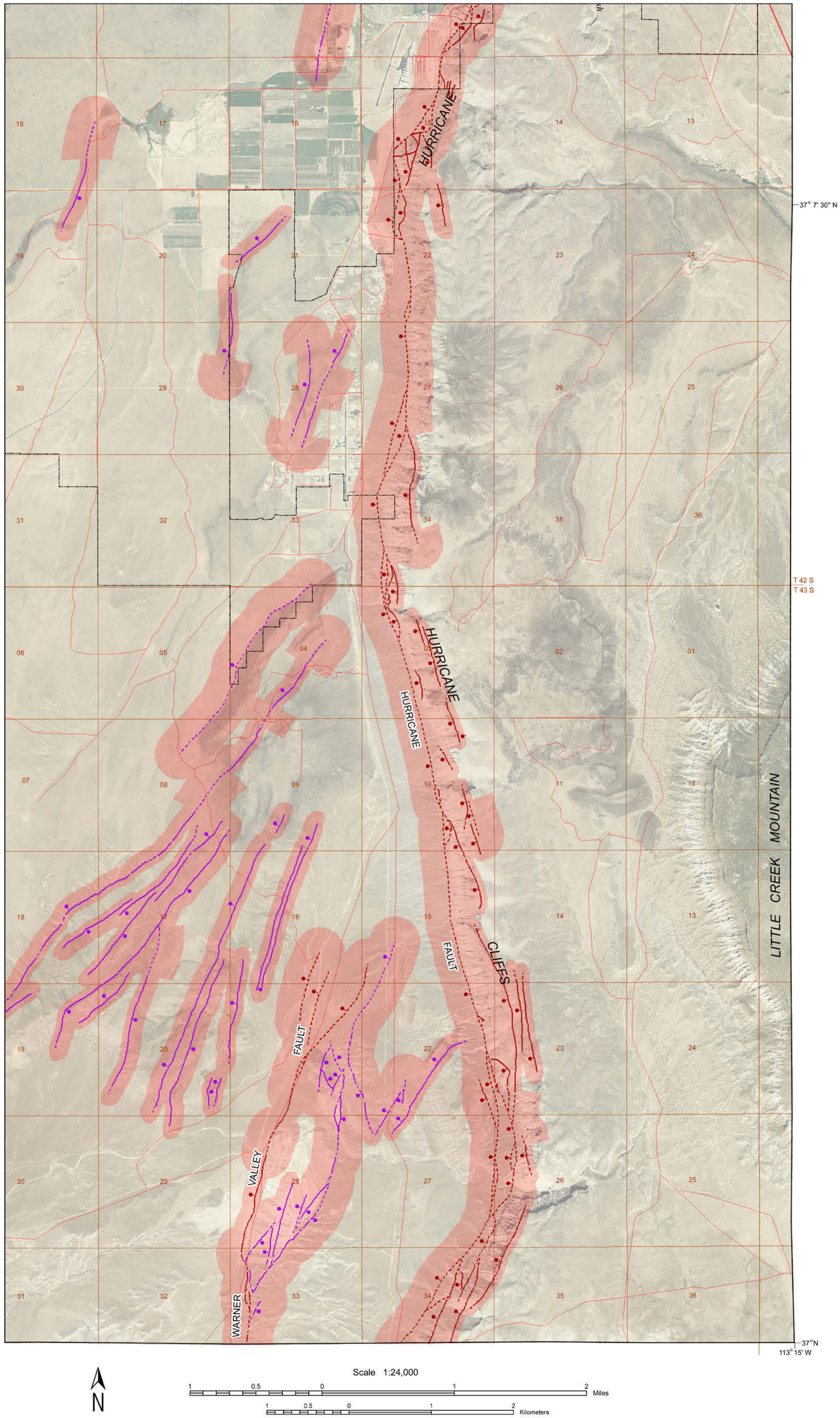

Figure 10. *Example of a surface-faulting special-study-area map along the Hurricane fault zone in southwestern Utah (from Lund and others, 2008). Site-specific investigations are required within the shaded areas to address surface-faulting hazard prior to approval of new development.*

review surface-faulting investigations, while others rely on non-technical staff to make the reviews.

Designing a building to withstand surface faulting has generally been considered impractical for economic, engineering, and architectural reasons, and it is only within the relatively recent past that the geotechnical community has begun a serious discussion regarding using engineering design to mitigate surface-faulting risk (e.g., Bray, 2015). Therefore, avoiding active fault traces that pose a surface-faulting hazard has been the risk-reduction measure most often applied in Utah. A typical surface-faulting investigation in Utah documents the presence or absence of faults determined to be active at a site. When active faults are present, a fault setback is recommended based on the width of the deformation zone and the amount and direction of displacement along the fault.

However, hazard ordinances adopted by the cities of Draper, Holladay, and Cottonwood Heights, and Salt Lake, Morgan, and Wasatch Counties allow exceptions to this norm, and permit construction across active faults expected to have ≤ 4 inches of future displacement, their reasoning being that a "normal" residential foundation system can withstand 4 inches of vertical displacement without catastrophic collapse. The Draper and Morgan County ordinances do not categorically exempt small-displacement faults from fault setback requirements. In those ordinances, if engineering-design surface-faulting mitigation is proposed for small displacement faults, the following criteria must be addressed: (1) reasonable geologic data must be available indicating that future surface displacement along the fault will not exceed 4 inches, (2) a structural engineer must provide an appropriate design to minimize structural damage, and (3) the design must receive adequate review.

Under a special City of Draper (2005) "Review Protocol" regulating issuance of building permits for structures astride active faults in subdivisions approved prior to adoption of Draper's geologic-hazard ordinance in 2003, it is permissible under specified conditions to construct "super-engineered" structures across subsequently discovered active faults within previously approved building lots. To obtain approval for a super-engineered structure, Draper requires (1) a statement from a Utah licensed geologist describing the most suitable location on the lot for the proposed structure, (2) a statement from a Utah licensed geotechnical engineer describing the suitability and constructability of the proposed structure at the location described by the geologist, and (3) a statement from a Utah licensed structural engineer stating that the geologic and geotechnical reports have been reviewed, and that the proposed structure is designed in accordance with their recommendations and accounts for the identified hazards in accordance with the International Building Code (IBC) (International Code Council [ICC], 2014a). When Draper approves construction of a structure astride an active fault pursuant to the review protocol, a disclosure of the geologic condition at the site must be recorded with the County Recorder on a form approved by the City as a condition of issuing a building permit. Under the review protocol, Draper has approved construction of structures across Holocene-active faults exhibiting as much as 6 feet of vertical displacement (David Dobbins, City of Draper Manager, verbal communication, 2015).

CHARACTERIZING FAULT ACTIVITY

In Utah, minimum requirements for surface-faulting investigations and implementing hazard-mitigation measures are predicated on the ability of the engineering geologist to characterize a fault's physical characteristics and recent earthquake history (strike, dip, sense of displacement, rupture complexity, and timing and displacement of the most recent surface-faulting earthquake). Where site geologic conditions are favorable and time and budget permit, it also may be possible to determine the timing and displacement for multiple paleoearthquakes, from which earthquake recurrence and fault slip rate can be calculated. Engineering geologists conducting surface-faulting investigations should be thoroughly familiar with the techniques of paleoseismic investigations (e.g., McCalpin, 2009; DuRoss, 2015; see also Investigator Qualifications section in chapter 2). Parameters required to fully characterize fault activity are briefly described in the following sections.

Rupture Complexity

Rupture complexity refers to the width and distribution of deformed land around a fault trace (Kerr and others, 2003; Treiman, 2010). Normal faults are by far the most common type of Quaternary fault in Utah; patterns of ground deformation resulting from past surface faulting are highly variable, and in some cases change significantly over short distances along the strike of the fault (figure 11). Geologic mapping and trench exposures across zones of surface-fault deformation show that common patterns of normal-slip faulting range from (1) very narrow zones where virtually all deformation takes place on a single master fault (e.g., DuRoss and others, 2014), (2) broader shear zones up to several feet wide with a master fault and several smaller, usually sympathetic, subsidiary faults (e.g., Lund and others, 2015), (3) grabens that range from a few to tens of feet wide and contain a few to numerous antithetic and sympathetic faults of variable displacement (e.g., Lund and others, 1991; Olig, 2011 [compiled in Bowman and Lund, 2013]), (4) bifurcated fault zones tens to hundreds of feet wide consisting of several individually prominent strands, not all of which may be active in every surface-faulting earthquake (e.g., Black and others, 1996; DuRoss and others, 2009), and (5) zones of folding, warping, and flexure that lack discrete fault rupture (e.g., Hylland and others, 2014).

Earthquake Timing and Recurrence

Minimum data necessary to characterize past fault activity and estimate the probability of surface faulting within a future time frame of interest include (1) timing of the most recent

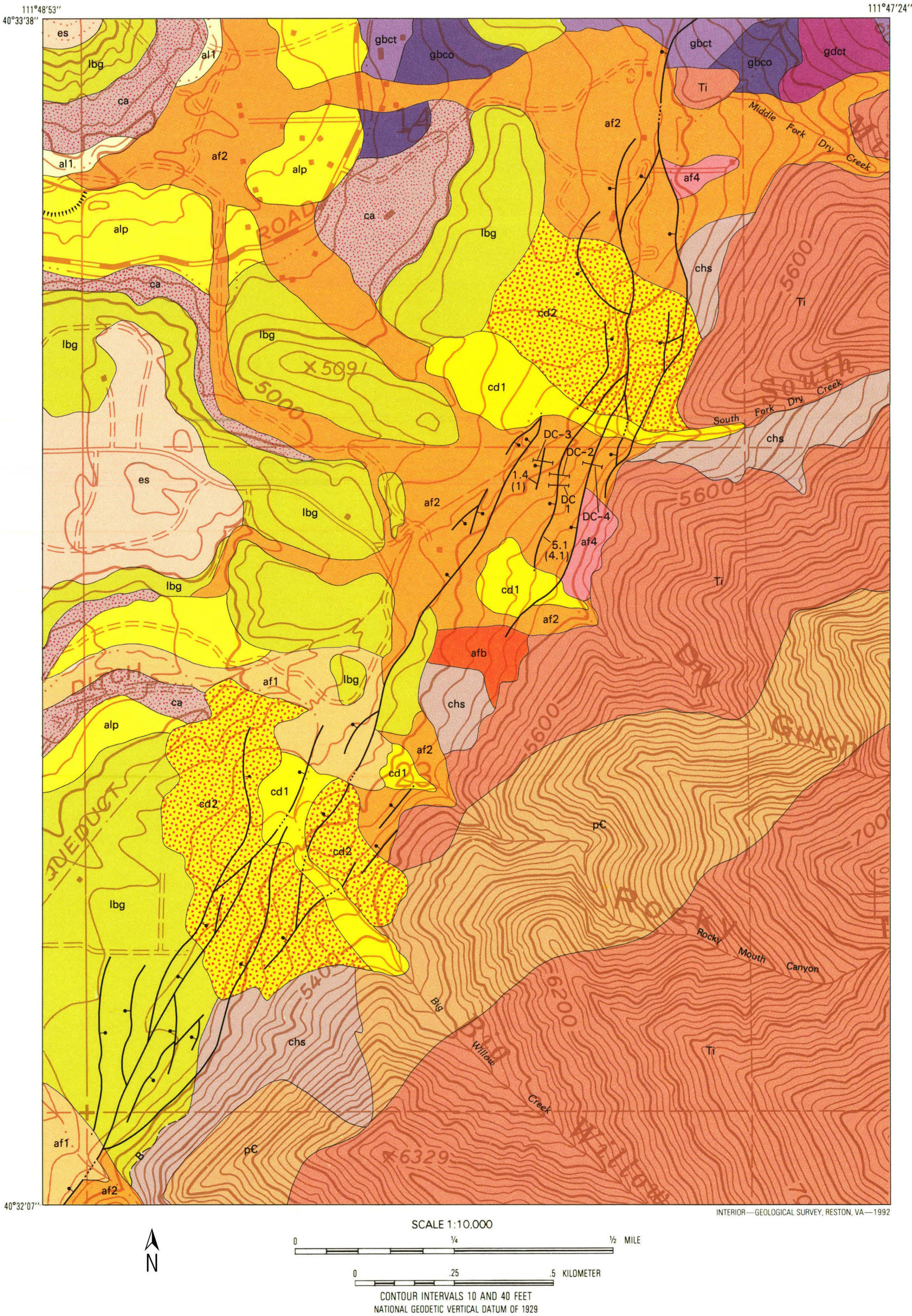

Figure 11. *Map view of rupture complexity along part of the Salt Lake City segment of the Wasatch fault zone (from Personius and Scott, 1992).*

surface-faulting earthquake, (2) a well-constrained average recurrence interval based on a recommended minimum of three closed earthquake cycles (four paleoearthquakes; more is better), and (3) the variability (uncertainty) associated with the timing of each paleoearthquake and resulting average recurrence interval. Paleoseismic trenching investigations show that individual recurrence intervals (time between two surface-faulting earthquakes) for Utah Quaternary faults range from several hundred to multiple thousands of years, and may exhibit uniform, quasi-uniform, or non-uniform recurrence.

The greater the number of past surface-faulting earthquakes identified and dated, the greater the confidence that the resulting average recurrence interval accurately reflects the fault's long-term activity level (Coppersmith and Youngs, 2000; DuRoss and others, 2011). Additionally, the greater the understanding of variability in recurrence intervals, the greater the confidence that the elapsed time since the most recent surface-faulting earthquake is a reliable indicator of where the fault lies in its current earthquake cycle. However, for fault-avoidance (fault setback) mitigation, it is only necessary to determine the timing of the most recent surface-faulting earthquake (see Hazardous Fault Avoidance section below).

Displacement

Utah's Quaternary faults typically exhibit normal-slip displacement with the master fault dipping at moderate to high angles (50° ± 15°; Lund, 2012; WGUEP, 2016) beneath the downthrown (hanging wall) block (figure 8). Single-event displacements from past Utah surface-faulting earthquakes range from about 20 inches (1934 Hansel Valley earthquake—Utah's only historical surface-faulting earthquake; Walter, 1934; figure 12) to > 15 feet (Olig, 2011 [compiled in Bowman and Lund, 2013]) on the five central, Holocene-active segments of the Wasatch fault zone. Single-earthquake displacements on other Utah Quaternary faults for which paleoseismic trenching data are available typically range from < 3 to about 10 feet (see UGS *Paleoseismology of Utah* series and Lund, 2005). The 1983 **M** 6.9 Borah Peak, Idaho, earthquake showed that normal-slip displacement can vary significantly along strike (Crone and others, 1987), and Lund and others (2015) reported an approximately 50 percent variation in displacement at a point in successive earthquakes on the Fort Pearce section of the Washington fault zone in southern Utah. Wesnousky (2008) discussed displacement and geometrical characteristics of earthquake surface faulting using a worldwide data set of historical surface-faulting earthquakes. His analysis showed that earthquake epicenters do not appear to have a systematic correlation with the maximum slip observed on a fault.

Displacements on sympathetic and antithetic faults in shear zones and grabens produced by surface-faulting earthquakes (figure 13) are generally less than 3 feet, but may be larger. Fault trenching investigations show that low-angle thrust faults and high-angle reverse faults may form in grabens along normal-slip master faults (e.g., Lund and others, 1991; Olig, 2011 [compiled in Bowman and Lund, 2013]; Crone and others, 2014; Simon and others, 2015). Such faults commonly have small displacements (tens of inches or less); however, a low-angle thrust fault formed at a complex bend in the otherwise normal-slip Washington fault zone exhibited multiple feet of reverse-fault displacement placing Mesozoic bedrock over Quaternary basin-fill deposits (Simon and others, 2015; figure 14).

Figure 12. *Surface faulting associated with the 1934 Hansel Valley, Utah, M 6.6 earthquake (photograph from the University of Utah Seismograph Stations photo archive).*

Slip Rate

Quaternary normal faults in the Basin and Range Province typically produce large, infrequent, nearly instantaneous displacements during earthquakes that are separated by recurrence intervals (time between two successive earthquakes) ranging from hundreds to thousands of years. A slip rate normalizes fault displacement over time by dividing a known per-event displacement by the known length of the previous recurrence interval. Slip rates are typically reported in mm/yr or m/kyr, and for a normal fault may either be calculated vertically, or in a down-dip direction (net slip) if a fault's dip at depth is known. A slip rate may be "open" or "closed" (Chang and Smith, 2002; McCalpin, 2009). A closed slip rate is determined by dividing a known per-event vertical displacement by the known length of the previous recurrence interval. It is implicit in a closed slip rate that the time interval of interest is bracketed (closed) by surface-faulting earthquakes of known age. Accurately characterizing a fault's long-term slip rate requires calculating a composite slip rate across multiple closed recurrence intervals to obtain a long-term average of

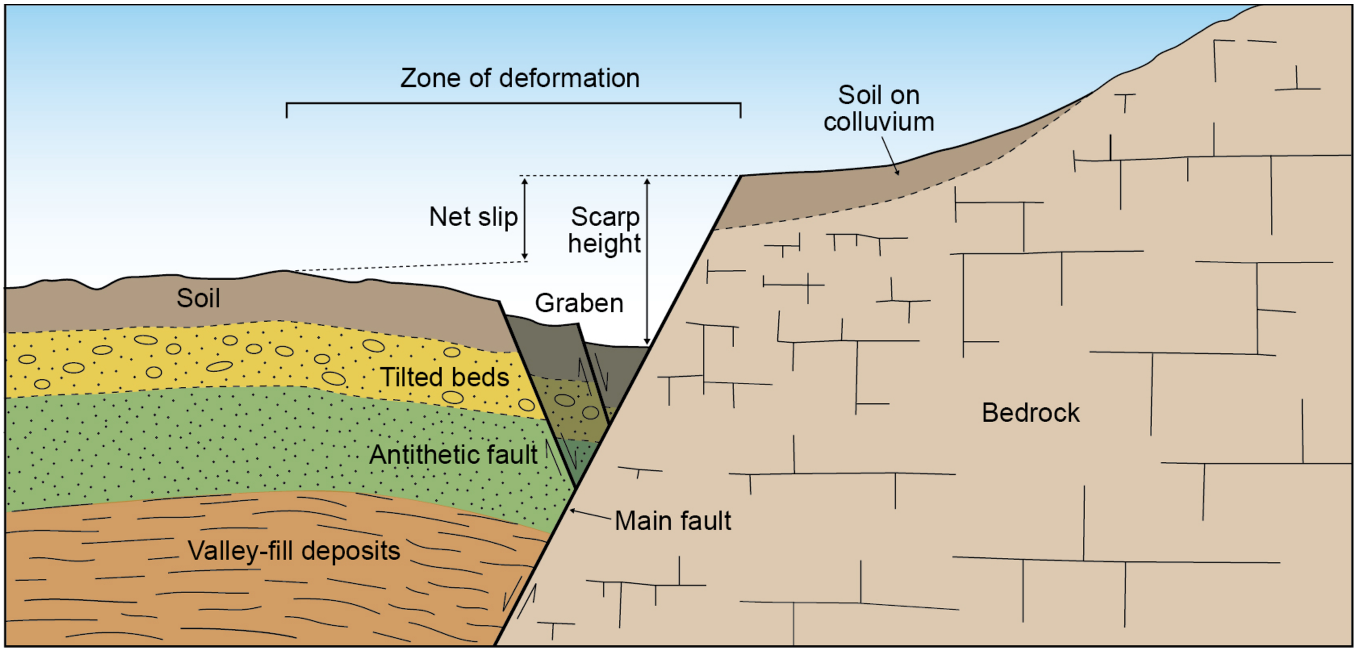

Figure 13. *Schematic cross section through a normal fault zone.*

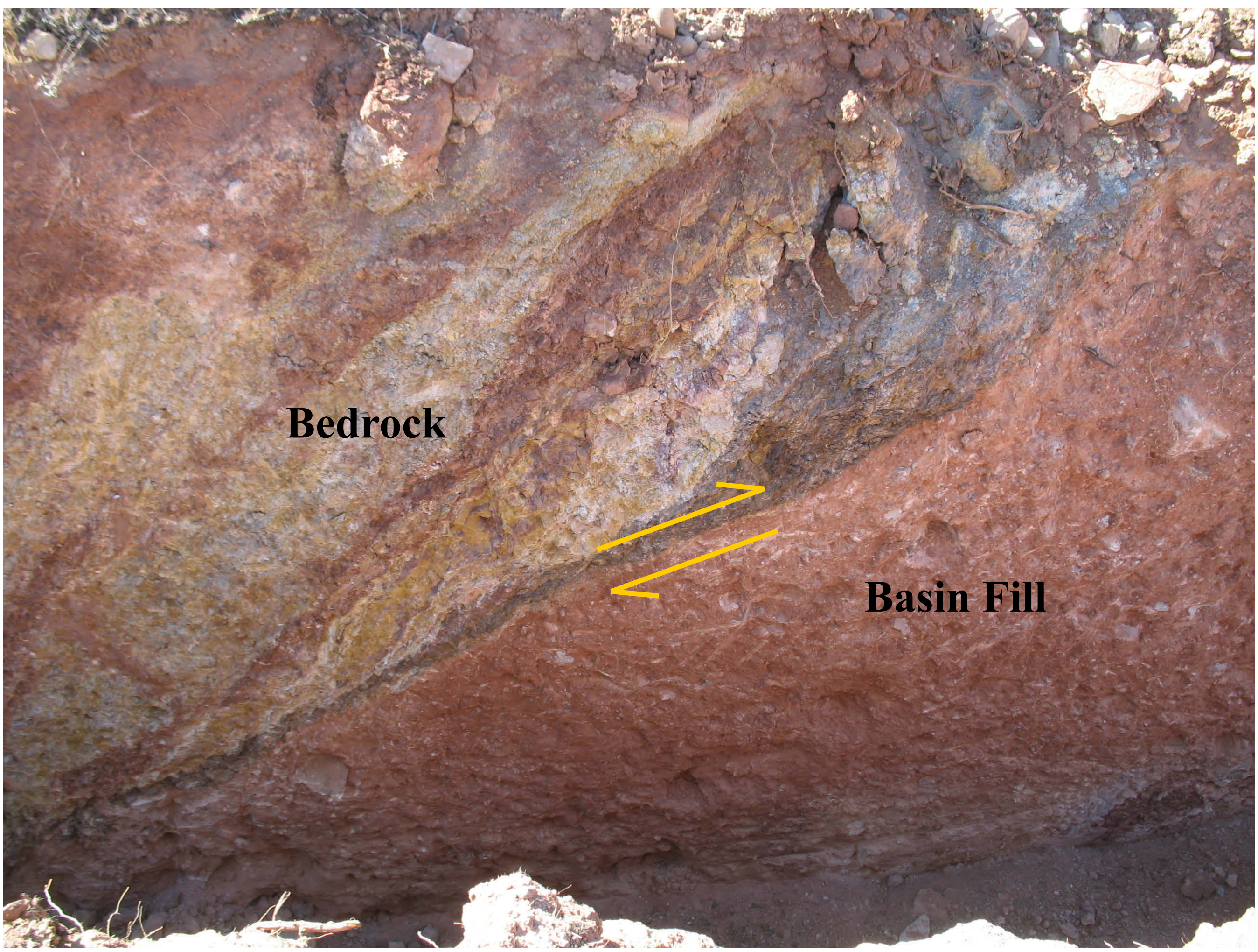

Figure 14. *Thrust fault exhibiting several feet of displacement at a complex bend in an otherwise normal-slip fault zone. The fault places Mesozoic bedrock on top of Quaternary basin-fill deposits. Photo taken in January 2012.*

fault activity. Generally, the higher the slip rate, the more active (hazardous) the fault.

Open-interval slip rates span the time and displacement between the oldest dated displaced deposit and the present. Open-interval slip rates are less precise than closed-interval slip rates because they typically include one partial earthquake cycle prior to the earliest fault displacement of the deposit, and a second partial cycle from the time of the most recent earthquake to the present. Information on earthquake timing and per-event displacement is not available for most of Utah's more than 200 known Quaternary faults/fault segments, but it may be possible in some instances to calculate an open slip rate from a displaced geologic feature or unit of known or estimated age (e.g., geomorphic surfaces related to Lake Bonneville). Some slip rates determined in this manner may be very long term and incorporate very broad estimates of displacement (sometimes thousands of feet) over very long time intervals (sometimes millions of years). In those instances, the resulting open slip rates may represent a reasonable estimate of long-term slip on a fault, but most open slip rates contain large time and displacement uncertainties that make them broadly constrained estimates at best, and of questionable value for surface-faulting investigations.

As discussed above, there are numerous caveats to consider when using slip rate to characterize fault activity. If the slip rate comes from the geologic literature (see Sources of Paleoseismic Information section below), questions when evaluating the applicability of the slip rate for use in a surface-faulting investigation include: (1) Is the slip rate a vertical or net slip rate? (2) Is the slip rate open or closed? (3) If closed, over what period of time and how many closed recurrence intervals does the slip rate characterize fault activity? (4) If open, how well constrained are the timing and displacement data used to calculate the rate? (5) If open, does the slip rate reflect relevant (late Quaternary) fault activity (a slip rate calculated over several millions of years, as is sometimes done, may incorporate changes in a region's tectonic setting and be of little value when characterizing contemporary surface-faulting hazard)? Additionally, because displacement typically varies along a rupture, slip rate depends on where along the fault displacement is measured (i.e., lower slip rate at fault tips compared to center). Where available, average displacement based on multiple site displacements is preferred when calculating a slip rate (e.g., DuRoss, 2008).

SOURCES OF PALEOSEISMIC INFORMATION

Detailed paleoseismic investigations of Utah Quaternary faults began in the 1970s and continue to the present day. The UGS has performed or assisted with numerous research paleoseismic investigations in Utah, and has published the results of many of those investigations in its *Paleoseismology of Utah* series (http://geology.utah.gov/hazards/technical-information/paleoseismology-of-utah-series/). The *Paleoseismology of Utah* series also includes compilations of early and now hard-to-find, "legacy" investigations and aerial photograph sets by Woodward-Lundgren and Associates (Bowman and others, 2015), the U.S. Bureau of Reclamation (Lund and others, 2011), the U.S. Soil Conservation Service (Bowman and others, 2011), and researchers funded through the National Earthquake Hazards Reduction Program (Bowman and Lund, 2013). Additionally, the Utah Quaternary Fault Parameters Working Group (UQFPWG, http://geology.utah.gov/hazards/earthquakes-faults/utah-earthquake-working-groups/quaternary-fault-parameters/) posts the results of their annual review of paleoseismic research conducted in Utah on the UGS website. Lund (2005) reported the results of the UQFPWG's initial evaluation of Utah paleoseismic trench data, and provided consensus recurrence-interval and vertical slip-rate parameters for Utah Quaternary faults with trenching data through 2004. Although superseded in some cases, the data for many faults in this compilation remain the best currently available. Lund (2014) revises and expands the Utah Hazus fault database to provide parameters for scenario earthquakes on all known Late Quaternary and younger faults/fault segments in Utah (82) thought capable of generating a ≥ **M** 6.75 earthquake.

The *Utah Quaternary Fault and Fold Database* (UGS, 2016) and the *Quaternary Fault and Fold Database of the United States* (USGS, 2015) contain summary paleoseismic information for Utah's known Quaternary faults. Both databases are periodically updated, although the national database may be updated less frequently than the Utah database. Therefore, engineering geologists conducting surface-faulting investigations should always search for the most recent paleoseismic information available for a Quaternary fault of interest. The paleoseismic data in the databases are reported as published in the geologic literature and are of variable quality—users must make their own evaluation of the data's suitability for their intended purpose. Additionally, the databases are limited to Utah's "known" Quaternary faults—other, as yet unrecognized, potentially hazardous faults may exist in Utah (e.g., McKean and Kirby, 2014), and engineering geologists performing surface-faulting investigations or hazard investigations for high-risk-category facilities regardless of location, should consider the possibility that an unrecognized fault may be present at or close to the site.

See the Literature Search and Information Resources section in chapter 2 for information on other geologic-hazard reports, maps, archives, and databases maintained by the UGS and others that may be relevant to surface-faulting-hazard investigations, as well as information on the UGS' extensive aerial photograph and light detection and ranging (lidar) imagery collections.

Finally, *Paleoseismology* (McCalpin, 2009) is a widely recognized general reference for conducting paleoseismic investigations and evaluating seismic risk. Much information contained in that publication is applicable to conducting site-specific, surface-faulting investigations for human-occupied structures and high-risk infrastructure.

SURFACE-FAULTING-HAZARD INVESTIGATION

When to Perform a Surface-Faulting-Hazard Investigation

Geologic hazards are best addressed prior to land development. In areas of known or suspected Quaternary faulting, the UGS recommends that a surface-faulting-hazard investigation be made for all new buildings for human occupancy and for modified IBC Risk Category II(a), II(b), III, and IV facilities (table 12, modified from IBC table 1604.5 [ICC, 2014a]). Utah jurisdictions that have adopted surface-faulting special-study maps identify zones along known hazardous faults within which they require a site-specific investigation. At a minimum, the UGS recommends that investigations as outlined in chapter 2 be conducted for all IBC Risk Category III and IV facilities, whether near a mapped Quaternary fault or not, to ensure that previously unknown faults are not present. If a hazard is found, the UGS recommends a comprehensive investigation be conducted. Additionally, in some instances an investigation may become necessary when existing infrastructure is discovered to be on or adjacent to a Quaternary fault.

The level of investigation conducted for a particular project depends on several factors, including (1) site-specific geologic conditions, (2) type of proposed or existing development, (3) level of acceptable risk, and (4) governmental permitting requirements, or regulatory agency rules and regulations. A surface-faulting-hazard investigation may be conducted separately, or as part of a comprehensive geologic-hazard and/or geotechnical site investigation (see chapter 2).

Minimum Qualifications of the Investigator

Surface-faulting related engineering-geology investigations and accompanying geologic-hazard evaluations performed before the public shall be conducted by or under the direct supervision of a Utah licensed Professional Geologist (Utah Code, Title 58-76) who must sign and seal the final report. Often these investigations are interdisciplinary in nature, and where required, must be performed by qualified, experienced, Utah licensed Professional Geologists (PG, specializing in engineering geology) and Professional Engineers (PE, specializing in geological and/or geotechnical engineering) working as a team. See Investigator Qualifications section in chapter 2.

Investigation Methods

Inherent in surface-faulting investigations is the assumption that future faulting will recur along pre-existing faults (Bonilla, 1970; McCalpin, 1987, 2009; Kerr and others, 2003) in a manner generally consistent with past displacements (Schwartz and Coppersmith, 1984; Crone and others, 1987; DuRoss and others, 2014). In Utah, minimum requirements for an investigation designed to mitigate surface-faulting hazard by setting back from active (hazardous) faults are (1) determine whether a Quaternary fault(s) is present at a site, (2) map fault complexity, (3) determine the timing of the most recent surface-faulting earthquake, and (4) determine the amount and direction (dip) of past displacement. Where site geologic conditions and time and budget permit, the UGS recommends determining the timing and displacement of multiple paleoearthquakes so average earthquake recurrence and associated variability, and a fault slip rate can be calculated to better characterize fault activity. Fully characterizing past fault activity in this manner is a necessary requirement for engineering-design mitigation of surface faulting (see Paleoseismic Data Required for Engineering-Design Mitigation of Surface Faulting section below).

A site-specific surface-faulting investigation typically includes at a minimum (1) literature review, (2) analysis of stereoscopic aerial photographs and other remote-sensing data, and (3) field investigation, usually including surficial geologic mapping and subsurface investigations typically consisting of excavating and logging trenches (see chapter 2).

Literature Review

Prior to the start of field investigations, an engineering geologist conducting a surface-faulting investigation should review published and unpublished (if available) geologic literature, geologic and topographic maps, consultant's reports, and records relevant to the site and region's geology (see also the Literature Searches and Information Resources section in chapter 2), with particular emphasis on information pertaining to the presence and activity level of Quaternary faults. The Sources of Paleoseismic Information section in this chapter presents numerous sources of information on Utah's Quaternary faults; however, the list of sources is not exhaustive, and engineering geologists should identify and review all available information relevant to their site of interest.

Analysis of Aerial Photographs and Remote Sensing Data

A surface-faulting investigation should include interpretation of stereoscopic aerial photographs (from multiple years if available), lidar imagery (appendix C—Lidar Background and Application), and other remotely sensed data (e.g., Bunds and others, 2015) for evidence of past surface faulting including fault scarps, other fault-related geomorphic features, and fault-related lineaments, including vegetation lineaments, gullies, vegetation/soil contrasts, and aligned springs and seeps (see also the Literature Searches and Information Resources section of chapter 2). Where possible, the analysis should in-

Table 12. *Fault setback recommendations and criticality factors (U) for modified IBC risk category of buildings and other structures (modified from ICC, 2014a, IBC table 1604.5)*[1].

IBC Risk Category[2]	Study and Fault Setback Recommendations[3] Fault Activity Classes			Criticality[4]	U[4]	Minimum Setback[5]
	Holocene	Late Quaternary	Quaternary			
I—Buildings and other structures that represent a low hazard to human life in the event of failure	Optional	Optional	Optional	4	–	–
II(a)— Single family dwellings, and apartment complexes and condominiums (<10 dwelling units)	Recommended	Prudent	Optional	3	1.5	15 feet
II(b)—Buildings and other structures except those listed in Risk Categories I, II(a), III, and IV	Recommended	Recommended	Prudent	2	2	20 feet
III—Buildings and other structures that represent a substantial hazard to human lives in the event of failure	Recommended	Recommended	Recommended[6]	1	3	50 feet
IV—Buildings and other structures designated as essential facilities	Recommended	Recommended	Recommended[6]	1	3	50 feet

[1] See ICC (2014a) chapter 3, Use and Occupancy Classification (p. 41) and chapter 16, Structural Design, table 1604.5 (p. 336) for a complete list of structures/facilities included in each IBC Risk Category. Check table 1604.5 if a question exists regarding which Risk Category a structure falls under.

[2] For purposes of these guidelines, Risk Category II has been divided into subcategories II(a) and II(b) to reflect the lower hazard associated with single family dwellings and apartment complexes and condominiums with <10 dwelling units.

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

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

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

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

Risk Category III—includes but not limited to:

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

Risk Category IV—includes but not limited to:

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

[3] Study and setback or other risk-reduction measure:

a. Recommended;
b. Prudent, but decision should be based on risk assessment; or
c. Optional, but need not be required by local government based on the low likelihood of surface faulting.
Appropriate disclosure is recommended in all cases.

[4] Criticality is a factor based on relative importance and risk posed by a building; lower numbers indicate more critical facilities. Criticality is included in fault-setback equations by the factor U. U is inversely proportional to criticality to increase fault setbacks for more critical facilities.

[5] Use minimum fault setback or the calculated fault setback, whichever is greater.

[6] Study recommended; fault setback or other risk-reduction measure considered prudent, but decision should be based on risk assessment; appropriate disclosure recommended.

clude both low-sun-angle and normal high-sun-angle stereoscopic aerial photography. Examination of the oldest available aerial photographs may show evidence of surface faulting subsequently obscured by later development or other ground disturbance. The area interpreted should extend beyond the site boundaries to identify faults that might affect the site and to adequately characterize patterns of surface faulting.

Google Earth and Bing Maps, among other providers of Internet-based, free aerial imagery, are becoming increasingly valuable as rapid site reconnaissance tools, and provide high-resolution, often color, non-stereoscopic aerial orthophotography of the entire state of Utah. For most locations, Google Earth also includes a historical imagery archive that permits evaluation of site conditions several years to decades before present.

Fault Mapping

Surface faulting can be a complex phenomenon involving both brittle fracture and plastic deformation (Treiman, 2010). The most direct surface method for locating faults and evaluating fault activity is to map fault scarps and surficial geology. Faults may be identified by examining geologic maps, aerial photographs and other remote-sensing imagery, and by directly observing fault-related geomorphic features. Topographic profiling of fault scarps can aid in estimating the number, age, and displacement of past surface-faulting earthquakes (Bucknam and Anderson, 1979; Andrews and Bucknam, 1987; Hanks and Andrews, 1989; Machette, 1989; Hylland, 2007; McCalpin, 2009). Detailed mapping helps identify fault scarps and other fault-related features such as sag ponds, springs, aligned or disrupted drainages, faceted spurs, grabens, and displaced landforms (e.g., terraces, shorelines) and/or geologic units. Site-specific surficial geologic mapping depicts relations between faults and geologic units to help determine the location and age of faults, and is necessary to identify potential trench locations. The area mapped should extend beyond the site boundaries as necessary to locate and evaluate evidence of other faults that may affect the site.

Special care is required when investigating faults that cross landslides. Geomorphic and subsurface features in fault zones and landslides may be similar, and investigations may be inconclusive regarding the origin of such features (e.g., Hart and others, 2012; Crone and others, 2014; Hoopes and others, 2014). Therefore, report conclusions should address uncertainties in the investigation, and recommendations for hazard reduction should consider both fault and landslide hazards when present.

See the Geologic Mapping section of chapter 2 for additional discussion on geologic mapping as it applies to geologic-hazard investigations.

Trenching

Trenching is generally required for surface-faulting investigations to accurately locate faults, determine paleoearthquake timing, document the nature and extent of rupture complexity, and measure fault displacements and orientations (Taylor and Cluff, 1973: Hathaway and Leighton, 1979; Slemmons and dePolo, 1992; Price, 1998; California Geological Survey, 2002; McCalpin, 2009; DuRoss, 2015). Trenches across normal faults are usually excavated perpendicular to the fault scarp. Because fault displacement may vary along strike, the investigation should determine the maximum displacement(s) along the fault trace(s) within the part of the site to be developed, and at least one trench should be excavated across the highest part of each scarp.

Zones of deformation are common along major normal fault traces (figure 11). Such deformation typically consists of a graben or multiple discrete displacements on secondary faults. The trench investigation should define the width of the deformation zone, and for sites in a graben, trenches should be excavated perpendicular to the bounding faults across the entire part of the site within the graben to investigate for faults and/or shears in the graben floor. Ground deformation in the absence of surface faulting may occur above buried normal faults. In those instances, trenching should extend across the entire deformation zone such that the deformation can be adequately documented and characterized.

Trench number and location: The purpose of a trenching investigation and objectives in locating trenches may vary depending on the type of development and project design phase during which the investigation is performed. When investigations are performed prior to site design, such as for multi-unit subdivisions, commercial development, etc., trenches are used to locate faults and recommend risk-mitigation measures to aid in project design. When investigations are performed after building locations have been laid out or structures already constructed and subsequently found to be on or near a hazardous fault, trenches may be used to identify faults trending through building footprints (figure 15). Trenches should be oriented perpendicular, or as close to perpendicular as possible, to the

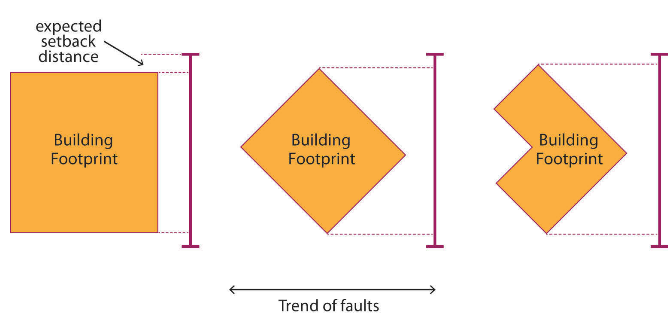

Figure 15. *Fault trench length and orientation to investigate a building footprint. Trenching must extend beyond the footprint of at least the expected setback distance for the IBC Building Risk Category class (from Christenson and others, 2003).*

trend of the mapped fault trace at or near the site, and be of adequate length to intercept faults projecting toward proposed or existing structures and potential setback areas. In some instances, placing trenches off-site on adjacent or nearby properties may be necessary to adequately characterize the hazard.

More than one trench may be necessary to investigate a site or building footprint, particularly when the proposed development is large, involves more than one building, and/or is characterized by complex faulting (figure 16). Trenches should provide continuous coverage across a site (one trench or overlapping trenches; figure 17). Geologic mapping (figure 11) and paleoseismic trenching (see publications in the UGS Paleoseismology of Utah series) have shown that patterns of ground deformation resulting from past surface faulting on normal faults in Utah are highly variable, and may change significantly over short distances along the strike of the fault. While a single trench provides data at a specific fault location, multiple trenches are often required to characterize along-strike variability of the fault and provide a more comprehensive understanding of faulting at the site. For that reason, the UGS recommends that subsurface data generally not be extrapolated more than 300 feet without additional subsurface information. Complex fault zones may require closer trench spacing. When trenches must be offset to accommodate site conditions, sufficient overlap should be provided to avoid gaps in trench coverage. Tightly spaced trenches may only need minor (a few tens of feet) overlap; however, more widely spaced trenches require greater overlap to ensure continuous site coverage. Care should be taken not to offset trenches at a common surficial feature that could be related to prehistoric surface faulting (e.g., a change in surface slope across the site).

Test pits may provide some useful information regarding subsurface site conditions; however, they are not an acceptable alternative to trenches for evaluating surface-faulting hazard. A series of aligned test pits perpendicular to the fault trend may

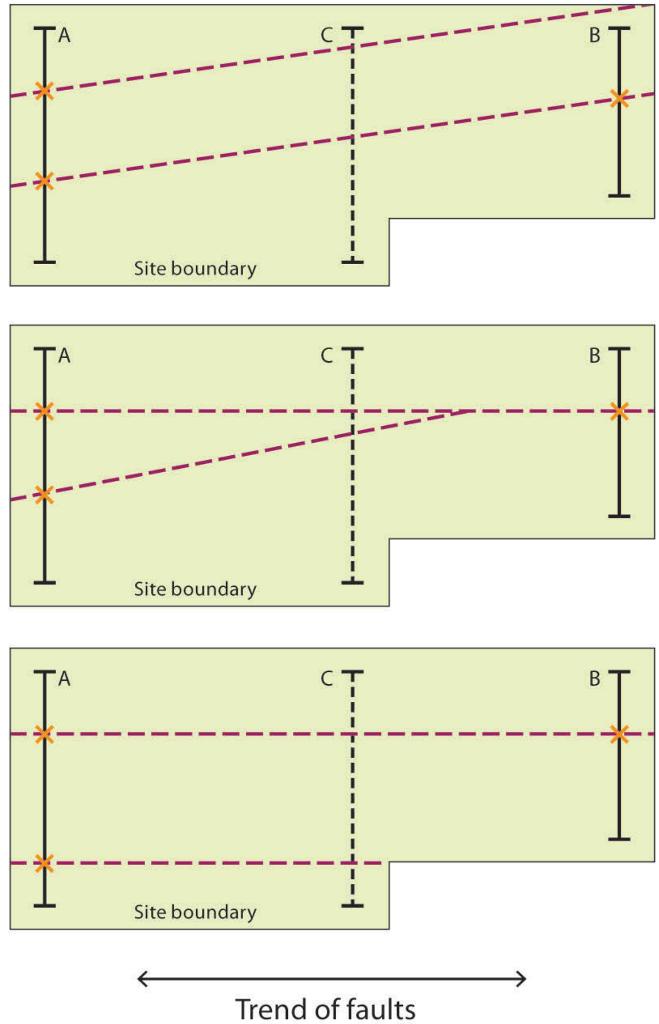

Figure 16. *Three possible fault configurations (dashed lines) from fault exposures (x) in only two trenches (A and B) showing the need to measure fault orientation and excavate additional trenches (C) to clarify fault-trend geometry, particularly when fault traces are not mappable at the surface (from Christenson and others, 2003).*

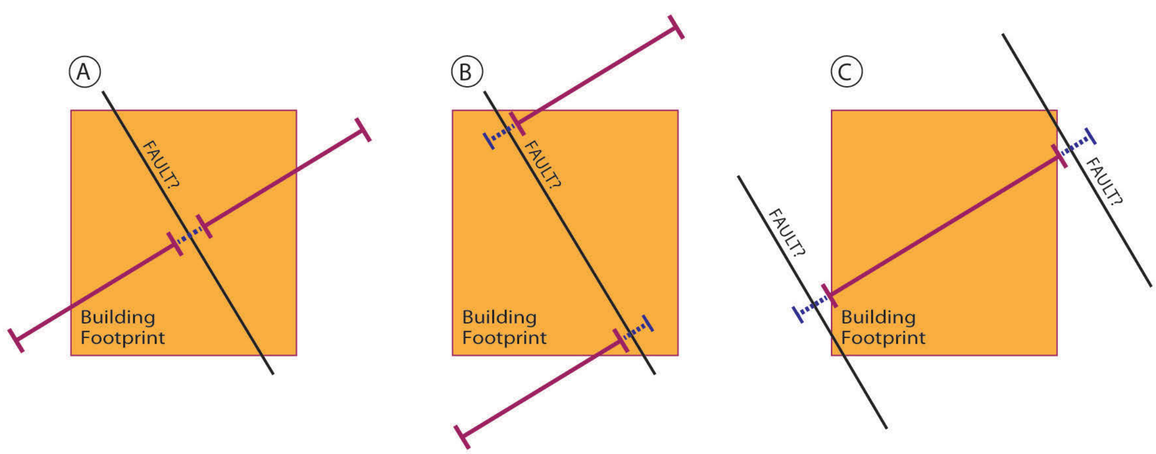

Figure 17. *Potential problems caused by improper trench locations: (A) gap between trenches, (B) trenches without adequate overlap, and (C) trench does not fully cover building footprint given fault trend. Dashed lines indicate additional trench length needed (from Christenson and others, 2003).*

help locate a main fault trace, but cannot conclusively demonstrate the presence or absence of faulting because faults trending between test pits would not be exposed.

Trenches and faults should be accurately located on site plans and fault maps. The UGS recommends that trenches and faults (projected to the ground surface) be surveyed rather than located using a hand-held GPS device.

Trench depth: Trenches should at a minimum be deep enough to expose (1) native, undisturbed geologic units, (2) evidence of the most recent surface faulting, and (3) all relevant aspects of fault geometry (dip, width of shear zones and grabens, and subsidiary hanging-wall and footwall faults). Ideally, to demonstrate a lack of faulting, trenches should extend to the base of Holocene deposits (for Holocene faults), late Quaternary deposits (for late Quaternary faults), and Quaternary deposits (for Quaternary faults). Each site and fault is unique and exceptions are possible, but in general, one recurrence interval (time between the most recent and penultimate surface-faulting earthquakes) is not sufficient to characterize surface-faulting recurrence or estimate the probability of the next surface-faulting earthquake. Therefore, where engineering-design is proposed to mitigate surface faulting and additional information on past earthquake displacement and timing is required for design purposes, deeper trenches may be necessary to adequately characterize the fault's earthquake history.

Where the maximum trench depth achievable, generally 15 to 20 feet, is not sufficient to adequately characterize past fault activity, and a potentially hazardous fault may be concealed by unfaulted younger deposits, the practical limitations of trenching should be acknowledged in the report and uncertainties should be reflected in report conclusions and recommendations. In cases where an otherwise well-defined hazardous fault is buried too deeply at a particular site to be exposed in trenches, the uncertainty in its location can be addressed by increasing fault setback distances along a projected trace (see Hazardous Fault Avoidance section below).

Trench investigations should be performed in compliance with current Occupational Safety and Health Administration (OSHA) excavation safety regulations and standards (http://www.osha.gov/SLTC/trenchingexcavation/construction.html) (see chapter 2, Excavation Safety section). Additionally, for some projects, the design engineer may want trenches to be backfilled as engineered (compacted) fill to avoid future soil settlement.

Trench logging and interpretation: In preparation for logging, trench walls should be carefully cleaned to permit direct observation of the geology. Trenches should be logged at a minimum scale of 1 inch equals 5 feet (1:60); in some instances, small but important features may be best documented with local detailed logs at larger scale (e.g., 1 inch = 1 foot [1:12]). All logs should be prepared in the field under the direct supervision of an experienced Utah licensed Professional Geologist. Vertical and horizontal logging control should be used and shown on the log. The logs should not be generalized or diagrammatic, and may be on a rectified photomosaic base. The log should document all pertinent information from the trench (e.g., Birkeland and others, 1991; U.S. Bureau of Reclamation, 1998b; Walker and Cohen, 2006; McCalpin, 2009; DuRoss, 2015), including:

- Trench and test-pit orientation and indication of which wall was logged
- Horizontal and vertical control
- Top and bottom of trench wall(s)
- Stratigraphic contacts
- Detailed lithology and soil classification and descriptions
- Contact descriptions
- Pedogenic soil horizons
- Marker beds
- Fissures and faults
- Fissure and fault orientations and geometry (strike and dip)
- Fault displacement
- Sample locations

Geochronology: The engineering geologist interprets the ages of sediments exposed in a trench to determine the timing of past surface faulting. In the Bonneville basin of northwestern Utah, the relation of deposits to latest Pleistocene Bonneville lake-cycle chronology (Gilbert, 1890; Currey, 1982, 1990; Currey and others, 1988; Oviatt and others, 1992; Godsey and others, 2005, 2011; Benson and others, 2011; Janecke and Oaks, 2011; Hylland and others, 2012; Miller and others, 2013; Oviatt, 2015) is commonly used to infer ages of sediments, and thus estimate the timing of surface faulting. The same is also true for Pleistocene-age glacial deposits found at the mouths of some Wasatch Range canyons. For example, unfaulted Lake Bonneville highstand sediments or glacial deposits in a trench provide evidence that faulting has not occurred at that site since the latest Pleistocene (past ~14 to 18 kyr). However, outside the Lake Bonneville basin, and within the basin above the highest lake shoreline, determining the age of surficial deposits is less straightforward and commonly requires advanced knowledge of local Quaternary stratigraphy and geomorphology, and familiarity with geochronologic dating methods.

At sites lacking deposits of known age, a variety of geochronologic methods are available to determine the age of deposits and constrain the timing of past surface faulting (see Geochronology section, chapter 2). Engineering geologists conducting surface-faulting investigations in Utah should have a proficient working knowledge of useful and commonly applied geochronologic techniques (see chapter 2, table 4). That knowledge must extend to evaluating sources of age uncertainty, in particular sample context uncertainty, and the proper protocols for collecting and handling samples to preserve sample integrity and prevent contamination. In instances where geochronologic data are critical to surface-faulting investigation and project design, the investigation may benefit from retaining an expert in the application and interpretation of geochronologic methodologies.

Numerical dating methods may include, but are not limited to, radiocarbon, optically stimulated luminescence and other luminescence techniques, $^{39}Ar/^{40}Ar$, K-Ar, tephrochronology, dendrochronology, and cosmogenic isotopes (Curtis, 1981; Forman, 1989; Noller and others, 2000; McCalpin, 2009; Gray and others, 2015). Relative dating techniques may be applied (but not limited) to, soil (pedogenic) profile development, slope morphometric dating, stratigraphic relations, relative geomorphic position, and fossils (Forman, 1989; Birkeland and others, 1991; Noller and others, 2000; McCalpin, 2009).

Other Subsurface Investigation Methods

Other investigation methods, such as cone penetrometer test soundings, boreholes, and geophysical techniques, can supplement trenching and extend the depth of investigation. The same depth relations for Holocene, late Quaternary, and Quaternary faults as described for trenching also apply to these other subsurface investigation methods.

Cone penetrometer test soundings: Although an indirect investigation method, cone penetrometer test (CPT) soundings are in some circumstances an applicable investigative method for evaluating the presence of faults where trenching is either not possible, or the deposits of interest are too thick to investigate with a trench. CPT soundings permit collection of data on geologic units and groundwater, and in some instances, can identify offset in geologic units indicative of faulting. The number and spacing of CPT soundings should be sufficient to reliably interpret site stratigraphy, correlations, and interpretations.

Boreholes: Boreholes are useful for general characterization of subsurface site conditions (e.g., geologic units, groundwater) where Quaternary faults are present, particularly where trenching is not possible. However, vertical boreholes generally do not provide sufficient resolution to confidently identify and characterize subsurface faults, and seldom can prove the presence or absence of a fault or determine the time of faulting. Better results identifying faults may be obtained where directional drilling and sampling are possible. However, continuous core and other sampling methods rarely yield 100 percent recovery, and may miss faults. Therefore, boreholes should only be used to supplement other subsurface investigation methods, or be utilized when no other method of subsurface investigation is feasible. When used, boreholes should be sufficient in number and adequately spaced to permit reliable correlations and interpretations.

Geophysical investigations: Geophysical investigations are indirect, non-destructive methods that can be reliably interpreted when site-specific surface and subsurface geologic conditions are known. Geophysical methods should seldom be employed without knowledge of site geology; however, where no other subsurface geologic information is available, geophysical methods may provide the only economically viable means to perform deep geologic reconnaissance (e.g., Chase and Chapman, 1976; Telford and others, 1990; Sharma, 1998; U.S. Bureau of Reclamation, 2001; Milsom and Eriksen, 2011; Reynolds, 2011).

Although geophysical methods may detect the presence and location of shallow fault planes, such methods alone never prove the absence of a fault at depth or the time (age) of faulting. Geophysical methods can provide critical stratigraphic information on both basin-fill and bedrock units that may not otherwise be available. Geophysical techniques used may include, but are not limited to, high-resolution seismic reflection, high-resolution seismic tomography, ground penetrating radar, seismic refraction, magnetic profiling, electrical resistivity, and gravity.

Special Case – Sub-Lacustrine Faults

Quaternary-active normal faults are present beneath Great Salt Lake (Great Salt Lake fault zone and Carrington fault) and Utah Lake (Utah Lake faults). There are currently no known subaerial exposures of these faults. The faults are identified and their lengths and segmentation defined based on seismic reflection and other geophysical studies (Mikulich and Smith, 1974; Cook and others, 1980; Viveiros, 1986; Mohapatra and Johnson, 1998; Dinter and Pechmann, 2000, 2005, 2015; Colman and others, 2002; Dinter, 2015).

Paleoseismic evidence (including stratigraphic displacements, subsidiary fault terminations, and differential tilting) interpreted from high-resolution seismic reflection profiles show that the Great Salt Lake fault zone consists of four seismically independent segments. Radiocarbon ages from event horizons sampled in drill cores indicate at least three large surface-faulting earthquakes have occurred on each of these segments in the past 12 kyr (Dinter and Pechmann, 2000, 2005, 2014, 2015). The Carrington fault is less well studied, but is ~19 miles long with scarps as high as 5 feet. Earthquake times are unconstrained on the Carrington fault, but based on similarities of other lakebed scarps, the slip rate and recurrence interval of the Carrington fault are thought to be similar to the segments of the Great Salt Lake fault zone (WGUEP, 2016).

The Utah Lake faults are a complex system of east- and west-dipping normal faults. Seismic reflection profiles suggest that as many as eight surface-rupturing, north-striking faults displace very young lake sediments 3 to 10 feet (Dinter, 2015). Because these faults occupy a similar hanging-wall position in relation to the Provo segment of the Wasatch fault zone as does the West Valley fault zone to the Salt Lake City segment of the Wasatch fault zone, best available information for the West Valley fault zone is currently used as an analog for the Utah Lake faults.

Based on available evidence, faults beneath Great Salt Lake and Utah Lake are potential sources of future large earthquakes. With no known subaerial exposures, the likelihood of surface-faulting displacement on any of these faults having a direct impact on the health, safety, or welfare of Utah citizens is low. Although subaerial fault exposures have not yet been identified, careful investigation for evidence of surface faulting remains prudent for projects proposed where faults beneath Great Salt Lake and Utah Lake project to the shoreline. If evidence of surface faulting is found, a subsurface investigation should be conducted to fully characterize the surface-faulting hazard. Additionally, future surface faulting on these faults could generate a tsunami (surface-faulting induced water wave) that may damage facilities along the shores of the lake, causing an indirect negative impact from surface faulting.

SURFACE-FAULTING MITIGATION

Background

Municipal and county geologic-hazard ordinances in Utah use the term “active” fault as a synonym for “hazardous,” and typically define activity (relative hazard) by applying an age criterion: “active” faults have evidence of displacement during the Holocene (approximately the past 11,700 years). The Holocene criterion has precedence, principally from past application in California for implementing the Alquist-Priolo Earthquake Zoning Act (Bryant, 2010; Tepel, 2010; California Geological Survey, 2011b, 2013), and in the Western States Seismic Policy Council’s (WSSPC) definitions of fault activity categories in the Basin and Range Province (WSSPC, 2011). However, several historical surface-faulting earthquakes in the Basin and Range Province occurred on normal faults with no evidence of previous Holocene activity (Walter, 1934; Bull and Pearthree, 1988; Bell and Katzer, 1990; Pearthree, 1990; Bell and others, 2004; Caskey and others, 2004; Suter, 2006; Wesnousky, 2008). Those earthquakes demonstrate that a single Holocene criterion is not sufficient to identify potentially hazardous faults in the interior western United States that may produce future surface faulting in a time frame relevant to land-use management and regulation.

Until recently (e.g., Bray 2001, 2009a, 2009b, 2015), designing a structure to withstand fault displacement at the ground surface was generally considered impractical. For that reason, the standard of practice in Utah has been to avoid construction on active faults by locating the fault and setting back a prescribed distance from it (Christenson and others, 2003). However, since the release of the Christenson and others (2003) guidelines, some Utah jurisdictions have adopted ordinances that permit construction across active faults that show ≤ 4 inches of displacement. Additionally, under a special “Review Protocol” the City of Draper (2005) permits “super-engineering” of foundations under limited circumstances (Dobbins and Simon, 2015) to mitigate surface-faulting displacements that are greater than the 4 inches permitted in the city’s current geologic-hazard ordinance. Super-engineered foundations designed to accommodate as much as 6 feet of vertical displacement have been approved by the City of Draper (David Dobbins, Draper City Manager, verbal communication, 2015).

Considering the limited paleoseismic data available for most Utah Quaternary faults, and the length of their surface-faulting recurrence intervals (typically hundreds to thousands of years), the UGS considers fault setback and avoidance the safest and most effective surface-faulting-mitigation option for most Utah faults. However, recognizing that engineering-design mitigation of surface faulting is now permitted by some Utah jurisdictions, these guidelines include a review of the fault parameter data required to fully characterize past fault activity, and recommendations regarding the kind and amount of paleoseismic data necessary for engineering-design mitigation of surface faulting (see Paleoseismic Data Required for Engineering-Design Mitigation of Surface Faulting section below).

Additionally, discussion has begun in Utah (UQFPWG, 2013; Lund, 2015) and elsewhere (e.g., Shlemon, 2010, 2015; Gath, 2015) regarding the appropriateness of using the long time interval represented by the Holocene for evaluating surface-faulting hazard. The Hazardous Fault Criteria section below discusses this issue relative to Utah’s normal-slip faults, and provides recommendations for the kind of information on past earthquake timing necessary for implementing data-driven decisions regarding surface-faulting mitigation.

Surface-Faulting Special-Study Maps

As a critical first step to ensure that surface-faulting hazard is adequately addressed in land-use planning and regulation, local governments should prepare surface-faulting special-study maps which define areas within which a surface-faulting investigation is required prior to development (figure 10). The UGS has prepared or assisted with preparation of surface-faulting special-study maps for Cache, Davis, Iron, Salt Lake, eastern Tooele, Utah, western Wasatch, and Weber Counties (on file with the respective municipal and county planning departments). Similar UGS special-study-area maps are available for the St. George-Hurricane metropolitan area (Lund and others, 2008), high-visitation areas in Zion National Park (Lund and others, 2010), the Magna and Copperton 7.5-minute quadrangle areas in Salt Lake Valley (Castleton and others, 2011, 2014), and the State Route 9 corridor between La Verkin and Springdale (Knudsen and Lund, 2013). The UGS is conducting a long-term, geologic-hazard-mapping initiative to prepare geologic-hazard-map sets for select 7.5-minute quadrangles in Utah (Castleton and McKean, 2012). Where Quaternary faults are present, these hazard-map sets will include surface-faulting special-study maps (e.g., Castleton and others, 2011).

When preparing a surface-faulting special-study map, the UGS recommends that the width of special-study areas defined along faults vary depending upon whether a fault is well defined (Bryant and Hart, 2007), approximately located, or buried. The trace of a well-defined fault is clearly detectable as a physical feature at the ground surface (typically shown as a solid line on a geologic map) by a geologist qualified to conduct surface-faulting investigations. For a well-defined fault, the UGS recommends that special-study areas extend horizontally 500 feet on the downthrown side and 250 feet on the upthrown side of mapped fault traces or the outermost faults in a fault zone (figure 10; e.g., Lund and others, 2008, 2010; Castleton and others, 2011, 2014; Knudsen and Lund, 2013). In areas of high scarps where 250 feet on the upthrown side does not extend to the top of the scarp, the UGS recommends that the special-study area increase to 500 feet on the upthrown side (Robison, 1993). An approximately located or buried fault is not evident at the ground surface for a significant distance, and is typically shown as a dashed line for approximately located faults and as a dotted line for buried faults on a geologic map. The UGS recommends that special-study areas for approximately located or buried faults extend horizontally 1000 feet on either side of the estimated fault location (e.g., Lund and others, 2008, 2010; Castleton and others, 2011, 2014; Knudsen and Lund, 2013).

Where special-study-area maps are not available, the first step in a surface-faulting investigation is to determine if the site is near a mapped Quaternary fault (see discussion of the *Quaternary Fault and Fold Database of the United States* [USGS, 2015] and *Utah Quaternary Fault and Fold Database* [UGS, 2016] in the Sources of Paleoseismic Information section above). If so, existing larger scale maps (if available) should be examined, aerial photographs and other remote-sensing data interpreted, and field investigations performed to produce detailed geologic maps as outlined in these guidelines to determine whether the fault is within 500 feet of the site if the fault is well defined, or within 1000 feet if the fault is approximately located or buried. If faults are found or suspected within these distances, the UGS recommends trenching or other subsurface investigations as outlined in these guidelines. Also, investigations as outlined in the Surface-Faulting-Hazard Investigation section should be conducted for all IBC Risk Category III and IV facilities (ICC, 2014a), whether near a mapped Quaternary fault or not, to ensure that previously unknown faults are not present. If evidence for a fault is found, the UGS recommends a subsurface investigation. See also the Engineering-Geology Investigations section of chapter 2 for additional information on performing geologic-hazard field investigations.

Hazardous Fault Avoidance

Utah's Quaternary faults exhibit a wide range of recurrence intervals and slip rates. Ideally, decisions regarding the need to mitigate surface faulting should be based on a risk assessment that considers the time of the most recent surface faulting and the average recurrence interval between previous surface-faulting earthquakes to determine the probability of surface faulting within a future time frame of interest (see Characterizing Fault Activity section above). However, with the possible exception of the five central, Holocene-active segments of the Wasatch fault zone (DuRoss and Hylland, 2015; DuRoss and others, 2016; WGUEP, 2016), available paleoseismic data for faults in Utah are generally insufficient to make such data-based risk determinations, and the ability to acquire the new earthquake timing, recurrence, and displacement data necessary to do so may be limited by site geologic conditions, property access, and/or budget and time constraints. Additionally, the natural variability of fault behavior (aleatory variability) and the uncertainty resulting from lack of necessary data to characterize fault activity (epistemic uncertainty) may combine to preclude the confident determination of the probability of future earthquake timing, displacement, and rupture complexity at a site. Therefore, setting back from and thereby avoiding potentially hazardous faults is often the most technically feasible and effective method to mitigate surface faulting. It is also the most satisfactory and safest (conservative) long-term solution for both current and future land owners, since the hazard is avoided regardless of the timing of the next surface-faulting earthquake. For those reasons, avoidance is the principal surface-faulting risk-mitigation technique specified by geologic-hazard ordinances in Utah, and the UGS considers avoidance the safest long-term surface-faulting mitigation option presently available.

Fault Activity Classes

A fault avoidance mitigation strategy relies on a "time-of-most-recent-rupture" fault activity classification to identify active (hazardous) faults for which avoidance is deemed necessary. The previous version of these guidelines (Christenson and others, 2003) adopted the then-current fault activity class definitions for the Basin and Range Province proposed by WSSPC (http://www.wsspc.org/). Those definitions were first adopted by WSSPC in 1997, and evolved through subsequent revisions in 2005, 2008, and 2011. Beginning in 2011, the policy recommendation included a substantial change to the fault activity class definition for the Quaternary to comply with revisions to the *Global Chronostratigraphical Correlation Table for the Last 2.7 Million Years, v. 2010* (International Commission on Stratigraphy, 2009; Cohen and Gibbard, 2010). These revisions redefined the lower boundary of the Quaternary from 1.8 to ~2.6 (actual 2.588) Ma. In compliance with the new standard (now generally accepted within the international geologic community), the UGS adopted 2.6 Ma as the lower boundary for the Quaternary for the *Utah Quaternary Fault and Fold Database*. Conversely, the USGS for purposes of seismic-hazard analysis continues to define the base of the Quaternary as 1.6 Ma in the *Quaternary Fault and Fold Database of the United States* (the USGS has adopted 2.6 Ma for other purposes). It is beyond the scope of these guidelines to resolve this discrepancy; the UGS recommends that both fault databases be consulted when performing a surface-faulting investigation.

For the purpose of these guidelines, the UGS follows the WSSPC (2011) definitions of fault activity classes:

- Holocene fault – a fault whose movement in the past 11,700 years before present [10,000 ^{14}C yr B.P.] has been large enough to break the ground surface.
- Late Quaternary fault – a fault whose movement in the past 130,000 years before present has been large enough to break the ground surface.
- Quaternary fault – a fault whose movement in the past 2.6 million years before present has been large enough to break the ground surface.

The last two classes are inclusive; that is, Holocene faults are included within the definition of Late Quaternary faults, and both Holocene and Late Quaternary faults are included in Quaternary faults. The activity class of a fault is the youngest class based on the demonstrated age of most recent surface faulting. The UGS recommends that in the absence of information to the contrary, all Quaternary faults be considered Holocene unless there are adequate data to confidently assign them to the Late Quaternary or Quaternary activity class.

The *Quaternary Fault and Fold Database of the United States* (USGS, 2015) and the *Utah Quaternary Fault and Fold Database* (UGS, 2016) summarize existing fault data for known Utah Quaternary faults, and estimate the timing of most recent surface faulting. However, neither fault compilation was prepared for use in assigning activity classes for land-use planning and regulation. The timing reported for the most recent surface faulting represents best (non-conservative) age estimates based on data in existing studies. These estimates, particularly for many pre-Holocene faults, typically are based on limited reconnaissance studies and are not adequate to determine activity classes to assess the need for site-specific surface-faulting investigations. Additionally, while the databases are periodically updated, new information for a fault may become available that has not yet been incorporated into the databases. It is the responsibility of the engineering geologist performing a surface-faulting investigation to ensure that all sources of paleoseismic data available for a site have been identified and reviewed.

Investigation Recommendations

When avoidance using fault setback is the risk-mitigation option selected, the UGS recommends that surface-faulting investigations be performed based on the modified IBC Risk Categories shown in table 12 and the following WSSPC (2011) fault activity classes:

- **Holocene faults** – recommended for all structures for human occupancy and all IBC Risk Category II(a), II(b), III, and IV structures.
- **Late Quaternary faults** – recommended for all IBC Risk Category II(b), III, and IV structures. Investigations for IBC Risk Category II(a) and other structures for human occupancy remain prudent, but local governments should base decisions 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. Earthquake risk-assessment techniques are summarized by Reiter (1990), Yeats and others (1997), and McCalpin (2009).
- **Quaternary faults** – studies are recommended for all IBC Risk Category III and IV structures. Investigations for IBC Risk Category II(b) structures and other structures for human occupancy remain prudent because a low likelihood of surface faulting still exists.

As noted above, the UGS recommends that in the absence of information to the contrary, all Quaternary faults be considered Holocene unless there are data to confidently assign them to a Late Quaternary or Quaternary activity class.

Fault Setbacks

The UGS recommends that Salt Lake County's formulas for calculating fault setbacks for normal faults (Batatian and Nelson, 1999; Salt Lake County, 2002b; Christenson and others, 2003) as presented below be used throughout Utah. Unlike a simple "one setback distance fits all" approach (i.e., McCalpin, 1987), the Salt Lake County setback formulas adjust setback distances based on maximum anticipated fault displacements (greater setbacks for greater displacements), and also account for deep foundations and basements in structures close to a fault trace on the downthrown side of the fault. The method should be used to calculate the recommended fault setback distance for structures, depending on their IBC Risk Category (ICC, 2014a) and fault activity class, as shown in table 12. Table 12 is a revision of table 1 in Christenson and others (2003), and replaces IBC Building Occupancy Classes with IBC Risk Categories (ICC, 2014a), thus tying setback distances directly to risk. Variables used in the equations are shown on figure 18, and an example of a fault setback calculation is given below. Note that where an antithetic fault(s) is present at a site, a fault setback distance must be determined for it as well. This calculation method is for use with normal faults only. If reverse, thrust, or strike-slip faults are present (e.g., figure 14), the engineering geologist should provide the geologic justification in the report for the fault setback determination method used. Faults and fault setbacks should be clearly identified on the site-specific geology or fault map (see Surface-Faulting-Investigation Report Guidelines section below).

Table 12 presents minimum fault setback recommendations for IBC Risk Categories (Risk Category II subdivided into categories II(a) and II(b) for purposes of these guidelines). The calculated fault setback using the formulas presented below is compared to the minimum fault setback in table 12, and the greater of the two is used. Minimum fault setbacks in

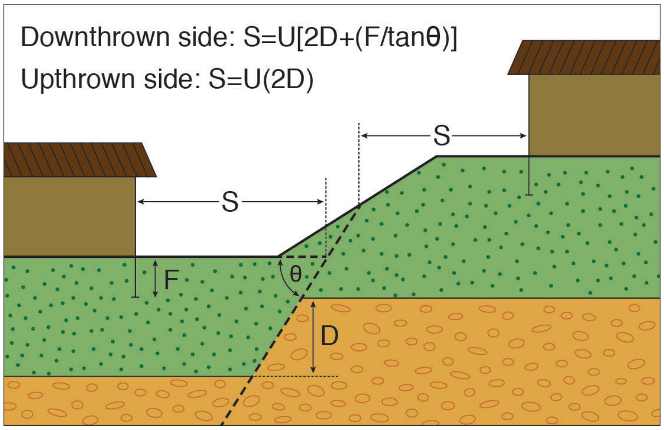

Figure 18. *Schematic diagram illustrating fault setback calculation (modified from Christenson and others, 2003).*

table 12 apply to both the downthrown and upthrown blocks. These fault setbacks apply only to surface faulting; greater setbacks may be necessary for slope, property boundary, or other considerations.

Downthrown block: The fault setback for the downthrown block is calculated using the formula:

$$S = U * \left[2D + \left(\frac{F}{\tan\theta}\right)\right]$$

where:

S = Fault setback distance within which buildings are not permitted (feet).

U = Criticality factor, based on IBC Risk Category (table 12).

D = Expected maximum fault displacement per earth quake (maximum vertical displacement) (feet).

F = Maximum depth of footing or subgrade portion of the building (feet).

θ = Fault dip (degrees).

Fault displacement is the maximum vertical displacement measured for an individual surface-faulting earthquake at the site (not necessarily the displacement of the most recent surface-faulting event). If a range of displacements is possible (e.g., because of uncertainty in how geologic layers or contacts are correlated or projected into the fault zone), the largest possible displacement value should be used. If per-earthquake displacements cannot be measured on site, the maximum displacement based on paleoseismic data from nearby paleoseismic investigations on the fault or segment may be used. In the absence of nearby data, consult DuRoss (2008) and DuRoss and Hylland (2015) for the range of displacements measured on the central segments of the Wasatch fault zone. Lund (2005) reports limited displacement information for some other Utah Quaternary faults.

Fault setback distances on the downthrown block are measured from where the fault intersects the final grade level for the building (figure 18). For dipping faults, if the fault trace daylights in the face of a scarp above final building(s) grade, the fault setback is taken from where the fault would intersect the final grade level for the building(s), rather than where it daylights in the scarp.

Upthrown block: Because the fault setback is measured from the portion of the building closest to the fault, whether subgrade or at grade, the dip of the fault and depth of the subgrade portion of the structure are irrelevant in calculating the fault setback on the upthrown block. The fault setback for the upthrown side of the fault is calculated as:

$$S = U * (2D)$$

Fault setback distances on the upthrown block are measured from where the fault trace daylights at the surface, commonly in a scarp. Minimum fault setback distances apply as discussed above. Note that S and D are measured in feet for comparison to minimum fault setbacks in table 12.

Example of a fault setback calculation: Here, we consider a hypothetical example where trenching along the Wasatch fault zone in southern Salt Lake County identified the main trace of the fault and an antithetic fault crossing a property. Maximum displacement (D) on the main fault for the most recent surface-faulting earthquake at the site was 8.5 feet. The main fault dipped 70 degrees (θ) to the west. Displacement on the antithetic fault was 2 feet, dipping 50 degrees to the east. Development plans call for a 250-seat theater (Risk Category II(b); criticality factor [U] = 2) with basements requiring 8-foot foundation depths (F). The setback from the main fault is calculated as follows:

Downthrown (western) block

$$\begin{aligned} &= U * \left[2D + \left(\frac{F}{\tan\theta}\right)\right] \\ &= 2 * \left[(2)(8.5\,feet) + \left(\frac{8\,feet}{\tan 70^{\circ}}\right)\right] \\ &= 2 * (17 \text{ feet} + 3 \text{ feet}) \\ &= 40 \text{ feet} \end{aligned}$$

Upthrown (eastern) block

$$\begin{aligned} &= U * (2D) \\ &= 2 * (2) * (8.5\,feet) \\ &= 34 \text{ feet} \end{aligned}$$

The 40- and 34-foot calculated setback distances are to be applied respectively, because they are greater than the 20-foot minimum fault setback (see table 12).

We do not know whether the 2-foot displacement on the antithetic fault represents cumulative displacements from multiple surface-faulting earthquakes, or resulted from a single surface-faulting earthquake; therefore, we must assume all displacement occurred during a single earthquake. The setback from the antithetic fault is calculated as follows:

Downthrown (eastern) block

$$= U * \left[2D + \left(\frac{F}{\tan\theta}\right)\right]$$

$$= 2 * \left[(2)(2\,feet) + \left(\frac{8\,feet}{\tan 50^{\circ}}\right)\right]$$

$$= 2 * (4 \text{ feet} + 7 \text{ feet})$$

$$= 22 \text{ feet}$$

Upthrown (western) block

$$= \text{U} * (2\text{D})$$

$$= 2 * (2) * (2 \text{ feet})$$

$$= 8 \text{ feet}$$

The 22-foot calculated fault setback is greater than the 20-foot minimum setback (see table 12); therefore, the fault setback on the downthrown block is 22 feet. Because 8 feet is less than the 20-foot minimum fault setback, the fault setback on the upthrown block is 20 feet.

Surface Deformation from Slip on a Buried Fault

Surface deformation (folding, warping, monoclinal flexures) from slip on a buried fault that did not produce discrete fault rupture at the ground surface has occurred along some Utah Quaternary faults (e.g., Keaton, 1986; Keaton and others, 1987b; Hylland and others, 2014). Zones of surface deformation can be narrow (a few feet to tens of feet) resulting from localized extensional or compressional strain at the axis of a fold or warp, or broad zones (tens to hundreds of feet) of tilting or rotation (Erslev, 1991; Kelson and others, 2001; Chen and others, 2007). Narrow zones of deformation may produce scarp-like geomorphic features (Keaton and others, 1987b; Hylland and others, 2014); broad zones may be subtle and difficult to detect at the ground surface. In some instances (typically trenches with well-defined stratigraphy), it is possible to determine net displacement across a fold or warp. Keaton and others (1987b) measured 3.9–4.9 feet of vertical displacement in a fold resulting from what they interpreted as a single earthquake on the central part of the Taylorsville fault. Hylland and others (2014) measured 1.6 feet of vertical displacement across a 26-foot-wide zone of broad warping on the Granger fault. Both the Taylorsville and Granger faults are part of the West Valley fault zone in Salt Lake Valley.

The potential surface-faulting hazard presented by tectonic surface deformation in the absence of discrete faulting is difficult to assess because past rupture on the causative fault did not extend to the ground surface. It is unknown whether future rupture on the fault will continue to deform the ground surface without surface faulting, or if future rupture will extend to the surface and create a surface-faulting hazard.

Surface deformation caused by slip on a buried fault lacks a discrete zone of displacement and in some cases may be many feet wide. Therefore, with the possible exception of the axis of a tight kink fold, establishing standard fault setback distances or implementing a standardized method for calculating fault setbacks for surface deformation as is done for surface faulting is generally not possible (see Hazardous Fault Avoidance section above). Past mitigation measures employed in Utah for structures built in surface deformation zones have consisted of engineering-design techniques such as reinforced slab-on-grade foundations and flexible utility lines and hookups (Bill Black, Western GeoLogic, written communication, 2014).

Quantifying the future effects of surface faulting at a site within a surface deformation zone may not be possible even after a careful investigation, because tectonic surface deformation may expand over time, or future rupture on the causative fault may eventually extend to the ground surface. Therefore, the UGS does not make a standard recommendation for mitigating tectonic surface deformation in the absence of discrete faulting, but rather recommends that the engineering geologist in responsible charge of the surface-faulting investigation make and justify an appropriate mitigation recommendation based on the results of a site-specific hazard investigation. Whether that recommendation is to set back from a narrow deformation zone or to implement engineering-design mitigation methods will depend on individual site conditions and project considerations. Barrell (2010) provides an example from New Zealand of the classification and proposed mitigation of tectonic surface deformation in the absence of surface faulting.

Paleoseismic Data Required for Engineering-Design Mitigation of Surface Faulting

Most geologic-hazard ordinances in Utah limit surface-faulting mitigation to setting back a prescribed distance from an active (hazardous) fault (see Hazardous Fault Avoidance section above). However, some Utah jurisdictions now permit construction across Holocene-active faults having ≤ 4 inches of displacement. Some of these ordinances specify that reasonable geologic data must be available to show that future surface displacement along the fault will not exceed 4 inches, and require that a structural engineer provide an appropriate engineering design to minimize structural damage. Additionally, under a special “Review Protocol” the City of Draper (2005) has permitted “super-engineered” foundations designed to accommodate surface-faulting displacements of as much as 6 feet (David Dobbins, Draper City Manager, verbal communication, 2015).

Utah’s engineering-design surface-faulting mitigation approaches are based on the assumptions that (1) a small displacement (≤ 4 inches) on a fault would not cause catastrophic structural collapse, and therefore does not represent a life-safety hazard to building occupants, and (2) a super-engineered foundation will provide life-safety protection in the event of much larger (multiple feet) displacements beneath an inhabited structure. Common to both approaches is the need to characterize past surface-faulting displacement to establish a reliable design displacement value for engineering-mitigation design. The design displacement value must be such that it will not be significantly exceeded (within 2σ uncertainty limits) during future surface-faulting earthquakes.

Displacement data for normal-slip faults in Utah (DuRoss, 2008), as well as worldwide datasets (e.g., Wesnousky, 2008; Hecker and others, 2013) show that considerable variation in displacement at a point may occur between successive earthquakes on a fault. Therefore, the displacement at a point produced by the most recent surface-faulting earthquake may not be a good predictor of future surface-faulting displacement at the same location. DuRoss (2008) documents as much as 6.9 feet difference in displacement at a point between successive surface-faulting earthquakes on the five central segments of the Wasatch fault zone. Lund and others (2015) reported ~50% variation in displacement at a point between the two most recent surface-faulting earthquakes on the Fort Pearce section of the Washington fault zone in northwestern Arizona. Hecker and others (2013) evaluated a worldwide dataset of faults having displacement information from multiple earthquakes, and determined that the coefficient of variation (standard deviation divided by the mean) for slip at a point is ~0.5, indicating significant displacement variability between earthquakes. McCalpin (1987) acknowledged the possible variability of displacement on secondary faults between earthquakes, and recommended that human-occupied structures not be sited across small-displacement faults (≤ 12 in) without careful subsurface documentation of the location and past displacement styles (direction and amount) of the faults.

A review of possible engineering-design methods to mitigate surface faulting is beyond the scope of these guidelines (see Bray, 2015, for a review of design techniques); however, all such methods rely on the ability of the engineering geologist to estimate within reasonable uncertainty limits (2σ) displacement at a point from future surface-faulting earthquakes. As discussed above, this is not a simple task, and can only be reliably achieved where site geology permits evaluating the fault's displacement history over multiple paleoearthquakes. Displacement data for a single paleoearthquake (most recent event) at a site does not provide a statistically significant basis for estimating probable future maximum earthquake displacement.

For engineering mitigation of surface faulting on normal-slip faults in Utah, the UGS recommends that displacements be determined for a minimum of three surface-faulting earthquakes at the site of interest (more if site geology permits), and that engineering-design mitigation be based on the maximum displacement observed on the fault in question including appropriate displacement uncertainty limits. Because displacement during a surface-faulting earthquake can vary significantly along fault strike (Crone and others, 1987; DuRoss, 2008; Hecker and others, 2013), displacement data used for engineering-design mitigation should be site specific; use of an offsite displacement value introduces an unacceptable level of uncertainty in the displacement design parameter.

Given the limited paleoseismic information available for most Utah Quaternary faults (the five central, Holocene-active segments of the Wasatch fault zone excepted), acquiring the detailed displacement data necessary for engineering mitigation of surface faulting will likely require a more detailed and costly (both in terms of time and money) paleoseismic investigation than is necessary to simply locate and setback from a potentially hazardous fault. Additionally, many sites will not possess the geologic conditions necessary to identify and characterize displacement for a minimum of three paleoearthquakes. For those reasons, the UGS believes fault setback and avoidance will remain the surface-faulting-mitigation option most frequently employed in Utah.

HAZARDOUS FAULT CRITERIA

Some geologists and engineers, chiefly in California, are reevaluating what constitutes a hazardous fault with regard to public health, safety, and welfare (e.g., Shlemon, 2010, 2015; Gath, 2015). As a result, the Holocene criterion used in California to define an "active" (hazardous) fault has been called into question as being unreasonably long when compared to the time intervals used to mitigate other kinds of natural hazards. Those geologists argue that no specific deterministic recurrence number should be used to define a hazardous fault, but rather mitigating surface faulting should be data driven, and rely on professional judgment, cost, available technology, and social constraints (acceptable risk) (Shlemon, 2010, 2015; Gath, 2015). Some Utah geologists have similarly begun discussing the appropriateness of the Holocene active-fault criterion as commonly applied in Utah (UQFPWG, 2013; Lund, 2015), and likewise advocate data-based decisions regarding surface-faulting mitigation when sufficient paleoseismic data are available.

Characterizing fault activity for engineering mitigation of surface faulting requires determining the fault's average surface-faulting recurrence and variability over multiple paleoearthquake cycles, as well as the time of most recent surface faulting. By comparing elapsed time since the most recent surface faulting earthquake with a well-constrained average recurrence interval, it is possible to estimate the probability that the fault will generate a future surface-faulting earthquake in a time interval of interest, although uncertainties may remain high, particularly for long-recurrence faults. Only when such detailed paleoseismic data are available can decisions regarding surface-faulting mitigation be reliably data driven. The following examples illustrate this point.

On the central Wasatch fault zone where earthquake timing and surface-faulting recurrence and variability are well constrained (figure 19), the average recurrence interval for surface faulting on the Salt Lake City segment for the past four surface-faulting earthquakes (three closed earthquake cycles) is 1300 ± 100 years, and the elapsed time since the most recent surface faulting is 1300 ± 200 years (DuRoss and Hylland, 2015; DuRoss and others, 2016), indicating that the Salt Lake City segment has met or exceeded its average recurrence interval and may produce a surface-faulting earthquake at any time. A note of caution: when evaluating average surface-faulting recurrence, "at any time" may range from now to hundreds of years from now. Individual recurrence intervals for the four most recent Salt Lake City segment earthquakes range from 800 ± 300 years to 1900 ± 300 years (DuRoss and Hylland, 2015). Conversely, the elapsed time since the most recent surface faulting on the Nephi segment is 200 ± 70 years (Crone and others, 2014; DuRoss and others, 2016), and the average recurrence for the past two earthquake cycles (three earthquakes) is 1100 ± 200 years, indicating that the Nephi segment may not generate another surface-faulting earthquake for several hundred years. Available paleoseismic data show that on average the Salt Lake City segment is more hazardous than the Nephi segment, even though both segments have experienced multiple Holocene earthquakes, and as such would be treated in the same manner when implementing a fault avoidance strategy to mitigate surface faulting (see Hazardous Fault Avoidance section above). Whether mitigating surface faulting differently on the Nephi and Salt Lake City segments based on available paleoseismic data is advisable,

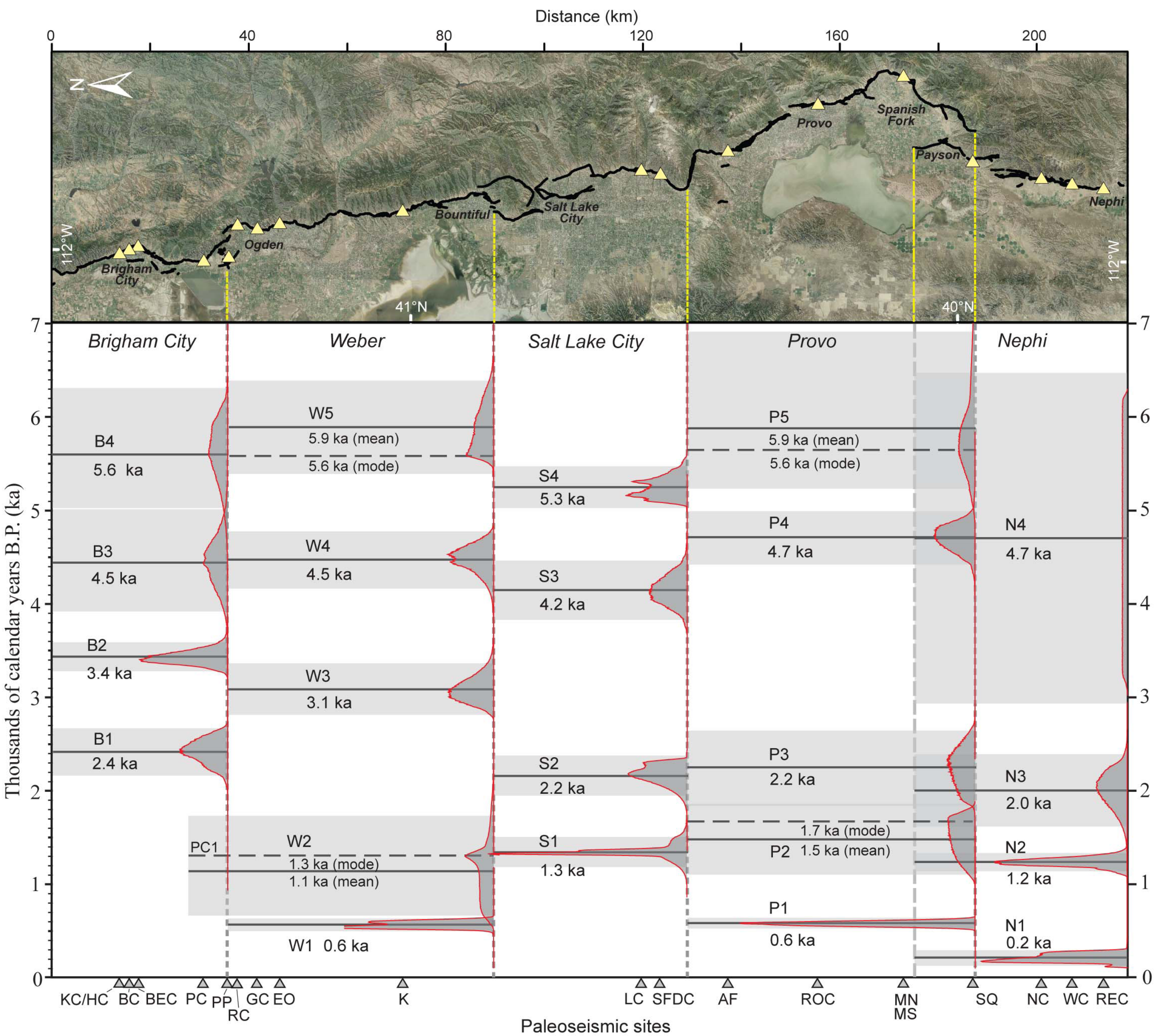

Figure 19. *Distribution of probability density functions showing timing of single segment surface-faulting earthquakes on the five central segments of the Wasatch fault zone for the past ~6500 years (from WGUEP, 2016).*

and what form different mitigation strategies might take, depends on society's ability to accept seismic risk, and remains a matter for future policy discussion.

Conversely, trenching by Olig and others (1999, 2000, 2001 [compiled in Bowman and Lund, 2013]) on the Mercur fault (Southern Oquirrh Mountains fault zone) identified a Holocene earthquake between 1500 and 4000 years ago, thus placing the Mercur fault in the Holocene activity class (see Hazardous Fault Avoidance section above). However, average surface-faulting recurrence on the Mercur fault is 13,000–19,000 years over the past 90,000 years. Therefore, even though the uncertainty in average recurrence is high (intervals vary from 2000 to 40,000 years), the likelihood of future rupture in a planning time frame is probably low on the Mercur fault, possibly lower than for many Late Quaternary faults that lack Holocene surface faulting.

These examples illustrate that fully characterizing surface-faulting hazard requires more paleoseismic information than simply determining the timing and displacement of the most recent surface-faulting earthquake. Timing and displacement data for multiple surface-faulting earthquakes (recommend a minimum of three closed earthquake cycles [four earthquakes]) is necessary to (1) compare the elapsed time since the most recent surface-faulting earthquake with an even minimally statistically relevant average recurrence, and (2) estimate the probability of future surface faulting within a time frame of interest. A Late Quaternary fault with a recurrence interval ≥ 10,000 years may be approaching or have exceeded its average recurrence, and be potentially more hazardous than either the Nephi segment, which has experienced multiple Holocene surface-faulting earthquakes, or the Mercur fault, which experienced surface faulting ~1500–4000 years ago, but has highly non-uniform earthquake recurrence. Consequently, the Holocene-activity criterion as currently applied in Utah to implement fault setback requirements may result in overly conservative risk-mitigation measures in some instances, and in other cases contribute to ignoring possible hazardous Late Quaternary faults that are near or beyond their average recurrence interval.

The UGS recommends that where sufficient paleoseismic data are available to characterize earthquake timing and displacement over multiple earthquake cycles (see recommendation above), those data may be used in conjunction with good professional judgment to replace the Holocene-activity criterion for a hazardous fault, and be used to determine which faults require surface-faulting risk mitigation, and which may require lesser or no mitigation, regardless of activity class. Where paleoseismic data are lacking or are insufficient to fully characterize earthquake activity as described above, the UGS recommends that those faults be treated as Holocene active and appropriate fault setbacks determined and applied (see Hazardous Fault Avoidance section above). We reiterate that the safest form of surface-faulting mitigation remains avoidance, which places a structure out of harm's way regardless of future earthquake timing or displacement.

SURFACE-FAULTING-INVESTIGATION REPORT

The report prepared for a site-specific surface-faulting investigation in Utah should, at a minimum, address the topics below. Site conditions may require that additional items be included; these guidelines do not relieve engineering geologists from their duty to perform additional geologic investigations as necessary to adequately assess surface-faulting hazard at a site. The report presenting the investigation results must be prepared, stamped, and signed by a Utah licensed Professional Geologist (Utah Code, 2011) with experience in conducting surface-faulting investigations. Reports co-prepared by a Utah licensed Professional Engineer must include the engineer's stamp and signature. The guidelines below pertain specifically to surface-faulting investigations, and expand on the general guidance provided in the Engineering-Geology Investigations and Engineering-Geology Reports sections of chapter 2.

A. Text

   a. Purpose and scope of investigation. Describe the location and size of the site and proposed type and number of buildings if known.

   b. Geologic and tectonic setting. The report should contain a clear and concise statement of the general geologic and tectonic setting of the site vicinity. The section should include a discussion of active faults in the area, paleoseismicity of the relevant fault system(s), historical seismicity, geodetic measurements where pertinent, and should reference relevant published and unpublished geologic literature.

   c. Site description and conditions. Include information on geologic and soil units, geomorphic features, graded and filled areas, vegetation, existing structures, and other factors that may affect fault recognition, choice of investigative methods, and interpretation of data.

   d. Methods and results of investigation.

      1. Literature Review. Summarize published and unpublished maps, literature, and records concerning geologic and soil units, faults, surface water and groundwater, topography, and other relevant factors pertinent to the site.

      2. Interpretation of Remote-Sensing Imagery. Describe the results of remote-sensing-imagery interpretation, including stereoscopic aerial photographs, lidar, and other remote-sensing data (e.g., Bunds and others, 2015) as available, conducted to identify fault-related topog-

raphy, vegetation or soil contrasts, and other lineaments of possible fault origin. List source, date, flight-line numbers, and scale of aerial photos or other imagery used.

3. Surface Investigations. Describe pertinent surface features, both onsite and offsite, including mapping of geologic units; geomorphic features such as scarps, springs and seeps (aligned or not), faceted spurs, and disrupted drainages; and geologic structures. Describe and assign ages to features associated with earthquake-induced strong ground shaking such as sand blows, lateral spreads, and other evidence of liquefaction and ground settlement. Describe the results of scarp profiling including age and displacement estimates for past surface-faulting earthquakes. Landslides, although they may not be conclusively associated with an earthquake cause, should be identified and described, particularly if they affect fault recognition and mapping.

4. Subsurface Investigations. Describe fault trenching and other subsurface investigations conducted to evaluate surface faulting at the site. The strike, dip, and vertical displacement (or minimum displacement if total displacement cannot be determined) of faults should be recorded. Trench logs should be included with the report and should be prepared in the field at a scale of 1 inch = 5 feet or larger. Describe the criteria used to determine the age and geologic origin of the deposits in the trenches, and clearly evaluate the evidence for the presence or absence of Holocene, Late Quaternary, or Quaternary faults.

5. Other Investigation Methods. When special conditions or requirements for critical facilities demand a more intensive investigation, describe the methods used to supplement the trenching program and the purpose/result of those methods. These may include, but are not limited to: (a) boreholes and test pits, (b) CPT soundings, (c) geophysical investigations, and (d) geochronology (see Other Subsurface Investigation Methods section above).

e. Conclusions.

1. Conclusions must be supported by adequate data, and the report should present those data in a clear and concise manner.

2. Data provided should include evidence establishing the presence or absence of faulting, fault location(s), fault geometry, earthquake timing, and displacement (at a minimum the most recent surface-faulting earthquake), including ages and geologic origin of faulted and unfaulted geologic units and surfaces. If engineering mitigation of surface faulting is proposed, the UGS recommends that paleoearthquake displacement information be obtained for a minimum of the three most recent surface-faulting earthquakes at the site, and that engineering design be based on the largest displacement observed and account for any uncertainty in the displacement measurement.

3. Degree of confidence in, and limitations of, the data and conclusions.

f. Recommendations.

1. Recommendations must be supported by the report conclusions and be presented in a clear and concise manner.

2. Fault setback recommendations should include justification for the fault setback distance chosen with supporting data.

3. When engineering-design mitigation of surface faulting is recommended, design recommendations must be data driven and based on sufficient paleoseismic information that epistemic uncertainty regarding the fault's past and probable future displacement is minimized and aleatory variability is adequately characterized (see Paleoseismic Data Required for Engineering-Design Mitigation of Surface Faulting and Hazardous Fault Criteria sections above).

4. Other recommended building restrictions, use limitations, or risk-reduction measures such as placement of detached garages or other non-habitable structures in fault zones, or use of engineering-design mitigation for small-displacement faults.

5. Limitations on the investigation and recommendations for additional investigation to better quantify the hazard if necessary.

B. References

a. Literature and records cited or reviewed; citations should be complete (see References section of this publication for examples).

b. Remote-sensing images interpreted including type, date, project identification codes, scale, source, and photo index numbers.

c. Other sources of information used, including well records, personal communication, and other data sources.

C. Illustrations. Should include at a minimum:

a. Location map. A general location map should show the site and significant physiographic and cultural features, generally at 1:24,000 scale or larger and indicating the Public Land Survey System ¼-section, township, and range; and the site latitude and longitude to four decimal places with datum.

b. Site development map. The development map should show site boundaries, existing and proposed structures, graded and filled areas (including engineered and non-engineered fill), and streets. The map scale may vary depending on the size of the site and area covered by the study; the minimum recommended scale is 1 inch = 200 feet (1:2400) or larger when necessary. The site development map may be combined with the site-specific geology map (below).

c. Regional geology map. A regional-scale (1:24,000 to 1:50,000) map should show the geologic setting, including geologic units, Quaternary and other faults, and general geologic structures within a 10-mile radius of the site.

d. Site-specific geology map. A site-scale geologic map should show (1) geologic units, (2) faults, (3) seeps or springs, (4) landslides, (5) lineaments investigated for evidence of faulting, (6) other geologic features existing on and near the site, and (7) locations of trenches, test pits, boreholes, CPT soundings, and geophysical lines as appropriate. Scale of site geologic maps will vary depending on the size of the site and area of study; minimum recommended scale is 1 inch = 200 feet (1:2400) or larger when necessary. If site-specific investigations reveal the presence of a hazardous Quaternary fault and fault avoidance is the mitigation strategy employed, an appropriate fault setback should be shown either on the site-specific geology map, or on a separate surface-fault-rupture-hazard map depending on site scale and complexity.

e. Geologic/topographic cross sections. Site geologic cross sections should be included as needed to illustrate three-dimensional geologic relations.

f. Trench and test pit log(s). Logs are required for each trench and test pit excavated as part of the investigation whether faults are encountered or not. Logs are hand- or computer-drawn maps of excavation walls that show details of geologic units and structures. Logs should be to scale and not generalized or diagrammatic, and may be on a rectified photomosaic base. The scale (horizontal and vertical) should be 1 inch = 5 feet (1:60) or larger as necessary and with no vertical exaggeration. Logs should be prepared in the field and accurately reflect the features observed in the excavation, as noted below. Photographs are not a substitute for trench logs.

   Logs should include (1) trench and test-pit orientation and indication of which wall was logged, (2) horizontal and vertical control, (3) top and bottom of trench wall(s), (4) stratigraphic contacts, (5) detailed lithology and soil classification and descriptions, (6) contact descriptions, (7) pedogenic soil horizons, (8) marker beds, (9) faults and fissures, (10) fault orientation and geometry (strike and dip), (11) fault displacement, and (12) sample locations (e.g., Birkeland and others, 1991; Bonilla and Lienkaemper, 1991; U.S. Bureau of Reclamation, 1998b; Walker and Cohen, 2006; McCalpin, 2009; DuRoss, 2015).

   Other features of tectonic significance should be shown, including but not limited to (1) open or infilled fissures, (2) colluvial wedges, (3) drag folds, (4) rotated clasts, (5) lineations, and (6) liquefaction features including sand dikes and blows (e.g., DuRoss and others, 2014; DuRoss, 2015).

   Logs should include interpretations and evidence for the age and origin of geologic units. Study limitations should be clearly stated for suspected Holocene faults where unfaulted Holocene deposits are deeper than practical excavation depths.

g. Borehole and CPT logs. Boreholes and CPT logs should include the geologic interpretation of deposit genesis for all layers and whether or not evidence of faulting was encountered. Logs should not be generalized or diagrammatic. Because boreholes are typically multipurpose, borehole logs may also contain standard geotechnical, geologic, and groundwater data.

h. Geophysical data and interpretations.

i. Photographs that enhance understanding of site surface and subsurface (trench and test pit walls) conditions with applicable metadata.

D. Authentication

The report must be stamped and signed by a Utah licensed Professional Geologist in principal charge of the investigation (Title 58-76-10 – Professional Geologists Licensing Act [Utah Code, 2011]). Final geologic maps, trench logs, cross sections, sketches, drawings, and plans prepared by, or under the supervision of, a professional geologist also must bear the stamp of the professional geologist (Utah Code, 2011). Reports co-prepared by a Utah licensed Professional Engineer and/or Utah licensed Professional Land Surveyor must include the engineer's and/or surveyor's stamp and signature.

E. Appendices

Include supporting data relevant to the investigation not given in the text such as maps; trench, test pit, and borehole logs; cross sections; conceptual models; fence diagrams; survey data; water-well data; geochronology laboratory reports; and qualifications statements/resume.

FIELD REVIEW

The UGS recommends a field review of trenches and trench logs by the regulatory-authority geologist once a surface-faulting hazard investigation is complete. The field review should take place after trenches or test pits are logged, but before they are closed so subsurface site conditions can be directly observed and evaluated. See Field Review section in chapter 2.

REPORT REVIEW

The UGS recommends regulatory review of all reports by a Utah licensed Professional Geologist experienced in surface-faulting hazard investigations and acting on behalf of local governments to protect public health, safety, and welfare, and to reduce risks to future property owners (Larson, 1992, 2015). See Report Review section in chapter 2.

DISCLOSURE

The UGS recommends disclosure during real-estate transactions whenever an engineering-geology investigation has been performed. See Disclosure section in chapter 2.

ACKNOWLEDGMENTS

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CHAPTER 4
GUIDELINES FOR EVALUATING LANDSLIDE HAZARDS IN UTAH

by
Gregg S. Beukelman, P.G., and Michael D. Hylland, P.G.

Landslide near 4785 Brentwood Circle, Provo. Photo date: March 30, 2011.

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CHAPTER 4: GUIDELINES FOR EVALUATING LANDSLIDE HAZARDS IN UTAH

by Gregg S. Beukelman, P.G., and Michael D. Hylland, P.G.

INTRODUCTION

These guidelines outline the recommended minimum acceptable level of effort for evaluating landslide hazards in Utah. Guidelines for landslide-hazard investigations in Utah were first published by the Utah Geological Survey (UGS) in 1996 as *Guidelines for Evaluating Landslide Hazards in Utah* (Hylland, 1996) and are updated here. The objective of these guidelines is to promote uniform and effective statewide implementation of landslide investigation and mitigation measures to reduce risk. These guidelines do not include systematic descriptions of all available investigative or mitigation techniques or topics, nor is it suggested that all techniques or topics are appropriate for every project. Variations in site conditions, project scope, economics, and level of acceptable risk may require that some topics be addressed in greater detail than is outlined in these guidelines. However, all elements of these guidelines should be considered in landslide-hazard investigations, and may be applied to any project site, large or small.

Purpose

These guidelines were developed by the UGS to assist geologists and geotechnical engineers performing landslide-hazard investigations, and to help technical reviewers rigorously assess the conclusions and recommendations in landslide-hazard-investigation reports. These guidelines are applicable to both natural and development-induced landslide hazards, and are limited to evaluating the potential for rotational and translational slides (classification after Cruden and Varnes, 1996). The guidelines do not address other types of mass movement such as debris flows or rockfalls, or phenomena such as land subsidence and earth fissures. Debris-flow-hazard investigations are addressed in chapter 5 of this publication, land-subsidence and earth-fissure investigations in chapter 6, and rockfall-hazard investigations in chapter 7.

These landslide guidelines are intended to:

- protect the health, safety, and welfare of the public by minimizing the potentially adverse effects of landslides (figure 20 shows examples of damage from a recent urban landslide);
- assist local governments in regulating land use in hazardous areas and provide standards for ordinances;
- assist property owners and developers in conducting reasonable and adequate landslide investigations;
- provide engineering geologists with a common basis for preparing proposals, conducting investigations, and recommending landslide-mitigation strategies; and
- provide an objective framework for preparation and review of reports.

These guidelines do not supersede pre-existing state or federal regulations or local geologic-hazard ordinances, but provide useful information to (1) supplement adopted ordinances/regulations, and (2) assist in preparation of new ordinances. If study or risk-mitigation requirements in a local government ordinance exceed recommendations given here, ordinance requirements take precedence.

Background

A landslide can be defined as a downslope movement of rock, soil, or both, in which much of the material moves as a coherent or semi-coherent mass with little internal deformation, and movement occurs on either a curved (rotational slide) or planar (translational slide) rupture surface (Highland and Bobrowsky, 2008). Occasionally, individual landslides may involve multiple types of movement if conditions change as the displaced material moves downslope. For example, a landslide may initiate as a rotational slide and then become a translational slide as it progresses downslope. These guidelines address evaluating the potential for new or reactivated rotational and translational slides, but do not address liquefaction-induced landslides such as lateral spreads. Snow avalanches and ice falls are likewise not discussed. Figure 21 shows the position and terms used for the different parts of a landslide. These and other relevant terms are defined in the glossary in appendix B.

Landslides include both natural and human-induced variables, making landslide-hazard investigation a complex task. Slope instability can result from many factors, including geomorphic, hydrologic, and geologic conditions, and modification of these conditions by human activity; the frequency and intensity of precipitation; and seismicity. Existing landslides can represent either marginally stable slopes or unstable slopes that are actively moving. Site conditions must be evaluated in terms of proposed site modifications associated with structure size and placement, slope modification by cutting and filling, and changes to groundwater conditions.

Figure 20. August 2014 Parkway Drive landslide, North Salt Lake, Utah. The effects of this landslide illustrate how damage can occur at various parts of the slide. The landslide severely damaged the Eagle Ridge Tennis and Swim Club (white tent structure), and one house (directly above the tent structure) at its toe, partially destroyed a home's backyard along its left flank (behind orange fencing near center of photograph), and threatened streets and pipelines near the crown. Photo date August 14, 2014.

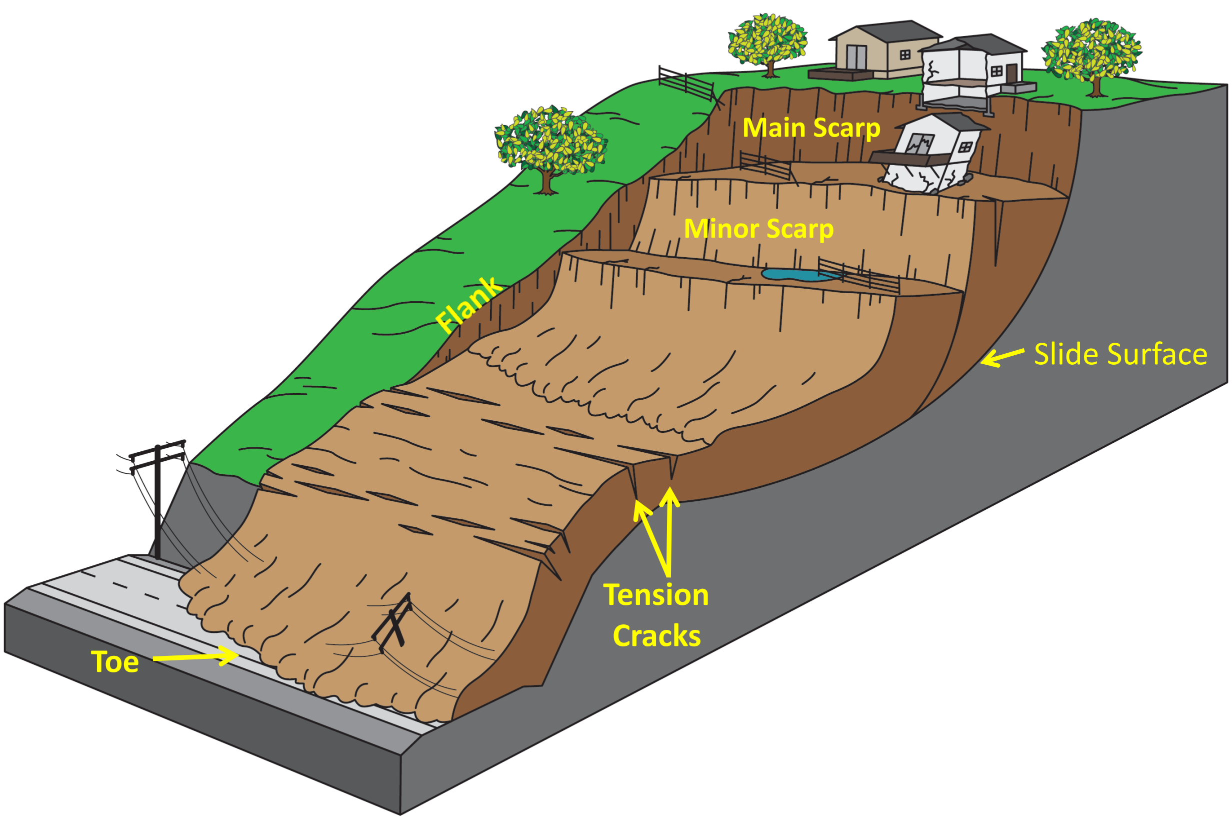

Figure 21. *Diagram of an idealized landslide showing commonly used nomenclature for its parts.*

Many Utah landslides are considered dormant, but recent slope failures are commonly reactivations of pre-existing landslides, suggesting that even so-called dormant landslides may continue to exhibit slow creep or are capable of renewed movement if stability thresholds are exceeded (Ashland, 2003). Past slope failures can be used to identify the geologic, hydrologic, and topographic conditions that may reactivate existing landslides and initiate new landslides. In addition to natural conditions that contribute to landsliding, human-induced conditions, such as modification of slopes by grading or a human-caused change in hydrologic conditions, can create or increase an area's susceptibility to landsliding. Investigation of landslide hazards should be based on the identification and understanding of conditions and processes that promote instability.

Slope steepness is an important factor in slope stability. In Salt Lake County, 56 percent of all slope failures occurred on hillsides where slopes range between 31 and 60 percent which prompted Salt Lake County to lower the maximum allowable buildable slope from 40 percent to 30 percent in 1986 (Lund, 1986).

Landslides occur in all 50 states; however, the coastal states and the Intermountain West are the primary regions of landslide activity. Nationally, landslides result in 25 to 50 deaths annually, and cause approximately $3.5 billion (2001 dollars) in damage (Highland, 2004). In 2014, an approximately 650-foot-high slope near Oso, Washington, underlain by glacial till and lacustrine deposits and having a history of previous landsliding, failed and rapidly inundated a neighborhood claiming the lives of 43 people, making it the deadliest landslide in United States history (Keaton and others, 2014).

Annual losses from landslide damage in Utah vary, but are often in the millions of dollars. For example, during the wet year of 1983, Utah landslides had a total estimated direct cost exceeding $250 million dollars (Anderson and others, 1984). The 1983 Thistle landslide (figure 22), Utah's single most destructive failure of a natural slope, is recognized in terms of direct and indirect costs as one of the most expensive individual landslides in United States history with damage costs over $688 million in 2000 dollars (Highland and Schuster, 2000). Although landslide losses in Utah are poorly documented, Ashland (2003) estimated losses from damaging landslides in 2001 exceeded $3 million including the costs to repair and stabilize hillsides along state and federal highways. This estimate remains the most recent landslide damage estimate for Utah; however, total losses during that year are unknown because of incomplete cost documentation of landslide activity.

Landslide Causes

Landslides can have several contributing causes, but only one trigger (Varnes, 1978; Cruden and Varnes, 1996). Contributing causes may include, but are not limited to, geological conditions such as weak, weathered, or sheared rock or sediment; morphologic modification processes like tectonic uplift or fluvial erosion at the toe of a slope; physical processes such

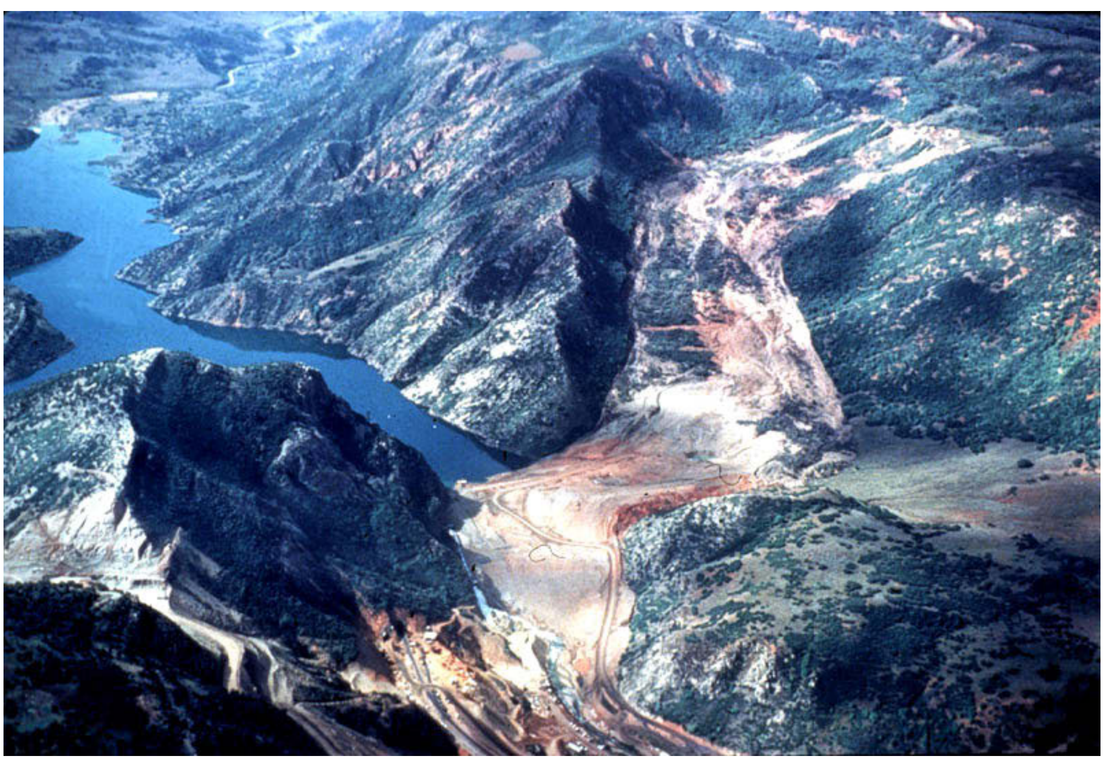

Figure 22. *The 1983 Thistle, Utah, landslide buried parts of two State highways and the Denver and Rio Grande Railroad. The landslide also dammed two streams, resulting in a 3-mile-long and 200-foot-deep lake that inundated the town of Thistle and posed a flooding hazard to communities downstream. Aerial photograph provided by the USGS National Landslide Information Center.*

as earthquakes; or human-related causes such as grading of a slope or modification of groundwater conditions. By definition, a trigger is an external force that causes a near-immediate response in the form of slope deformation by rapidly increasing the stresses or reducing the strength of slope materials (Wieczorek, 1996). Engineering geologists investigating existing landslides should look for dominant causes and the trigger of the landslide to ensure that the cause of the slope failure will be corrected by any proposed mitigation.

In Utah, natural landslides are primarily triggered by intense rainfall, rapid snowmelt, rapid stream erosion, water level change or, to a much lesser degree, seismic activity. Slopes can become unstable as they are saturated by intense rainfall, snowmelt, and changes in groundwater levels. Rapid erosion due to surface-water changes along earth dams and in the banks of lakes, reservoirs, canals, and rivers can undercut banks and increase the possibility of landsliding. Earthquakes in steep landslide-prone areas, such as northern Utah, greatly increase the likelihood of landslides because of ground shaking, liquefaction of susceptible deposits, or dilation of soil, which allows rapid infiltration of water. Utah's best-documented earthquake-induced landslide is the Springdale landslide in the southwestern part of the state which was triggered by the 1992 magnitude 5.8 St. George earthquake (Jibson and Harp, 1995). The potential for earthquake-triggered landslides along the Wasatch Front has long been recognized (Keaton and others, 1987a; Solomon and others, 2004; Ashland, 2008), but no mapped landslide in this area, excluding liquefaction-induced lateral spreads (Hylland and Lowe, 1998; Harty and Lowe, 2003), has been documented as having been conclusively triggered by a major earthquake.

Humans can contribute to landslides by improper grading, such as undercutting the bottom or loading the top of a slope, disturbing drainage patterns, changing groundwater conditions, and removing vegetation during development. In addition, landscape irrigation, on-site wastewater disposal systems, or leaking pipes can promote landsliding in once-stable areas. Identification of a site's susceptibility to landsliding followed by proper engineering and hazard mitigation can improve the long-term stability of the site and reduce risk from future slope failures.

Landslide Hazards

Landslides account for considerable property damage and a potential loss of life in areas having steep slopes and abundant rainfall. The potential benefit of landslide-hazard investigations is achieving a meaningful reduction in losses through awareness and avoidance. Landslides may affect developed areas whether the development is directly on or only near a landslide. Landslides can occur either over a wide area where many homes, businesses, or entire developments are involved, or on a local scale where a single structure or part of a structure is affected. Buildings constructed on landslides without proper engineering and hazard mitigation can experience distress or complete destruction. Landslides can also do indirect damage to dwellings or businesses by affecting common utilities such as sewer, water, and storm drain pipes, electrical and gas lines, and roadways.

Fast-moving landslides are typically the most destructive, particularly if they move so rapidly that they overwhelm pre-slide mitigation measures or move too fast for mitigation measures to be designed and implemented (see figure 23). Whereas a fast-moving landslide may completely destroy a structure, a slower landslide may only slightly damage it, and may provide time to implement mitigation measures. However, left unchecked, even a slow landslide can destroy structures over time. In North Salt Lake City, Utah, the very slow moving Springhill landslide affected a residential development from 1998 to 2014, until a total of 18 houses on the slide were either destroyed by landslide movement or deemed unfit for occupancy and demolished. An open-space geologic park has now been constructed on the landslide footprint (Beukelman, 2012). Landslides often continue to move for days, weeks, months, or years, and may become dormant for a time only to reactivate again later. It is therefore prudent not to rebuild on a landslide unless effective mitigation measures are implemented; even then, such efforts may not guarantee future stability.

LANDSLIDE-HAZARD INVESTIGATION

When to Perform a Landslide-Hazard Investigation

Geologic hazards are best addressed prior to land development. The UGS recommends that a landslide-hazard investigation be made for all new buildings for human occupancy and for modified International Building Code (IBC) Risk Category II(a), II(b), III, and IV facilities (table 1604.5 [International Code Council (ICC), 2014a]) that are proposed on slopes. Utah jurisdictions that have adopted landslide-special-study maps identify zones of known landslide susceptibility within which they require a site-specific investigation. The UGS recommends that investigations as outlined in these guidelines be conducted in slope areas for all IBC Risk Category III and IV facilities, whether near a mapped landslide-susceptible area or not, to ensure that previously unknown landslides are not present. If a hazard is found, the UGS recommends a comprehensive investigation be conducted. Additionally, in some instances an investigation may become necessary when existing infrastructure is discovered to be on or adjacent to a landslide.

The level of investigation conducted for a particular project depends on several factors, including (1) site-specific geologic conditions, (2) type of proposed or existing development, (3) level of acceptable risk, and (4) governmental permitting requirements, or regulatory agency rules and regulations. A landslide-hazard investigation may be conducted separately,

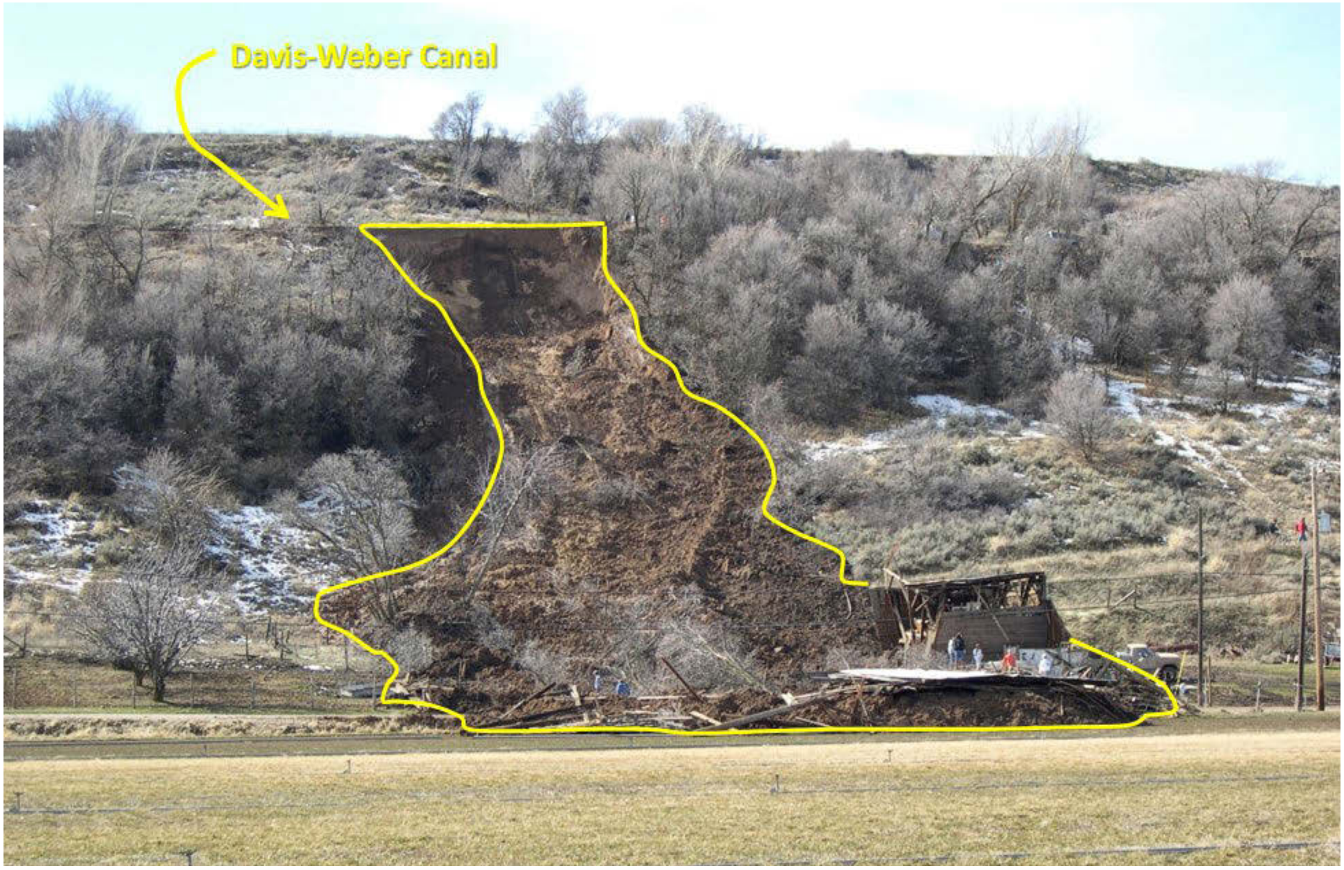

Figure 23. *The 2005 landslide below the Davis-Weber Canal in South Weber, Davis County, that demolished a barn and covered part of State Route 60. The landslide occurred in one of the steeper parts of the slope composed of prehistoric landslide deposits that reactivated.*

or as part of a comprehensive geologic-hazard and/or geotechnical site investigation (see chapter 2).

Minimum Qualifications of Investigator

Landslide-related engineering-geology investigations and accompanying geologic-hazard evaluations performed before the public shall be conducted by or under the direct supervision of a Utah licensed Professional Geologist (Utah Code, Title 58-76) who must sign and seal the final report. Often these investigations are interdisciplinary in nature, and where required, must be performed by qualified, experienced, Utah licensed Professional Geologists (PG, specializing in engineering geology) and Professional Engineers (PE, specializing in geological and/or geotechnical engineering) working as a team. See Investigator Qualifications section in chapter 2.

Investigation Methods

In evaluating landslide hazards the geologic principle of *"the past is the key to the future"* proves useful. This principle means that future landslides are most likely to result from the same geologic, geomorphic, and hydrologic conditions that produced landslides in the past. Estimating the types, extent, frequency, and perhaps even consequences of future landslides is often possible by a careful analysis of existing landslides. Caution is required, however, as the absence of past landslides does not rule out the possibility of future landslides, particularly those resulting from human-induced changes such as site grading or changes in groundwater conditions.

These guidelines present two levels of landslide-hazard investigation: (1) geologic and (2) geotechnical engineering. In general, a geologic investigation is performed by an engineering geologist. A geotechnical-engineering investigation is an extension of the geologic investigation and is primarily a quantitative slope-stability analysis. This analysis is generally performed by a geotechnical engineer with input from an engineering geologist. All levels of investigation require an initial in-depth review of existing information including published and unpublished literature and available remote-sensing data.

Literature Review

Existing maps and reports are important sources of background information for landslide-hazard investigations. Published and unpublished geologic and engineering literature, maps, cross sections, and records relevant to the site and site region's topography, geology, hydrology, and past history of landslide activity should be reviewed in preparation for landslide-hazard investigations. The objective of a literature review is to obtain information that will aid in the identification of potential landslide hazards, and to help in planning the most efficient and effective surface mapping and subsurface exploration program.

The UGS and the U.S. Geological Survey (USGS) provide useful resources for landslide-hazard investigations. UGS maps show known landslides at a statewide scale (1:500,000; Harty, 1991) and at 30 x 60-minute quadrangle scale (1:100,000; Elliott and Harty, 2010). However, these small-scale maps may not be suitable as the only resource for landslide locations for a site- or even development-scale investigation. Additionally, Giraud and Shaw (2007) prepared a statewide landslide susceptibility map of Utah at a scale of 1:500,000. Large landslide deposits are commonly shown on modern geologic maps, and the UGS and others commonly map surficial (Quaternary) geology on USGS 7.5-minute quadrangle maps (1:24,000 scale [1″ = 2000′]). Additional sources of relevant information including links to several UGS-maintained web pages are presented in the Literature Searches and Information Resources section in chapter 2.

Analysis of Remote-Sensing Data

Landslides leave geomorphic signatures in the landscape, many of which can be recognized in various kinds of remote-sensing imagery. Analysis of remote-sensing data should include interpretation of stereoscopic aerial photographs, and if available, light detection and ranging (lidar) imagery and other remotely sensed images. Interferometric synthetic aperture radar (InSAR) data may prove useful when investigating large, complex landslides. Where possible, the aerial photography analysis should include both stereoscopic low-sun-angle and vertical imagery. Landslide evidence visible on aerial photographs and lidar often includes main and internal scarps formed by surface displacement, hummocky topography, toe thrusts, back-rotated blocks, chaotic bedding in displaced bedrock, denuded slopes, shear zones along the landslide flanks, vegetation lineaments, and vegetation/soil contrasts. Examination of repeat aerial photographs and/or lidar and InSAR imagery from multiple years may help reconstruct the history of landslide movement. The area analyzed should extend sufficiently beyond the site boundaries to identify off-site landslides that might affect the site. In addition, nearby landsliding affecting a geologic unit that extends onsite should be evaluated for landslide susceptibility of that unit.

A variety of remote-sensing data is available for much of Utah. For information on availability of remote sensing data see the Aerial Photography section in chapter 2, and the lidar and InSAR discussions in appendices C and D, respectively.

Geologic Investigations

The primary purpose of a geologic investigation is to determine a hazard's potential relative to proposed development, and evaluate the need for additional geotechnical-engineering studies. In general, a geologic investigation should address site geologic conditions that relate to slope stability such as topography, the nature and distribution of soil and rock, landforms, vegetation patterns, hydrology, and existing landslides. The study should extend beyond the site boundaries as necessary to adequately characterize the hazard. Comprehensive information for landslide identification and investigation is provided by Hall and others (1994), Turner and Schuster (1996), and Cornforth (2005).

A geologic-hazard investigation must include a site visit to document surface and shallow subsurface conditions such as topography, type and relative strength of soil and rock, nature and orientation of bedrock discontinuities such as bedding or fractures, groundwater depth, and active erosion. Mapping and related field studies also help unravel the geologic history of slope stability, which may help in estimating past movement parameters. Engineering geologic mapping at various scales is relevant for different purposes. Investigators should map the site surficial geology in sufficient detail to define the geologic conditions present both at and adjacent to the site, placing special emphasis on geologic units of known landslide susceptibility. Baum and others (2008) suggest that large-scale mapping (1:50–1:1000) showing geologic (lithology, structure, geomorphology) and hydrologic (springs, sag ponds) details are needed for investigations of landslides and landslide-prone sites, and mapping at small (1:25,000–1:100,000) and intermediate scales is more appropriate to put landslides and landslide-prone areas in context with regional and local geology. For most purposes, published geologic maps are not sufficiently detailed to provide a basis for understanding site-specific conditions, and new, larger scale, independent geologic mapping is necessary; however, features such as slope inclination, height, and aspect can be schematically illustrated on the geologic map if a detailed topographic base map is not available.

During site geologic mapping, particular attention should be paid to mapping landslide features with accompanying photos, detailed notes, and sketches where appropriate. Evidence of recent landslide activity, including scarps, hummocky topography, shear zones, and disturbed vegetation (e.g., "jack-strawed" trees), should be described and located. The landslide type, relative age, and cause of movement need to be evaluated for existing slope failures. The site geologic map should also show areas of surface water and evidence for shallow groundwater (such as phreatophyte vegetation, springs, or modern tufa deposits).

If the site has been developed previously, structures that show signs of distress, both on and near the site, should be mapped. Cracks in pavement, foundations, and other brittle materials can provide information about the stress regime produced by landslide movement, and should be mapped in detail with special attention paid to rigid linear infrastructure such as curbs, gutters, and sidewalks. Surface observations should be supplemented by subsurface exploration using a backhoe, drill rig, and/or hand tools such as a shovel, auger, or probe rod where appropriate.

Careful mapping and characterization of rock and soil units are critical to any geologic-hazards evaluation. Several classification systems have been developed to guide the investigator during this process including the Unified Soil Classification System (ASTM, 2002) that provides information on geotechnical behavior of unconsolidated deposits. The Unified Rock Classification System (Williamson, 1984) provides a systematic and reproducible method of describing rock weathering, strength, discontinuities, and density in a manner directly usable by engineering geologists and engineers. The Geological Strength Index (GSI) provides a system to describe rock mass characteristics and estimate strength (Marinos and Hoek, 2000; Marinos and others, 2005; Hoek and others, 2013). For altered materials, Watters and Delahaut (1995) provide a classification system that can be incorporated into an overall rock classification. The method described by Williamson and others (1991) for constructing field-developed cross sections can facilitate topographic profiling and subsurface interpretation.

Landslide features become modified with age. Evaluation of the timing of the most recent movement of a slide can provide important information for landslide-hazard assessments. Active landslides have sharp, well-defined surface features, whereas landslides that have been inactive for tens of thousands of years have features that are subdued and poorly defined (Keaton and DeGraff, 1996). The change of landslide features from sharp to subdued with age is the basis of an age classification developed by McCalpin (1984). Features included in this classification system include main scarp, lateral flanks, and surface morphology, as well as vegetation patterns and landslide toe relationships. Wieczorek (1984) developed a classification system based on activity, degree of certainty of identification of the landslide boundaries, and the dominant movement type. These two systems were combined into the Unified Landslide Classification System (Keaton and DeGraff, 1996) outlined in table 13.

Christenson and Ashland (2006) suggested that care be taken when applying these classifications and inferring that a mature or old geomorphic expression implies adequate stability and suitability for development. They report that many historical landslides in Utah have involved partial reactivations of old landslides—in particular, clay-rich landslides that typically move at very slow rates for short periods of time. For such landslides, geomorphic expression may not be a reliable indicator of stability.

Pertinent data and conclusions from the landslide-hazard geologic investigation must be adequately documented in a written report. The report should note distinctions between observed and inferred features and relationships, and between measured and estimated values. Although geologic investigations will generally result in a qualitative hazard assessment (for example, low, moderate, or high), the report should clearly state if a hazard exists and comment on development feasibility and implications relative to landsliding. If a hazard is found and the proposed development is considered feasible, the report should both clearly state the extent of the hazard and give justification for accepting the risk, or recommend appropriate hazard-reduction measures or more detailed study. Kockelman (1986), Rogers (1992), Turner and Schuster (1996), and Cornforth (2005) describe numerous techniques for reducing landslide hazards. Hazard-reduction measures (for example, building setbacks or special foundations) must be based on supporting data, such as measured slope inclination; height, thickness, and physical properties of slope materials; groundwater depth; and projections of stable slopes. The basis for all conclusions and recommendations must be presented so that a technical reviewer can evaluate their validity. Guidelines for reports are provided in the Landslide-Investigation Report section below.

Table 13. *Unified Landslide Classification System (from Keaton and Rinne, 2002).*

Age of Most Recent Activity[1]		Dominant Material[2]		Dominant Type of Slope Movement[2]	
Symbol	**Definition**	**Symbol**	**Definition**	**Symbol**	**Definition**
A	Active	R	Rock	L	Fall
R	Reactivated	S	Soil	T	Topple
S	Suspended	E	Earth	S	Slide
H	Dormant-historic	D	Debris	P	Spread
Y	Dormant-young			F	Flow
M	Dormant-mature				
O	Dormant-old				
T	Stabilized				
B	Abandoned				
L	Relict				

See appendix B for definition of terms. Landslides classified using this system are designated by one symbol from each group in the sequence activity-material-type. For example, MDS signifies a mature debris slide, HEF signifies a historic earth flow, and ARLS signifies an active rock fall that translated into a slide.

[1] Based on activity state (see Cruden and Varnes, 1996, table 3-2, page 38) and age classification (see Keaton and DeGraff, 1996, table 9-1, page 186).

[2] See Keaton and DeGraff (1996), table 3-2, page 38.

Geotechnical-Engineering Investigations

A detailed geotechnical-engineering investigation generally should be performed as part of final design/mitigation activities when a geologic evaluation indicates the existence of a hazard. A geotechnical-engineering investigation, which involves a quantitative slope-stability analysis, requires subsurface exploration, geotechnical laboratory testing, topographic profiling, and preparation of geologic cross sections. Some investigations may include slope-movement monitoring or deformation analysis using photogrammetric or remote sensing methods, high resolution GPS surveys, inclinometers, piezometers, and/or extensometers. The results of the investigation must be validated by adequate documentation of appropriate input parameters and assumptions, and all supporting data for conclusions and recommendations must be included in the report to permit a detailed technical review. Subsurface exploration locations must be accurately shown on site plans and geologic maps. Where precise locations are necessary, they should be surveyed rather than located using a hand-held GPS device.

Slope stability is affected by soil, rock, and groundwater conditions. Engineering properties of earth materials and characterization of geologic structures can be inferred from surface conditions, but subsurface exploration is required to obtain definitive data and samples for laboratory testing. Development of a subsurface exploration plan and selection of methods should be based on the results of a geologic investigation, considerations of study objectives, surface conditions, and size of landslide. The exploration program should provide values for the undisturbed and residual shear strength and friction angle of all geologic materials, and depth to groundwater. If a landslide is present, subsurface exploration must be of sufficient scope to determine slide geometry with relative confidence. At a minimum, a "best estimate" of the slide geometry should be made and appropriate analyses performed using the best-estimate geometry.

Drilling and trenching are the most commonly used methods for subsurface exploration of landslides. Geophysical techniques are sometimes used where drilling is not feasible or to aid extrapolating measurements between boreholes. The most commonly used geophysical techniques include seismic refraction, seismic reflection, ground-penetrating radar, and methods based on electrical resistivity. Geotechnical laboratory testing should be performed on samples obtained from the ground surface or from subsurface exploration to evaluate physical and engineering characteristics such as unit weight, moisture content, plasticity, friction angle, and cohesion. McGuffey and others (1996) and Cornforth (2005) give detailed descriptions of various types of available sampling techniques.

In some cases, samples can be used to determine the geologic age of slope materials and possibly the age of previous landslide movement. For example, radiometric analysis of wood or charcoal fragments found beneath the toe of a landslide may be useful in determining the approximate age of landslide movement (Baum and others, 2008). However, care should be taken in the collection of samples to ensure that they are relevant to understanding the behavior of the landslide. The heterogeneous nature and complex history of most landslides make it important that the relationship of samples and their locations to the structure and overall geometry of the landslide is well understood.

At least one geologic cross section should be constructed through the slope(s) of concern to evaluate subsurface geologic conditions relative to the topographic profile. Cross sections should extend at least to the maximum postulated depth of potential slip surfaces and be at an appropriate scale (generally between 1:120 [1 inch = 10 feet] and 1:600 [1 inch = 50 feet]) for the size of the slope, type of proposed development, and purpose of investigation.

Geotechnical-engineering investigations should include static and pseudostatic analyses of the stability of existing and proposed slopes using appropriate shear-strength parameters, under existing and development-induced conditions, and considering the likely range of groundwater conditions. Numerous computer software packages are available for quantitative slope-stability analysis, including deterministic and probabilistic soil- and rock-slope models. A slope-stability evaluation addressing post-earthquake conditions may be warranted in some cases. Blake and others (2002) provide a detailed discussion of landslide analysis and mitigation.

Slope-Stability Analysis

Geotechnical-engineering investigations include a quantitative slope-stability (factor-of-safety of static and seismic conditions) analysis of existing and proposed slopes. The factor of safety (FS) is defined as:

$$FS = \frac{\textit{Resisting forces}}{\textit{Driving forces}}$$

When the FS equals one (available soil shear strength exactly balances the shear stress induced by gravity, groundwater, and seismicity), slope loading is considered to be at the point of failure (Blake and others, 2002). The analysis requires measured profiles of existing slopes and other input parameters (e.g., shear strength, groundwater levels, and slope loading; see figure 24).

Static Slope-Stability Analysis

The static stability of slopes is usually analyzed by segmenting a profile of the soil into a series of slices and calculating the average FS for all those slices using a limit equilibrium method. Such analyses require knowledge of the slope geometry and estimates of soil-strength parameters. As a general

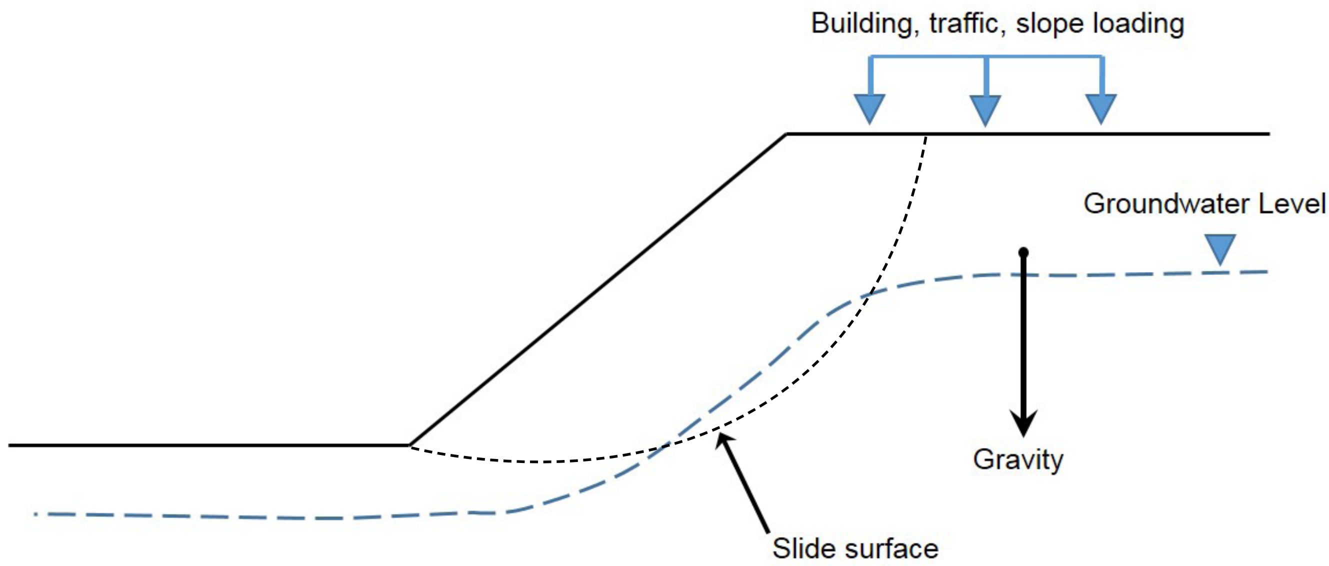

Figure 24. *Cross section of typical rotational landslide. Development activities can affect the equilibrium between driving and resisting forces by either increasing driving forces (e.g., construction of building stock, roadways, and grading activities) or decreasing resisting forces (e.g., landscape watering that raises groundwater levels).*

guideline, the UGS recommends a static FS greater than 1.5 for peak-strength conditions and/or where site characteristics and engineering properties of the geologic materials involved are well constrained. Where these characteristics and properties are not well understood, a higher FS is warranted. For existing landslides where measured residual-strength parameters are available and a back analysis is completed, a minimum FS of 1.3 is acceptable.

Seismic Slope-Stability Analysis

Methods for assessing slope stability during earthquakes have evolved since the mid-twentieth century when Terzhagi (1950) formalized the pseudostatic analysis technique. Methods developed to assess stability of slopes during earthquakes now fall into three general categories: (1) pseudostatic analysis, (2) stress-deformation analysis, and (3) permanent-displacement analysis (Jibson, 2011). Each of these types of analysis has strengths and weaknesses, and each can be appropriately applied in different situations. Pseudostatic analysis, because of its crude characterization of physical processes, tends to yield inconsistent and often conservative results (Jibson, 2011), making it most suitable for preliminary or screening analyses. Stress-deformation analysis is very complex and expensive for routine applications, and is best suited for large earth structures such as dams and embankments. For a pseudostatic FS, the UGS recommends using an appropriate seismic coefficient (typically 1/3 to 2/3 of a peak horizontal ground acceleration [PGA]) with a minimum FS $\geq$ 1.1 representing stable slope conditions, using low-range strength values and conservative groundwater levels.

Permanent-displacement analysis bridges the gap between the overly simplistic pseudostatic analysis and overly complex stress-deformation analysis. Newmark's (1965) permanent-displacement method estimates the displacement of a potential landslide block subjected to seismic shaking from a specific strong-motion record. A modification of this method (Jibson and Jibson, 2003) now permits modeling landslides that are not assumed to be rigid blocks and does a better job of modeling the dynamic response of the landslide material, thus yielding a more accurate displacement estimate (Jibson, 2011).

Estimation of Displacement

Despite advances in modeling of landslide displacement and runout, precisely predicting or estimating the velocity or total displacement of landslide materials is still beyond the capability of modern modeling methods (Baum and others, 2008). The most reliable methods of estimating future landslide movements continue to rely on the presence of preexisting landslide deposits. Preexisting landslides provide "ground-truth" data (Baum and others, 2008) from which estimates of future landslide movement can be based, with the confidence that these estimates include site conditions and slope characteristics similar to those under consideration.

Other Investigation Methods

In addition to the methods described above, other methods may be used in landslide-hazard investigations where conditions permit or when requirements for critical structures or facilities include more intensive investigation or monitoring over extended time periods. Other methods may include, but are not limited to:

- Aerial reconnaissance flights, including high-resolution aerial photography, lidar, and other remote-sensing imagery.

- Installation of piezometers.
- Installation of inclinometers.
- Local high-precision surveying or geodetic measurements, including comparison surveys with infrastructure design grades and long-term monitoring employing repeat surveys. Highly stable survey monuments are required, such as those developed by UNAVCO; see http://facility.unavco.org/kb/questions/104/UNAVCO+Resources%3A+GNSS+Station+Monumentation for details.
- Geochronologic analysis, including but not limited to radiometric dating (e.g., ^{14}C, $^{40}Ar/^{39}Ar$), luminescence dating, soil-profile development, fossils, tephrochronology, and dendrochronology (see Geochronology section of chapter 2).

LANDSLIDE-HAZARD MITIGATION

Avoidance or mitigation may be required where slope-stability factors of safety are lower than required by the governing agency, or for slopes that have unacceptably large calculated earthquake-induced displacements. Even slopes proven during analysis to be stable may require mitigation to avoid degradation of shear strengths from weathering if site grading exposes weak geologic materials, or to remain stable under anticipated future conditions such as higher groundwater levels, toe erosion, or increased loading of the landslide mass during development (see table 14). The most common methods of mitigation are (1) hazard avoidance, (2) site grading to improve slope stability, (3) improvement of the soil or reinforcement of the slope, and (4) reinforcement of structures built on the slope to tolerate the anticipated displacement (Blake and others, 2002).

LANDSLIDE-INVESTIGATION REPORT

Landslide-hazard reports prepared for investigations in Utah should, at a minimum, address the topics below. Individual site conditions may require that additional items be included. The report should be prepared, stamped, and signed by a Utah licensed Professional Geologist with experience in conducting landslide-hazard investigations. Reports co-prepared by a Utah licensed Professional Engineer should include the engineer's stamp and signature. The report preparation guidelines below expand on the general guidance provided in chapter 2.

A. Text

a. Purpose and scope of investigation, including a description of the proposed project.

b. Geologic and hydrologic setting, including previous landslide activity on or near the site. Expected seasonal fluctuation of groundwater conditions.

c. Site description and conditions, including dates of site visits and observations. Include information on geologic and soil units, hydrology, topography, graded and filled areas, vegetation, existing infrastructure, presence of landslides on or near the site, evidence of landslide-related distress to existing infrastructure, and other factors that may affect the choice of investigative methods and interpretation of data.

d. Methods and results of investigation.

1. Review of published and unpublished maps, literature, and records regarding geologic units, geomorphic features, surface water and groundwater, and previous landslide activity.
2. Results of interpretation of remote-sensing imagery including stereoscopic aerial photographs, lidar, and other remote-sensing data as available.
3. Results of GPS surveying of ground surface.
4. Results of surface investigation including mapping of geologic and soil units, landslide features if present, other geomorphic features, and landslide-related distress to existing infrastructure.
5. Results of subsurface exploration including trenching, boreholes, and geophysical investigations.
6. Results of field and laboratory testing of geologic materials.

e. Conclusions.

1. Existence (or absence) and location of landslides on or adjacent to the site and their spatial relation to existing/proposed infrastructure.
2. Statement of relative risk that addresses the probability or relative potential for future landsliding and, if possible, the rate and amount of anticipated movement. This may be stated in semi-quantitative terms such as low, moderate, or high as defined within the report, or quantified in terms of landslide movement rates.
3. Degree of confidence in, and limitations of, the data and conclusions. Evidence on which the conclusions are based should be clearly stated and documented in the report.

f. Recommendations.

1. If a landslide-hazard exists on the site, provide setback or other mitigation recommendations as necessary, and justify based on regional and site-specific data.
2. Limitations on the investigation, and recommendations for additional investigation to better understand or quantify hazards.
3. Construction testing, observation, inspection, and long-term monitoring.

Table 14. *Summary of landslide mitigation approaches (modified from Holtz and Schuster, 1996).*

Procedure	Best Application	Limitations	Remarks
Avoid Problem			
Relocate facility	As an alternative anywhere	None if studied during planning phase; large cost if location already is selected and design is complete; large cost if reconstruction is required	Detailed studies of proposed relocation should ensure improved conditions
Completely or partially remove unstable materials	Where small volumes of excavation are involved and where poor soils are encountered at shallow depths	May be costly to control excavation; may not be best alternative for large landslides; may not be feasible because of property rights	Analytical studies must be performed; depth of excavation must be sufficient to ensue firm support
Install bridge	At side-hill locations with shallow soil movements	May be costly and not provide adequate support capacity for lateral forces to restrain landslide mass	Analysis must be performed for anticipated loadings as well as structural capability
Reduce Driving Forces			
Drain surface	In any design scheme; must also be part of any remedial design	Will only correct surface infiltration or seepage due to surface infiltration	Slope vegetation should be considered in all cases
Drain subsurface	On any slope where lowering of groundwater table will increase slope stability	Cannot be used effectively when sliding mass is impervious	Stability analysis should include consideration of seepage forces
Reduce weight	At any existing or potential slide	Requires lightweight materials that may be costly or unavailable; excavation waste may create problems	Stability analysis must be performed to ensure proper placement of lightweight materials
Increase Resisting Forces			
Apply external force			
Use buttress and counter weight fills; toe berms	At an existing landslide; in combination with other methods	May not be effective on deep-seated landslides; must be founded on a firm foundation	Consider reinforced steep slopes for limited property access
Use structural systems	To prevent movement before excavation; where property access is limited	Will not stand large deformations; must penetrate well below sliding surface	Stability and soil-structure analyses are required
Install anchors	Where property access is limited	Requires ability of foundation soils to resist shear forces by anchor tension	Study must be made of in situ soil shear strength; economics of method depends on anchor capacity, depth, and frequency
Increase internal strength			
Drain subsurface	Where water table is above shear surface	Requires experienced personnel to install and ensure effective operation	
Use reinforced backfill	On embankments and steep fill slopes; landslide reconstruction	Requires long-term durability of reinforcement	Must consider stresses imposed on reinforcement during construction
Install in situ reinforcement	As temporary structures in stiff soils	Requires long-term durability of nails, anchors, and micropiles	Requires thorough soils investigation and properties testing
Biotechnical stabilization	On soil slopes of modest heights	Climate; may require irrigation in dry seasons; longevity of selected plants	Design is by trial and error plus local experience

B. References

a. Literature and records cited or reviewed; citations should be complete (see References section of this publication for examples).

b. Remote-sensing images interpreted; list type, date, project identification codes, scale, source, and index numbers.

c. Other sources of information, including well records, personal communication, and other data sources.

C. Illustrations

a. Location map—showing site location and significant physiographic and cultural features, generally at 1:24,000 scale or larger and indicating the Public Land Survey System ¼-section, township, and range; and the site latitude and longitude to four decimal places with datum.

b. Site development map—showing site boundaries, existing and proposed structures, graded and filled areas (including engineered and non-engineered fill), streets, exploratory test pits, trenches, boreholes, and geophysical traverses. The map scale may vary depending on the size of the site and area covered by the study; the minimum recommended scale is 1 inch = 200 feet (1:2400) or larger where necessary.

c. Geologic map(s)—showing distribution of bedrock and unconsolidated geologic units, faults or other geologic structures, extent of existing landslides, geomorphic features, and, if appropriate, features mapped using lidar data. Scale of site geologic maps will vary depending on the size of the site and area of study; minimum recommended scale is 1 inch = 200 feet (1:2400) or larger where necessary. For large projects, a regional geologic map and regional lidar coverage may be required to adequately depict all important geologic features and recent landslide activity.

d. Geologic cross sections, if needed, to provide three-dimensional site representation.

e. Logs of exploratory trenches, test pits, cone penetrometer test soundings, and boreholes—showing details of observed features and conditions. Logs should not be generalized or diagrammatic. Trench and test pit logs should show geologic features at the same horizontal and vertical scale and may be on a rectified photomosaic base.

f. Geophysical data and interpretations.

g. Photographs that enhance understanding of site surface and subsurface (trench and test pit walls) conditions with applicable metadata.

D. Authentication

Report signed and sealed by a Utah licensed Professional Geologist in principal charge of the investigation (Title 58-76-10 – Professional Geologists Licensing Act [Utah Code, 2011]). Final geologic maps, trench logs, cross sections, sketches, drawings, and plans prepared by, or under the supervision of, a professional geologist also must bear the seal of the professional geologist (Utah Code, 2011). Reports co-prepared by a Utah licensed Professional Engineer and/or Utah licensed Professional Land Surveyor must include the engineer's and/or surveyor's stamp and signature.

E. Appendices

Supporting data not included in the body of the report (e.g., water-well data, survey data, groundwater and deformation monitoring data, etc.).

FIELD REVIEW

The UGS recommends a technical field review by the regulatory-authority geologist once a landslide-hazard investigation is complete. The field review should take place after any trenches or test pits are logged, but before they are closed so subsurface site conditions can be directly observed and evaluated. See Field Review section in chapter 2.

REPORT REVIEW

The UGS recommends regulatory review of all reports by a Utah licensed Professional Geologist experienced in landslide-hazard investigations and acting on behalf of local governments to protect public health, safety, and welfare, and to reduce risks to future property owners (Larson, 1992, 2015). See Report Review section in chapter 2.

DISCLOSURE

The UGS recommends disclosure during real-estate transactions whenever an engineering-geology investigation has been performed. See Disclosure section in chapter 2.

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CHAPTER 5
GUIDELINES FOR THE GEOLOGIC INVESTIGATION OF DEBRIS-FLOW HAZARDS ON ALLUVIAL FANS IN UTAH

by
Richard E. Giraud, P.G.

September 12, 2002, fire-related debris flow in Santaquin subdivision following the 2001 Mollie wildfire.

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CHAPTER 5: GUIDELINES FOR THE GEOLOGIC INVESTIGATION OF DEBRIS-FLOW HAZARDS ON ALLUVIAL FANS IN UTAH

by Richard E. Giraud, P.G.

INTRODUCTION

These guidelines outline the recommended minimum acceptable level of effort for evaluating debris-flow hazards on alluvial fans in Utah. These guidelines were originally published in 2005 (Giraud, 2005). The guidelines below provide updated information on debris-flow-hazard investigation in Utah. The objective of these guidelines is to promote uniform and effective statewide implementation of debris-flow hazard investigation and mitigation measures to reduce risk. These guidelines do not include systematic descriptions of all available investigative or mitigation techniques or topics, nor is it suggested that all techniques or topics are appropriate for every project. Variations in site conditions, project scope, economics, and level of acceptable risk may require that some topics be addressed in greater detail than is outlined in these guidelines. However, all elements of these guidelines should be considered in debris-flow hazard investigations, and may be applied to any project site, large or small.

Background

Debris flows and related sediment flows are fast-moving flow-type landslides composed of a slurry of rock, mud, organic matter, and water that move down drainage-basin channels onto alluvial fans (figure 25). Debris flows generally initiate on steep slopes or in channels by the addition of water from intense rainfall or rapid snowmelt. Flows typically incorporate additional sediment and vegetation as they travel down-channel. When flows reach an alluvial fan and lose channel confinement, they spread laterally and deposit the entrained sediment. In addition to being debris-flow-deposition sites, alluvial fans are also favored sites for urban development; therefore, a debris-flow-hazard investigation is necessary when developing on alluvial fans. The hazard investigation may indicate that risk reduction is necessary for sustainable development on the alluvial fan. A debris-flow-hazard investigation requires an understanding of the debris-flow processes that govern sediment supply, sediment bulking, flow volume, flow frequency, and deposition. However, a uniform level of acceptable risk for debris flows based on recurrence or frequency/volume relations, such as the 100-year flood or the 2% in 50-year exceedance probability for earthquake ground shaking, has not been established in Utah.

Historical records of sedimentation events in Utah indicate that debris flows are highly variable in terms of size, material properties, travel distance, and depositional behavior; therefore, a high level of precision for debris-flow design parameters is not yet possible, and conservative engineering parameters and designs must be used where risk reduction is necessary. Debris-flow-hazard investigations follow the premise that areas where debris flows have deposited sediment in the recent geologic past are likely sites for future debris-flow activity. Debris-flow-hazard investigations use geomorphic, sedimentologic, and stratigraphic information from existing debris-flow deposits and sediment-volume estimates from the feeder channel and drainage basin to estimate the hazard within the active depositional area of an alluvial fan. A complete debris-flow-hazard investigation typically involves geologic, hydrologic, hydraulic, and engineering evaluations. The nature of the proposed development and the anticipated risk-reduction measures required typically determine the scope of the hazard investigation.

Large-volume debris flows are low-frequency events, and the interval between large flows is typically deceptively tranquil. The debris-flow hazard on alluvial fans can be difficult to recognize, particularly on alluvial fans that are subject to high-magnitude, low-frequency events (Jakob, 2005). Debris flows pose a hazard very different from other types of landslides and floods due to their rapid movement and destructive power. Debris flows can occur with little warning. Fifteen people have been killed by debris flows in Utah (chapter 1, table 4). Thirteen of the victims died in two different night events when fast-moving debris flows allowed little chance of escape. In addition to threatening lives, debris flows can damage buildings and infrastructure by sediment burial, erosion, direct impact, and associated water flooding. The 1983 Rudd Canyon debris flow in Farmington deposited approximately 90,000 cubic yards of sediment on the alluvial fan, damaged 35 houses, and caused an estimated $3 million in property damage (Deng and others, 1992).

Variations in sediment-water concentrations produce a continuum of sediment-water flow types that build alluvial fans. Beverage and Culbertson (1964), Pierson and Costa (1987), Costa (1988), and Pierson (2005a, 2005b) describe the following flow types based on generalized sediment-water con-

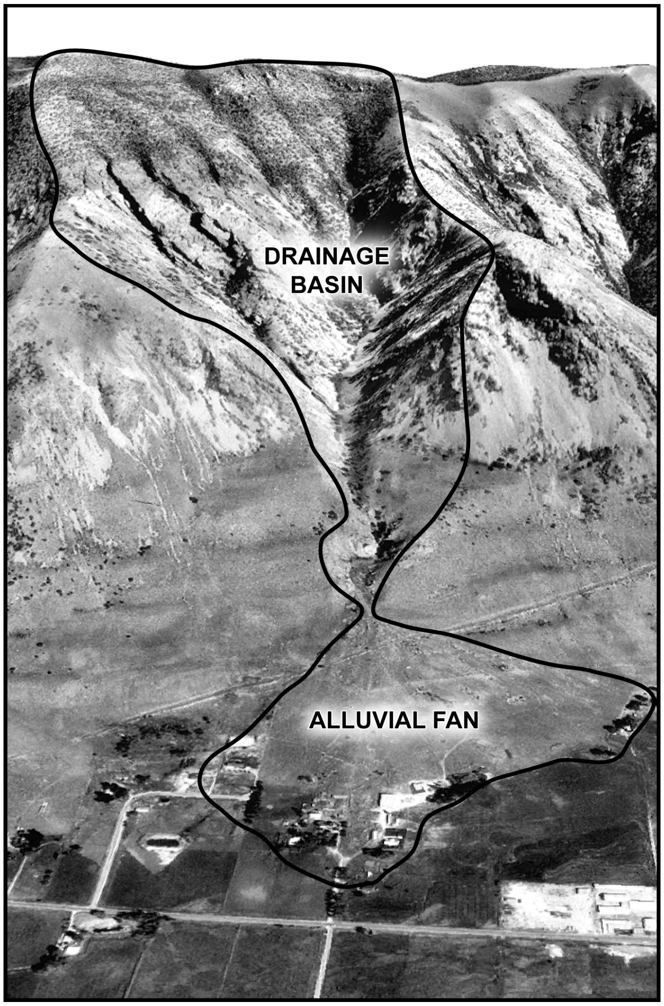

Figure 25. *Example of a drainage basin and alluvial fan at Kotter Canyon, north of Brigham City, Utah.*

centrations and resulting flow behavior: stream flow (less than 20% sediment by volume), hyperconcentrated flow (20 to 60% sediment by volume), and debris flow (greater than 60% sediment by volume). These categories are approximate because the exact sediment-water concentration and flow type depend on the grain-size distribution and physical-chemical composition of the flows. Also, field observations and video recordings of poorly sorted water-saturated sediment provide evidence that no unique flow type adequately describes the range of mechanical behaviors exhibited by these sediment flows (Iverson, 2003). All three flow types can occur during a single event. The National Research Council (1996) report *Alluvial-Fan Flooding* considers stream, hyperconcentrated, and debris-flow types of alluvial-fan flooding. The term debris flood has been used in Utah to describe hyperconcentrated flows (Wieczorek and others, 1983).

These guidelines address only hazards associated with hyperconcentrated- and debris-flow sediment-water concentrations and not stream-flow flooding on alluvial fans. The term debris flow is used here in a general way to include all flows within the hyperconcentrated- and debris-flow sediment-water concentration range. These are the most destructive flows, and it can be difficult to distinguish between hyperconcentrated and debris flows based on their deposits or their effect on infrastructure. Stream flow involves sediment transport by entrained bed load and suspended sediment load associated with water transport. Sheetfloods are unconfined stream flows that spread over the alluvial fan (Blair and McPherson, 1994). Debris-flow and stream-flow-flooding hazards may be managed differently in terms of land-use planning and protective measures, but because debris-flow and stream-flow hazards are often closely associated, concurrent investigations of both debris-flow and stream-flow components of alluvial-fan flooding is often beneficial.

Purpose

The Utah Geological Survey (UGS) developed these guidelines to help engineering geologists evaluate debris-flow hazards on alluvial fans to ensure safe and sustainable development. The purpose of a debris-flow-hazard investigation is to determine whether or not a debris-flow hazard exists, describe the hazard, and if needed, provide geologic parameters necessary for hydrologists and engineers to design risk-reduction measures. The objective is to determine active depositional areas, frequency and magnitude (volume) of previous flows, and likely impacts of future sedimentation events. Dynamic analysis of debris flows using hydrologic, hydraulic, and other engineering methods to design site-specific risk-reduction measures is not addressed by these guidelines.

These guidelines will assist engineering geologists in evaluating debris-flow hazards in Utah, engineers in designing risk-reduction measures, and land-use planners and technical reviewers in reviewing debris-flow-hazard reports. The engineering geologist has the responsibility to (1) conduct a study that is thorough and cost effective, (2) be familiar with and apply appropriate investigation methods, (3) record accurate observations and measurements, (4) use proper judgment, and (5) present valid conclusions and recommendations supported by adequate data and sound interpretations. The geologist must also understand and clearly state the uncertainties and limitations of the investigative methods used and the uncertainties associated with design-parameter estimates.

SOURCES OF DEBRIS-FLOW INFORMATION

Sources of information for debris-flow-hazard investigations include U.S. Geological Survey (USGS) and UGS maps that show debris-flow source areas at a nationwide scale (1:2,500,000; Brabb and others, 2000), statewide scale (1:500,000; Brabb and others, 1989; Harty, 1991), and 30 x 60-minute quadrangle scale (1:100,000) for the entire state (Elliott and Harty, 2010). The 30 x 60-minute quadrangle maps show both the source and depositional areas of some historical debris flows. Alluvial-fan deposits are commonly shown on modern geologic maps, and the UGS and others map surficial (Quaternary) geology on USGS 7½-minute-scale quadrangle maps (1:24,000). Wasatch Front counties have maps available in county planning offices showing special-study areas where debris-flow-hazard investigations are required. Surficial geologic maps generally show alluvial-fan deposits of different ages and differentiate stream alluvium from alluvial-fan deposits.

Numerous investigators have studied debris-flow processes and performed debris-flow-hazard investigations in Utah. Many studies address the 1983 and 1984 debris flows that initiated during a widespread rapid-snowmelt period. Christenson (1986) discussed mapping, hazard evaluation, and mitigation measures following the debris flows of 1983. Wieczorek and others (1983, 1989) described the potential for debris flows and debris floods and mitigation measures along the Wasatch Front between Salt Lake City and Willard. Lips (1985, 1993) mapped 1983 and 1984 landslides and debris flows in central Utah. Paul and Baker (1923), Woolley (1946), Bailey and others (1947), Croft (1962), Butler and Marsell (1972), Marsell (1972), Keate (1991), Elliott and Kirschbaum (2007), and Elliott and Harty (2010) documented different debris-flow events in Utah. Other debris-flow events and investigation reports can be found in the GeoData Archive System (http://geodata.geology.utah.gov/), a collection of consultant's and other geologic-hazard reports and data maintained by the UGS (see chapter 2).

Several researchers investigated different aspects of the 1983 and 1984 Davis County debris flows. Pack (1985), for the purpose of landslide susceptibility mapping, used a multivariate analysis to evaluate factors related to initiation of debris slides in 1983 that then transformed into debris flows. Pierson (1985) described flow composition and dynamics of the 1983 Rudd Canyon debris flow in Farmington. Santi (1988) studied the kinematics of debris-flow transport and the bulking of colluvium and channel sediment during a 1984 debris flow in Layton. Mathewson and others (1990) studied bedrock aquifers and the location of springs and seeps that initiated colluvial slope failures in 1983 and 1984 that then transformed into debris flows. Keaton (1988) and Keaton and others (1991) developed a probabilistic model to assess debris-flow hazards on alluvial fans. Williams and Lowe (1990) estimated channel sediment bulking rates by comparing cross-channel profiles of channels that discharged historical debris flows with channels that had not discharged flows in historical time. Deng and others (1992) studied debris-flow impact forces, types of house damage, and economic losses from the 1983 Rudd Canyon debris flow.

Outside of Utah others have outlined approaches for evaluating debris-flow hazards and methods for estimating design parameters for debris-flow-risk reduction. Hungr and others (1984) described approaches to estimate debris-flow frequency, volume, peak discharge, velocity, and runout distance in western Canada. VanDine (1985) described conditions conducive to debris flows, triggering events, effects, and mitigation in the southern Canadian Cordillera. Hungr and others (1987) described debris-flow-engineering concepts and risk reduction in source, transport, and deposition zones in British Columbia. Jackson (1987) outlined methods for evaluating debris-flow hazards on alluvial fans in the Canadian Rocky Mountains based on the presence of debris-flow deposits, alluvial-fan geomorphic features, deposit ages, debris-flow frequency, and basin conditions. Jackson (1987) also provided a flow chart summarizing debris-flow-hazard evaluation. Jackson and others (1987) used geomorphic and sedimentologic criteria to distinguish alluvial fans prone to debris flows and those dominated by stream-flow processes. Ellen and others (1993) used digital simulations to map debris-flow hazards in the Honolulu District of Oahu, Hawaii. VanDine (1996) summarized the use of debris-flow control structures for forest engineering applications in British Columbia. Boyer (2002) discussed acceptable debris-flow-risk levels for subdivisions in British Columbia and provided a suggested outline for debris-flow studies on alluvial fans. Jakob and Hungr (2005) are editors of *Debris-flow Hazards and Related Phenomena*, a book that provides an excellent overview of debris-flow science, mitigation, and case histories.

U.S. Natural Resources Conservation Service (NRCS, formerly Soil Conservation Service) soil surveys show soils on alluvial fans and in drainage basins. These soil surveys provide information on soil type, depth, permeability, erodibility, slope steepness, vegetation, and parent material. Some soil surveys document historical debris-flow activity.

Newspaper articles and event reports often provide descriptions of historical debris flows and photographs showing impacts on developed areas (Elliott and Kirschbaum, 2007). Written observations and photographs of historical debris flows provide useful information on flow volume, flow velocity, flow depth, deposit thickness, deposit areas, and building damage. Comparison of historical debris-flow deposits with prehistoric deposits indicates whether the historical debris flow is a typical event relative to other flows preserved in the sedimentary record.

Stereoscopic aerial photographs are a fundamental tool for evaluating drainage basins and alluvial fans. Interpretation of aerial photographs can provide information on historical debris-flow events, surficial geology, soils, bedrock exposures, channel characteristics, landslides, previous debris flows, relative deposit ages, erosional areas, land use, vegetation types, and time brackets for historical debris flows. Reviewing the oldest and most recent photos available is useful to evaluate drainage-basin and alluvial-fan changes through time. Obtaining aerial photographs taken after historical debris flows allows direct mapping of sediment sources and deposits. The UGS maintains a database of historical aerial photography in Utah (https://geodata.geology.utah.gov/imagery/).

DEBRIS-FLOW-HAZARD INVESTIGATION

A debris-flow-hazard investigation is necessary when developing on active alluvial fans where relatively recent debris deposition has occurred. The investigation requires application of quantitative and objective procedures to estimate the location and recurrence of flows, assess their impacts, and provide recommendations for risk-reduction measures if necessary. The hazard investigation must consider the intended land use because site usage has direct bearing on the degree of risk to people and structures. The UGS recommends critical facilities and structures for human occupancy not be placed in active debris-flow travel and deposition areas unless methods are used to either eliminate or reduce the risk to an acceptable level. In some cases, risk-reduction measures may be needed retroactively to protect existing development.

To evaluate the hazard on active alluvial fans, the frequency, magnitude or volume (deposit area and thickness), and runout distance of past debris flows must be determined. The geologic methods presented here rely on using the geologic characteristics of existing alluvial-fan deposits as well as drainage-basin and feeder-channel sediment-supply conditions to estimate the characteristics of past debris flows. Historical records can provide direct evidence of debris-flow volume, frequency, and depositional area. However, the observation period in Utah is short, and in many areas debris flows either have not occurred or have not been documented. Therefore, geologic methods provide the principal means of determining the history of debris-flow activity on alluvial fans. Multiple geologic methods should be used whenever possible to compare results of different methods to understand the appropriateness, validity, and limitations of each method and increase confidence in the hazard investigation.

Where stream flow dominates on an alluvial fan, a stream-flow-flooding investigation is necessary, but a debris-flow-hazard investigation is not required. The National Research Council (1996) report *Alluvial-Fan Flooding* and the Federal Emergency Management Agency (2003) *Guidance for Alluvial Fan Flooding Analysis and Mapping* provide guidance for evaluating the stream-flow component of alluvial-fan flooding.

When to Perform a Debris-Flow-Hazard Investigation

Geologic hazards are best addressed prior to land development. The UGS recommends that a debris-flow-hazard investigation be made for all new buildings for human occupancy and for modified International Building Code (IBC) Risk Category II(a), II(b), III, and IV facilities (see table 12 in chapter 3 of this publication, modified from IBC table 1604.5 [International Code Council, 2014a]) on or adjacent to alluvial fans. Utah jurisdictions that have adopted debris-flow special-study maps identify zones in known debris-flow-susceptible areas within which they require site-specific investigation. The UGS recommends that investigations as outlined in these guidelines be conducted for sites on or adjacent to alluvial fans for all IBC Risk Category III and IV facilities, whether near a mapped debris-flow susceptible area or not, to ensure that a previously unknown debris-flow hazard is not present. If a hazard is found, the UGS recommends a comprehensive investigation be conducted. Additionally, in some instances an investigation may become necessary when existing infrastructure is discovered to be on or adjacent to a debris-flow-susceptible area.

The level of investigation conducted for a particular project depends on several factors, including (1) site-specific geologic conditions, (2) type of proposed or existing development, (3) level of acceptable risk, and (4) governmental permitting requirements, or regulatory agency rules and regulations. A debris-flow-hazard investigation may be conducted separately, or as part of a comprehensive geologic-hazard and/or geotechnical site investigation (see chapter 2).

Minimum Qualifications of Investigator

Debris-flow-related engineering-geology investigations and accompanying geologic-hazard evaluations performed before the public shall be conducted by or under the direct supervision of a Utah licensed Professional Geologist (Utah Code, Title 58-76-10) who must sign and seal the final report. Often these investigations are interdisciplinary in nature, and where required, must be performed by qualified, experienced, Utah licensed Professional Geologists (PG, specializing in engineering geology) and Professional Engineers (PE, specializing in geological and/or geotechnical engineering) working as a team. See Investigator Qualifications section in chapter 2.

Alluvial-Fan Evaluation

Alluvial fans are landforms composed of a complex assemblage of debris-, hyperconcentrated-, and stream-flow deposits. Alluvial-fan geomorphology, sedimentology, and stratigraphy provide a long-term depositional history of the frequency, volume, and depositional behavior of past flows, and provide a geologic basis for estimating debris-flow hazards.

Defining the Active-Fan Area

The first step in an alluvial-fan evaluation is determining the active-fan area using mapping and alluvial-fan dating techniques. The active-fan area is where relatively recent deposition, erosion, and alluvial-fan flooding have occurred (figure 26). In general, sites of sediment deposition during Holocene time (past 11,700 years; post-Lake Bonneville in northwest Utah) are considered active unless proven otherwise. Aerial photographs, detailed topographic maps, and field verification of the extent, type, character, and age of alluvial-fan deposits are used to map active-fan areas. Some areas of Utah have light detection and ranging (lidar) coverage, and the lidar data

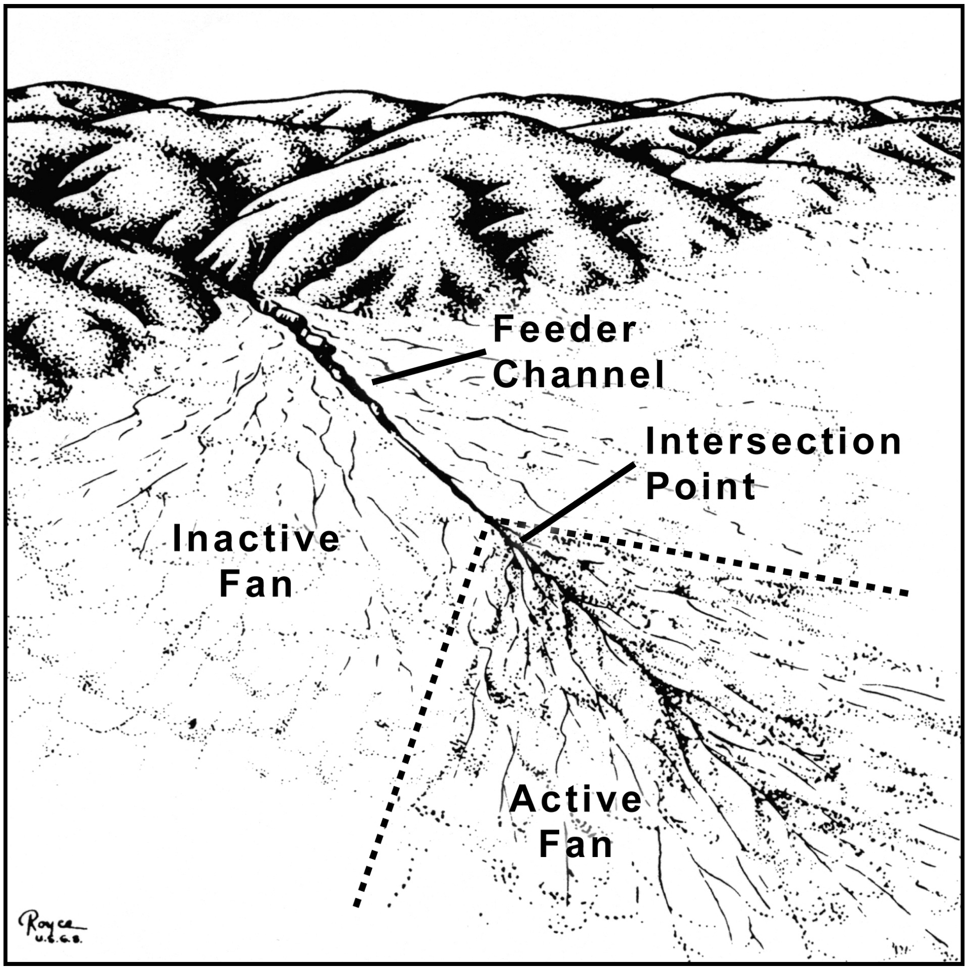

Figure 26. *Active and inactive alluvial fans, feeder channel, and intersection point. Modified from Bull (1977). Reproduced with permission by Edward Arnold (Publishers) Ltd., London.*

can be used to develop detailed topographic maps and hillshade images to aid in mapping alluvial-fan deposits. The UGS maintains an archive of lidar data (http://geology.utah.gov/resources/data-databases/lidar-elevation-data/).

The youngest debris-flow deposits generally indicate debris flows produced during the modern climate regime, and are important for estimating the likely volume and runout of future flows. The active fan is often used as a zoning tool to identify special-study areas where detailed debris-flow-hazard investigations are required prior to development. The National Research Council (1996) report *Alluvial-Fan Flooding* provides criteria for differentiating active and inactive alluvial fans.

Mapping Alluvial-Fan and Debris-Flow Deposits

Geologic mapping is critical for identifying and describing the active areas of alluvial fans. Mapping of debris-flow and other deposits generally focuses on landforms; the extent, type, character, and age of geologic deposits, specifically individual debris flows; and stratigraphic relations between deposits. Recent debris-flow deposits are generally mapped based on their distinctive surface morphology and composition. Peterson (1981), Christenson and Purcell (1985), Wells and Harvey (1987), Bull (1991), Whipple and Dunne (1992), Doelling and Willis (1995), Hereford and others (1996), and Webb and others (1999) provide examples and suggestions for mapping alluvial-fan deposits.

The geomorphic, sedimentologic, and stratigraphic relations recognized during mapping of alluvial-fan deposits provide insight into debris-flow recurrence, volumes, and depositional behavior, and therefore debris-flow hazard in the proximal, medial, and distal fan areas (figure 27). The intersection point or apex of the active fan is where the feeder channel ends and sediment flows lose confinement and begin to spread laterally, thin, and deposit sediment (figure 26; Blair and McPherson, 1994). Most feeder channels lose confinement on the upper fan, but others may incise the inactive upper fan and convey sediment and flood flows farther downfan via a fanhead trench or channel (figure 26).

In proximal fan areas, debris flows generally have the highest velocity and greatest flow depth and deposit thickness, and are therefore the most destructive. In distal fan areas, debris flows generally have lower velocities and shallower flow depths and

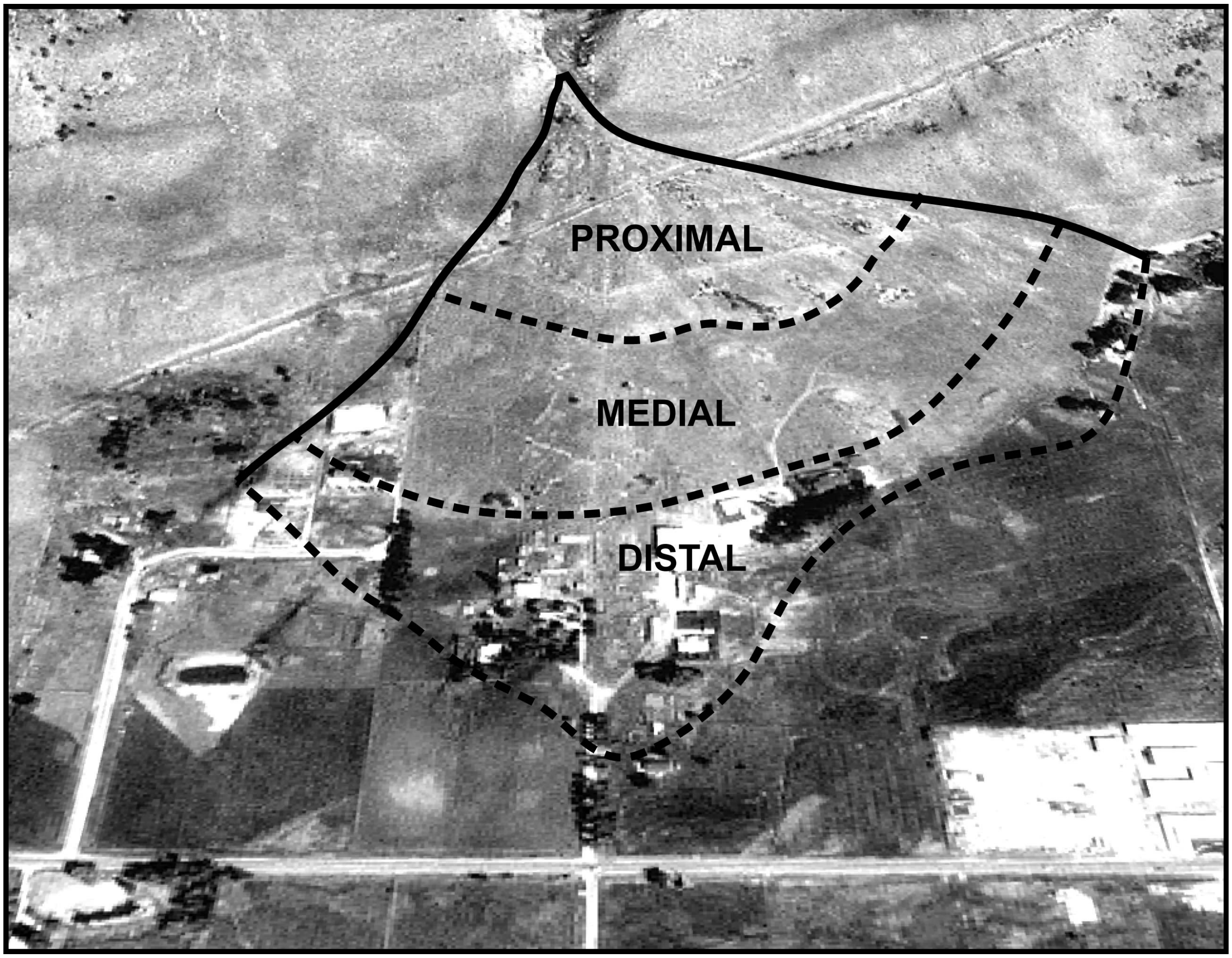

Figure 27. *Approximate proximal, medial, and distal fan areas on the Kotter Canyon alluvial fan, north of Brigham City, Utah.*

deposits, and therefore are less destructive. Often, distal fan areas are dominated by stream-flow processes only. However, some debris flows may create their own channels by producing levees on the fan and convey sediment farther downfan, or block the active channel and avulse (make an abrupt change in course) to create new channels. Unpredictable flow behavior is typical of debris flows and must be considered when evaluating debris-flow depositional areas, runout distances, and depositional behavior on alluvial fans.

The proximal part of an alluvial fan is generally made up of vertically stacked debris-flow lobes and levees that result in thick, coarse deposits that exhibit the roughest surface on the fan (figure 27). Hyperconcentrated flows may be interbedded with debris flows in the proximal fan area, but are generally thinner and have smoother surfaces due to their higher initial water content. Proximal fan deposits generally transition to thinner and finer grained deposits downfan, resulting in smoother fan surfaces in medial and distal fan areas (figure 27). Coarser grained sedimentary facies grade downfan into finer grained facies deposited by more dilute sediment flows. The downfan decrease in grain size generally corresponds with a decrease in fan-slope angle. Coarser grained debris-flow deposits generally create steeper proximal-fan slopes (6°–8°), while finer grained stream-flow deposits form gentle distal-fan slopes (2°–3°) (National Research Council, 1996).

Differences in bedding, sediment sorting, grain size, and texture are useful to distinguish debris-, hyperconcentrated-, and stream-flow deposits. Costa and Jarrett (1981, p. 312–317), Wells and Harvey (1987, p. 188), Costa (1988, p. 118–119), Harvey (1989, p. 144), the National Research Council (1996, p. 74), and Meyer and Wells (1997, p. 778) provide morphologic and sedimentologic criteria (surface morphology, internal structures, texture, grain size, and sorting) for differentiating the three flow types. In general, debris-flow deposits are matrix supported and poorly sorted, hyperconcentrated-flow deposits are clast supported and poorly to moderately sorted, and stream-flow deposits are clast supported and moderately to well sorted. Table 15 is modified from Costa (1988) and shows geomorphic and sedimentologic characteristics of debris-, hyperconcentrated-, and stream-flow deposits. Grain-size analysis is useful in classifying deposits into the different flow types (Pierson, 1985). In addition to the primary process of debris-flow deposition, secondary processes of weathering and erosion by fluvial and/or eolian activity can rework de-

Table 15. *Geomorphic and sedimentologic criteria for differentiating water and sediment flows (modified from Costa, 1988, and Pierson, 2005a).*

Flow Type	Landforms and Deposits	Sedimentary Structures	Sediment Characteristics
Stream flow	Bars, fans, sheets, splays; channels have large width-to-depth ratio	Horizontal or inclined stratification to massive; weak to strong imbrication; cut-and-fill structures; ungraded to graded	Beds well to moderately sorted; clast supported
Hyperconcentrated flow	Similar to water flood, rectangular channel	Weak stratification to massive; weak imbrication; thin gravel lenses; normal and reverse grading	Poorly to moderately sorted; clast supported
Debris flow	Marginal levees, terminal lobes, trapezoidal to U-shaped channel	No stratification; weak to no imbrication; inverse grading at base; normal grading near top	Very poor to extremely poor sorting; matrix supported; extreme range of particle sizes; may contain megaclasts

bris-flow deposits. The subsequent reworking of debris-flow deposits can change the morphology and texture of the fan surface and can introduce uncertainty of mapping individual debris-flow deposits.

More than one flow type may occur during a sedimentation event. Keaton (1988) described an ideal vertical alluvial-fan stratigraphic sequence based on deposits in Davis County and published eyewitness accounts. The ideal sequence resulting from a single debris flow consists of a basal plastic debris-flow deposit, sequentially overlain by a viscous debris-flow, hyperconcentrated-flow, and finally a stream-flow deposit owing to time-varying availability of sediment and water. Janda and others (1981) identified a similar vertical sequence in debris-flow deposits at Mount St. Helens, Washington, and attributed the vertical sequence to rapid transitions between flow types.

Lidar is a powerful tool for mapping alluvial-fan deposits (appendix C). The digital elevation model and derived detailed topography, hillshade, and hillslope maps aid the debris-flow investigator in characterizing the alluvial-fan feeder channel, the fan surface, fan deposits, fan channels, and presenting the alluvial-fan-hazard information.

Determining the Age of Debris-Flow Deposits

Both relative and numerical geochronologic techniques (Noller and others, 2000; Geochronology section in chapter 2) are useful for dating debris-flow deposits and determining the frequency of past debris flows on a fan. Relative dating methods include geomorphic position of debris-flow deposits, boulder weathering, rock varnish, soil-profile development (including pedogenic carbonate accumulation), lichen growth, and vegetation age and pattern. The amount of soil development on a buried debris-flow surface is an indicator of the relative amount of time between debris flows at a particular location. Numerical dating techniques include sequential photographs, historical records, vegetation age, and isotopic dating, principally radiocarbon. Radiocarbon ages of paleosols buried by debris flows can provide closely limiting maximum ages of the overlying flow (Forman and Miller, 1989). Radiocarbon ages of detrital charcoal within a debris-flow deposit provide a more broadly limiting maximum age. The applicability and effectiveness of radiocarbon dating of debris-flow events is governed by the presence and type of datable material and available financial resources (Lettis and Kelson, 2000).

Subsurface Exploration

Subsurface exploration using test pits, trenches, and natural exposures is useful in obtaining sedimentologic and stratigraphic information regarding previous debris flows. Test-pit and trench excavations can provide information on flow type, thickness, the across-fan and downfan extent of individual flows, and volume based on thickness and area. The type, number, and spacing of excavations depend on the purpose and scale of the hazard investigation, geologic complexity, rate of downfan and across-fan transitions in flow type and thickness, and anticipated risk-reduction measures. T-shaped test pits or trenches expose three-dimensional deposit relations. Excavations in the proximal fan areas generally need to be deeper due to thicker deposits. To evaluate the entire fan, tens of excavations may be required.

Mulvey (1993) used subsurface stratigraphic data from seven test pits to estimate flow types, deposit thicknesses, the across-fan and downfan extent of deposits, deposit volumes, and age of deposits to interpret the depositional history of a 2-acre post-Bonneville fan in Centerville. On the Jones Creek fan in Washington State, Jakob and Weatherly (2005) used subsurface stratigraphic data and radiocarbon ages from trenches to determine the frequency of debris flows; a subsequent risk analysis demonstrated the need for mitigation measures. Blair and McPherson (1994) used across-fan and downfan stratigraphic cross sections to display, analyze, and interpret the surface and subsurface interrelations of fan slope, deposit levees and lobes, deposit and sediment facies, and grain size. However stratigraphic interpretation can be problematic. Debris-flow deposits in a sedimentary sequence that have similar grain sizes and lack an intervening paleosol or other distinct layer may be difficult to distinguish. The lack of distinction between individual debris-flow deposits can lead to underestimating debris-flow recurrence and overestimating debris-flow magnitude (Major, 1997).

Drainage-Basin and Channel Evaluation

Drainage-basin and channel evaluations determine the conditions and processes that govern sediment supply and transport to the fan surface, and provide an independent check of alluvial-fan evaluations. Drainage-basin and channel evaluation involves estimating the erosion potential of the basin and feeder channel and the volume, grain size, and gradation of sediment that could be incorporated into a debris flow. The evaluation also considers different debris-flow initiation mechanisms. The results of the drainage-basin and channel evaluation are used to estimate the probability of occurrence and design volumes of future debris flows. In some cases, evaluation of the drainage basin and channel may be performed independently of the alluvial-fan evaluation. For example, a wildfire in a drainage basin may initiate a post-burn analysis of the drainage basin and channels to estimate or revise the erodible sediment volume and the probability of post-fire debris flows.

Debris-Flow Initiation

Debris flows initiate in the drainage basin and require a hydrologic trigger such as intense or prolonged rainfall, rapid snowmelt, and/or groundwater discharge. Intense thunderstorm rainfall, often referred to as cloudburst storms by early debris-flow investigators in Utah (for example, Woolley, 1946; Butler and Marsell, 1972), has generated numerous debris flows. Conditions in the drainage basin important in initiating debris flows are the basin relief, channel gradient, bedrock and surficial geology, vegetation and wildfire, and land use. Exposed bedrock on hillsides promotes rapid surface-water runoff, which helps generate debris flows. Wildfires can destroy rainfall-intercepting vegetation and create conditions that promote rapid surface-water runoff. All of these conditions may work in combination to promote debris flows.

In Utah, above-normal precipitation from 1980 through 1986 produced numerous snowmelt-generated landslides (mostly debris slides) that transformed into debris flows and then traveled down channels (Brabb and others, 1989; Harty, 1991). Many of these debris flows occurred during periods of rapid snowmelt and high stream flows, when Santi (1988) indicates that saturated channel sediment is more easily entrained into debris flows. Above-normal snowpacks in 2005 and 2011 also produced snowmelt debris flows, but the rapid snowmelt pattern was not as widespread as the 1980–86 period.

In contrast to wet climate conditions, dry conditions often lead to wildfires that partially or completely burn drainage-basin vegetation, creating conditions for increased runoff and erosion. Relatively small amounts of intense thunderstorm rainfall (a few tenths of an inch per hour) are capable of triggering fire-related debris flows (McDonald and Giraud, 2010; Cannon and others, 2008).

During the drought years of 1999–2004 in northern Utah, 26 debris flows occurred in 7 wildfire areas, including repeated flows from single drainages in different storms and multiple flows from different drainages during the same storm (Giraud and McDonald, 2007). The fire-related debris flows were generated by erosion and progressive sediment bulking of runoff rather than by landslides. These debris flows initiated in a similar manner to the 1920s and 1930s debris flows from overgrazed and burned watersheds in northern Utah studied by Bailey and others (1947) and Croft (1962), and burned areas in the western U.S. studied by Cannon (2001). The debris flows produced from the drainage basins show a wide range of channel sediment-bulking rates, flow volumes, and runout distances (Giraud and McDonald, 2007).

Debris-flow-hazard investigations following a wildfire address burn severity and hillslope and channel conditions. Wells (1987), Florsheim and others (1991), Cannon and others (1995), Meyer and others (1995), Cannon and Reneau (2000), Kirkham and others (2000), Robichaud and others (2000), and Cannon (2001) discuss post-burn conditions and debris-flow susceptibility following wildfires. Cannon and others (2010) developed empirical models based on statistical data from recently burned basins in the Intermountain Western United States including Utah, to predict the probability and volume of post-fire debris flows. Input data include topographic parameters, soil characteristics, burn severity, and rainfall totals and intensities. Cannon and others' (2010) methodology estimates probability and volume of debris flows at a specific point in time following a wildfire. As vegetation regrows and soil conditions return to pre-burn conditions the probability of a debris flow decreases. Gartner and others (2008) found that most fire-related debris flows generally occur within two years following the wildfire. Post-fire debris-flow methodology is not appropriate for determining the volume and probability of non-fire-related debris flows, which generally are larger volume and less frequent.

Debris-Flow Susceptibility of the Basin

Debris-flow susceptibility is related to the runoff, erosion, and landslide potential of drainage-basin slopes and the volume of erodible sediment stored in drainage-basin channels. Characterizing drainage-basin morphologic parameters, mapping bedrock and surficial geology, and estimating the volume of erodible channel sediment provides information on the likelihood and volume of future debris flows.

Important basin parameters include area, relief, and length and gradient of channels. A description of the types and density of vegetation and land use provides information on the possible effects of wildfire and land use on surface-water runoff and erosion. Small, steep drainage basins are well suited for generating debris flows because of their efficiency in concentrating and accelerating overland surface-water flow.

Both surficial and bedrock geology play a role in the susceptibility of drainage basins to produce flows. Some bedrock weathers rapidly and provides an abundant supply of channel sediment, whereas resistant bedrock supplies sediment at a slower rate. Exposed cliff-forming bedrock greatly increases runoff.

Some bedrock, such as shale, weathers and generates fine-grained clay-rich sediment, whereas other bedrock types generate mostly coarse sediment. The clay content of debris flows directly influences flow properties. Costa (1984) states that small changes (1% to 2%) in clay content in a debris flow can greatly increase mobility due to reduced permeability and increased pore pressure. The presence of silt and clay in a slurry aids in maintaining high pore pressure to enhance flow mobility and runout (Iverson, 2003).

Surficial geologic deposits that influence the sediment supply include (1) colluvium on steep slopes susceptible to forming debris slides, (2) partially detached shallow landslides, (3) foot-slope colluvium filling the drainage-basin channel that may contribute sediment by bank erosion and sloughing, and (4) stream-channel alluvium.

Mapping debris slides in a drainage basin and determining their potential to transform into debris flows is important in evaluating debris-flow susceptibility. Most of the 1983–84 debris flows along the Wasatch Front initiated as shallow debris slides in steep colluvial slopes below the retreating snowline (Anderson and others, 1984; Pack, 1985). Aerial-photograph analysis can show colluvium on steep slopes and previous debris slides or partially detached debris slides. A literature search of historical debris slides in the area and in areas of similar geology may help identify debris-slide susceptibility. For example, documented relations exist between debris slides and debris flows in drainage basins in the Precambrian Farmington Canyon Complex of Davis County (Pack, 1985) and in the Tertiary-Cretaceous rocks of the Wasatch Plateau (Lips, 1985).

Drainage basins that experience rapid snowmelt events have an increased debris-flow hazard. Sustained rapid snowmelt can produce large volumes of melt water with melt rates averaging 1.5 inches of water per day for 12 days or more (Giraud, 2010; Giraud and Lund, 2010). Pack (1985) and Mathewson and others (1990) determined that in the 1983–84 Davis County debris flows, water infiltration into fractured bedrock aquifers from rapid snowmelt perched and increased pore-water pressure in steep colluvial slopes that triggered localized colluvial landslides (debris slides) that transformed into debris flows. Trandafir and others (2015) found that rapid snowmelt, water infiltration, and increased pore-water pressure in steep moraine slopes can also trigger landslides that transform into debris flows. Santi (1988) suggested that sediment bulking is more likely when passage of a debris flow occurs during periods of stream flow and associated saturated channel sediment, and will result in larger debris-flow volumes.

Wieczorek and others (1983, 1989) used groundwater levels, the presence of partially detached landslide masses, and estimates of channel sediment bulking to evaluate debris-flow potential along the Wasatch Front between Salt Lake City and Willard. Superelevated levees, mud lines, and trim lines along channels are evidence of peak discharge. Measurements from these features are useful in estimating velocity and peak flow (Johnson and Rodine, 1984). Determining the age of vegetation growing on the levees provides a minimum age of past debris-flow activity.

Land use and land-use changes within a drainage basin may also influence debris-flow susceptibility. Land development often creates impervious surfaces that increase the rate and volume of runoff. Development may also remove vegetation and expose soils, promoting erosion, increasing sediment yield, and decreasing natural slope stability within the drainage basin. Debris-flow-hazard investigations must address development-induced conditions where applicable.

Channel Sediment Bulking and Flow-Volume Estimation

Sediment supply, erosion conditions, and hydrologic conditions of the drainage basin and channel determine the sediment and water concentration (flow type) and flow volume that reaches an alluvial fan. Estimating channel sediment volume available for entrainment or bulking is critical because study of historical debris flows indicates 80% to 90% of the debris-flow volume comes from the channel (Croft, 1967; Santi, 1988; Keaton and Lowe, 1998). Most estimates of potential sediment bulking are based on a unit-volume analysis of erodible sediment stored in the channel, generally expressed in cubic yards per linear foot of channel (Hungr and others, 1984; VanDine, 1985; Williams and Lowe, 1990; Hungr and others, 2005). The sediment volume stored in individual relatively homogeneous channel reaches is estimated, and then the channel-reach volumes are summed to obtain a total volume. The total channel volume is an upper bound volume and needs to be compared to historical (VanDine, 1996) and mapped alluvial-fan flow volumes to derive a design volume. If easily eroded soils and slopes prone to landsliding are present, then appropriate volumes for landslide and hillslope contributions determined from other drainage-basin landslide volumes should be added to the channel volume.

Estimating a potential sediment-bulking rate requires field inspection of the drainage basin and channels. Channel sediment-bulking estimates cannot rely on empirical methods because they are only approximate and have low reliability due to the wide scatter of data which reflects the wide range of topographical, geological, and climatic environments in Utah. Field inspection and channel sediment-bulking rate measurements of the material likely to be mobilized are the best methods to arrive at more precise estimates of debris-flow volume. Measuring cross-channel profiles and estimating the erodible depth of channel sediment is necessary to estimate the sediment volume available for bulking (figure 28). Even though a great deal of geologic judgment may be required to make the volume estimate, this is probably the most reliable and practical method for bedrock-floored channels. The design volume should not be based solely on empirical bulking of specific flood flows (for example, bulking a 100-year flood with sediment) because empirical bulking does not consider shallow landslide-generated debris flows (National Research Council, 1996), channel bedrock reaches with no stored sediment, and the typically longer recurrence period of debris flows. The channel inspection should also provide a description of the character and gradation of sediment and wood debris that could be incorporated into future debris flows.

Figure 28. *Channel sediment and cross section used to estimate sediment volume available for bulking. (a) Channel erosion from the September 10, 2002, fire-related debris flow on Dry Mountain east of Santaquin, Utah. Solid line shows the eroded channel after the debris flow, dashed line shows the estimated channel prior to debris-flow passage. (b) Sketch of channel cross section showing stored channel sediment above bedrock. Dashed line shows the estimated upper bound width and depth of channel sediment available for sediment bulking.*

Hungr and others (1984), VanDine (1985), and Williams and Lowe (1990) used historical flow volumes and channel sediment bulking rates to estimate potential debris-flow volumes. Williams and Lowe (1990), following the 1983 debris flows in Davis County, compared cross-channel profiles of drainages that had discharged historical debris flows with those that had not to estimate the amount of channel sediment bulked by historical flows. They estimated an average bulking rate of 12 yd^3/ft of channel for historical debris flows and used it to estimate flow volumes for drainage basins lacking historical debris flows, but recommended using this estimate only for perennial streams in Davis County. Bulking rates for intermittent and ephemeral streams are generally lower. For example, Mulvey and Lowe (1992) estimated a bulking rate of 5 yd^3/ft for the 1991 Cameron Cove debris flow in Davis County. The 1999–2004 fire-related debris flows in northern Utah have a wide range of estimated bulking rates (0.01 to 2.02 yd^3/ft; Giraud and McDonald, 2007). Santi and others (2008) studied 46 fire-related debris flows in Utah, Colorado, and California, and similarly found a wide range of bulking rates (0.12 to 4.0 yd^3/ft). Hungr and others (1984), VanDine (1985, 1996), and Williams and Lowe (1990) all concluded that channel length and channel sediment storage are the most important factors in estimating future debris-flow volumes.

Some drainage basins may have recently discharged a debris flow, leaving little sediment available in the feeder channel for sediment bulking for future debris flows. Keaton and others (1991) stated that channels with recent debris flows will discharge future flows of less volume until the feeder channel has recharged with sediment. In these situations, an evaluation must consider remaining channel sediment as well as the rate of sediment recharge to the channel (National Research Council, 1996; Bovis and Jakob, 1999). The percent of channel length lined by bedrock is a distinct indication of the volume of sediment remaining because sediment cannot be scoured from bedrock reaches. Williams and Lowe (1990) suggested that in Davis County the drainage basins capable of producing future large debris flows are basins that have not discharged historical debris flows. However, drainage basins having a limited debris-flow volume potential due to lack of channel sediment may still have a high stream-flow-flooding potential.

DEBRIS-FLOW-RISK REDUCTION

Eisbacher and Clague (1984), Hungr and others (1987), VanDine (1996), and Huebl and Fiebiger (2005) group debris-flow-risk reduction into two categories: passive and active. Passive methods involve avoiding debris-flow-hazard areas either permanently or at times of imminent danger. Passive methods do not prevent, control, or modify debris flows. Active methods modify the hazard using debris-flow-control structures to prevent or reduce the risk. These types of structures require engineering design using appropriate geologic inputs. In terms of development on alluvial fans, active risk-reduction measures with control structures generally attempt to maximize the buildable space and provide a reasonable level of protection.

Hungr and others (1987) and VanDine (1996) divide debris-flow-control structures along lower channel reaches and on alluvial fans into two basic types: open structures (which constrain flow) and closed structures (which contain debris). Examples of open debris-flow-control structures include unconfined deposition areas, impediments to flow (baffles), check dams, lined channels, lateral walls or berms, deflection walls or berms, and terminal walls, berms, or barriers. Examples of closed debris-flow-control structures include debris racks, or other forms of debris-straining structures located in the channel, and debris barriers and associated storage basins with a debris-straining structure (outlet) incorporated into the design.

In Utah, engineered sediment storage basins are the most common type of control structure used to reduce debris-flow risks. These structures generally benefit the community as well as the individual developer or landowner, but they are typically expensive, require periodic maintenance and sediment removal, and must often be located in areas not owned or controlled by an individual developer. For these reasons, debris-flow- and flood-risk-reduction structures are commonly government public works or shared public-private responsibilities, rather than solely a developer or landowner responsibility. This is particularly true in urban settings where the delineated hazard area may include more than one subdivision and other pre-existing development. In some cases, local flood-control agencies such as Davis County Flood Control manage both debris-flow and stream-flooding hazards.

DESIGN CONSIDERATIONS FOR RISK REDUCTION

The debris-flow hazard at a particular site depends on the site's location on the alluvial fan. Both debris-flow impact and sediment burial are more likely and of greater magnitude in proximal fan areas than in medial and distal fan areas (figure 27). Decisions regarding acceptable risk and appropriate control-structure design involve weighing the probability of occurrence in relation to the consequences of a debris flow and the residual risk level after implementing risk-reduction measures. Therefore, hazard investigations estimate the likely size, frequency, and depositional area of debris flows on an alluvial fan as accurately as possible.

Considering Frequency and Magnitude in Design

The frequency and magnitude of past debris flows are fundamental indicators of future debris-flow activity. To address the past frequency and volume of debris flows, detailed geologic studies involving geochronology are generally required. Little information exists on the past frequency of debris flows on most alluvial fans in Utah. Studies by Keaton (1988), Lips (1993), and Mulvey (1993) indicate that large-volume, destructive debris flows on the alluvial fans they studied have return periods of a few hundred to thousands of years. Fire-related debris flows in Utah are more frequent and vegetation types for fires that produced fire-related debris flows have fire-return periods of 0 to 300 years for stand-replacing fires (Giraud and McDonald, 2007). However, return periods vary widely among alluvial fans and few data exist to quantify debris-flow frequency-magnitude relations. Other difficulties in quantifying debris-flow frequency-magnitude relationships include:

- Frequencies are time-dependent. Many drainages must recharge channel sediment following a large-volume debris flow; the magnitude and frequency of future debris flows depend on the size of and time since the last event.
- Statistically-based cloudburst rainfall volumes typically used for stream-flooding evaluations (for example, the 100-year storm) are not applicable to debris-flow volumes because debris-flow discharges do not relate directly to flood discharges, and in Utah many debris flows are caused by rapid snowmelt rather than cloudburst storms.
- Wildfires and land-use changes in the drainage basin introduce significant uncertainty because they can temporarily greatly increase debris-flow frequency.

Because of these complexities, generally accepted return periods for design of debris-flow risk-reduction measures based on probabilistic models do not exist, unlike for earthquake ground shaking and flooding, which have established design return periods of 2500 years (International Building Code) and 100 years (FEMA's National Flood Insurance Program), respectively.

Although Keaton (1988) and Keaton and others (1991) developed a probabilistic model for debris flows in Davis County where a relatively complete record of historical debris flows exists, the high degree of irregularity and uncertainty in return periods limited their results and the practical application of their model. In some cases rather than assigning an absolute probability of debris-flow occurrence, many debris-flow practitioners assign a relative probability of occurrence (VanDine, 1996) based on frequencies in similar basins and fans in the geographic areas that have experienced historical debris flows.

The UGS believes Holocene-age (past 11,700 years) debris-flow deposits on an alluvial fan are sufficient evidence of a potential hazard to warrant site-specific debris-flow-hazard studies and appropriate implementation of risk-reduction measures. Holocene sediments were deposited under climatic conditions similar to the present and therefore indicate a current hazard unless geologic and topographic conditions on the alluvial fan have changed. If site-specific data on debris-flow recurrence are sufficient to develop a probabilistic model, then the model may be used in consultation with local government regulators to help determine an appropriate level of risk reduction.

Debris-Flow-Hazard Zones

Debris-flow-hazard zones identify potential impacts and associated risks, help determine appropriate risk-reduction measures, and aid in land-use planning decisions. Hungr and others (1987) outline three debris-flow-hazard zones: (1) a direct impact zone where high-energy flows increase the risk of impact damage due to flow velocity, flow thickness, and the maximum clast size; (2) an indirect impact zone where impact risk is lower, but where damage from sediment burial and debris-flow and water transport is high; and (3) a flood zone potentially exposed to flooding due to channel blockage and water draining from debris deposits. These zones roughly equate to proximal, medial, and distal fan areas, respectively (figure 27). Historical debris-flow records, deposit characteristics, and detailed topography are required to outline these hazard zones. Site-specific studies are required to define which zone applies to a particular site and to determine the most appropriate land use and risk-reduction techniques to employ.

Estimating Geologic Parameters for Engineering Design

Geologic estimates of debris-flow design parameters are necessary for engineering design of risk-reduction structures. The most appropriate data often come from historical or late Holocene debris flows that can be mapped on the fan surface. Flow and deposit characteristics are also necessary to estimate peak discharge and calibrate computer-based hydraulic flow routing models (O'Brien and Julien, 1997).

Geologic parameters required for engineering design vary depending on the risk-reduction structure proposed. Engineering designs for debris-flow risk-reduction structures are site specific (VanDine and others, 1997), and generally involve quantifying specific fan, feeder channel, deposit, and flow parameters. Geomorphic fan parameters include areas of active deposition, surface gradients, surface roughness (channels, levees, lobes), and topography. Feeder channel parameters include channel gradient, channel capacity, and indications of previous flows. Deposit parameters include area, thickness, volume, surface gradient, gradation, and largest clast size. Due to their perishable nature, flow parameters are difficult to determine unless measured immediately after an event, and are often inferred from deposit characteristics or evidence from the feeder channel. The flow parameters include estimates of flow type(s), volume, frequency, depth, velocity, peak discharge, and runout distance.

Debris flows can have significantly higher peak discharge than stream-flow flooding. Estimating peak discharge is critical because it controls maximum velocity and flow depth, impact forces, ability to overrun protective barriers, and runout distance (Hungr, 2000). VanDine (1996) stated that debris-flow discharges can be up to 40 times greater than a 200-year flood, which shows the importance of carefully estimating peak discharge when designing protective structures. Pierson (1985) described flow composition and dynamics of the 1983 Rudd Canyon debris flow in Davis County, and included some flow properties typically considered in engineering design. Costa (1984) also listed specific physical properties of debris flows. Keaton (1990) described field and laboratory methods to predict slurry characteristics based on sedimentology and stratigraphy of alluvial-fan deposits. Flow characteristics are also important to help estimate associated water volume. Prochaska and others (2008) provided debris basin and deflection berm design criteria for fire-related debris-flow risk reduction.

Estimating debris-flow volume is necessary where debris storage basins are planned (Santi, 2014). Because debris-flow behavior is difficult to predict and flows difficult to route, debris storage basins and deflection walls or berms are common methods of debris-flow risk reduction. The routing of debris flows off an alluvial fan is a difficult and complex task. O'Brien and Julien (1997) stated that channel conveyance of debris flows off an alluvial fan is not recommended because there are numerous factors that can cause the flow to plug the conveyance channel. Debris basins typically capture sediment at the drainage mouth before the debris flow travels unpredictably across the alluvial fan. For debris basin capacity, the thickness and area of individual flows on the alluvial fan and erodible channel sediment volumes are needed to estimate design debris volumes. Estimates of sediment stored in channels are usually maximum or "worst-case" volumes that represent an upper volume limit. Channel estimates may exceed the alluvial-fan estimates because typically not all channel sediment is eroded and deposited on the fan, and the channel estimate includes suspended sediment transported off the fan by stream flows. Conversely, the alluvial-fan estimate may exceed the channel estimate if a recent large flow has removed most channel sediment. VanDine (1996) considered the design volume to be the reasonable upper limit of material that will ultimately reach the fan. In a study on the precision and accuracy of debris-flow volume measurement for historical debris flows, Santi (2014) found that volume measurement uncertainty is typically at least ± 10%–20%. Estimates of prehistoric debris flow volumes likely have greater uncertainty.

Flow volume is also important in modeling runout and deposition. O'Brien and Julien (1997), in their hydraulic modeling of debris-flow runout, emphasized the importance of making conservative estimates of the available volume of sediment in the drainage basin, and comparing that volume to alluvial-fan deposit volumes to determine an appropriate modeling volume.

Geologic design parameters are also needed for the design of other types of engineered risk-reduction structures. For deflection walls and berms or for foundation reinforcement, fan gradient, flow type (debris versus hyperconcentrated versus stream), flow depth, peak flow, flow velocity, and debris size and gradation are important to ensure that the structure has the appropriate height, side slope, and curvature to account for run-up and impact forces. For design of debris barriers, flow volume, depth, deposition area, and gradient are needed to determine the appropriate storage volume. The size and gradation of debris, flow velocity, and the anticipated flow type are important in the design of debris-straining structures. Flow types are important to help estimate associated water volumes. Baldwin and others (1987), VanDine (1996), Deng (1997), and VanDine and others (1997) have described other design considerations for debris-flow-control structures.

Even though geologic investigations use quantitative and objective procedures, estimating design parameters for risk-reduction structures has practical limits. As stated earlier, historical records of debris flows show flows to be highly variable in terms of size, material properties, and travel and depositional behavior. Many debris-flow design-parameter estimates have high levels of uncertainty and often represent a best approximation of a complex natural process; therefore, appropriate limitations and engineering factors of safety must be incorporated in risk-reduction-structure design. Investigators must clearly state the limitations of the investigation methods employed and the uncertainties associated with design-parameter estimates.

DEBRIS-FLOW-INVESTIGATION REPORT

The UGS recommends that a report prepared for a site-specific debris-flow investigation in Utah at a minimum address the topics below. Site conditions may require that additional items be included to fully evaluate debris-flow hazard at a site; these guidelines do not relieve engineering geologists from their duty to perform additional geologic investigations as necessary to adequately assess the debris-flow hazard. The report guidelines below pertain specifically to debris-flow investigations on alluvial fans, and expand on the general report preparation guidance provided in the Engineering-Geology Investigations and Engineering-Geology Reports sections of chapter 2.

A. Text

a. Purpose and scope of investigation. Describe the location and size of the site and proposed type and number of buildings or other infrastructure if known.

b. Geologic and topographic setting. The report should contain a clear and concise statement of the site and site region's geologic and topographic setting. The section should include a discussion of debris-flow activity in the area and should reference pertinent published and unpublished geologic literature.

c. Site description and conditions. Include dates of site visits and observations. Include information on surficial and bedrock geology, topography, vegetation, existing structures, evidence of previous debris flows on or near the site, and other factors that may affect the choice of investigative methods and interpretation of data.

d. Methods and results of investigation.

1. Literature Review. Summarize published and unpublished topographic and surficial and bedrock geologic maps, literature, historical records regarding debris flows and alluvial-fan flooding, and other relevant factors pertinent to the site.

2. Interpretation of Remote-Sensing Imagery. Describe the results of remote-sensing-imagery interpretation, including stereoscopic aerial photographs, lidar, and other remote-sensing data when available. List source, date, flight-line numbers, and scale of aerial photos or other imagery used.

3. Alluvial Fan Evaluation. Include a site-scale geologic map showing areas of active-fan deposition (generally Holocene-age alluvial fans) and other surficial deposits, including older debris-flow and alluvial-fan deposits and their relative age. Include test pit and trench logs (generally at 1 inch = 5 feet) showing descriptions of geologic units, layer thicknesses, maximum grain sizes, and interpretation of flow types. Show basis for design flow-volume estimates (deposit thickness and area estimates); a range of estimates is suggested based on maximum, average, and minimum thickness and area estimates. Indicate runout distance, spatial extent, thickness, flow type, and deposit characteristics of historical flows, if present. Provide deposit age estimates or other evidence used to estimate the frequency of past debris flows. Evaluate the debris-flow hazard based on anticipated probability of occurrence and volume, flow type, flow depth, deposition area, runout, gradation of debris, flow impact forces, and stream-flow inundation and sediment burial depths.

4. Drainage Basin and Channel Evaluation. Include a vicinity geologic map (1:24,000 scale) on a topographic base of the drainage basin showing bedrock and surficial geology, including shallow landslides (debris slides) and a measurement of drainage-basin morphologic parameters. Provide an estimate of the susceptibility of the drainage basin to shallow landsliding, likely landslide volume(s), and volume of historical landslides, if present. Provide an estimate of the susceptibility of the drainage basin slopes to erosion. Include a longitudinal channel profile, showing gradients from headwaters to the alluvial fan. Include cross-channel profiles and a map showing their locations. Provide a basis for channel volume estimates including initial debris slides, total feeder channel length, length of channel lined by bedrock, cross-channel profiles, and estimated volume of channel sediment available for sediment bulking including estimated bulking rate(s) in cubic yards per linear foot of channel.

e. Conclusions.

1. Conclusions must be supported by adequate data, and the report should present those data in a clear and concise manner.

2. Provide the probability of debris-flow occurrence (if possible), estimates of debris-flow volume, a map showing hazard areas, and a discussion on the likely effects of debris flows on the proposed development.

3. Degree of confidence in, and limitations of, the data and conclusions.

f. Recommendations.

1. Recommendations must be supported by the report conclusions and be presented in a clear and concise manner.

2. Provide recommendations for hydrologic, hydraulic, and engineering studies to define buildable and non-buildable areas (if appropriate) and design risk-reduction measures.

3. Provide geologic design parameters for debris-flow-control structures, as appropriate.

4. Discuss implications of risk-reduction measures on adjacent properties, and the need for long-term maintenance.

5. If recommendations are provided for debris-storage basins, both alluvial-fan and channel volume estimates must be compared to select an appropriate design debris volume. For flows that may initiate as debris slides, an appropriate debris-slide volume must be included. Due to uncertainties inherent in both methods, the volume estimates may differ significantly. Rationale for the chosen volume estimate must be provided.

6. If recommendations are provided for debris-flow-deflection structures or debris-flow-resistant construction (reinforcement of foundations, flood-proofing), hydraulic modeling of debris-flow discharge, run-up, and runout, and calculation of impact forces is recommended. Specific information on flow type(s), deposit distribution and thickness, flow velocity, peak flow, and runout is necessary to calibrate models.

7. Discuss residual risk to development (if appropriate) after risk-reduction measures are in place.

As noted in f (2) above, the geologic evaluation is often only the first step in the debris-flow-hazard investigation and risk-reduction process. Depending on the risk-reduction techniques considered, subsequent hydrologic, hydraulic, and/or engineering studies may be needed to estimate peak flows and water volumes, route sediment, and design control structures. Geologists, hydrologists, and engineers must work as a team to recommend reasonable, appropriate, cost-effective risk-reduction techniques.

B. References

a. Literature and records cited or reviewed; citations should be complete (see References section of this publication for examples).

b. Remote-sensing images interpreted; list type, date, project identification codes, scale, source, and index numbers.

c. Other sources of information, personal communication, and other data sources.

C. Illustrations. Should include at a minimum:

a. Location map. Showing the site and significant physiographic and cultural features, generally at 1:24,000 scale or larger and indicating the Public Land Survey System ¼-section, township, and range; and the site latitude and longitude to four decimal places with datum.

b. Site development map. Showing site boundaries, existing and proposed structures, other infrastructure, and site topography. The map scale may vary depending on the size of the site and area covered by the study; the minimum recommended scale is 1 inch = 200 feet (1:2400) or larger when necessary. The site development map may be combined with the site-specific geology map (see item “c” below).

c. Site-specific geology map. A site-scale geology map of the drainage basin and alluvial fan as discussed above. Scale of site-specific geology maps will vary depending on the size of the site and area of study; minimum recommended scale is 1 inch = 200 feet (1:2400) or larger when necessary.

d. Debris-flow hazard map. Showing the debris-flow hazard on different parts of the alluvial fan based on results of the investigation.

e. Photographs that enhance understanding of the debris-flow hazard at the site with applicable metadata.

D. Authentication

The report must be signed and stamped by a Utah licensed Professional Geologist in principal charge of the investigation (Title 58-76-10 – Professional Geologists Licensing Act [Utah Code, 2011]). Final geologic maps, trench logs, cross sections, sketches, drawings, and plans, prepared by or under the supervision of a professional geologist, also must bear the stamp of the professional geologist (Utah Code, 2011). Reports co-prepared by a Utah licensed Professional Engineer and/or Utah licensed Professional Land Surveyor must include the engineer’s or surveyor’s stamp and signature.

F. Appendices

Include supporting data relevant to the investigation not given in the text such as maps, cross sections, conceptual models, survey data, geochronology laboratory reports, laboratory test data, and qualifications statements/resume.

FIELD REVIEW

The UGS recommends a technical field review by the regulatory-authority geologist once a debris-flow-hazard investigation is complete. The field review should take place after any trenches or test pits are logged, but before they are closed so subsurface site conditions can be directly observed and evaluated. See Field Review section in chapter 2.

REPORT REVIEW

The UGS recommends regulatory review of all reports by a Utah licensed Professional Geologist experienced in debris-flow-hazard investigations and acting on behalf of local governments to protect public health, safety, and welfare, and to reduce risks to future property owners (Larson, 1992, 2015). See Report Review section in chapter 2.

DISCLOSURE

The UGS recommends disclosure during real-estate transactions whenever an engineering-geology investigation has been performed. See Disclosure section in chapter 2.

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CHAPTER 6
GUIDELINES FOR EVALUATING LAND-SUBSIDENCE AND EARTH-FISSURE HAZARDS IN UTAH

by
William R. Lund, P.G.

Displacement across an earth fissure that formed in response to groundwater mining in Cedar Valley, Utah.

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CHAPTER 6: GUIDELINES FOR EVALUATING LAND-SUBSIDENCE AND EARTH-FISSURE HAZARDS IN UTAH

by William R. Lund, P.G.

INTRODUCTION

Land subsidence and earth fissures related to groundwater mining (long-term groundwater pumping in excess of aquifer recharge) are human-caused geologic hazards, and as such must be addressed during land development in subsiding areas. These guidelines present the recommended minimum acceptable level of effort for investigating land subsidence and earth fissures related to groundwater mining in Utah at both basin-wide and site-specific scales. Basin-wide investigations rely on a combination of remote sensing methods and high-precision surveying to identify subsidence area boundaries, subsidence rates, and earth-fissure locations. Site-specific investigations evaluate the effects of land subsidence and earth fissures at a site, and typically include a literature review, aerial-photograph and other remote-sensing data analysis, and field investigation, usually including surficial geologic mapping and trenching, and in some instances boreholes, cone penetrometer test (CPT) soundings, and geophysical investigations. The Utah Geological Survey (UGS) recommends a land-subsidence and earth-fissure investigation for all new buildings for human occupancy and International Building Code (IBC) Risk Category II, III, and IV facilities (International Code Council [ICC], 2014a) proposed in areas of known or suspected susceptibility to land subsidence and earth fissures.

The intent of these guidelines is to assist engineering geologists performing land-subsidence and earth-fissure investigations, and to reduce, to the lowest level possible, epistemic uncertainty (lack of necessary data) in evaluating land-subsidence and earth-fissure hazards by conducting adequate hazard investigations. Aleatory variability (natural randomness) in the occurrence of subsidence and formation of earth fissures cannot be reduced; therefore, predicting exactly where and when future land subsidence and earth fissures will occur is not possible. As long as groundwater mining continues, new areas of land subsidence may appear and earth fissures may form. For those reasons, developing property in or near areas of land subsidence and earth fissures will always involve a level of irreducible, inherent risk. Additionally, even with innovative engineering design, limiting certain kinds of land use (e.g., water conveyance or retention structures, pipelines and canals, liquid waste disposal systems, hazardous materials processing and storage facilities) may be necessary in areas of rapid subsidence and/or earth fissuring.

These guidelines outline (1) appropriate investigation methods, (2) report content, (3) map, trench log, and illustration criteria and scales, (4) mitigation recommendations, (5) minimum criteria for review of reports, and (6) recommendations for geologic-hazard disclosure. However, these guidelines do not include systematic descriptions of all available investigative techniques or topics, nor are all techniques or topics appropriate for every hazard investigation.

Considering the complexity of evaluating land-subsidence and earth-fissure hazards, additional effort beyond the minimum criteria recommended in these guidelines may be required to adequately evaluate such hazards. The information presented in these guidelines does not relieve engineering geologists of the duty to perform additional geologic investigations necessary to fully assess these hazards either at regional or site-specific scales. As required by Utah state law (Utah Code, 2011), land-subsidence and earth-fissure investigation reports and supporting documents must be signed and stamped by the licensed Utah Professional Geologist in responsible charge of the investigation.

Purpose

These guidelines apply specifically to land subsidence and earth fissures caused by groundwater pumping in excess of recharge. These guidelines may also be applicable in whole or part for evaluating land subsidence and earth fissures resulting from other causes (e.g., near-surface soil desiccation [giant desiccation cracks], collapsible soil, highly organic soil, karst sinkhole formation, soil piping, underground mining, and oil and gas pumping).

The purpose of these guidelines is to provide appropriate minimum land-subsidence and earth-fissure investigation and report criteria to:

- protect the health, safety, and welfare of the public by minimizing the potentially adverse effects of land subsidence and earth fissures;
- assist local governments in regulating land use in hazardous areas and provide standards for ordinances;
- assist property owners and developers in conducting reasonable and adequate investigations;
- provide engineering geologists with a common basis for preparing proposals, conducting investigations, and

recommending land-subsidence- and earth-fissure-mitigation strategies; and

- provide an objective framework for preparation and review of reports.

These guidelines are not intended to supersede pre-existing state or federal regulations or local geologic-hazard ordinances, but provide useful information to supplement adopted ordinances/regulations, and assist in preparation of new ordinances. The UGS believes adherence to these guidelines will help ensure adequate, cost-effective investigations and minimize report review time.

Background

Subsidence and earth fissures related to groundwater mining occur when groundwater is pumped from an aquifer at a rate greater than aquifer recharge, resulting in dewatering of the aquifer. Bringing recharge and discharge into balance will slow or stop land-subsidence and earth-fissure formation—a process successfully implemented in some areas experiencing land-subsidence and earth-fissure problems (Ingebritsen and Jones, 1999; Bell and others, 2002). Both the cause and cure for groundwater-mining-related land subsidence and earth fissures are typically societal in nature. It is rare that a single groundwater producer (individual or organization) causes land-subsidence and earth-fissure formation, and it is equally rare that a single producer can effect a cure. This is particularly true of Utah's alluvial valleys, each with many stakeholders, where only collective action by all involved (producers, consumers, managers, and regulators) can prevent or reverse groundwater mining.

Land-Subsidence and Earth-Fissure Formation

In the United States, more than 17,000 square miles in 45 states have been directly affected by land subsidence, and more than 80% of the subsidence has occurred because of groundwater mining (Galloway and others, 1999). Land subsidence due to groundwater mining in thick, unconsolidated sediments results from a decrease in fluid (pore water) pressure as the water in fine-grained sediments moves into adjacent coarser grained sediments as the aquifer is dewatered (Leake, 2004). The decrease in pressure increases the effective stress in the dewatered portion of the aquifer and transfers the entire overburden stress (weight) to the aquifer matrix. The change in effective stress causes the aquifer matrix to change volume (compact) (Galloway and others, 1999). Initial matrix compaction is elastic and will recover if the aquifer is recharged. However, once collapse exceeds the elastic limit of the matrix material, compaction becomes permanent, aquifer storage is reduced, and land subsidence ensues (Galloway and others, 1999).

As an aquifer is dewatered, most subsidence results from the compression of fine-grained sediment layers (aquitards; figure 29) as they drain into adjacent coarser grained aquifer material. Silt and clay layers have higher porosity, lower permeability, and lower matrix strength than coarse-grained sediment (sand and gravel). Coarse granular materials may settle almost instantaneously after dewatering, but because of their much lower permeability, fine-grained layers may require decades to fully drain and compress, and may continue to compress even after groundwater withdrawal is brought into equilibrium with recharge (Bell and others, 2002; Budhu and Shelke, 2008). The relation between groundwater-level decline and land subsidence is complex and varies as a function of total aquifer thickness, composition, and compressibility. In some areas of Arizona, about 300 feet of groundwater decline produced only 0.6 foot of subsidence. In other areas, a similar water-level decline generated land subsidence of as much as 18 feet (Arizona Land Subsidence Group, 2007).

Earth fissures are linear cracks in the ground that form in response to horizontal tensional stresses that develop when land subsidence causes different parts of an aquifer to compact by different amounts (figure 30) (Leake, 2004; Arizona Division of Emergency Management, 2007). Earth fissures may be hundreds of feet deep, range from a few feet to miles long, and can be expressed as hairline cracks (figure 31), aligned sinkholes (figure 32), or gullies tens of feet wide (figure 33) where fissures intercept surface flow and are enlarged by erosion (Carpenter, 1999). Earth fissures typically form along the edge of basins, usually parallel to mountain fronts; over zones of changing sediment characteristics and density; or above subsurface bedrock highs often coincident with pre-existing bedrock faults (figure 30) (Arizona Land Subsidence Group, 2007). Some earth fissures exhibit differential displacements of several inches to several feet as aquifers compact unevenly across them (figure 34).

Land-Subsidence Hazards

Land-subsidence hazards may include (1) change in elevation and slope of streams, canals, and drains, (2) damage to bridges, roads, railroads, storm drains, sanitary sewers, water lines, canals, airport runways, and levees, (3) damage to private and public buildings, and (4) failure of well casings from forces generated by compaction of fine-grained layers in aquifer systems (Leake, 2004; Lin and others, 2009). Over half of the area of the San Joaquin Valley in California has subsided due to groundwater mining, resulting in one of the largest human-caused alterations of Earth's surface topography (Galloway and others, 1999). Near Mendota, California, in the San Joaquin Valley, subsidence in excess of 28 feet necessitated expensive repairs to two major central California water projects (California Aqueduct and Delta-Mendota Canal; Galloway and others, 1999). In Mexico City, rapid land subsidence caused by groundwater mining and associated aquifer compaction has damaged colonial-era buildings, buckled highways, and disrupted water supply and wastewater drainage (Viets and others, 1979; Galloway and others, 1999). Early oil and gas production and a long history of groundwater pumping in the Houston-Galveston area, Texas, have

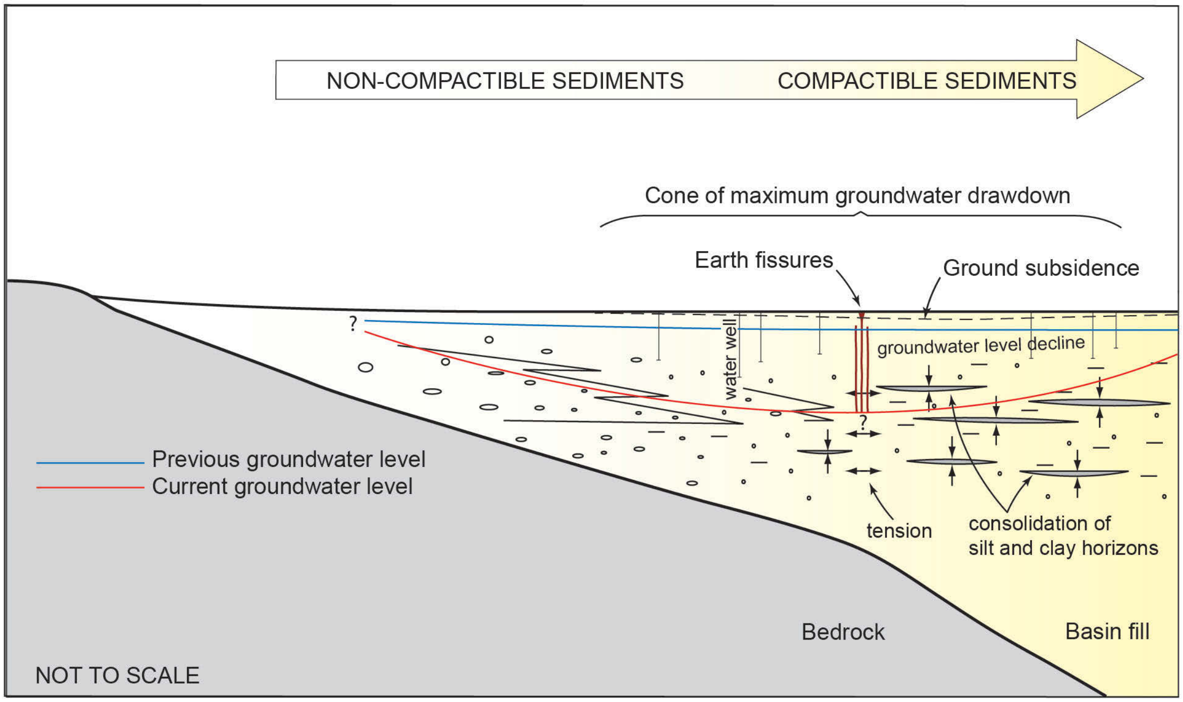

Figure 29. *Schematic cross section of a typical Utah alluvial basin showing the effect of groundwater-level decline on the compaction of fine-grained horizons and resulting ground subsidence within the alluvial basin-fill aquifer. Note that as groundwater levels decline fine-grained horizons begin to compact both above and below the water table.*

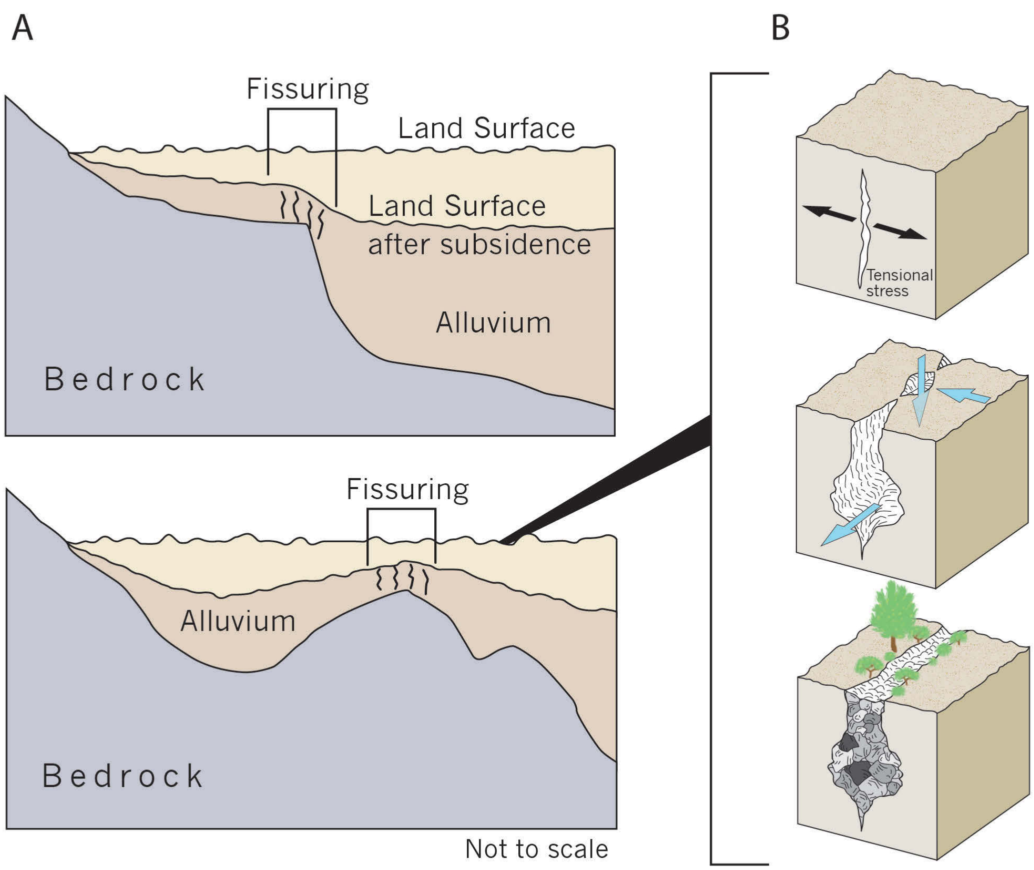

Figure 30. *(A) Schematic section of a valley basin showing how buried bedrock topography affects the formation and location of earth fissures. (B) Schematic diagram showing initiation of earth fissures at depth due to horizontal tension stress, and development of fissures expressed at the surface as hairline cracks, aligned sinkholes, and erosional gullies (after Carpenter, 1999).*

Figure 31. *Earth fissure in Cedar Valley expressed as an uneroded primary ground crack. This fissure could be traced for 900 feet before becoming obscured by recent agricultural activity. Photo taken in August 2009.*

Figure 32. *Sinkholes aligned along an earth fissure in Cedar Valley. Photo taken in May 2009.*

created severe and costly coastal-flooding hazards associated with land subsidence (Galloway and others, 1999; Harris-Galveston Subsidence Districts, 2010). Lin and others (2009) reported significant land-subsidence and earth-fissure damage related to groundwater mining in the Beijing area, including damage to the new Capital International Airport.

Earth-Fissure Hazards

Earth-fissure hazards may include (1) creating conduits that connect nonpotable or contaminated surface and near-surface water to a principal aquifer used for public water supply (Pavelko and others, 1999; Bell, 2004) (figure 35), (2) changing runoff/flood patterns, (3) deforming or breaking buried utilities and well casings, (4) causing buildings and other infrastructure to deform or collapse, and (5) endangering livestock and wildlife, and posing a life-safety hazard to humans (Arizona Division of Emergency Management, 2007). Although known earth fissures in Utah are chiefly limited to rural areas (Escalante Desert—Lund and others, 2005; Cedar Valley—Knudsen and others, 2014), elsewhere in the western United States, earth fissures related to land subsidence have become a major factor in land development in urban areas (Shlemon, 2004). Examples from Arizona and Nevada show the extent of damage that can result from earth fissures related to groundwater mining.

Earth fissures were first recognized in Arizona in 1927; since that time their number and frequency have increased as land subsidence due to groundwater mining has likewise increased (Arizona Division of Emergency Management, 2007). More than 1100 square miles of Arizona, including parts of the Phoenix and Tucson metropolitan areas, are now affected by subsidence and numerous associated earth fissures (figure 36) (Arizona Land Subsidence Group, 2007; Conway, 2013). Damage caused by earth fissures in Arizona currently totals in the tens of millions of dollars, and includes cracked, displaced, or collapsed freeways and secondary roads; broken pipes and utility lines; damaged and breached canals (figure 37); cracked building foundations; deformed railroad tracks; collapsed and sheared well casings; damaged dams and flood-control structures; and livestock deaths (Viets and others, 1979; Arizona Division of Emergency Management, 2007; Arizona Land Subsidence Group, 2007).

Likewise, long-term groundwater mining in excess of recharge in Nevada's Las Vegas Valley has produced water-table declines of 100 to 300 feet (Pavelko and others, 1999) and as much as 6 feet of land subsidence (Bell and others, 2002; Bell and Amelung, 2003). By the early 1990s, the Windsor Park subdivision in North Las Vegas was so impacted by earth fissures (figure 38) that 135 homes had to be abandoned and removed at a cost of about $20 million, and another 105 homes

Figure 33. *Earth fissure in Escalante Valley eroded after intercepting surface water runoff. Photo taken in January 2005.*

required significant repairs (Bell, 2003; Saines and others, 2006). Most earth fissures in Las Vegas Valley are associated with pre-existing bedrock faults (Bell and Price, 1991; Bell and others, 2002; Bell and Amelung, 2003; Bell, 2004). Artificial aquifer recharge has caused a decline in subsidence rates in Las Vegas Valley since 1991 of 50%–80%, depending upon location (Bell and others, 2002).

SOURCES OF LAND-SUBSIDENCE AND EARTH-FISSURE INFORMATION

The UGS has investigated land subsidence and earth fissures over the past decade in selected areas of Utah (DuRoss and Kirby, 2004; Lund and others, 2005; Forester, 2006, 2012; Katzenstein, 2013; Knudsen and others, 2014). Additionally, see the Literature Searches and Information Resources section in chapter 2 for information on other geologic-hazard reports, maps, archives, and databases maintained by the UGS that may be relevant to land subsidence and earth fissures, as well as information on the UGS' extensive aerial photograph and light detection and ranging (lidar) imagery collections.

Water-level data are available from the U.S. Geological Survey National Water Information System (http://waterdata.usgs.gov/nwis) and UGS Groundwater Monitoring Data Portal (http://geology.utah.gov/resources/data-databases/groundwater-monitoring/).

Figure 34. *Damage to street pavement by an earth fissure in Cedar Valley across which differential displacement is occuring at a rate of about 2 inches per year. Photo taken July 2015.*

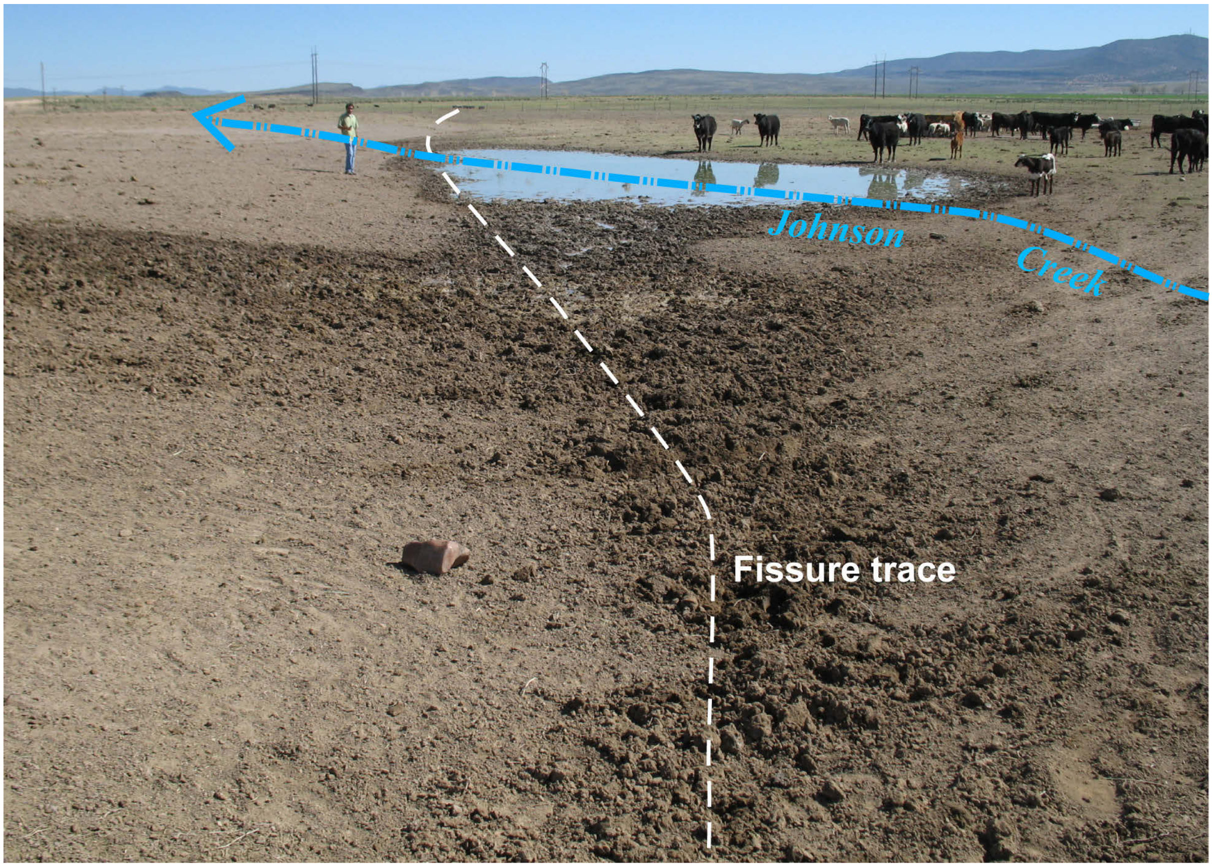

Figure 35. *Earth-fissure scarp in Cedar Valley blocking an ephemeral drainage and causing water to pond along the fissure in a feed lot. Photo taken in May 2009.*

Figure 36. *Earth fissure in a subdivision near Phoenix, Arizona, enhanced by erosion during a cloudburst storm. Photo credit: Brian Conway.*

Figure 37. *Earth fissure intersecting an irrigation canal embankment near Phoenix, Arizona. Photo credit U.S. Bureau of Reclamation (after Carpenter, 1999).*

LAND-SUBSIDENCE AND EARTH-FISSURE INVESTIGATION

Disclaimer

Land subsidence and earth fissures related to groundwater mining are geologic hazards, and as such must be addressed during land development in subsiding areas. However, land subsidence and earth fissures will likely continue to occur and expand as long as groundwater mining continues. Additionally, given the low permeability of many fine-grained sediment layers in Utah's basin-fill aquifers, subsidence may continue in a diminishing fashion for some time (possibly decades) after recharge and discharge are balanced as dewatered fine-grained deposits continue to drain and compact (Galloway and others, 1999).

The fact that land subsidence is not currently occurring in an area experiencing groundwater mining provides no guarantee that subsidence will not commence there in the future. Likewise, the absence of detectable earth fissures at the ground surface in a subsiding area provides no assurance that fissures are not present in the shallow subsurface or will not form in the future. As long as groundwater mining continues, land subsidence and earth fissures present long-term hazards to infrastructure that a hazard investigation, no matter how detailed, can only partially identify and mitigate. For those reasons, it is not possible to establish a standardized method for

Figure 38. *Remains of a home severly damaged by an earth fissure and eventually torn down in the Windsor Park subdivision, Las Vegas, Nevada.*

calculating setbacks from earth fissures as is done for Utah's hazardous faults (chapter 3). Setback distances from fissures or from areas of anticipated future fissure growth, or other forms of land-subsidence and earth-fissure mitigation should be designed and justified based on site-specific data. To fully ensure the safety of existing infrastructure and future development in subsiding areas, it is necessary to bring aquifer discharge and recharge into balance so that groundwater mining stops and hazards dissipate.

When to Perform a Land-Subsidence and Earth-Fissure-Hazard Investigation

Geologic hazards are best addressed prior to land development in affected areas. The UGS recommends that a land-subsidence and earth-fissure-hazard investigation be made for all new buildings for human occupancy and for modified IBC Risk Category II(a), II(b), III, and IV facilities (see table 12 in chapter 3, modified from IBC table 1604.5 [ICC, 2014a]) that are proposed in confirmed or suspected land-subsidence areas. Utah jurisdictions that have adopted land-subsidence and earth-fissure special-study maps identify zones in known land-subsidence and earth-fissure-susceptible areas within which they require site-specific investigations. The UGS recommends that investigations as outlined in these guidelines be conducted in alluvial valleys for all IBC Risk Category III and IV facilities to ensure that previously unknown land-subsidence areas and earth-fissures are not present. If a hazard is found, the UGS recommends a comprehensive investigation be conducted. Additionally, in some instances an investigation may become necessary when existing infrastructure is discovered to be on or adjacent to a subsiding area.

The level of investigation conducted for a particular project depends on several factors, including (1) site-specific geologic conditions, (2) type of proposed or existing development, (3) level of acceptable risk, and (4) governmental permitting requirements, or regulatory agency rules and regulations. A land-subsidence and earth-fissure-hazard investigation may be conducted separately, or as part of a comprehensive geologic-hazard and/or geotechnical site investigation (see chapter 2).

Minimum Qualifications of Investigator

Land-subsidence and earth-fissure-related engineering-geology investigations and accompanying geologic-hazard evaluations performed before the public shall be conducted by or under the direct supervision of a Utah licensed Professional Geologist (Utah Code, Title 58-76) who must sign and seal the final report. Often these investigations are interdisciplinary in nature, and where required, must be performed by qualified, experienced, Utah licensed Professional Geologists (PG, specializing in engineering geology) and Professional Engineers (PE, specializing in geological and/or geotechnical engineering) working as a team. See Investigator Qualifications section in chapter 2.

Basin-Wide Investigation Guidelines

Land subsidence typically affects a large area (tens to hundreds of square miles) within groundwater basins subject to groundwater mining. The first consideration when evaluating land subsidence and earth fissures as geologic hazards is to determine whether a proposed site and/or project is inside or outside of a subsiding area. If outside, land subsidence and earth fissures are not hazards; if inside or if in an adjacent area that may be affected by future subsidence and fissuring, a variety of negative consequences become possible and require careful evaluation. Within a subsiding area, the rate of subsidence and location of existing earth fissures are critical considerations for hazard investigations. Therefore, identifying and periodically monitoring basin-wide subsidence boundaries (subject to change over time with continued groundwater mining), subsidence amount and rate (likely also variable over time) within those boundaries, and the location of existing earth fissures are first-order, basin-wide priorities for land-subsidence and earth-fissure investigations.

Available techniques for identifying subsidence boundaries, subsidence rates, and earth-fissure locations on a basin-wide scale fall into two principal categories: remote-sensing applications and high-precision Global Positioning System (GPS)/Global Navigation Satellite System (GNSS) monitoring networks (surveyed benchmarks).

Remote Sensing

Remote-sensing applications directly applicable to land-subsidence and earth-fissure investigations include analysis of stereoscopic aerial photographs (from multiple years if available), interferometric synthetic aperture radar (InSAR) imagery, lidar imagery, and other remote sensing data as available.

Aerial photographs: Analysis of stereoscopic aerial photograph pairs is a standard remote-sensing technique long applied to many kinds of geologic investigations, and requires little further explanation here. Where possible, the analysis should include both stereoscopic low-sun-angle and vertical aerial photography. Applicable to both basin-wide and site-specific investigations, aerial photograph analysis can reveal the presence of earth fissures, particularly those subject to erosion or across which differential displacement is occurring, as well as other geomorphic evidence of land subsidence (sinkholes, local subsidence bowls, displaced or warped linear infrastructure, road damage, etc.). Examination of repeat aerial photographs from multiple years may show fissure growth (Knudsen and others, 2014), or the progressive development of other subsidence-related features.

Google Earth and Bing Maps, among other providers of Internet-based, free aerial imagery, are becoming increasingly valuable as rapid reconnaissance tools, and provide high-resolution, often color, non-stereoscopic aerial orthophotographs.

For many locations, Google Earth includes a historical imagery archive that permits evaluation of site conditions several years to decades before present.

InSAR: InSAR is a side-looking, active (produces its own illumination) radar imaging system that transmits a pulsed microwave signal toward the Earth and records both the amplitude and phase of the back-scattered signal that returns to the antenna (Arizona Department of Water Resources [ADWR], no date, 2010; Zebker and Goldstein, 1986; Zebker and others, 1994; appendix D – InSAR Background and Application). InSAR uses interferometric processing to compare the amplitude and phase signals received during one pass of the SAR (synthetic aperture radar) platform (typically Earth-orbiting satellites) over a specific geographic area, with the amplitude and phase signals received during a second pass over the same area but at a different time (ADWR, no date). InSAR's chief advantage for subsidence monitoring is that it offers an accurate, rapid, and cost-efficient way to determine the horizontal and vertical extent of land subsidence and subsidence rate variability over a large area to an accuracy of about 1 centimeter. Forster (2006, 2012) demonstrated that long-term subsidence in southwest Utah is detectable and measurable with InSAR, and Katzenstein (2013) used InSAR to identify an approximately 100-square-mile area in Cedar Valley, Iron County, Utah, affected by subsidence resulting from groundwater mining.

Lidar: Lidar is a remote sensing, laser system that measures the properties of scattered light to accurately determine the distance to a target (reflective surface). Lidar is similar to radar, but uses laser pulses instead of radio waves, and commonly is collected from fixed-wing aircraft or helicopters. Lidar produces a rapid collection of points (typically more than 70,000 per second) that results in very dense and accurate elevation data over a large area (National Oceanic and Atmospheric Administration [NOAA], 2008). The resulting highly accurate, georeferenced elevation points can be used to generate three-dimensional representations of the Earth's surface and its features (NOAA, 2008). After processing, lidar data can be used to produce a "bare-earth" terrain model (e.g., figure 39), in which vegetation and manmade structures have been removed. Lidar has several advantages over traditional photogrammetric methods; chief among them are (1) high accuracy, (2) high point density, (3) large coverage area, and (4) the ability to resample areas quickly and efficiently, which creates the ability to map discrete elevation changes over time at a very high resolution (NOAA, 2008).

Lidar offers two important advantages over conventional aerial photography for documenting and mitigating land subsidence and earth fissures. First, high-resolution, bare-earth lidar images can be used to identify and map currently unrecognized earth fissures that are not apparent on conventional aerial photography (Knudsen and others, 2014). Second, repeat lidar surveys can be used to generate displacement maps to define the boundaries of subsidence areas, and may allow

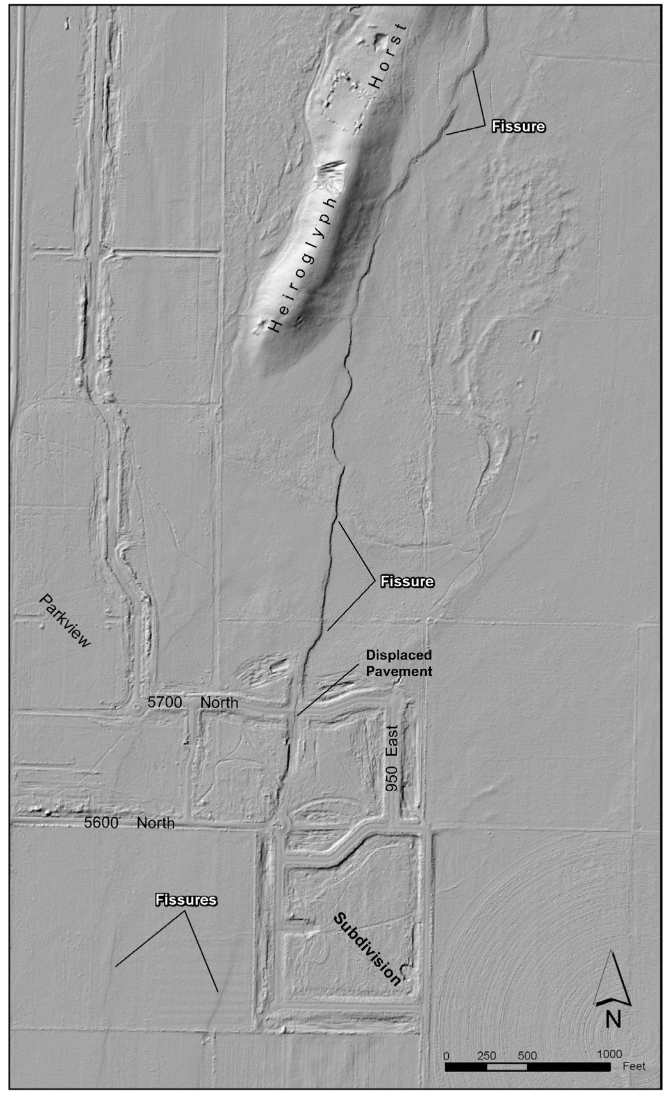

Figure 39. *Bare-earth lidar image of earth fissures in Cedar Valley, Utah. These fissures exhibit vertical down-to-the-east displacement and are well expressed on lidar imagery (hillshade image, illumination from the northwest).*

monitoring of existing earth fissure growth and new fissure formation. Appendix C (Lidar Background and Application) presents additional information about lidar technology, imagery acquisition and processing, and cost.

High-Precision GPS/GNSS Survey Network

The accuracy and coverage of benchmark networks in Utah's alluvial valleys are variable. In many areas, benchmarks, particularly older monuments, have been destroyed or disturbed by agricultural or development activities. Constraints on the number and locations of existing benchmarks may allow for only a general determination of the areal and vertical extent of land subsidence in valley areas, and may not permit adequate monitoring of either the rate or distribution of ongoing subsidence. Additionally, reported elevations of many older benchmarks (e.g., disturbed benchmarks, vertical angle benchmarks, and some third-order leveled benchmarks) may not be sufficiently accurate to permit meaningful comparisons with new GPS/GNSS-derived survey data. Estimated uncertainties associated with both historical leveling and GNSS elevation data should be discussed and included in subsidence calculations.

Where accurate, long-term monitoring of subsidence is important for aquifer management or hazard investigations, the UGS recommends that following acquisition of InSAR and lidar data to better define the basin-wide boundaries of subsiding areas and earth-fissure locations, those data be used to site a network of high-precision GPS/GNSS survey monuments in subsidence and fissure "hot spots." Periodic resurveying of the benchmarks using GPS/GNSS methods permits repeated high-precision (1–5 mm horizontal/vertical) subsidence monitoring in areas most important for implementing best aquifer management practices and hazard evaluation and mitigation. For increased accuracy, detailed subsidence studies typically employ static GPS survey methods rather than RTK surveys (http://www.azwater.gov/AzDWR/Hydrology/Geophysics/GPS.htm).

GPS/GNSS surveys should follow the latest versions of the National Geodetic Survey guidelines for establishing ellipsoid (Zilkoski and others, 1997) and orthometric (Zilkoski and others, 2008) heights. High-quality floating sleeved rod or other appropriate monuments that reduce near-surface soil movements, such as from expansive soils, are recommended for precise vertical measurements. For bedrock sites, UNAVCO has developed stable mounting structures to isolate GPS/GNSS instruments from near-surface soil movements (http://pbo.unavco.org/instruments/gps/monumentation).

Site-Specific Investigation Guidelines

Literature Review

The following published and unpublished information (as available) should be reviewed in preparation for both basin-wide and site-specific land-subsidence and earth-fissure investigations:

1. Published and unpublished geologic and engineering literature, maps, cross sections, and records relevant to the site and site region's geology and hydrology, and past history of land subsidence and earth-fissure formation.
2. Survey data that may indicate past land subsidence, particularly as-built plans of linear infrastructure such as roads, canals, dams, airport runways, and levees for historical elevation data, or as-built design grades that can be compared to current elevations. Be aware of any historical vertical datum changes and/or shifts, including geoid changes.
3. Maintenance records of nearby wells for signs of subsidence-related damage.
4. Water-level data and subsurface geologic units from nearby water-well and geotechnical borehole logs.
5. Borehole geophysical data from deep wells in the area.
6. Pumping history of nearby water wells.

The Sources of Land Subsidence and Earth-Fissure Information section above provides information on Utah's geology and past significant instances of land subsidence and earth fissure formation; however, that list of sources is not exhaustive, and engineering geologists should identify and review all available information relevant to their site of interest.

Analysis of Aerial Photographs and Remote Sensing Data

Analysis of remote sensing data should include interpretation of stereoscopic aerial photographs (from multiple years if available), InSAR and lidar imagery, and other remotely sensed images as available for evidence of land-subsidence- and earth-fissure-related lineaments, including vegetation lineaments, gullies, scarps formed by surface displacement across fissures, and vegetation/soil contrasts. Where possible, the analysis should include both stereoscopic low-sun-angle and vertical aerial photography. Examination of repeat aerial photographs and/or lidar imagery from multiple years may show fissure growth (Knudsen and others, 2014). The area interpreted should extend sufficiently beyond the site boundaries to identify off-site subsidence areas or fissures that might affect the site. Note that analysis of InSAR and lidar data has become "state of practice" for land-subsidence and earth-fissure investigations; therefore, investigations not employing those techniques are at best reconnaissance-level investigations.

Surface Investigation

Surface investigations should include mapping of (1) geologic and soil units, (2) fissures and sinkholes, (3) faults and other geologic structures, (4) geomorphic features and surfaces, (5) vegetation lineaments, (6) animal burrowing patterns, and (7) deformation of engineered structures both on and beyond the site, as appropriate. Special attention should be paid to linear infrastructure such as roadways, railroads, canals, dams, levees, airport runways, etc. Level surveys of linear infrastructure and comparison with as-built elevations may detect the presence or absence of measurable subsidence, and in the case of dams, levees, and other fluid conveyance and retention facilities, should be made to determine if infrastructure integrity and safety have been compromised. Protruding well heads often provide evidence of land subsidence, and in some instances may allow measurement of subsidence at a point (figure 40). Observed features should be documented with detailed photographs, including metadata (date, location, feature observed, etc.).

Subsurface Investigation

Earth fissures related to groundwater mining tend to be vertical to near-vertical features (figures 30 and 41) extending to hundreds of feet deep. In an uneroded state, the aperture of an

Figure 40. *Protruding well head due to land subsidence resulting from groundwater mining. Photo taken September 2014.*

Figure 41. *Vertical earth fissure in Cedar Valley exposed in the end of an erosional gully formed along the fissure by infiltration of surface runoff. Photo taken August 2009.*

earth fissure may be 0.25 to 1 inch or less (figure 31), and may be open or filled. Situations may arise where surficial expression of earth fissures is lacking, but the presence or absence of shallow subsurface earth fissures that could lead to future surface expression should be assessed. Lateral subsurface investigation methods such as trenching or shallow geophysics tend to be most effective in these situations. Subsurface characterization may be especially important when assessing whether subsurface conditions are consistent with a surface feature being a subsidence-related earth fissure or a less hazardous giant desiccation crack. Subsurface investigation techniques may include, but are not limited to:

1. Trenching or test pits with appropriate logging and documentation to permit detailed and direct observation of continuously exposed geologic units, soils, fissures, and other geologic features. This includes trenching across known or suspected earth fissures and fissure zones to determine their location and width, geometry and depth, and displacement. When uneroded or filled, earth fissures are often very subtle features, so logging should be performed in sufficient detail to detect their presence.

   In preparation for logging, trench walls should be carefully cleaned to permit direct observation of the geology. Trenches should be logged at a minimum scale of 1 inch = 5 feet (1:60), and all logs should be prepared in the field under the direct supervision of a Utah licensed Professional Geologist. Vertical and horizontal logging control should be used and shown on the log. The logs should not be generalized or diagrammatic, and may be on a rectified photomosaic base. The log should document all pertinent information from the trench, including (1) trench orientation and indication of which wall was logged, (2) horizontal and vertical control, (3) top and bottom of trench wall(s), (4) stratigraphic contacts, (5) lithology and soil classification, (6) pedogenic soil horizons, (7) marker beds, (8) fissures and faults, (9) fissure/ fault orientations and geometry (strike and dip), (10) fissure displacement and aperture, and (11) sample locations (e.g., Birkeland and others, 1991; Bonilla and Lienkaemper, 1991; U.S. Bureau of Reclamation, 1998b; Walker and Cohen, 2006; McCalpin, 2009). Logs should be prepared for all trenches, even if fissures are not encountered.

2. The trench should be deep enough to expose all relevant aspects of fissure geometry (dip, width, associated subsidiary features). Where the maximum trench depth achievable, generally 15 to 20 feet, is not sufficient to adequately characterize suspected fissures, the practical limitations of trenching should be acknowledged in the report and uncertainties should be reflected in report conclusions and recommendations. Boreholes, CPT soundings, and geophysical techniques (see no. 4 below) may help extend the depth of investigation.

   More than one trench may be necessary to investigate a site or building footprint, particularly when the proposed development is large, involves more than one building, and/or is characterized by complex fissure patterns. Generally, subsurface data should not be extrapolated more than 300 feet without additional subsurface information. Complex fissure zones may require closer trench spacing. When trenches must be offset to accommodate site conditions, sufficient overlap should be provided to avoid gaps in trench coverage perpendicular to the fissure. Tightly spaced trenches may only need minor (a few tens of feet) overlap; however, more widely spaced trenches require greater overlap to ensure continuous site coverage.

Test pits may provide useful information regarding site subsurface conditions; however, test pits are not an acceptable alternative to trenches. A series of aligned test pits perpendicular to the fissure trend cannot adequately demonstrate the presence or absence of fissuring because fissures trending between test pits may not be detected.

Trenches and fissures should be accurately located on site plans and geologic maps. The UGS recommends that trenches and fissures (projected to the ground surface) be surveyed rather than located using a hand-held GPS device.

Trench investigations should be performed in compliance with current Occupational Safety and Health Administration (OSHA) excavation safety regulations and standards (http://www.osha.gov/SLTC/trenchingexcavation/construction.html). See Excavation Safety section in chapter 2 for additional information.

3. Boreholes and CPT soundings permit collection of data on geologic units and groundwater, and may verify fissure plane geometry. Vertically focused investigation methods such as boreholes and CPT soundings are useful for general subsurface characterization in a potential fissure zone; however, an uneroded earth fissure in the subsurface is a very small target for vertically directed investigation methods. CPT soundings should be done in conjunction with continuously logged boreholes to correlate CPT data with the physical characteristics of subsurface geologic units. Data points should be sufficient in number and adequately spaced to permit reliable correlations and interpretations; however, it may not be possible to detect an earth fissure in a borehole or CPT sounding.

4. Geophysical investigations are indirect, non-destructive methods that can be reliably interpreted when site-specific surface and subsurface geologic conditions are known. Geophysical methods should seldom be employed without knowledge of site geology; however, where no other subsurface geologic information is available, geophysical methods may provide the only economically viable means of deep geologic reconnaissance (e.g., Chase and Chapman, 1976; Telford and others, 1990; Sharma, 1998; U.S. Bureau of Reclamation, 2001; Milsom and Eriksen, 2007; Reynolds, 2011).

   Although geophysical methods can be used to detect the presence and location of shallow earth fissures, such methods alone never prove the absence of a fissure at depth. Geophysical methods can provide critical information concerning subsidence potential, especially compressible basin-fill and bedrock geometry that may not otherwise be available. Geophysical techniques may include, but are not limited to, high-resolution seismic reflection, ground penetrating radar, seismic refraction, magnetic profiling, electrical resistivity, and gravity.

Other Investigation Methods

Other methods may be incorporated in land-subsidence and earth-fissure investigations when conditions permit or requirements for critical structures or facilities require more intensive investigation or monitoring over extended time periods. Possible methods may include, but are not limited to:

1. Aerial reconnaissance flights, including high-resolution aerial photography.
2. Installation of piezometers.
3. Local high-precision surveying or geodetic measurements, including comparison surveys with infrastructure design grades and long-term monitoring employing repeat surveys.
4. Strain (displacement) measurement both at the surface and in boreholes as part of a long-term monitoring program (Galloway and others, 1999).
5. Geochronologic analysis, including but not limited to radiometric dating (e.g., ^{14}C, $^{40}Ar/^{39}Ar$), luminescence dating, soil-profile development, fossils, tephrochronology, and dendrochronology (see Geochronology section of chapter 2).

LAND-SUBSIDENCE AND EARTH-FISSURE MITIGATION

Early recognition and avoidance of areas subject to land subsidence and earth fissures are the most effective means of mitigating land-subsidence and earth-fissure hazards. However, because avoidance may not always be a viable or cost-effective option, especially for existing facilities (figures 34, 37, and 38), the UGS provides the following general recommendations (modified from Price and others [1992], Ken Euge [Geological Consultants, Inc., written communication, 2010], and Knudsen and others [2014]) to reduce the impact of land subsidence and earth fissures. However, other mitigation techniques may be available/appropriate at a specific site, and the engineering geologist should base mitigation recommendations on site-specific data.

- Stop mining groundwater and manage basin-fill aquifers as renewable resources. Adopt best aquifer management practices to bring long-term recharge of basin-fill aquifers into balance with long-term discharge. Possible strategies for achieving safe yield include:
   a. Import water from other basins.
   b. Recharge aquifers artificially, including aquifer storage and recovery projects.

c. Relocate concentrations of high-discharge wells to dispersed locations away from subsiding areas.

d. Establish a subsidence abatement district responsible for setting water policy and priorities (such as reducing water rights, permitting production wells, or taxing groundwater pumping) and for developing continued subsidence mitigation strategies. This function may naturally fall to water conservancy districts, where such districts already exist.

e. Implement water conservation practices to reduce groundwater consumption over time (reduce groundwater pumping) to achieve safe yield.

- Define basin-wide land-subsidence- and earth-fissure-hazard zones and require that land subsidence and earth fissures be carefully investigated on a site-specific basis in those areas prior to new development.
- Avoid land-subsidence areas and earth fissures where and when possible.
- When avoidance is not possible, land subsidence and earth fissures should be integrated into project design to provide a factor of safety for development. Because earth fissures caused by groundwater mining may expand over time and new fissures may form if groundwater mining persists, it is not possible to establish standard setback distances or implement a standardized method for calculating fissure setbacks as is done for hazardous faults (chapter 3). Therefore, the UGS does not make a standard setback recommendation, but rather recommends that the engineering geologist in responsible charge of the land-subsidence and earth-fissure investigation make and justify an appropriate setback based on the results of a site-specific hazard investigation.
- Keep water out of earth fissures to prevent erosion; control surface runoff.
- Limit irrigation in earth-fissure areas; landscape with drought-resistant native vegetation.
- Prevent construction of retention basins or dry wells and avoid effluent disposal (including on-site wastewater disposal) in earth-fissure areas.
- Establish a long-term, basin-wide monitoring program (InSAR, lidar, high-precision GPS/GNSS surveying) to track the occurrence, magnitude, and growth of subsidence areas and earth fissures.
- Recognize that without effective mitigation of groundwater mining, the long-term consequences of land subsidence and earth fissures are potentially serious. Because areas of land subsidence and earth fissures will expand over time with continued groundwater mining, quantifying the future effects of land subsidence and earth fissures at a site may not be possible even after a careful hazard investigation. Additionally, even with innovative engineering design, limiting certain kinds of land use (e.g., water conveyance or retention structures, pipelines and canals, liquid waste disposal systems, hazardous materials processing and storage facilities) may be necessary in areas of rapid ongoing subsidence or rapid earth fissuring.
- Disclose the presence of land subsidence and earth fissures during real-estate transactions so prospective property owners can make their own informed decisions regarding risk.

LAND-SUBSIDENCE AND EARTH-FISSURE INVESTIGATION REPORT

The UGS recommends that a report prepared for a land-subsidence and earth-fissure investigation in Utah should, at a minimum, address the topics below. Site conditions may require that additional items be included to fully evaluate these hazards; these guidelines do not relieve engineering geologists from their duty to perform additional geologic investigations as necessary to adequately assess land-subsidence and earth-fissure hazards. The report presenting the investigation results must be prepared, stamped, and signed by a Utah licensed Professional Geologist (Utah Code, 2011) with experience in conducting land-subsidence and earth-fissure investigations. Reports co-prepared by a Utah licensed Professional Engineer or Utah licensed Professional Land Surveyor must include the engineer's and/or surveyor's stamp and signature. The report guidelines below pertain to investigations of land-subsidence and earth-fissure hazards resulting from groundwater mining, and expand on the general guidance provided in the Engineering-Geology Investigations and Engineering-Geology Reports sections of chapter 2.

A. Text

a. Purpose and scope of investigation. If a site-specific investigation, describe the location and size of the site and proposed type and number of buildings or other infrastructure if known.

b. Geologic, topographic, and hydrologic setting. The report should contain a clear and concise statement of the region/site's geologic, topographic, and hydrologic setting. The section should include a discussion of known land subsidence or earth fissures in the area, and should reference pertinent published and unpublished geologic literature.

c. Site description and conditions. Include dates of site visits and observations. Include information on geologic and soil units, hydrology, topography, distribution and condition of existing benchmarks, graded and filled areas, vegetation, existing structures, presence of fissures on or near the site, evidence of land subsidence, and other factors that may affect the choice of investigative methods and interpretation of data.

d. Methods and results of investigation.

1. Literature Review. Summarize published and unpublished topographic and geologic maps, literature, and records regarding geologic units, faults, geomorphic features, surface water and groundwater, benchmark elevation data, previous land subsidence and earth fissures, and other relevant factors pertinent to the site.
2. Interpretation of Remote-Sensing Imagery. Describe the results of remote-sensing-imagery interpretation, including stereoscopic aerial photographs, InSAR, lidar, and other remote-sensing data when available, conducted to identify evidence of land subsidence and earth fissures. List source, date, flight-line numbers, and scale of aerial photos or other imagery used.
3. Surface Investigation. Describe pertinent surface features including mapping of geologic and soil units; geomorphic features such as scarps, springs, and seeps; fissures; faults; and describe methodology and quality of data used to determine the amount and distribution of subsidence including sources of historical elevation data, surveying methods, and accuracy/uncertainties involved with subsidence calculations.
4. Subsurface Investigation. Describe trenching and other subsurface investigations (test pits, borings, CPT soundings, geophysics) conducted to evaluate earth fissures at the site. The strike, dip, and vertical displacement (or minimum displacement if total displacement cannot be determined) across fissures should be recorded. Trench logs should be included with the report and should be prepared in the field at a scale of 1 inch = 5 feet or larger.

e. Conclusions.

1. Conclusions must be supported by adequate data, and the report should present those data in a clear and concise manner.
2. Data provided should include evidence establishing the presence or absence of land subsidence and earth fissures on or near a site and relation to proposed or existing infrastructure. Report displacement across earth fissures if present.
3. Statement of relative risk that addresses the probability or relative potential for growth of existing or future earth fissures and the rate and amount of anticipated land subsidence. This may be stated in semi-quantitative terms such as low, moderate, or high as defined within the report, or quantified in terms of fissure growth rates or land subsidence rates.
4. Degree of confidence in, and limitations of, the data and conclusions.

f. Recommendations.

1. Recommendations must be supported by the report conclusions and be presented in a clear and concise manner.
2. If earth fissures are present on site, provide setback or other mitigation recommendations as necessary, and justify based on site-specific data.
3. Mitigation measures to control fissure growth and reduce risk from land subsidence, such as preventing surface water from entering fissures, strengthening structures that must bridge fissures, and using flexible utility connections in subsidence areas or where utilities cross fissures displaying differential displacement.
4. Construction testing, observation, inspection, and long-term monitoring.
5. Limitations on the investigation and recommendations for additional investigation to better understand or quantify hazards.

B. References

a. Literature and records cited or reviewed; citations should be complete (see References section of this publication for examples).

b. Remote-sensing images interpreted; list type, date, project identification codes, scale, source, and index numbers.

c. Other sources of information, including survey data, well records, personal communication, and other data sources.

C. Illustrations. Should include at a minimum:

a. Location map. Showing the area investigated (region or site specific) and significant physiographic and cultural features, generally at 1:24,000 scale or larger and indicating the Public Land Survey System ¼-section, township, and range; and the site latitude and longitude to four decimal places with datum.

b. Site development map. For site-specific investigations showing site boundaries, existing and proposed structures, other infrastructure, and site topography. The map scale may vary depending on the size of the site and area covered by the study; the minimum recommended scale is 1 inch = 200 feet (1:2400) or larger when necessary. The site development map may be combined with the site-specific geology map (see below).

c. Regional geology/land-subsidence map. A regional-scale (1:24,000 to 1:50,000) map showing the investigation area's geologic setting, including geologic units, faults, other geologic structures, areas of land subsidence, and earth fissures within a 10-mile radius of the development site. Depending on project size and complexity, it may be necessary to show a larger area.

d. Site-specific geology map. For site-specific investigations, a site-scale geology map showing (1) distribution of geologic and soil units, (2) earth fissures, (3) land-subsidence areas, (4) faults, (5) springs and seeps, whether aligned or not, (6) other relevant geomorphic features, and (7) trench and boring locations, wells and piezometers, geophysical transects, survey lines, relevant benchmarks, and other kinds of monitoring locations. Scale of site geologic maps will vary depending on the size of the site and area of investigation; minimum recommended scale is 1 inch = 200 feet (1:2400) or larger when necessary.

   If on-site investigations reveal the presence of land subsidence or earth fissures, the boundary and magnitude of the subsiding area and earth-fissure locations should be shown on either the site-specific geologic map or on a separate land-subsidence and earth-fissure-hazard map depending on site scale and complexity. If earth-fissure avoidance is the mitigation strategy employed, an appropriate setback should be shown either on the site-specific geology map, or on a separate land-subsidence and earth-fissure-hazard map.

e. Geologic/topographic cross sections. Site geologic cross sections should be included as needed to illustrate three-dimensional geologic relations.

f. Trench and test pit log(s). Logs are required for each trench and test pit excavated as part of the investigation whether earth fissures are encountered or not. Logs are hand- or computer-drawn maps of excavation walls that show details of geologic units and structures. Logs should be to scale and not generalized or diagrammatic, and may be on a rectified photomosaic base. The scale (horizontal and vertical) should be 1 inch = 5 feet (1:60) or larger as necessary and with no vertical exaggeration. Logs should be prepared in the field and accurately reflect the features observed in the excavation, as noted below. Photographs are not a substitute for trench logs.

   The log should document all pertinent information from the trench, including (1) trench and test-pit orientation and indication of which wall was logged, (2) horizontal and vertical control, (3) top and bottom of trench wall(s), (4) stratigraphic contacts, (5) lithology and soil classification, (6) pedogenic soil horizons, (7) marker beds, (8) fissures and faults, (9) fissure orientations and geometry (strike and dip), (10) fissure displacement, and (11) sample locations (e.g., Birkeland and others, 1991; U.S. Bureau of Reclamation, 1998b; Walker and Cohen, 2006; McCalpin, 2009). Logs should be prepared for all trenches, even if fissures are not encountered. Logs should include interpretations and evidence for the age and origin of geologic units. Study limitations should be clearly stated for suspected earth fissures where un-fissured deposits are deeper than practical excavation depths.

g. Borehole and CPT sounding logs. Borehole and CPT sounding logs should include the geologic interpretation of deposit genesis for all layers encountered; logs should not be generalized or diagrammatic. Because boreholes are typically multipurpose, borehole logs may also contain standard geotechnical, geologic, and groundwater data.

h. Geophysical data and interpretations.

i. Photographs that enhance understanding of site surface and subsurface (trench and test pit walls) conditions with applicable metadata.

D. Authentication

   The report must be signed and sealed by a Utah licensed Professional Geologist in principal charge of the investigation (Title 58-76-10 – Professional Geologists Licensing Act [Utah Code, 2011]). Final geologic maps, trench logs, cross sections, sketches, drawings, and plans, prepared by or under the supervision of a professional geologist, also must bear the seal of the professional geologist (Utah Code, 2011). Reports co-prepared by a Utah licensed Professional Engineer and/or Utah licensed Professional Land Surveyor must include the engineer's or surveyor's stamp and signature.

E. Appendices

   Include supporting data relevant to the investigation not given in the text such as maps, boring logs, cross sections, conceptual models, fence diagrams, survey data, water-well data, geochronology laboratory reports, laboratory test data, and qualifications statements/resume.

FIELD REVIEW

The UGS recommends a technical field review by the regulatory-authority geologist once a land-subsidence and earth-fissure-hazard investigation is complete. The field review should take place after any trenches or test pits are logged, but before they are closed so subsurface site conditions can be directly observed and evaluated. See Field Review section in chapter 2.

REPORT REVIEW

The UGS recommends regulatory review of all reports by a Utah licensed Professional Geologist experienced in land-subsidence and earth-fissure-hazard investigations and acting on behalf of local governments to protect public health, safety, and welfare, and to reduce risks to future property owners (Larson, 1992, 2015). See Report Review section in chapter 2.

DISCLOSURE

The UGS recommends disclosure during real-estate transactions whenever an engineering-geology investigation has been performed. See Disclosure section in chapter 2.

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CHAPTER 7
GUIDELINES FOR EVALUATING ROCKFALL HAZARDS IN UTAH

by
William R. Lund, P.G., and Tyler R. Knudsen, P.G.

Rockfall in 2013 that damaged a residence in St. George, Utah, and severly injured the occupant.

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CHAPTER 7: GUIDELINES FOR EVALUATING ROCKFALL HAZARDS IN UTAH

by William R. Lund, P.G., and Tyler R. Knudsen, P.G.

INTRODUCTION

These guidelines present the recommended minimum acceptable level of effort for investigating rockfall hazards in Utah, and are intended for site-specific investigations for new structures for human occupancy and for International Building Code (IBC) Risk Category II, III, and IV facilities (International Code Council [ICC], 2014a). The intent of these guidelines is to assist engineering geologists performing rockfall investigations, and to reduce, to the lowest level possible, epistemic uncertainty (lack of necessary data) in evaluating rockfall hazard by conducting adequate hazard investigations. Aleatory variability (natural randomness) in rockfall behavior cannot be reduced; therefore, predicting exactly when and where future rockfalls will occur and how large they will be is not possible. For that reason, developing property on or near rockfall-susceptible areas will always involve a level of irreducible, inherent risk.

These guidelines outline (1) appropriate investigation methods, (2) report content, (3) map and illustration criteria and scales, (4) mitigation recommendations, (5) minimum criteria for review of reports, and (6) recommendations for geologic-hazard disclosure. However, these guidelines do not include systematic descriptions of all available investigative techniques or topics, nor does the UGS suggest that all techniques or topics are appropriate for every hazard investigation.

Considering the complexity of evaluating rockfall hazard, additional effort beyond the minimum criteria recommended in these guidelines may be required at some sites to adequately address rockfall hazard. The information presented in these guidelines does not relieve engineering geologists of the duty to perform additional geologic investigations necessary to fully assess the rockfall hazard at a site. As required by Utah state law (Utah Code, 2011), rockfall investigation reports and supporting documents must be signed and stamped by the licensed Utah Professional Geologist in responsible charge of the investigation.

Purpose

A rockfall-hazard investigation uses the characteristics of past rockfalls at a site as a scientific basis for providing recommendations to reduce the risk for damage and injury from future, presumably similar, rockfalls.

The purpose of these guidelines is to provide appropriate minimum rockfall investigation and report criteria to:

- protect the health, safety, and welfare of the public by minimizing the adverse effects of rockfalls;
- assist local governments in regulating land use in hazardous areas and provide standards for ordinances;
- assist engineering geologists in conducting reasonable and adequate investigations;
- provide engineering geologists with a common basis for preparing proposals, conducting investigations, and recommending rockfall-mitigation strategies; and
- provide an objective framework for preparation and review of reports.

These guidelines are not intended to supersede pre-existing state or federal regulations or local geologic-hazard ordinances, but provide useful information to supplement adopted ordinances/regulations, and assist in preparation of new ordinances. The UGS believes adherence to these guidelines will help ensure adequate, cost-effective investigations and minimize report review time.

Background

Rockfall is a natural mass-wasting process that involves the dislodging and rapid downslope movement of individual rocks and rock masses (Cruden and Varnes, 1996). The widespread combination of steep slopes capped by well-jointed bedrock makes rockfall among the most common slope-failure types in Utah. Rockfall poses a hazard because falling, rolling, or bouncing rocks and boulders can cause significant property damage and be life threatening (Smith and Petley, 2009) (figure 42). At least 20 deaths directly attributable to rockfalls have occurred in Utah since 1850 (Hylland, 1995; Case, 2000; Castleton, 2009; Lund and others, 2010, 2014; chapter 1). Significant damaging or fatal rockfalls in Utah include Big Cottonwood Canyon and the San Juan River in 1999 (Castleton, 2009); the Town of Rockville in 2002 (Lund, 2002a, 2002b; Rowley and others, 2002), 2010 (Knudsen, 2011), and 2013 (Lund and others, 2014); Provo in 2005 (Giraud and Christenson, 2010) and 2009 (Giraud and others, 2010); State Route 14 in 2009 (Lund and others 2009a, 2009b); and St. George in 2013 (Lund, 2013). See Case (2000) for a list of notable Utah rockfalls in the 1980s and 1990s.

Figure 42. *Rockfall damage to a house in southern Utah. Rockfall boulder leaning against wall passed entirely through the house and struck a vehicle in the driveway. Photo credit: Dave Black, Rosenberg Associates, photo taken February 2010.*

Figure 43. *Site showing rockfall source (cliff at top of slope), acceleration zone (steep slope below cliff), and runout zone (base of steep slope near barn and corral). See figure 46 for related information. Photo credit: Dave Black, Rosenberg Associates, photo taken February 2010.*

Rockfalls occur where a source of rock exists above a slope steep enough to allow rapid downslope movement of dislodged rocks by falling, rolling, bouncing, and sliding (figure 43). Rockfall 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 rockfall hazard, but other less obvious areas may also be vulnerable (Lund and others, 2010). Slope modifications such as cuts for roads and building pads and clearing slope vegetation for development or from wildfire can increase or create rockfall hazards, as can construction of non-engineered and/or poorly constructed rockery walls, which are becoming increasingly common in Utah urban areas (figure 44).

Rockfalls may be triggered by freeze/thaw action, rainfall, changes in groundwater conditions, weathering and erosion of the rock and/or surrounding material, and root growth (Smith and Petley, 2009). Rockfall is the most common type of mass movement caused by earthquakes. Keefer (1984) stated that earthquakes as small as magnitude (M) 4.0 can trigger rockfalls. In Utah, the 1988 M_L 5.3 San Rafael Swell earthquake triggered multiple rockfalls (figure 45) (Case, 2000), and the 1992 M_L 5.8 St. George earthquake caused numerous rockfalls in Washington County (Black and others, 1995). However, many rockfalls occur with no identifiable trigger. Although not well documented, rockfalls in Utah appear to occur more frequently during spring and summer months (Case, 2000). This is likely due to spring snowmelt, summer cloudburst storms, and large daily temperature variations (Castleton, 2009).

SOURCES OF ROCKFALL INFORMATION

The Utah Geological Survey (UGS) has investigated numerous rockfalls over the past three and a half decades (see Background section above). Additionally, the Literature Searches and Information Resources section in chapter 2 provides information on other geologic-hazard reports, maps, archives, and databases maintained by the UGS and others that may be relevant to rockfalls, as well as information on the UGS' extensive aerial photograph and light detection and ranging (lidar) imagery collections.

Rockfall Characterization and Control (Turner and Schuster, 2012) is the best currently available general reference for investigating and mitigating rockfall hazard. Although chiefly concerned with the effects of rockfall on transportation corridors, much of the information contained in this comprehensive publication is directly applicable to site-specific investigations for human-occupied structures and high-risk infrastructure.

ROCKFALL-HAZARD INVESTIGATION

When to Perform a Rockfall-Hazard Investigation

Geologic hazards are best addressed prior to land development. The UGS recommends that a rockfall-hazard investigation be made for all new buildings for human occupancy and for modified IBC Risk Category II(a), II(b), III, and IV facilities (modified from IBC table 1604.5 [ICC, 2014a]; see table 12 in chapter 2) that are proposed on or adjacent to areas where bedrock crops out on steep slopes. Utah jurisdictions that have adopted rockfall special-study maps identify zones in known rockfall-susceptible areas within which they require a site-specific investigation. The UGS recommends that investigations as outlined in these guidelines be conducted for all IBC Risk Category III and IV facilities on or adjacent to areas where bedrock crops out on steep slopes, whether near a mapped rockfall area or not, to ensure that a previously un-

Figure 44. *Unreinforced rockery wall typical of many constructed in recent years in Utah. Strong ground shaking during an earthquake may cause such walls to fail and generate urban rockfalls. Photo taken January 2013.*

Figure 45. *Dust clouds created by numerous rockfalls during the 1988 M 5.3 San Rafael Swell earthquake (photo courtesy of Terry A. Humphrey, U.S. Bureau of Land Management).*

known rockfall hazard is not present. If a hazard is found, the UGS recommends a comprehensive investigation be conducted. Additionally, in some instances an investigation may become necessary when existing infrastructure is discovered to be on or adjacent to a rockfall-susceptible area.

The level of investigation conducted for a particular project depends on several factors, including (1) site-specific geologic conditions, (2) type of proposed or existing development, (3) level of acceptable risk, and (4) governmental permitting requirements, or regulatory agency rules and regulations. A landslide-hazard investigation may be conducted separately, or as part of a comprehensive geologic-hazard and/or geotechnical site investigation (see chapter 2).

Minimum Qualifications of Investigator

Rockfall-related engineering-geology investigations and accompanying geologic-hazard evaluations performed before the public shall be conducted by or under the direct supervision of a Utah licensed Professional Geologist (Utah Code, Title 58-76) who must sign and seal the final report. Often these investigations are interdisciplinary in nature, and where required, must be performed by qualified, experienced, Utah licensed Professional Geologists (PG, specializing in engineering geology) and Professional Engineers (PE, specializing in geological and/or geotechnical engineering) working as a team. See Investigator Qualifications section in chapter 2.

Investigation Methods

Inherent in rockfall investigations is the assumption that future rockfalls will in most instances occur in areas subject to previous rockfalls, and in a manner generally consistent with past rockfall events. A site-specific rockfall investigation typically includes at a minimum:

- Literature review.
- Analysis of stereoscopic aerial photographs and other remote-sensing imagery.
- Site characterization, usually including surficial geologic mapping, measuring rockfall shadow angles, and characterizing rockfall source areas, acceleration zones, and runout areas.
- Other investigations as necessary to fully evaluate the rockfall hazard at a site (e.g., computer modeling, boreholes, geophysics, slope and groundwater instrumentation and monitoring) (see also chapter 2).

Literature Review

Prior to the start of field investigations, an engineering geologist conducting a rockfall investigation should review published and unpublished (as available) geologic literature, geologic and topographic maps, cross sections, consultant's reports, and records relevant to the site and site region's geology (see the Literature Searches and Information Resources section in chapter 2), with particular emphasis on information pertaining to the presence of known rockfall sources and the past history of rockfalls at or near the site of interest. The Sources of Rockfall Information section above provides information on Utah's geology and past significant rockfalls; however, the list of sources is not exhaustive, and engineering geologists should identify and review all available information relevant to their site of interest.

Analysis of Aerial Photographs and Remote-Sensing Data

A rockfall investigation should include interpretation of stereoscopic aerial photographs (from multiple years if available), available lidar imagery (appendix C), and other remotely sensed data for evidence of rockfall sources and past rockfall activity (see the Literature Searches and Information Resources section in chapter 2). Examination of the oldest available aerial photographs may show evidence of rockfalls subsequently obscured by development or other ground disturbance. The area interpreted should extend sufficiently beyond the site boundaries to identify evidence of off-site rockfall sources that might affect the site and adequately characterize patterns of rockfall occurrence. Aerial photographs and other remote-sensing imagery may prove useful in identifying and mapping local joints, faults, and other bedrock discontinuities, and regional geologic structures that may contribute to rockfall hazard at a site.

Google Earth and Bing Maps, among other providers of Internet-based, free aerial imagery, are becoming increasingly valuable as rapid site-reconnaissance tools, and provide high-resolution, often color, non-stereoscopic aerial orthophotographs of many sites of interest. For many locations, Google Earth also includes a historical imagery archive that permits evaluation of site conditions several years to decades before present.

Site Characterization

Rockfall is a surface phenomenon, and as such, the presence and severity of a rockfall hazard depend chiefly on site topography and the characteristics of the rockfall source. Higgins and Andrew (2012a, table 2-1) identify several types of rock slope failures ranging from simple to complex that may contribute to rockfalls. Readers requiring information on rockfall failure mechanisms are directed to Higgins and Andrew (2012a) for a discussion of each failure type and the conditions under which they occur. Climatic factors such as precipitation and temperature affect erosion, freeze-thaw cycles, and groundwater conditions, and are common rockfall triggers. Earthquakes are a less common phenomena, but earthquakes may trigger numerous nearly simultaneous rockfalls.

A first-order consideration when performing a rockfall investigation is whether or not the conditions for rockfall are present at or near the site of interest. If either a rock source or a slope steep enough to permit rockfall debris to move rapidly downslope are absent, there is no rockfall hazard. The determination of whether a rockfall hazard is present or not can often be made quickly from analysis of aerial photographs or other remote sensing data, or from a brief site reconnaissance.

If conditions for rockfall are present on or adjacent to a site (a rockfall may not follow a direct path downslope), evaluating the severity of the hazard requires determining the characteristics of three rockfall-hazard components: (1) the rock source, which generally consists of a bedrock unit that exhibits a relatively consistent pattern of rockfall susceptibility where it crops out on or above steep slopes (e.g., the Shinarump Conglomerate Member of the Chinle Formation in southwestern Utah), although talus, cliff-retreat deposits, glacial moraines, and any steep slope in unconsolidated deposits that contain large cobbles and boulders may also source rockfalls, (2) the acceleration zone, where the rockfall debris gains momentum as it travels downslope; this zone often includes a talus slope, which becomes less apparent with decreasing relative hazard and may be absent where the hazard is low, and (3) the runout zone, which includes gentler slopes and valley bottoms at the base of the acceleration-zone slope where boulders roll or bounce as they decelerate and eventually come to a stop (figure 46) (Evans and Hungr, 1993; Wieczorek and others, 1998; Higgins and Andrews, 2012b).

Rockfall investigations should include mapping susceptible geologic units and talus slopes, and topographic features that may affect rockfall hazard. Rockfall sources should be evaluated for (1) rock type (lithology; e.g., U.S. Bureau of Reclamation, 1998b; Walker and Cohen, 2006), (2) weathering, (3) discontinuities (bedding, joints, faults, shear zones, foliation, schistosity, veins, etc.; e.g., U.S. Bureau of Reclamation, 1998b), and (4) potential clast size. The presence of bedrock discontinuities in a rock source, and their relation to cliff faces/slope are of particular importance. Discontinuities may divide a rock source into blocks or wedges and enhance the ability of a bedrock unit to source rockfalls (provide detachment surfaces), and can also affect the size and shape of rockfall debris. Important properties of discontinuities include (1) orientation, (2) spacing, (3) persistence, (4) roughness, (5) weathering, (6) aperture width, (7) aperture filling, and (8) seepage (U.S. Bureau of Reclamation, 1998b; Higgins and Andrew, 2012b). Discontinuity spacing and other rock-mass data are normally recorded by making a scanline survey along a rock outcrop surface or from rock cores (U.S. Bureau of Reclamation, 1998b; Higgins and Andrews, 2012b).

Groundwater conditions should be carefully investigated. The presence of groundwater can greatly increase the potential for rockfall by (1) reducing shear strength along failure surfaces, (2) decreasing cohesion in infilling materials, (3) increasing forces that may induce pressure along discontinuities, and (4)

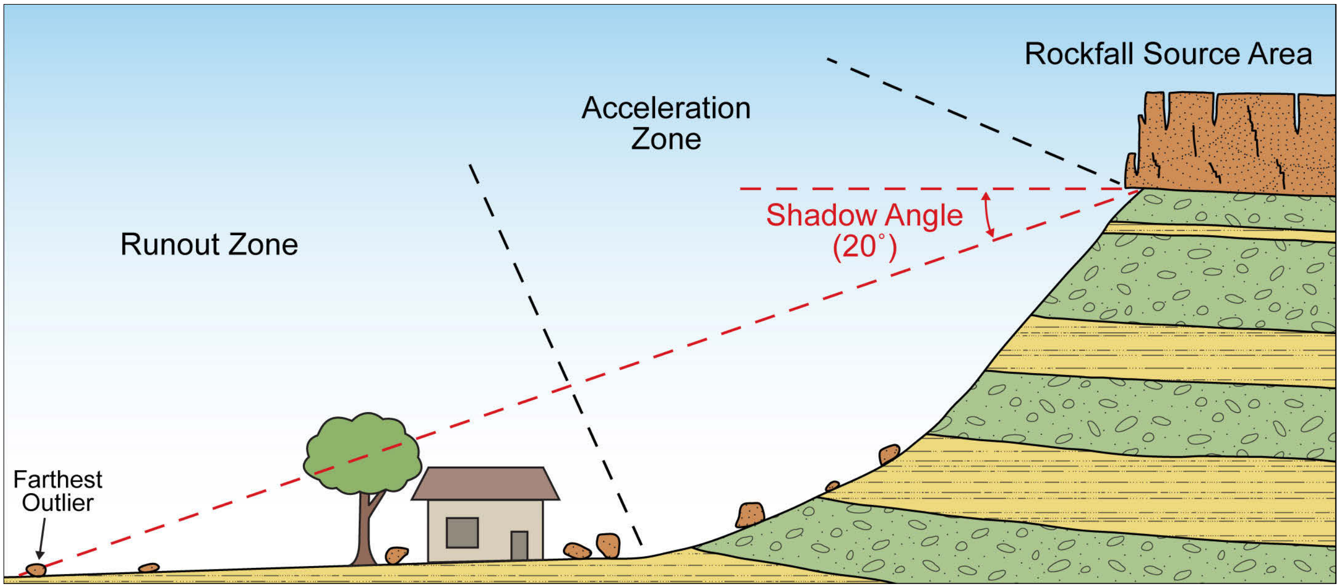


Figure 46. *Typical rockfall path profile and components of a rockfall shadow angle (modified from Lund and others, 2008).*

enhancing freeze-thaw cycles (Higgins and Andrew, 2012a). Groundwater conditions may exhibit seasonal variations, and thus may require long-term monitoring to accurately gauge their effect on rockfall conditions.

The acceleration zone should be evaluated for (1) slope angle, (2) aspect, (3) substrate, (4) surface roughness, (5) vegetation, and (6) launch points (abrupt changes in slope) that may cause rockfall debris to become airborne. The presence of gullies, previously fallen boulders, and other sometimes subtle geomorphic or topographic features in the acceleration zone can deflect the path of a rockfall toward a site, even though the rockfall source is not directly above the site of interest. In runout zones, rockfall deposits should be evaluated for (1) distribution, (2) clast size, (3) amount of embedding, and (4) weathering of rockfall boulders as an indicator of rockfall age (figure 47).

Rockfall shadow angle: At undeveloped sites, or where rockfall debris has not been disturbed or removed from the runout zone, empirically establishing the outer boundary of the area affected by rockfall is often possible by measuring a rockfall shadow angle (Evans and Hungr, 1993; Wieczorek and others, 1998; Turner and Duffy, 2012). A shadow angle is the angle between a horizontal line and a line extending from the base of the rock source to the outer limit of the runout zone as defined by the farthest outlier rockfall debris at a site (figure 46). Shadow angles vary depending on (1) rock type, (2) rock shape, (3) slope steepness, (4) slope characteristics (such as surface roughness, vegetation, etc.), and (5) rock source height (Knudsen and Lund, 2013). Multiple measurements are necessary to establish a representative shadow angle; for example, Lund and others (2010) and Knudsen and Lund (2013) measured dozens of shadow angles in Zion Canyon in southwestern Utah to determine that an angle of 22° is generally applicable to the geologic and topographic conditions found there. Structures and other infrastructure that are set back from the boundary of the runout zone determined using the shadow-angle technique are at greatly reduced risk from rockfall.

The UGS recommends establishing the extent of the rockfall runout zone at a site using a shadow angle based on the distribution of past rockfall debris, since each past rockfall represents a field test of rockfall susceptibility at the site. However, where rockfall debris has been disturbed or removed, determining the limit of the runout-zone boundary can be difficult or impossible. In those situations, it may be necessary to determine a shadow angle at a nearby undisturbed site with similar geologic and topographic conditions, which can then be applied to the site of interest. Alternatively, in some instances it may be possible to estimate the boundary of the runout zone below a rock source using rockfall modeling software.

Figure 47. *Weathered rockfall boulder with subsequent erosion of soil from around the boulder base indicating that this rockfall occurred in the distant past and the area may no longer be in an active rockfall-hazard area. Photo taken March 2004.*

Rockfall modeling software: The numerical simulation of rockfall trajectories is chiefly based on the principles of Newtonian mechanics and can provide reasonably precise estimates of rockfall trajectories, velocities, and kinetic energies (Turner and Duffy, 2012). Numerous rockfall computer models incorporating a variety of assumptions have been developed over the past three decades. Two-dimensional (2-D) simulations based on a "typical" slope profile have been most commonly applied (e.g., Colorado Rockfall Simulation Program [Jones and others, 2000]; Rocfall [RocScience, 2011]); however, it has long been recognized that 2-D models only partially reflect the realities of a three-dimensional (3-D) slope (Turner and Duffy, 2012). Multiple 2-D profiles need to be run to help account for the 3-D nature of rockfalls and the surrounding topography. Appropriate input data are critical, and therefore, the use of "typical" values should be avoided. Often, extensive fieldwork is needed to determine rock shape, surface roughness, vegetation, etc. for model input values. Attempts have been and are being made to develop 3-D rockfall models, although most current models require significantly greater computational capability and considerable experience to apply and interpret properly. Geographic information system (GIS) software is increasingly being used to evaluate landslide and rockfall hazards. Soeters and van Westen (1996) provided a comprehensive review of GIS techniques and how they can be used to assess slope instability and establish hazard zones. More recently, Fell and others (2008a, 2008b) defined and elaborated on the role of GIS analysis in landslide susceptibility, hazard, and risk zoning, and Van Westen and others (2008) provided a review of spatial information and GIS techniques in landslide hazard assessment (Turner and Duffy, 2012).

Providing detailed information on the use of rockfall simulation software is beyond the scope of these guidelines. Investigators may wish to consult Turner and Duffy (2012) for an extensive summary of the uses and limitations of current computational rockfall modeling techniques. Most analytical methods only model the interaction between a single rock block and the ground surface during successive impacts as the block rolls or bounces downslope. Collisions or impacts among multiple moving blocks are typically not evaluated, unless sophisticated discrete element numerical modeling is used. Interactions among multiple rock blocks frequently occur during rockfalls; thus, most analytical models represent a significant simplification over reality (Turner and Jayaprakash, 2012). Therefore, rockfall computer simulation models are only reliable when they have been carefully calibrated against field observations (Turner and Duffy, 2012).

Rockfall probability: A rockfall investigation, performed as described above, will establish the presence or absence of a rockfall hazard at a site and define a boundary beyond which the risk from future rockfalls is much reduced. However, determining (predicting) the exact timing of future rockfalls is not possible, and is not likely to become possible in the foreseeable future. As a general rule, the more rockfall debris on or at the base of a slope, the more frequent rockfalls are, and the higher the hazard. However, with sufficient data it is possible to estimate the probability (x % chance in y years) of future rockfalls at a site. Conducting a probabilistic analysis requires information on both the number and timing of past rockfalls (Turner, 2012). Only a few areas in Utah have both a high rockfall hazard and a history of rockfall damage to structures to have produced a significant record of historical rockfalls. Rockville, Utah, is one such place, where six large rockfalls have occurred over the past 13 years (figure 48) (Knudsen, 2011; Lund and others, 2014), resulting in an average recurrence interval (average repeat time) for large rockfalls of 2.2 years. The annual probability of a large rockfall in Rockville based on the 13-year record is 46%. Three of the rockfalls struck and damaged inhabited structures, and one of the three caused two fatalities (figure 49). Such well-documented rockfall histories are rare, so in most instances, timing of past rockfalls must be determined by other means. In Yosemite National Park, Stock and others (2012a, 2012b) used cosmogenic beryllium-10 exposure ages to date the surfaces of rockfall boulders exposed to cosmogenic radiation for the first time following the rockfall. They integrated the number of identified rockfall events, rockfall timing data, and computer simulations of rockfall runout to develop a hazard boundary with a 10% probability of exceedance in 50 years for rockfall-susceptible areas of Yosemite Valley. Such detailed probabilistic rockfall-hazard investigations are costly both in terms of time and money, and are beyond the scope of most rockfall investigations. However, a probabilistic rockfall investigation may be required when evaluating hazard and risk for high-value infrastructure or for areas of prolonged high human occupancy in rockfall-susceptible areas.

Other Investigation Methods

Other investigation methods may be incorporated in rockfall investigations when conditions permit or requirements for critical structures or facilities make more intensive investigation or monitoring necessary. Possible investigation methods may include, but are not limited to:

- Aerial reconnaissance flights.
- Instrumentation and monitoring, which may include conventional high-precision surveying or geodetic measurements, terrestrial photogrammetry, airborne and/or terrestrial lidar and radar technologies, strain (displacement) measurement both at the surface and in boreholes, and groundwater piezometers (Andrew and others, 2012).
- Drilling to recover rock core for characterizing rock sources, installing slope monitoring instruments, and investigating and monitoring groundwater conditions.
- Geophysical investigations to better define discontinuity patterns in rockfall source areas. Geophysical techniques may include (1) high-resolution seismic reflection, (2) ground penetrating radar, (3) seismic refraction, (4) refraction microtremor (ReMi), (5) magnetic profiling, (6) electrical resistivity, and (7) gravity.

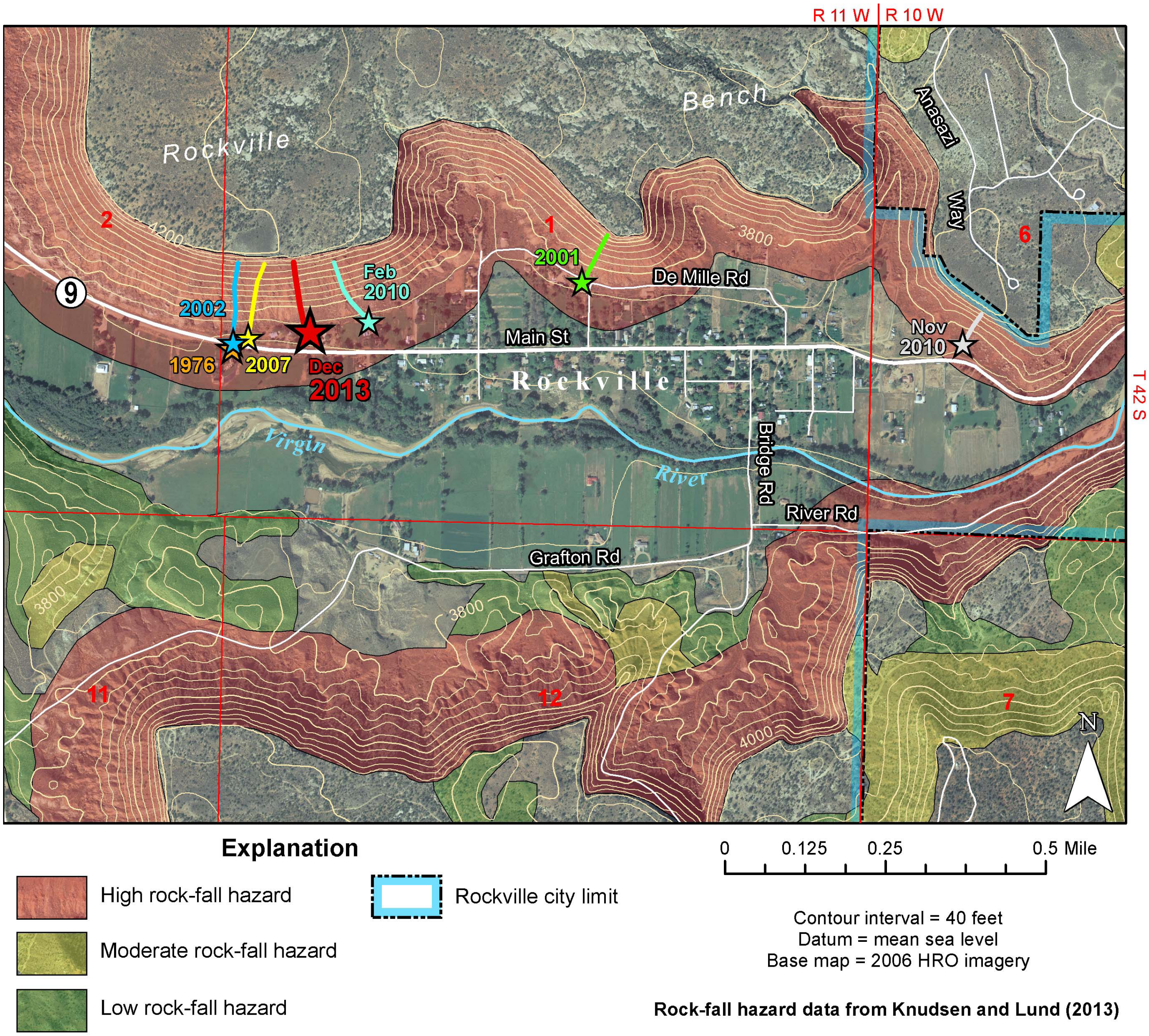


Figure 48. *Rockfall-hazard zones mapped by the UGS, and historical rockfalls and their travel paths in the Town of Rockville, Utah.*

Geophysical methods should not be employed without knowledge of site geology; however, where no other subsurface geologic information is available, geophysical methods may provide the only economically viable means to characterize rock-mass discontinuities (e.g., Telford and others, 1990; U.S. Bureau of Reclamation, 2001; Milsom and Eriksen, 2011; Reynolds, 2011).

- Geochronologic analysis, chiefly, but not limited to, application of various cosmogenic isotope dating techniques to rockfall-boulder surfaces to estimate times of boulder emplacement.

ROCKFALL MITIGATION

Early recognition and avoidance of areas subject to rockfall are the most effective means of mitigating rockfall hazard. Determining the boundary of the rockfall runout zone and siting all new buildings for human occupancy and IBC Risk Category II, III, and IV facilities (ICC, 2014a) outside that zone will substantially reduce rockfall risk. However, because the boundary of a rockfall runout zone seldom can be established with a high level of precision, the UGS recommends that structures for human occupancy or high-risk facilities be set back an appropriate distance from the runout-zone boundary to provide an additional factor of safety from rockfalls. Rockfall hazard is highly dependent on site geologic and topographic conditions; therefore, the UGS does not make a standard setback recommendation, but rather recommends that the engineering geologist in responsible charge of the rockfall investigation make and justify an appropriate setback based on the results of the site-specific hazard investigation. Where investigation results provide confidence in the runout-zone boundary, additional setback can be minimized. Where the boundary is uncertain, a larger setback is appropriate.

A

B

Figure 49. (A) House in Rockville, Utah, September 2010. (B) The same house in December 2013, destroyed by a large rockfall. The two occupants in the house were killed.

A

B

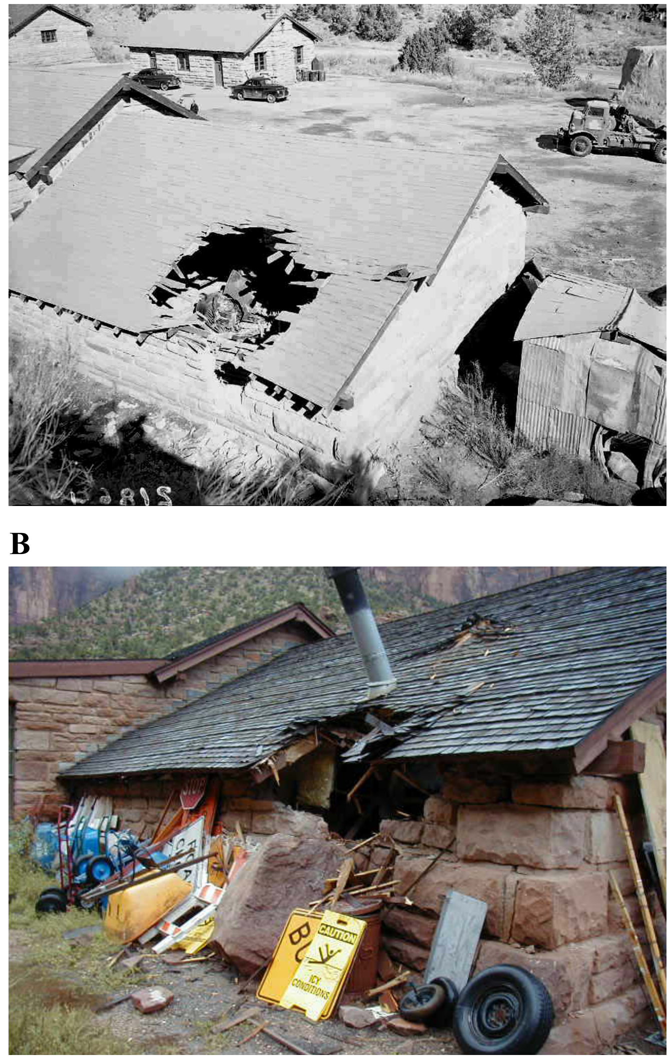


Figure 50. (A) Rockfall in 1947 through the roof of a maintenance building in Zion National Park. (B) Rockfall in 2010 through the roof of the same maintenance building. Photos courtesy of National Park Service.

Avoidance may not always be a viable or cost-effective option, especially for existing facilities (figure 50), and many techniques are available to mitigate rockfall hazard. Rockfall mitigation is often conducted by specialized design-build manufacturers and/or contractors, often using proprietary techniques and/or materials. Mitigation techniques include, but are not limited to, (1) rock stabilization, (2) engineered structures, and (3) 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, scaling, or shotcrete on susceptible outcrops. Engineered catchment or deflection structures such as rockfall fences (figure 51), berms, or benches can be placed below source areas, or at-risk structures themselves can be designed to stop, deflect, retard, or retain falling rocks. Such methods, however, may increase rockfall hazard if not properly designed and maintained. Detailed information on rockfall mitigation techniques is given in "Part 3: Rockfall Mitigation" of *Rockfall Characterization and Control* (Turner and Schuster, 2012). Conversely, in areas where a site-specific investigation indicates that rockfalls are possible but the hazard is low, it may be possible to conclude that the level of risk is acceptable and that no hazard-reduction measures are required (Lund and others, 2010). However, disclosure of the presence of a rockfall hazard at a site during real-estate transactions is necessary to ensure that prospective property owners can make their own informed decision regarding rockfall risk (Knudsen and Lund, 2013; see also Disclosure section below).

ROCKFALL-INVESTIGATION REPORT

The UGS recommends that a report prepared for a site-specific rockfall investigation in Utah at a minimum address the topics below. Site conditions may require that additional items

Figure 51. *Rockfall fence installed to mitigate the rockfall hazard and protect the Zion National Park maintenance building. Photo taken June 2014.*

be included to fully evaluate rockfall hazard at a site; these guidelines do not relieve engineering geologists from their duty to perform additional geologic investigations as necessary to adequately assess rockfall. The report guidelines below pertain specifically to rockfall investigations, and expand on the general report preparation guidance provided in the Engineering-Geology Investigations and Engineering-Geology Reports sections of chapter 2.

A. Text

a. Purpose and scope of investigation. Describe the location and size of the site and proposed type and number of buildings or other infrastructure if known.

b. Geologic and topographic setting. The report should contain a clear and concise statement of the site and site region's geologic and topographic setting. The section should include a discussion of rockfall activity in the area, historical seismicity if relevant to rockfall susceptibility, and should reference pertinent published and unpublished geologic literature.

c. Site description and conditions. Include dates of site visits and observations. Include information on geologic units, topography, vegetation, existing structures, evidence of previous rockfalls on or near the site, and other factors that may affect the choice of investigative methods and interpretation of data.

d. Methods and results of investigation.

1. Literature Review. Summarize published and unpublished topographic and geologic maps, literature, and records regarding geologic units; rock sources; faults, joints, and other discontinuities; surface water and groundwater; topographic and geomorphic features; previous rockfalls; and other relevant factors pertinent to the site.

2. Interpretation of Remote-Sensing Imagery. Describe the results of remote-sensing-imagery interpretation, including stereoscopic aerial photographs, lidar, and other remote-sensing data when available. List source, date, flight-line numbers, and scale of aerial photos or other imagery used.

3. Surface Investigations. Describe pertinent surface features including mapping of rockfall sources (geologic units, talus slopes, precarious boulders, etc.) and discontinuities (bedding, joints, faults, foliation, schistosity, etc.), and other structural or geomorphic features that may affect the location, size, frequency, and path of rockfalls.

4. Shadow-Angle Analysis and/or Rockfall Computer Modeling. Describe the methods and results of shadow-angle analysis or computer modeling used to identify rockfall runout-zone boundaries, including a description and listing of the input parameters and how they were obtained.

5. Rockfall Pathway Analysis. Describe gullies, previously fallen rockfall debris, and other geomorphic or topographic features in the rockfall acceleration and runout zones that may affect the rockfall path. Note that when struck by rapidly moving rockfall debris, previously fallen boulders often shatter in whole or part and contribute material (including flyrock) to the rockfall rather than effectively shielding the site from hazard (Knudsen, 2011; Lund and others, 2014).

6. Other Investigation Methods. When special conditions or requirements for critical facilities demand a more intensive investigation, describe the methods used to supplement the rockfall investigation and the purpose/result of those methods. These may include, but are not limited to (a) aerial reconnaissance, (b) drilling and rock core analysis, (c) geophysical investigations, (d) slope and groundwater instrumentation and monitoring, and (e) geochronology.

B. Conclusions.

a. Conclusions must be supported by adequate data, and the report should present those data in a clear and concise manner.

b. Data provided should include evidence establishing the presence or absence of a rockfall hazard on or adjacent to the site and relation to existing or proposed infrastructure.

c. Statement of relative risk that addresses the relative potential for future rockfalls. This may be stated in semi-quantitative terms such as low, moderate, or high as defined within the report, or as a probability if combined with information on the number and timing of past rockfalls.

d. Degree of confidence in, and limitations of, the data and conclusions.

C. Recommendations.

a. Recommendations must be supported by the report conclusions and be presented in a clear and concise manner.

b. Rockfall runout-zone boundaries and additional setbacks should include the justification for the setback distance chosen based on shadow angle and/or rockfall computer modeling, and include an appropriate statement or measure of boundary confidence/uncertainty.

c. Other recommended mitigation methods such as building/structure design or use restrictions, risk-reduction measures such as placement of detached garages or other non-habitable structures in rockfall zones, or engineering-design methods in the rockfall source area or runout zone to mitigate rockfall risk.

d. Recommendations for long-term monitoring if necessary.

e. Limitations on the investigation and recommendations for additional investigation to better understand or quantify the hazard.

D. References

a. Literature and records cited or reviewed; citations should be complete (see References section of this publication for examples).

b. Remote-sensing images interpreted; list type, date, project identification codes, scale, source, and index numbers.

c. Other sources of information, including well records, personal communication, and other data sources.

E. Illustrations. Should include at a minimum:

a. Location map. Showing the site and significant physiographic and cultural features, generally at 1:24,000 scale or larger and indicating the Public Land Survey System ¼-section, township, and range; and the site latitude and longitude to four decimal places with datum.

b. Site development map. Showing site boundaries, existing and proposed structures, other infrastructure, and site topography. The map scale may vary depending on the size of the site and area covered by the study; the minimum recommended scale is 1 inch = 200 feet (1:2400) or larger when necessary. The site development map may be combined with the site-specific geology map (see item "c" below).

c. Site-specific geology map. A site-scale geology map showing (1) geologic units, (2) bedding, faults, joints, other discontinuities, and relevant geologic structures, (3) distribution of bedrock and unconsolidated-deposit rockfall sources, (4) rockfall pathways and runout zones, (5) seeps or springs, (6) other slope failures, and (7) boreholes, geophysical transects, scanline transects, and slope and groundwater-monitoring locations. Scale of site-specific geology maps will vary depending on the size of the site and area of study; minimum recommended scale is 1 inch = 200 feet (1:2400) or larger when necessary.

d. Geologic/topographic cross sections. Site geologic cross sections should be included as needed to illustrate three-dimensional geologic relations.

e. Rockfall hazard map. If site-specific investigations reveal the presence of a rockfall hazard, rockfall runout zones and appropriate additional recommended setbacks based on shadow angle and/or rockfall computer modeling should be shown either on a rockfall-hazard map, or on the site-specific geology map depending on site scale and complexity.

f. Borehole logs. Borehole logs should include the geologic interpretation of deposit genesis for all layers encountered; logs should not be generalized or diagrammatic. Because boreholes are typically multipurpose, borehole logs may also contain standard geotechnical, geologic, and groundwater data.

g. Geophysical data and interpretations.

h. Photographs that enhance understanding of the rockfall hazard at the site with applicable metadata; photographs of rock core if acquired during drilling.

F. Authentication

a. The report must be signed and stamped by a Utah licensed Professional Geologist in principal charge of the investigation (Title 58-76-10 – Professional Geologists Licensing Act [Utah Code, 2011]). Final geologic maps, trench logs, cross sections, sketches, drawings, and plans, prepared by or under the supervision of a professional geologist, also must bear the stamp of the professional geologist (Utah Code, 2011). Reports co-prepared by a Utah licensed Professional Engineer and/or Utah licensed Professional Land Surveyor must include the engineer's or surveyor's stamp and signature.

G. Appendices

a. Include supporting data relevant to the investigation not given in the text such as maps, boring logs, cross sections, conceptual models, fence diagrams, survey data, water-well data, geochronology laboratory reports, laboratory test data, and qualifications statements/resume.

FIELD REVIEW

The UGS recommends a technical field review by the regulatory-authority geologist once a rockfall-hazard investigation is complete. See Field Review section in chapter 2.

REPORT REVIEW

The UGS recommends regulatory review of all reports by a Utah licensed Professional Geologist experienced in rockfall-hazard investigations and acting on behalf of local governments to protect public health, safety, and welfare, and to reduce risks to future property owners (Larson, 1992, 2015). See Report Review section in chapter 2.

DISCLOSURE

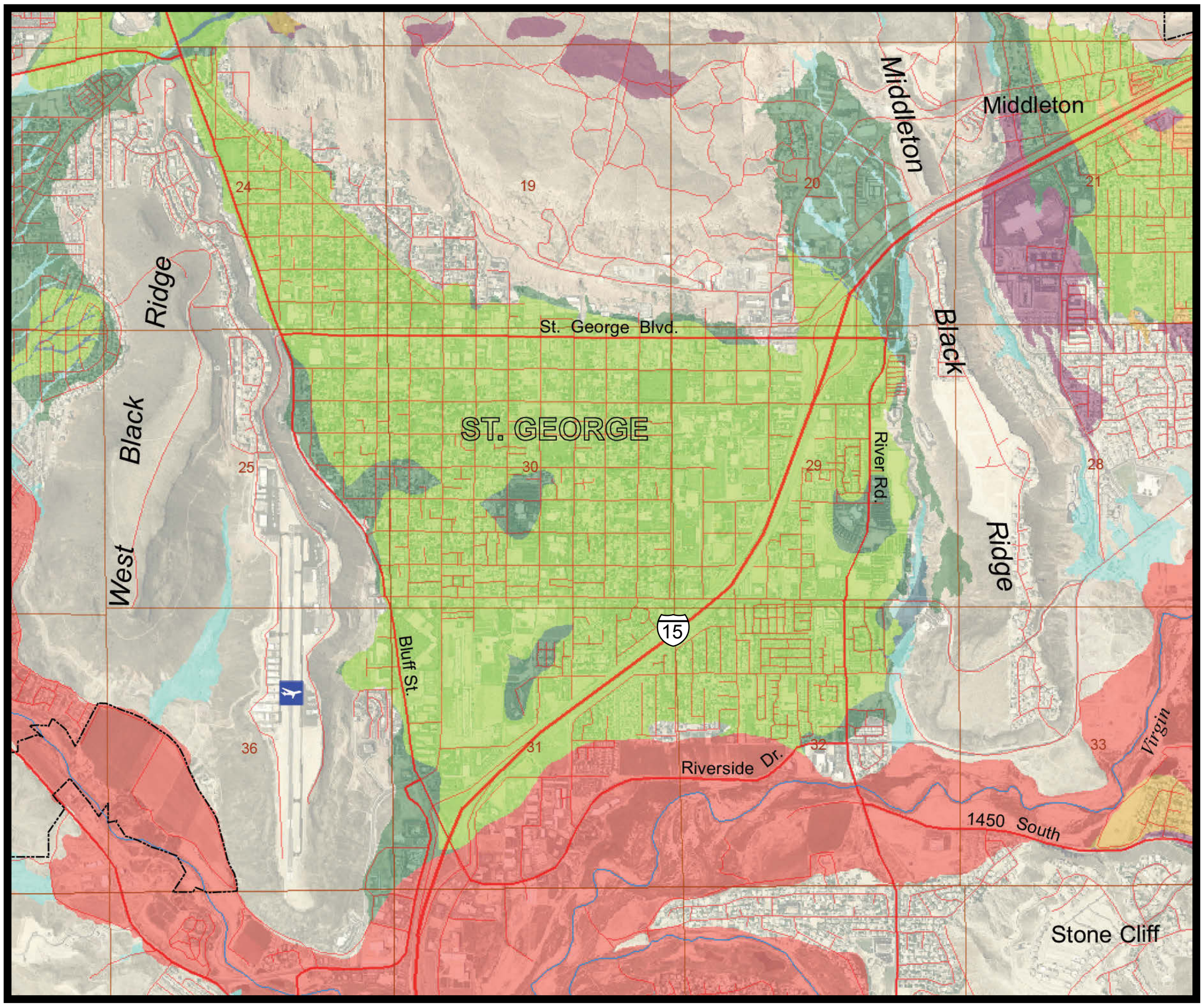
The UGS recommends disclosure during real-estate transactions whenever an engineering-geology investigation has been performed. See Disclosure section in chapter 2.

ACKNOWLEDGMENTS

Ken Euge (Geological Consultants, Inc.), David Black (Rosenberg Associates), and Gregg Beukelman, Steve Bowman, Rich Giraud, and Adam McKean (Utah Geological Survey) provided insightful comments and additional data that substantially improved the utility of these guidelines.

CHAPTER 8
SUGGESTED APPROACH TO GEOLOGIC-HAZARD ORDINANCES IN UTAH

by
William R. Lund, P.G., Steve D. Bowman, Ph.D., P.E., P.G., and Gary E. Christenson, P.G.



Shallow groundwater geologic-hazard special study map of part of St. George, Utah, from UGS Special Study 127.

Suggested citation: Lund, W.R., Bowman, S.D., and Christenson, G.E., 2016, Suggested approach to geologic-hazard ordinances in Utah, *in* Bowman, S.D., and Lund, W.R., editors, Guidelines for investigating geologic hazards and preparing engineering-geology reports, with a suggested approach to geologic-hazard ordinances in Utah: Utah Geological Survey Circular 122, p. 125–131.

CHAPTER 8: SUGGESTED APPROACH TO GEOLOGIC-HAZARD ORDINANCES IN UTAH

by William R. Lund, P.G., Steve D. Bowman, Ph.D., P.E., P.G., and Gary E. Christenson, P.G.

INTRODUCTION

This chapter updates and revises Utah Geological and Mineral Survey Circular 79, *Suggested Approach to Geologic Hazards Ordinances in Utah* (Christenson, 1987), and is intended for municipal and county officials responsible for planning for and permitting future land development in their jurisdictions. While the 2015 International Building Code (IBC) and International Residential Code (IRC) are adopted statewide as part of the State Construction and Fire Codes Act (http://le.utah.gov/xcode/Title15A/15A.html), geologic hazards are typically not a part of these codes. A geologic-hazard ordinance protects the health, safety, and welfare of citizens by minimizing the adverse effects of geologic hazards (see chapter 1 of this publication for a definition of a geologic hazard). Geologic hazards can be considered at various times during planning and development, but generally are best addressed early in the process before development proceeds. Some geologic hazards cannot be mitigated, or are too costly to mitigate, and therefore should be avoided. Other hazards can be effectively mitigated by means other than avoidance, and need not affect land use significantly, as long as the hazard is identified, characterized, and accommodated in project planning and design. Conversely, failure to identify and mitigate geologic hazards may result in significant additional construction and/or future maintenance costs or result in property damage, injury, and/or death. Castleton and McKean (2012) discuss the various geologic hazards commonly encountered in Utah.

Where master plans and zoning ordinances have already been adopted, amendments can be used to address geologic hazards, although it may be too late to change the existing land use to one more compatible with the hazards. Geologic-hazard or sensitive-land overlay zones are effective for areas where zoning ordinances are already in place. The overlay zone (or zones, if hazards are considered separately) includes areas where hazards have been identified and places restrictions on development. Overlay zones may be placed over existing zone maps requiring that development conform to overlay regulations. Geologic hazards may also be addressed in development codes and subdivision ordinances.

PURPOSE

This chapter presents a suggested approach for implementing a geologic-hazard ordinance at the municipal or county level in Utah. Effective geologic-hazard ordinances are science based, and it is chiefly the science-based (technical) components of a geologic-hazard ordinance that are discussed here. Administrative aspects of ordinance adoption and implementation are left to the specific requirements and needs of individual jurisdictions; however, the Utah Geological Survey (UGS) recommends that ordinances include (1) a requirement for a thorough regulatory review (Larson, 2015) of engineering-geology reports and other geological documents submitted as part of the development permitting process, and (2) an enforcement requirement, including site inspection, to ensure that geologic-hazard mitigation recommendations are in fact incorporated in project construction as approved.

This chapter is not a comprehensive review of all possible approaches or types of ordinances, overlay zones, or development codes in which geologic hazards may be addressed. Nor is it a model ordinance, although it is based in part on proven-effective ordinances in Utah (e.g., Salt Lake City [updated 2014], Salt Lake County [2002a], City of Draper [2010], and Iron County [2011]) that could serve as models for future geologic-hazard ordinances in other jurisdictions. Additional recommendations for reducing losses from geologic hazards, including those related to ordinances, were outlined by the 2006–2007 Governor's Geologic Hazards Working Group (Christenson and Ashland, 2008).

Other chapters in this publication address (1) minimum acceptable requirements for engineering-geology investigations and subsequent reports prepared in support of the development permitting process (chapter 2), and (2) the minimum acceptable level of effort recommended to investigate surface-fault-rupture, landslide, debris-flow, ground-subsidence and earth-fissure, and rockfall hazards (chapters 3–7). As the UGS develops additional geologic-hazard guidelines in the future, the new guidelines will be incorporated in updates of this publication. The UGS recommends that, at a minimum, municipalities and counties incorporate the standards presented in this publication in their geologic-hazard ordinances. Experience has shown that requirements established in a geologic-hazard ordinance, even if identified as minimum acceptable standards, typically become the maximum level of effort expended in the development permitting process (Slosson, 1984). Therefore, it is incumbent on municipalities and counties to establish science-based technical requirements and standards in their ordinances that ensure that geologic hazards are adequately identified, characterized, reported upon, and mitigated in their jurisdictions.

ORDINANCE DEVELOPMENT

A comprehensive geologic-hazard ordinance helps protect the health, safety, and welfare of citizens by minimizing the adverse effects of geologic hazards. In almost all cases, it is more cost effective to perform a comprehensive engineering-geology investigation to identify and characterize geologic hazards and implement appropriate mitigation in project design and construction, rather than relying on additional maintenance over the life of the project, incurring costly change orders during construction, and/or increasing public liability to hazards. Often, local governments are left to mitigate geologic-hazard issues after an event, such as a landslide (for example, the 2014 Parkway Drive landslide in North Salt Lake), which in many cases is costly to taxpayers and may have been avoided.

Geologic-hazard ordinances should, at a minimum, consider the hazards known within that jurisdiction. Higher levels of safety can be achieved by investigating all of the geologic hazards commonly encountered in Utah (see chapter 1 and appendix B of this publication, and Neuendorf and others [2011] for geologic-hazard definitions). While not all of these hazards are likely to be present within every local jurisdiction, those not present can quickly be eliminated from further consideration by a comprehensive engineering-geology investigation. Documenting the absence of a hazard is often as important as documenting the presence of one.

When to Perform a Geologic-Hazard Investigation

Geologic hazards are best addressed prior to land development in affected areas. The UGS recommends that a comprehensive geologic-hazard investigation be performed for all new buildings for human occupancy, and for all IBC Risk Category II, III, and IV facilities (IBC table 1604.5 [International Code Council, 2014a]) proposed in areas of known or suspected geologic hazards. The level of investigation conducted for a particular project depends on several factors, including (1) site-specific geologic conditions, (2) type of proposed or existing development, use, and operation, (3) level of acceptable risk, and (4) governmental permitting requirements, or regulatory agency rules and regulations. A geologic-hazard investigation may be conducted separately, or as part of a comprehensive engineering-geology and/or geotechnical site investigation (chapter 2).

Minimum Qualifications of the Investigator

Minimum qualifications for the geologist in responsible charge of an engineering-geology investigation and for regulatory-authority geologists are detailed in chapter 2. In addition, geologic-hazard ordinances should specify conflict of interest requirements. It is imperative that regulatory-authority geologists hold themselves to the highest ethical standards to eliminate conflicts of interest and bias that may jeopardize the review process.

Geologic-Hazard Special Study Maps

A critical first step to ensure that geologic hazards are adequately addressed in land-use planning and regulation is preparation by local jurisdictions of geologic-hazard special study maps, which define areas where geologic-hazard investigations are required prior to development. The UGS publishes geologic-hazard special study maps for selected areas in Utah, showing delineated special-study areas where detailed investigations are recommended. These maps are prepared by qualified, experienced geologists using best available scientific information, but are necessarily generalized and designed only to indicate areas where hazards may exist and where site-specific geologic-hazard investigations are necessary. Because geologic-hazard special study maps are prepared at a non-site-specific scale (generally 1:24,000 or smaller), hazards may exist but not be shown in some areas on the maps. The fact that a site is not in a geologic-hazard study area for a particular hazard does not exempt the engineering geologist in responsible charge of the investigation from evaluating a hazard if evidence is found that one exists.

Utah Geological Survey Geologic-Hazard Maps

The UGS has prepared or assisted with preparation of geologic-hazard special study maps for Cache, Davis, Iron, Salt Lake, eastern Tooele, Utah, western Wasatch, and Weber Counties (on file with the respective county planning departments and may be available at http://geology.utah.gov/map-pub/maps/geologic-hazard-maps/). Many of these maps have become dated, only a few hazards were mapped, and more accurate mapping methods are now available. The current UGS Geologic Hazards Program (http://geology.utah.gov/about-us/geologic-programs/geologic-hazards-program/) Geologic Hazards Mapping Initiative develops modern, comprehensive geologic-hazard map sets on U.S. Geological Survey 1:24,000-scale quadrangles in urban areas of Utah (Bowman and others, 2009; Castleton and McKean, 2012) as PDFs and full GIS products. These map sets typically include 10 or more individual geologic-hazard maps (liquefaction, surface-fault rupture, flooding, landslides, rockfall, debris flow, radon, collapsible soils, expansive soil and rock, shallow bedrock, and shallow groundwater). Some quadrangles may have additional maps of wind-blown sand, piping and erosion, land subsidence and earth fissures, or other geologic hazards identified within the mapped area.

The Magna and Copperton quadrangle map sets (Castleton and others, 2011, 2014) within Salt Lake Valley have been published, with mapping continuing in Salt Lake and Utah Valleys. Similar UGS geologic-hazard map sets are available for the St. George–Hurricane metropolitan area (Lund and others, 2008), high-visitation areas in Zion National Park (Lund and others, 2010), and the State Route 9 corridor between La Verkin and Springdale (Knudsen and Lund, 2013). Additionally, detailed surface-fault-rupture-hazard maps have been published for the Levan, Fayette, and southern half of the Collinston segments of the Wasatch fault zone (Harty and McKean, 2015; Hiscock and Hylland, 2015) with mapping on other segments ongoing. The UGS routinely partners with local governments to expedite the publication of geologic-hazard special study maps in critical areas and can provide guidance on how to use and interpret the maps.

Where Geologic-Hazard Maps Are Not Available

Where geologic-hazard special study maps are not available, the local government should consider partnering with the UGS to develop the appropriate maps consistent with those available in other areas. The UGS creates these special study area maps for local and state agencies as delegated by Utah Code.

If funding or other impediments to preparing geologic-hazard special study maps occur, geologic-hazard ordinances should state that the first step in a geologic-hazard investigation is to determine if the site is near mapped or otherwise known geologic hazards. If so, larger scale maps (if available) should be examined, aerial photograph and other remote sensing imagery interpreted, and a field investigation performed to produce a detailed geologic map as outlined in chapter 2 to determine if a geologic hazard(s) is present that will affect the site. If evidence for a hazard(s) is found, the UGS recommends that a site investigation be performed in accordance with the guidelines presented in chapter 2, and in chapters 3–7 as applicable.

Scoping Meeting

Due to the interdisciplinary and complex nature of many geologic-hazard investigations, the UGS recommends that geologic-hazard ordinances include a provision for a pre-investigation scoping meeting between the permitting authority (municipality or county) and the consultant performing the investigation (and project owner if needed) to discuss any building code and/or local ordinance requirements that apply to the project. These meetings can reduce the uncertainty regarding applicable requirements and speed the project/permit approval process. The geologist representing the permitting/regulatory entity, building official, and planner should attend at a minimum. Several scoping meetings and/or site visits may be needed on complex projects.

ENGINEERING-GEOLOGY INVESTIGATIONS AND REPORTS

Chapter 2 provides guidelines for conducting site-specific engineering-geology investigations and preparing engineering-geology reports. Chapters 3–7 provide guidelines for investigating surface-fault-rupture, landslide, debris-flow, ground-subsidence and earth-fissure, and rockfall hazards. These chapters are intended as guidance for consultants characterizing site geologic conditions; investigating geologic hazards; and reporting investigation results, conclusions, and recommendations. Local governments may adopt these guidelines by reference into geologic-hazard ordinances to establish minimum engineering-geology investigation and report requirements and minimum criteria for investigating geologic hazards in their jurisdictions.

For purposes of land development, an engineering-geology investigation should address all aspects of site geology that affect or are likely to be affected by the proposed development. A site-specific engineering-geology investigation should focus on the geologic hazards present at a site and their potential effect on the proposed project if not avoided or mitigated. In some instances, an investigation may be specific to a single hazard (e.g., a surface-fault-rupture investigation along the Wasatch fault zone), but more typically an engineering-geology investigation will address all hazards at the site. If the investigation identifies a hazard(s) that presents an unacceptable risk to development if not mitigated, the report must include a hazard-mitigation plan that defines how hazards will be addressed in project design. The plan should be in sufficient detail and with sufficient supporting data to allow local governments to evaluate the effectiveness and adequacy of proposed mitigation measures.

PROJECT REVIEW

Effective project review, including field and report review, is necessary to ensure the project conforms to applicable codes and ordinances.

Field Review

As part of the project review, upon completion of fieldwork for a site-specific engineering-geology investigation, a technical field review by the regulatory-authority geologist is critical to ensure that the investigation adequately identified and characterized all geologic hazards at the site. The field review should take place before any test pits or trenches excavated for the investigation, and that may expose evidence of geologic hazards, are closed. Although not required, the UGS appreciates being afforded the opportunity to participate in geologic-hazard field reviews and particularly surface-fault-rupture investigation trenches. Contact the UGS Geologic Hazards Program in Salt Lake City at (801) 537-3300, or the UGS Southern Regional Office in Cedar City at (435) 865-9036.

Report Review

Before final design and permit approval, a qualified, Utah-licensed Professional Geologist, specializing in engineering geology (i.e., regulatory-authority geologist), should review engineering-geology reports and other geologic materials (maps, cross sections, etc.) submitted in support of the development permitting process. The same minimum qualifications recommended for an investigator (see the Investigator Qualifications section in chapter 2) apply to the regulatory-authority engineering geologist. If a geotechnical report or other engineering analysis and/or recommendations are included with the engineering-geology report, a qualified, Utah-licensed Professional Engineer, specializing in geological and/or geotechnical engineering, must review the report or pertinent sections and, as necessary, participate in field reviews. If the report is deemed adequate, the permitting process may proceed and report recommendations may be implemented (see Enforcement section below). If the report is deemed inadequate, further work can be required or the development can be denied.

Appendix A presents checklists for reviewing an engineering-geology report and for reviewing surface-fault-rupture-, landslide-, debris-flow-, ground-subsidence and earth-fissure-, and rockfall-hazard investigations. These checklists, which follow the recommendations in chapter 2 and chapters 3–7, give a concise view of engineering-geology report requirements and geologic-hazard-investigation criteria, respectively, and can provide report authors with valuable feedback information to revise their reports following a thorough review by the regulatory-authority geologist and engineer as necessary. Digital files of these checklists are provided as Microsoft Word 2007+ (docx) form document files. The reviewer should complete the Report and Review section, select the appropriate section information check box (either adequately documented or additional information needed) and enter comments for each section in the Review Comments field, which will automatically expand as text is entered, and enter any other comments and notes in the last section, along with affixing a Utah Professional Geologist stamp.

Local governments or other agencies that do not have a qualified engineering geologist on staff, should retain a licensed Professional Geologist with the recommended qualifications to perform field and report reviews as needed. This individual should not be employed by, subcontracted to, or have any significant contact with the consultants or firms that performed the investigations and reports under review to eliminate any real or perceived conflict of interest.

Report Archiving

The UGS requests reviewing local governments to submit copies (an original preferred) of final engineering-geology reports for scanning, digital cleanup, and entry into the UGS GeoData Archive System (https://geodata.geology.utah.gov) so these reports will be available for the preparation of future UGS geologic hazard maps and for reference by the local government and other users. If original PDF files are available (not scanner derived), a paper copy is not needed; however, the UGS would prefer to scan paper copies to retain high quality control and for conformance with archive project specifications. Paper copies will be returned to the local government once digital archiving of the report is complete, along with text-searchable PDF files for each report, if requested. Please submit reports for archiving to:

Utah Geological Survey
Geologic Hazards Program-GeoData
1594 W. North Temple, P.O. Box 146100
Salt Lake City, Utah 84114

with a return address and contact information.

ENFORCEMENT

Identification and characterization of geologic hazards and incorporation of subsequent mitigation recommendations into project planning and design are critical steps for protecting the health, safety, and welfare of Utah's citizens. However, these efforts are ineffective if hazard-mitigation procedures required for project approval are not followed during construction. An effective geologic-hazard ordinance must contain an enforcement provision to ensure that mitigation requirements are implemented. Most Utah municipalities and counties do not have a qualified engineering geologist or geotechnical engineer on staff or retainer to regularly perform the construction observation, inspection, and compliance documentation necessary to verify that the geologic-hazard mitigation requirements have been followed. In those instances, the UGS recommends that a qualified representative (engineering geologist and/or geotechnical engineer as appropriate) from the consulting firm that made the hazard-mitigation recommendations be retained by the developer to monitor project construction and document compliance with mitigation requirements. Large and/or complex projects may also require a consulting firm retained by the local permitting authority as part of a comprehensive quality assurance/quality control (QA/QC) program.

Final, as-built project drawings and other documentation, as appropriate, and a document stating that report recommendations were implemented, should be stamped and signed by the geologist/engineer making the inspections and submitted to the regulatory authority to verify that the required hazard-mitigation provisions were satisfactorily implemented. This provision may be added as part of the final building inspection and approval process.

DISCLOSURE

The UGS recommends disclosure during real-estate transactions whenever an engineering-geology investigation has been performed for a property to ensure that prospective property owners are made aware of geologic hazards present on the property, and can make their own informed decision regarding risk. Disclosure should include a Disclosure and

Acknowledgment Form provided by the jurisdiction, which indicates an engineering-geology report was prepared and is available for public inspection.

Additionally, prior to approval of any development, subdivision, or parcel, the UGS recommends that the regulating jurisdiction require the owner to record a restrictive covenant with the land identifying any geologic hazard(s) present. Where geologic hazards are identified on a property, the UGS recommends that the jurisdiction require the owner to delineate the hazards on the development plat prior to receiving final plat approval.

CHAPTER 9
ENGINEERING-GEOLOGY INVESTIGATION AND REPORT GUIDELINES FOR NEW UTAH PUBLIC SCHOOL BUILDINGS (UTAH STATE OFFICE OF EDUCATION)

by

Steve D. Bowman, Ph.D., P.E., P.G., Richard E. Giraud, P.G., and William R. Lund, P.G.

Public school building in North Ogden, Utah, with Ben Lomond Peak in background.

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CHAPTER 9: ENGINEERING-GEOLOGY INVESTIGATION AND REPORT GUIDELINES FOR NEW UTAH PUBLIC SCHOOL BUILDINGS (UTAH STATE OFFICE OF EDUCATION)

by Steve D. Bowman, Ph.D., P.E., P.G., Richard E. Giraud, P.G., and William R. Lund, P.G.

INTRODUCTION

To ensure that proposed schools are protected from geologic hazards, the Utah State Office of Education (USOE) recommends that an engineering-geology investigation be performed to investigate possible geologic hazards at new school sites and that subsequent reports prepared by Utah-licensed Professional Geologists be reviewed by the Utah Geological Survey (UGS) (http://www.schools.utah.gov/finance/Facilities.aspx). The purpose of the UGS review is to ensure that site-specific geologic-hazard investigations are sufficiently thorough, report conclusions are valid, proposed mitigation measures are reasonable, geologic hazards are addressed uniformly and effectively throughout the state, and school-site development consultants receive useful feedback related to geologic hazards. These guidelines are intended to be used in conjunction with the geologic-hazard guidelines presented in this publication (chapters 3–7).

SCHOOL SITE GEOLOGIC HAZARDS AND INVESTIGATION

Geologic hazards represent a safety issue for Utah schools. These guidelines and subsequent UGS review of engineering-geology reports are non-regulatory, but the guidelines cite relevant sections of the 2015 International Building Code (International Code Council, 2014a) adopted statewide that indicate specific geologic hazards that should be addressed in a geologic-hazard assessment of a proposed site. The need for detailed investigations can generally be assessed by consulting regional geologic-hazard maps (http://geology.utah.gov/map-pub/maps/geologic-hazard-maps/) available for various parts of the state; however, these maps are not a substitute for site-specific engineering-geology/geologic-hazard investigations.

The complex and interdisciplinary nature of geologic-hazard investigations often requires that engineering geologists, engineers, and other design professionals work together to investigate the hazards, prepare geologic-hazard reports, and integrate report recommendations into project design. Involvement of both engineering geologists and engineers, including geotechnical, civil, and structural, will generally provide greater assurance that geologic hazards are properly identified, assessed, and mitigated. Preparation of geologic-hazard reports must be performed by a Utah-licensed Professional Geologist, and should follow the engineering-geology report (chapter 2) and individual geologic-hazard guidelines contained in this publication (chapters 3–7).

The geologic-hazards section of the UGS website includes information for consultants and design professionals (http://geology.utah.gov/about-us/geologic-programs/geologic-hazards-program/for-consultants-and-design-professionals/) that contains these recommended guidelines (this publication); published UGS geologic-hazard maps, reports, site-specific studies, geologic maps, and hydrogeology publications; aerial photography; important external publications (including many of the papers cited in this volume); and links to relevant external websites. Although the UGS website contains many resources useful for engineering-geology investigations, it is not a complete source for all geologic-hazard information. As a result, a thorough literature search and review should always be performed for school-site investigations.

UGS SCHOOL SITE GEOLOGIC-HAZARD REPORT REVIEW

UGS review of engineering-geology school-site reports (http://geology.utah.gov/ghp/school-site_review/index.htm) encompasses 20 items associated with the project and geologic hazards as indicated on the Engineering-Geology Report Review Checklist in appendix A. UGS staff will review the submitted report for pertinent information related to each item, determine if the report adequately addresses each item, and provide brief comments on the items, as needed.

The UGS reviews engineering-geology reports from a geologic perspective; however, if hazard-investigation or risk-reduction measures include engineering analyses, design, specifications, and/or recommendations, a Utah-licensed Professional Engineer specializing in geotechnical engineering must also review the report.

To request an engineering-geology report review for a school site, contact the UGS School-Site Review Coordinator (see Contacts section below) for your particular site location.

CONTACTS

Utah Geological Survey (UGS), Geologic Hazards Program (GHP)

http://geology.utah.gov/ghp/index.htm

Program Manager – Steve Bowman [(801) 537-3304], stevebowman@utah.gov

Northern/Central Utah (Box Elder, Cache, Carbon, Daggett, Davis, Duchesne, Emery, Grand, Juab, Millard, Morgan, Rich, Salt Lake, Sanpete, Sevier, Summit, Tooele, Uintah, Utah, Wasatch, and Weber Counties)

Utah Department of Natural Resources Building
1594 West North Temple, P.O. Box 146100
Salt Lake City, Utah 84114-6100
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School-Site Review Coordinator – Richard Giraud [(801) 537-3351], richardgiraud@utah.gov

Southern Utah (Beaver, Garfield, Iron, Kane, Piute, San Juan, Washington, and Wayne Counties)

Southern Utah Regional Office
646 North Main Street
Cedar City, Utah 84721
(435) 865-9036, FAX (435) 865-2789

School-Site Review Coordinator – Tyler Knudsen [(435) 865-9036], tylerknudsen@utah.gov

REFERENCES

American Association of State Highway and Transportation Officials, 2014, AASHTO LRFD bridge design specifications, part II, sections 7-index, seventh edition, variously paginated.

American National Standards Institute/American Nuclear Society, 2008, Criteria for investigations of nuclear facility sites for seismic hazard assessments: American National Standards Institute/American Nuclear Society ANSI/ANS-2.27-2008, variously paginated.

Anderson, L.R., Keaton, J.R., Saarinen, T.F., and Wells, W.G., II, 1984, The Utah landslides, debris flows, and floods of May and June 1983: Washington, D.C., National Academy Press, 96 p.

Andrew, R.D., Arndt, A., and Turner, A.K., 2012, Chapter 7—instrumentation and monitoring technology, *in* Turner, A.K., and Schuster, R.L., editors, Rockfall characterization and control: Washington, D.C., Transportation Research Board of the National Academies, p. 212–284.

Andrews, D.J., and Bucknam, R.C., 1987, Fitting degradation of shoreline scarps by a model with nonlinear diffusion: Journal of Geophysical Research, v. 92, p. 12,857–12,867.

Arizona Department of Water Resources, 2010, Interferometric Synthetic Aperture Radar (InSAR): Hydrology Division, Geophysics/Surveying Unit: Online, http://www.azwater.gov/AzDWR/Hydrology/Geophysics/InSAR.htm, accessed October 23, 2010.

Arizona Department of Water Resources, no date, Monitoring the state's water resources—InSAR—ADWR's satellite based land subsidence monitoring program: Arizona Department of Water Resources Fact Sheet, 2 p.

Arizona Division of Emergency Management, 2007, Hazards and prevention—earth fissures: Arizona Division of Emergency Management, 1 p.

Arizona Land Subsidence Group, 2007, Land subsidence and earth fissures in Arizona—research and information needs for effective risk management: Arizona Geological Survey Contributed Report CR-07-C, 24 p.

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

Ashland, F.X., 2008, Reconnaissance of the Little Valley landslide, Draper, Utah—evidence for possible late Holocene, earthquake-induced reactivation of a large, preexisting landslide: Utah Geological Survey Open-File Report 520, 17 p.

Association of Engineering Geologists, Utah Section, 1986, Guidelines for preparing geologic reports in Utah: Utah Geological and Mineral Survey Miscellaneous Publication M, 2 p.

Association of Engineering Geologists, Utah Section, 1987, Guidelines for evaluating surface fault rupture hazards in Utah: Utah Geological and Mineral Survey Miscellaneous Publication N, 2 p.

ASTM International, 2002, Standard practice for description and identification of soils (visual-manual procedure): ASTM International Standard D2488-00 (v. 04.08).

ASTM International, 2003, Standard guide to site characterization for engineering design and construction purposes: ASTM International Standard D420-98 (v. 04.08).

ASTM International, 2009, Standard practice for radon control options for the design and construction of new low-rise residential buildings: ASTM International Standard E1465-08a.

ASTM International, 2011, Standard test method for standard penetration test (SPT) and split-barrel sampling of soils: ASTM International Standard D1586-11.

ASTM International, 2012a, Standard practice for minimum requirements for agencies engaged in the testing and/or inspection of soil and rock as used in engineering design and construction: ASTM International Standard D3740-01 (v. 04.08).

ASTM International, 2012b, Standard test method for electronic friction cone and piezocone penetration testing of soils: ASTM International Standard D5778-12.

Avery, T.E., and Berlin, G.L., 1992, Fundamentals of remote sensing and airphoto interpretation: New York, Macmillan Publishing Company, 472 p.

Bailey, R.W., Craddock, G.W., and Croft, A.R., 1947, Watershed management for summer flood control in Utah: U.S. Department of Agriculture, Forest Service, Miscellaneous Publication no. 639, 24 p.

Baldwin, J.E., II, Donley, H.J., and Howard T.R., 1987, On debris flow/avalanche mitigation and control, San Francisco Bay area, California, *in* Costa, J.E., and Wieczorek, G.F., editors, Debris flows/avalanches: Geological Society of America Reviews in Engineering Geology, Volume VII, p. 223–236.

Barrell, D.J.A., 2010, Assessment of active fault and fold hazards in the Twizel area, Mackenzie District, South Canterbury: Institute of Geological and Nuclear Sciences Limited Science Consultancy Report 2010/040, 22 p.

Batatian, L.D., and Nelson, C.V, 1999, Fault setback requirements to reduce fault rupture hazards in Salt Lake County [abs.]: Association of Engineering Geologists Abstracts with Programs, 42nd Annual Meeting, p. 59.

Baum, R.L., Galloway, D.L., and Harp, E.L., 2008, Landslide and land subsidence hazards to pipelines: U.S. Geological Survey Open-File Report 2008-1164, 192 p.

Bell, J.W., 2003, Las Vegas Valley—land subsidence and fissuring due to ground-water withdrawal: U.S. Geological Survey, 5 p.: Online, http://geochange.er.usgs.gov/sw/impacts/hydrology/vegas_gw, accessed March 29, 2010.

Bell, J.W., 2004, Fissure evolution—what we know after 30 years of observation, *in* Shlemon Specialty Conference—Earth Fissures, El Paso, Texas, April 1–3, 2004, Conference Materials: The Association of Engineering Geologists and Engineering Geology Foundation, unpaginated, CD.

Bell, J.W., and Amelung, F., 2003, The relation between land subsidence, active Quaternary faults, and earth fissures in Las Vegas, Nevada [abs.]: Geological Society of America Cordilleran Section 99th Annual Meeting: Online, https://gsa.confex.com/gsa/2003CD/finalprogram/abstract_52146.htm.

Bell, J.W., Amelung, F., Ramelli, A.R., and Blewitt, G., 2002, Land subsidence in Las Vegas, Nevada, 1935–2000—new geodetic data show evolution, revised spatial patterns, and reduced rates: Environmental and Engineering Geoscience, v. VIII, no. 3, p. 155–174.

Bell, J.W., Caskey, S.J., Ramelli, A.R., and Guerrieri, L., 2004, Pattern and timing of faulting in the central Nevada seismic belt and paleoseismic evidence for prior beltlike behavior: Bulletin of the Seismological Society of America, v. 94, no. 4, p. 1229–1254.

Bell, J.W., and Katzer, T., 1990, Timing of late Quaternary faulting in the 1954 Dixie Valley earthquake area, central Nevada: Geology, v. 18, p. 622–625.

Bell, J.W., and Price, J.G., 1991, Subsidence in Las Vegas Valley: Nevada Bureau of Mines and Geology Open-File Report 93-5, 182 p.

Benson, L.V., Lund, S.P., Smoot, J.P., Rhode, D.E., Spencer, R.J., Verosub, K.L., Louderback, L.A., Johnson, C.A., Rye, R.O., and Negrini, R.M., 2011, The rise and fall of Lake Bonneville between 45 and 10.5 ka: Quaternary International, v. 235, p. 57–69.

Beta Analytic Radiocarbon Dating, 2014, Radiocarbon dating charcoal: Online, http://www.radiocarbon.com/carbon-dating-charcoal.htm.

Beukelman, G.S., 2012, Springhill Landslide, North Salt Lake: Utah Geological Survey: Online, http://geology.utah.gov/hazards/landslides-rockfalls/springhill-landslide-north-salt-lake/update-on-springhill-landslide/, accessed April 2014.

Beverage, J.P., and Culbertson, J.K., 1964, Hyperconcentrations of suspended sediment: American Society of Civil Engineers, Journal of the Hydraulics Division, v. 90, no. HY6, p. 117−126.

Birkeland, P.W., Machette, M.N., and Haller, K.M., 1991, Soils as a tool for applied Quaternary geology: Utah Geological and Mineral Survey Miscellaneous Publication 91-3, 63 p.

Black, B.D., Lund, W.R., Schwartz, D.P., Gill, H.E., and Mayes, B.H., 1996, Paleoseismic investigation on the Salt Lake City segment of the Wasatch fault zone at the South Fork Dry Creek and Dry Gulch sites, Salt Lake County, Utah—Paleoseismology of Utah, Volume 7: Utah Geological Survey Special Study 92, 22 p.

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

Blair, T.C., and McPherson, J.G., 1994, Alluvial fan processes and forms, *in* Abrahams, A.D., and Parsons A.J., editors, Geomorphology of desert environments: London, Chapman and Hall, p. 355−402.

Blake, T.F., Hollingsworth, R.A., and Stewart, J.P., editors, 2002, Recommended procedures for implementation of DMG Special Publication 117, Guidelines for analyzing and mitigating landslide hazards in California: Los Angeles, Southern California Earthquake Center, 110 p., 1 appendix: Online, http://scecinfo.usc.edu/resources/catalog/LandslideProceduresJune02.pdf.

Bonilla, M.G., 1970, Surface faulting and related effects, *in* Wiegel, R.I., editor, Earthquake engineering: Englewood, N.J., Prentice-Hall, Inc., p. 47–74.

Bonilla, M.G., and Lienkaemper, J.J., 1991, Factors affecting the recognition of faults exposed in exploratory trenches: U.S. Geological Survey Bulletin 1947, 54 p.

Bovis, M.J., and Jakob, M., 1999, The role of debris supply conditions in predicting debris flow activity: Earth Surface Processes and Landforms, v. 24, p. 1039−1054.

Bowman, S.D., 2008, Aerial photo comparisons between 1938 and 2006 photos—four locations between Salt Lake City and Alpine, Utah: Utah Geological Survey: Online, http://geology.utah.gov/map-pub/publications/aerial-photographs/aerial-photo-comparisons/, accessed December 31, 2011, 1 p.

Bowman, S.D., 2012, Utah Geological Survey Geologic Data Preservation Project and new geologic data resources, *in* Hylland, M.D., and Harty, K.M., editors, Selected topics in engineering and environmental geology in Utah: Utah Geological Association Publication 41, p. 195–207.

Bowman, S.D., 2015, Emergency response and the Utah Geological Survey—what role do we serve and what services are provided?: Utah Geological Survey, Survey Notes, v. 47, no. 1, p. 1–3.

Bowman, S.D., Castleton, J.J., and Elliott, A.H., 2009, New geologic hazards mapping in Utah: Utah Geological Survey, Survey Notes, v. 41, no. 3, p. 1–3.

Bowman, S., Hiscock, A., Hylland, M., McDonald, G., and McKean, A., 2015a, LiDAR—valuable tool in the field geologist's toolbox: Utah Geological Survey, Survey Notes, v. 47, no. 1, p. 4–6.

Bowman, S.D., Hiscock, A.I., and Unger, C.D., 2015b, Compilation of 1970s Woodward-Lundgren & Associates Wasatch fault investigation reports and low-sun-angle aerial photography, Wasatch Front and Cache Valley, Utah and Idaho—Paleoseismology of Utah, Volume 26: Utah Geological Survey Open-File Report 632, variously paginated, 6 plates, 9 DVD set.

Bowman, S.D., and Lund, W.R., 2013, Compilation of U.S. Geological Survey National Earthquake Hazards Reduction program final technical reports for Utah—Paleoseismology of Utah, Volume 23: Utah Geological Survey Miscellaneous Publication 13-3, variously paginated.

Bowman, S.D., Young, B.W., and Unger, C.D., 2011, Compilation of 1982-83 seismic safety investigation reports of eight SCS dams in southwestern Utah (Hurricane and Washington fault zones) and low-sun-angle aerial photography, Washington and Iron Counties, Utah, and Mohave County, Arizona—Paleoseismology of Utah, Volume 21: Utah Geological Survey Open-File Report 583, variously paginated, 2 plates, six DVD set.

Boyer, D., 2002, Recommended procedure for conducting studies in support of land development proposals on alluvial and debris torrent fans, *in* Jordan, P., and Orban, J., editors, Terrain stability and forest management in the interior of British Columbia, workshop proceedings, May 23–25, 2001, Nelson, British Columbia, Canada: Online, https://www.for.gov.bc.ca/hfd/pubs/Docs/Tr/Tr003/Boyer2.pdf, accessed April 15, 2015.

Brabb, E.E., Colgan, J.P., and Best, T.C., 2000, Map showing inventory and regional susceptibility for Holocene debris flows and related fast-moving landslides in the conterminous United States: U.S. Geological Survey Miscellaneous Field Studies Map MF-2329, 42 p. pamphlet, scale 1:2,500,000.

Brabb, E.E., Wieczorek, G.F., and Harp, E.L., 1989, Map showing 1983 landslides in Utah: U.S. Geological Survey Miscellaneous Field Studies Map MF-2085, scale 1:500,000.

Bray, J.D., 2001, Developing mitigation measures for the hazards associated with earthquake surface fault rupture, *in* Konagai, K., A workshop on seismic-fault induced failures—possible remedies for damage to urban facilities: Japan Society for the Promotion of Science, University of Tokyo, Japan, p. 55–79.

Bray, J.D., 2009a, Earthquake surface fault rupture design considerations, *in* Proceedings, Sixth International Conference on Urban Earthquake Engineering: Center for Urban Earthquake Engineering, Tokyo Institute of Technology, Tokyo, Japan, p. 37–45.

Bray, J.D., 2009b, Designing buildings to accommodate earthquake surface rupture, *in* Goodno, B., editor, Applied Technology Council and Structural Engineers Institute 2009 Conference on Improving the Seismic Performance of Existing Buildings and Other Structures: American Society of Civil Engineers, December 9–11, 2009, San Francisco, California, p, 1270–1280.

Bray, J.D., 2015, Engineering mitigation of surface-fault rupture, *in* Lund, W.R., editor, Proceedings Volume—Basin and Range Province Seismic Hazards Summit III: Utah Geological Survey Miscellaneous Publication 15-5, variously paginated, CD.

Bronk Ramsey, C., 1995, Radiocarbon calibration and analysis of stratigraphy—the OxCal program: Radiocarbon, v. 37, no. 2, p. 425–430.

Bronk Ramsey, C., 2001, Development of the radiocarbon program OxCal: Radiocarbon, v. 43, no. 2a, p. 355–363.

Bronk Ramsey, C., 2008, Depositional models for chronological records: Quaternary Science Reviews, v. 27, no. 1-2, p. 42–60.

Bronk Ramsey, C., 2009, Bayesian analysis of radiocarbon dates: Radiocarbon, v. 51, no. 4, p. 337–360.

Bronk Ramsey, C., 2010, OxCal Program, v. 4.1.7: Radiocarbon Accelerator Unit, University of Oxford: Online, https://c14.arch.ox.ac.uk/oxcal.html.

Brough, R.C., Jones, D.L., and Stevens, D.J., 1987, Utah's comprehensive weather almanac: Salt Lake City, Utah, Publishers Press, 517 p.

Bryant, W.A., 2010, History of the Alquist-Priolo Earthquake Fault Zoning Act, California, USA: Environmental and Engineering Geoscience, v. XVI, no. 1, pp. 7–18.

Bryant, W.A., and Hart, E.W., 2007, Fault-rupture hazard zones in California—Alquist-Priolo Earthquake Fault Zoning Act with index to earthquake fault zone maps: California Geological Survey Special Publication 42 [Interim Revision 2007], 42 p.: Online, ftp://ftp.consrv.ca.gov/pub/dmg/pubs/sp/Sp42.pdf.

Bucknam, R.C., and Anderson, R.E., 1979, Estimation of scarp ages from a scarp-height–slope-angle relationship: Geology, v. 7, p. 11–14.

Budhu, M., and Shelke, A., 2008, The formation of earth fissures due to groundwater decline, *in* 12th International Conference, Goa, India, 1–6 October, 2008: International Association for Computer Methods and Advances in Geomechanics, p. 3051–3059.

Bull, W.B., 1977, The alluvial fan environment: Progress in Physical Geography, v. 1, no. 2, p. 222–270.

Bull, W.B., 1991, Geomorphic responses to climatic change: New York, Oxford University Press, 326 p.

Bull, W.B., and Pearthree, P.A., 1988, Frequency and size of Quaternary surface ruptures of the Pitaycachi fault, northeastern Sonora, Mexico: Bulletin of the Seismological Society of America, v. 78, p. 956–978.

Bunds, M., Toké, N., Walther, S., Fletcher, A., and Arnoff, M., 2015, Applications of structure from motion software in earthquake geology investigations—examples from the Wasatch, Oquirrh, and San Andreas faults [poster], *in* Lund, W.R., editor, Proceedings Volume—Basin and Range Province Seismic Hazards Summit III: Utah Geological Survey Miscellaneous Publication 15-5, variously paginated, CD.

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

California Board for Geologists and Geophysicists, 1998a, Guidelines for engineering geologic reports: California Board for Geologists and Geophysicists, 8 p.

California Board for Geologists and Geophysicists, 1998b, Geologic guidelines for earthquake and/or fault hazard reports: California Board for Geologists and Geophysicists, 7 p.

California Board for Geologists and Geophysicists, 1998c, Guidelines for groundwater investigation reports California Board for Geologists and Geophysicists, 7 p.

California Board for Geologists and Geophysicists, 1998d, Guidelines for geophysical reports for environmental and engineering geology: California Board for Geologists and Geophysicists, 5 p.

California Division of Mines and Geology, 1973, Guidelines to geologic/seismic reports: California Division of Mines and Geology Note 37, 2 p.

California Division of Mines and Geology, 1975a, Recommended guidelines for preparing engineering geologic reports: California Division of Mines and Geology Note 44, 2 p.

California Division of Mines and Geology, 1975b, Checklists for the review of geologic/seismic reports: California Division of Mines and Geology Note 48, 2 p.

California Division of Mines and Geology, 1975c, Guidelines for evaluating the hazard of surface fault rupture: California Division of Mines and Geology Note 49, 4 p.

California Geological Survey, 2002, Guidelines for evaluating the hazard of surface fault rupture: California Geological Survey Note 49, 4 p.: Online, http://www.conservation.ca.gov/cgs/information/publications/cgs_notes/note_49/Documents/note_49.pdf.

California Geological Survey, 2011a, Checklist for the review of engineering geology and seismology reports for California public schools, hospitals, and essential service buildings: California Geological Survey Note 48, 2 p.

California Geological Survey, 2011b, Natural hazards disclosure—Alquist-Priolo earthquake fault zones: Online, http://www.conservation.ca.gov/cgs/rghm/ap/Pages/disclose.aspx.

California Geological Survey, 2013, The Alquist-Priolo Earthquake Zoning Act: Online, http://www.conservation.ca.gov/cgs/rghm/ap/Pages/main.aspx.

Cannon, S.H., 2001, Debris-flow generation from recently burned watersheds: Environmental and Engineering Geoscience, v. 12, no. 4, p. 321−341.

Cannon, S.H., Gartner, J.E., Rupert, M.G., Michael, J.A., Rea, A.H., and Parrett, C., 2010, Predicting the probability and volume of postwildfire debris flows in the intermountain western United States: Geological Society of America Bulletin, v. 122, p. 127−144.

Cannon, S.H., Gartner, J.E., Wilson, R.C., Bowers, J.C., and Laber, J.L., 2008, Storm rainfall conditions for floods and debris flows from recently burned areas in southwestern Colorado and southern California: Geomorphology, v. 96, no. 3-4, p. 250−269.

Cannon, S.H., Powers, P.S., Pihl, R.A., and Rogers, W.P., 1995, Preliminary evaluation of the fire-related debris flows on Storm King Mountain, Glenwood Springs, Colorado: U.S. Geological Survey Open-File Report 95-508, 38 p.

Cannon, S.H., and Reneau, S.L., 2000, Conditions for generation of fire-related debris flows, Capulin Canyon, New Mexico: Earth Surface Processes and Landforms, v. 25, no. 10, p. 1103−1121.

Carpenter, M.C., 1999, South-central Arizona—earth fissures and subsidence complicate development of desert water resources, *in* Galloway, D., Jones, D.R., and Ingebritsen, S.E., editors, Land subsidence in the United States: U.S. Geological Survey Circular 1182, variously paginated.

Carter, W., Shrestha, R., Tuell, G., Bloomquist, D., and Sartori, M., 2001, Airborne laser swath mapping shines new light on Earth's topography: EOS Transactions, v. 82, no. 46, p. 549–555.

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

Caskey, S.J., Bell, J.W., Wesnousky, S.G., and Ramelli, A.R., 2004, Historical surface faulting and paleoseismology in the area of the 1954 Rainbow Mountain–Stillwater sequence, central Nevada: Bulletin of the Seismological Society of America, v. 94, no. 4, p. 1255–1275.

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

Castleton, J.J., Elliott, A.H., and McDonald, G.N., 2011, Geologic hazards of the Magna quadrangle, Salt Lake County, Utah: Utah Geological Survey Special Study 137, 73 p., 10 plates, scale 1:24,000.

Castleton, J.J., Elliott, A.H., and McDonald, G.N., 2014, Geologic hazards of the Copperton quadrangle, Salt Lake County, Utah: Utah Geological Survey Special Study 152, 24 p., 10 plates, scale 1:24,000.

Castleton, J.J., and McKean, A.P., 2012, The Utah Geological Survey Geologic Hazards Mapping Initiative, *in* Hylland, M.D., and Harty, K.M., editors, Selected topics in engineering and environmental geology in Utah: Utah Geological Association Publication 41, p. 51–67.

Chang, W.L., and Smith, R.B., 2002, Integrated seismic-hazard analysis of the Wasatch Front, Utah: Bulletin of the Seismological Society of America, v. 92, no. 5, p. 1904–1922.

Chase, G.W., and Chapman, R.H., 1976, Black-box geology—uses and misuses of geophysics in engineering geology: California Geology, v. 29, p. 8–12.

Chen, Y., Lai, K., Lee, Y., Suppe, J., Chen, W., Lin, Y.N., Wang, Y., Hung, J., and Kuo, Y., 2007, Coseismic fold scarps and their kinematic behavior in the 1999 Chi-Chi earthquake Taiwan: Journal of Geophysical Research, v. 112, B03S02, 15 p., doi:10.1029/2006JB004388.

Christenson, G.E., 1986, Debris-flow mapping and hazards assessment in Utah, *in* Kusler, J., and Brooks, G., editors, Improving the effectiveness of floodplain management in arid and semi-arid regions, March 24–26, 1986, Proceedings: Association of State Floodplain Managers, Inc., p. 74−77.

Christenson, G.E., 1987, Suggested approach to geologic hazards ordinances in Utah: Utah Geological and Mineral Survey Circular 79, 16 p.

Christenson, G.E., 1993, The Wasatch Front County Hazards Geologist Program, *in* Gori, P.L., editor, Applications of research from the U.S. Geological Survey program, Assessment of Regional Earthquake Hazards and Risk along the Wasatch Front, Utah: U.S. Geological Survey Professional Paper 1519, p. 114–120.

Christenson, G.E., and Ashland, F.X., 2006, Assessing he stability of landslides—overview of lessons learned from historical landslides in Utah, Proceedings for the 40th Symposium on Engineering Geology and Geotechnical Engineering 2006, Logan, Utah State University, 17 p.

Christenson, G.E., and Ashland, F.X., 2008, A plan to reduce losses from geologic hazards in Utah—recommendations of the Governor's Geologic Hazards Working Group 2006–2007: Utah Geological Survey Circular 104, 30 p.

Christenson, G.E., Batatian, L.D., and Nelson, C.V., 2003, Guidelines for evaluating surface-fault-rupture hazards in Utah: Utah Geological Survey Miscellaneous Publication 03-6, 14 p.

Christenson, G.E., and Bryant, B.A., 1998, Surface-faulting hazards and land-use planning in Utah, *in* Lund, W.R., editor, Western States Seismic Policy Council proceedings volume, Basin and Range Province Seismic-Hazards Summit: Utah Geological Survey Miscellaneous Publication 98-2, p. 63–73.

Christenson, G.E., and Purcell, C., 1985, Correlation and age of Quaternary alluvial-fan sequences, Basin and Range Province, southwestern United States, *in* Weide, D.L., editor, Soils and Quaternary geology of the southwestern United States: Geological Society of America Special Paper 203, p. 115−122.

Christenson, G.E., and Shaw, L.M., 2008, Geographic information system database showing geologic-hazard special study areas, Wasatch Front, Utah: Utah Geological Survey Circular 106, 7 p., GIS data, scale 1:24,000, CD.

City of Draper, 2005, Review protocol for an administrative interpretation of Sections 9-10-070 and 9-19-080 of the Draper Municipal Code regarding the issuance of building permits for structures astride active faults in subdivisions approved prior to the adoption of the Draper City hazard ordinance: Online, http://www.draper.ut.us/DocumentCenter/View/989, 3 p.

City of Draper, 2010, Title 9 Land use and development code for Draper City—Chapter 9-19 Geologic hazards ordinance: Online, http://www.draper.ut.us/documentcenter/view/379, 66 p.

City of North Salt Lake, 2011, Springhill landslide mitigation project—overall benefit-cost ratio determination, October 2011: Unpublished grant application to the Federal Emergency Management Agency, 3 p.

Cluff, L.S., Brogan, G.E., and Glass, C.E., 1970, Wasatch fault, northern portion, earthquake fault investigation and evaluation, a guide to land use planning: Oakland, California, Woodward-Clyde and Associates, unpublished consultant's report for the Utah Geological and Mineralogical Survey, variously paginated, compiled *in* Bowman, S.D., Hiscock, A.I., and Unger, C.D., 2015, Compilation of 1970s Woodward-Lundgren & Associates Wasatch fault investigation reports and low-sun-angle aerial photography, Wasatch Front and Cache Valley, Utah and Idaho—Paleoseismology of Utah, Volume 26: Utah Geological Survey Open-File Report 632, variously paginated, 6 plates, 9 DVD set.

Cluff, L.S., Brogan, G.E., and Glass, C.E.,1973, Wasatch fault, southern portion, earthquake fault investigation and evaluation, a guide to land use planning: Oakland, California, Woodward-Lundgren and Associates, unpublished consultant's report for the Utah Geological and Mineralogical Survey, variously paginated, compiled *in* Bowman, S.D., Hiscock, A.I., and Unger, C.D., 2015, Compilation of 1970s Woodward-Lundgren & Associates Wasatch fault investigation reports and low-sun-angle aerial photography, Wasatch Front and Cache Valley, Utah and Idaho—Paleoseismology of Utah, Volume 26: Utah Geological Survey Open-File Report 632, variously paginated, 6 plates, 9 DVD set.

Cluff, L.S., Glass, C.E., and Brogan, G.E., 1974, Investigation and evaluation of the Wasatch fault north of Brigham City and Cache Valley faults, Utah and Idaho, a guide to land-use planning with recommendations for seismic safety: Oakland, California, Woodward-Lundgren and Associates, unpublished Final Technical Report for the U.S. Geological Survey National Earthquake Hazards Reduction Program, contract no. 14-08-001-13665, variously paginated, compiled *in* Bowman, S.D., Hiscock, A.I., and Unger, C.D., 2015, Compilation of 1970s Woodward-Lundgren & Associates Wasatch fault investigation reports and low-sun-angle aerial photography, Wasatch

Front and Cache Valley, Utah and Idaho—Paleoseismology of Utah, Volume 26: Utah Geological Survey Open-File Report 632, variously paginated, 6 plates, 9 DVD set.

Cohen, K.M., and Gibbard, P.L., 2010, Global chronostratigraphical correlation table for the last 2.7 million years, v. 2010: Subcomission on Quaternary Stratigraphy of the International Union of Geological Sciences, 2010 documentation, online, http://quaternary.stratigraphy.org/charts/.

Colman, S.M., Kelts, K., and Dinter, D., 2002, Depositional history and neotectonics in Great Salt Lake, Utah, from high-resolution seismic stratigraphy: Sedimentary Geology, v. 148. p. 61–78.

Colman, S.M., and Pierce, K.L., 2000, Classification of Quaternary geochronologic methods, *in* Noller, S.M., Sowers, J.M., and Lettis, W.R., editors, Quaternary geochronology—methods and applications: Washington, D.C., American Geophysical Union Reference Shelf 4, p. 2–5.

Committee on Ground Failure Hazards, 1985, Reducing losses from landslides in the U.S: Washington, D.C., Commission on Engineering and Technological Systems, National Research Council, 41 p.

Conway, B.D., 2013, Land subsidence monitoring report, Number 1: Arizona Department of Water Resources, 30 p.: Online, http://www.azwater.gov/AzDWR/Hydrology/Geophysics/documents/ADWRLandSubsidenceMonitoringReport_Number1_Final.pdf, accessed September 10, 2013.

Cook, K.L., Gray, E.F., Iverson, R.M., and Strohmeier, M.T., 1980, Bottom gravity meter regional survey of the Great Salt Lake, Utah, *in* Gwynn, J.W., editor, Great Salt Lake—a scientific, historical, and economic overview: Utah Geological and Mineral Survey Bulletin 116, p. 125–143.

Coppersmith, K.J., and Youngs, R.R., 2000, Data needs for probabilistic fault displacement hazard analysis: Journal of Geodynamics, v. 29, p. 329–343.

Cornforth, D.H., 2005, Landslides in practice—investigation, analysis, and remedial/preventative options in soils: Hoboken, New Jersey, John Wiley & Sons, Inc., 395 p.

Costa, J.E., 1984, Physical geomorphology of debris flows, *in* Costa, J.E., and Fleisher, P.J., editors, Developments and applications of geomorphology: New York, Springer-Verlag, p. 268−317.

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

Costa, J.E., and Jarrett, R.D., 1981, Debris flows in small mountain stream channels of Colorado and their hydrologic implications: Bulletin of the Association of Engineering Geologists, v. 18, no. 3, p. 309−322.

Croft, A.R., 1962, Some sedimentation phenomena along the Wasatch Mountain Front: Journal of Geophysical Research, v. 67, no. 4, p. 1511−1524.

Croft, A.R., 1967, Rainstorm debris floods, a problem in public welfare: University of Arizona, Agricultural Experiment Station Report 248, 35 p.

Crone, A.J., Machette, M.N., Bonilla, M.B., Lienkaemper, J.J., Pierce, K.L., Scott, W.E., and Bucknam, R.C., 1987, Surface faulting accompanying the Borah Peak earthquake and segmentation of the Lost River fault, central Idaho: Bulletin of the Seismological Society of America, v. 77, no. 3, p. 739–770.

Crone, A.J., Personius, S.P., DuRoss, C.B., Machette, M.N., and Mahan, S.A., 2014, History of late Holocene earthquakes at the Willow Creek site on the Nephi segment, Wasatch fault zone, Utah—Paleoseismology of Utah, Volume 25: Utah Geological Survey Special Study 151, 55 p., CD.

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

Currey, D.R., 1982, Lake Bonneville—selected features of relevance to neotectonic analysis: U.S. Geological Survey Open-File Report 82-1070, 30 p., 1 plate, scale 1:500,000.

Currey, D.R., 1990, Quaternary paleolakes in the evolution of semidesert basins, with special emphasis on Lake Bonneville and the Great Basin, U.S.A.: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 76, p. 189–214.

Currey, D.R., Berry, M.S., Green, S.A., and Murchison, S.B., 1988, Very late Pleistocene red beds in the Bonneville basin, Utah and Nevada [abs.]: Geological Society of America Abstracts with Programs, v. 20, no. 6, p. 411.

Curtis, G.H., 1981, A guide to dating methods for the determination of the last time of movement of faults: U.S. Nuclear Regulatory Commission NUREG/CR-2382, 314 p.

Deng, Z., 1997, Impact of debris flows on structures and its mitigation: Salt Lake City, University of Utah, Ph.D. thesis, 242 p.

Deng, Z., Lawton, E.C., May, F.E., Smith, S.W., and Williams, S.R., 1992, Estimated impact forces on houses caused by the 1983 Rudd Creek debris flow, *in* Conference on Arid West Floodplain Management Issues, Las Vegas, Nevada, December 2–4, 1992, Proceedings: Association of State Floodplain Managers Inc., p. 103−115.

dePolo, C.M., 2011, The recovery of Wells, Nevada from the 2008 earthquake disaster, *in* The 21 February 2008 M_w 6.0 Wells, Nevada earthquake: Nevada Bureau of Mines and Geology Special Publication 36, variously paginated: Online, http://data.nbmg.unr.edu/Public/freedownloads/sp/sp036/, accessed September 28, 2015.

Deseret News, 1986, Utah's worst avalanche disaster crippled Bingham Canyon in 1926: Deseret News, February 20–21, 1986, p. 4B.

Dinter, D.A., 2015, Paleoseismology of faults submerged beneath Utah Lake [poster], *in* Lund, W.R., editor, Proceedings Volume, Basin and Range Province Seismic Hazards Summit III: Utah Geological Survey Miscellaneous Publication 15-5, variously paginated, CD.

Dinter, D.A., and Pechmann, J.C., 2000, Paleoseismology of the East Great Salt Lake fault: Final Technical Report to the U.S. Geological Survey National Earthquake Hazards Reduction Program, award no. 98HQGR1013, 6 p.

Dinter, D.A., and Pechmann, J.C., 2005, Segmentation and Holocene displacement history of the Great Salt Lake fault, Utah, *in* Lund, W.R., editor, Basin and Range Province Seismic Hazards Summit II: Utah Geological Survey Miscellaneous Publication 05-2, variously paginated, CD.

Dinter, D.A., and Pechmann, J.C., 2014, Paleoseismology of the Promontory segment, East Great Salt Lake fault: Final Technical Report to the U.S. Geological Survey National Earthquake Hazards Reduction Program, award no. 02HQGR0105, 23 p.

Dinter, D.A., and Pechmann, J.C., 2015, Paleoseismology of the northern segments of the Great Salt Lake fault [poster], *in* Lund, W.R., editor, Proceedings Volume, Basin and Range Province Seismic Hazards Summit III: Utah Geological Survey Miscellaneous Publication 15-5, variously paginated, CD.

Dobbins, D., and Simon, D., 2015, One city's perspective on what local governments need from geoscientists, *in* Lund, W.R., editor, Proceedings Volume, Basin and Range Province Seismic Hazards Summit III: Utah Geological Survey Miscellaneous Publication 15-5, variously paginated, CD.

Doelling, H.H., and Willis, G.C., 1995, Guide to authors of geological maps and text booklets of the Utah Geological Survey: Utah Geological Survey Circular 89, 30 p., 11 appendices.

DuRoss, C.B., 2008, Holocene vertical displacement on the central segments of the Wasatch fault zone, Utah: Bulletin of the Seismological Society of America, v. 98, no. 6, p 2918–2933 (doi: 10.1785/0120080119).

DuRoss, C.B., 2015, Characterizing hazardous faults—techniques, data needs, and analysis [short course manual], *in* Lund, W.R., editor, Proceedings Volume, Basin and Range Province Seismic Hazards Summit III: Utah Geological Survey Miscellaneous Publication 15-5, CD.

DuRoss, C.B., and Hylland, M.D., 2015, Synchronous ruptures along a major graben-forming fault system—Wasatch and West Valley fault zones, Utah: Bulletin of the Seismological Society of America, v. 105, no. 1, p. 14–37 (doi: 10.1785/0120140064).

DuRoss, C.B., Hylland, M.D., McDonald, G.N., Crone, A.J., Personius, S.F., Gold, R.D., and Mahan, S.A., 2014, Holocene and latest Pleistocene paleoseismology of the Salt Lake City segment of the Wasatch fault zone, Utah, at the Penrose Drive trench site, *in* DuRoss, C.B., and Hylland, M.D., 2014, Evaluating surface faulting chronologies of graben-bounding faults in Salt Lake Valley, Utah—new paleoseismic data from the Salt Lake City segment of the Wasatch fault zone and the West Valley fault zone—Paleoseismology of Utah, Volume 24: Utah Geological Survey Special Study 149, 39 p., 6 appendices, CD.

DuRoss, C.B., and Kirby, S.M., 2004, Reconnaissance investigation of ground cracks along the western margin of Parowan Valley, Iron County, Utah: Utah Geological Survey Report of Investigation 253, 17 p., CD.

DuRoss, C.B., Personius, S.F., Crone, A.J., McDonald, G.N., and Lidke, D.J., 2009, Paleoseismic investigation of the northern Weber segment of the Wasatch fault zone at the Rice Creek trench site, North Ogden, Utah—Paleoseismology of Utah, Volume 18: Utah Geological Survey Special Study 130, 37 p., 2 plates, CD.

DuRoss, C.B., Personius, S.F., Crone, A.J., Olig, S.S., Hylland, M.D., Lund, W.R., and Schwartz, D.P., 2016, Fault segmentation—New concepts from the Wasatch fault zone, Utah, USA: Journal of Geophysical Research—Solid Earth, v. 121, 27 p. (doi:1002/2015JB012519).

DuRoss, C.B., Personius, S.F., Crone, A.J., Olig, S.S., and Lund, W.R., 2011, Integration of paleoseismic data from multiple sites to develop an objective earthquake chronology—application to the Weber segment of the Wasatch fault zone, Utah: Bulletin of the Seismological Society of America, v. 101, no. 6, p. 2765–2781 (doi: 10.1785/0120110102).

Earthquake Engineering Research Institute, Utah Chapter, 2015, Scenario for a magnitude 7.0 earthquake on the Wasatch fault–Salt Lake City segment—hazards and loss estimates: Earthquake Engineering Research Institute, Utah Chapter, 53 p.: Online, https://ussc.utah.gov/pages/help.php?section=EERI+Salt+Lake+City+M7+Earthquake+Scenario, accessed September 28, 2015.

Eisbacher, G.H., and Clague, J.J., 1984, Destructive mass movements in high mountains—hazard and management: Geological Survey of Canada Paper 84-16, 230 p.

Ellen, S.D., Mark, R.K., Cannon, S.H., and Knifong, D.L., 1993, Map of debris-flow hazard in the Honolulu District of Oahu, Hawaii: U.S. Geological Survey Open-File Report 93-213, 25 p., scale 1:90,000.

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

Elliott, A.H., and Kirschbaum, M.J., 2007, The preliminary landslide history database of Utah, 1850−1978: Online, http://geology.utah.gov/resources/data-databases/landslide-history/, accessed July 20, 2015.

Environmental Protection Agency, 1994, Radon prevention in the design and construction of schools and other large buildings: Environmental Protection Agency Publication 625-R-92-016, 50 p.

Erslev, E.A., 1991, Trishear fault-propagation folding: Geology, v. 19, p. 617–620.

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

Federal Emergency Management Agency, 2003, Guidelines and specifications for flood hazard mapping partners, appendix G—guidance for alluvial fan flooding analyses and mapping: Online, http://www.fema.gov/media-library-data/1387818091947-c2fd64ab6948e3d-6e3d6cfbe945a8d19/Guidelines%20and%20Specifications%20for%20Flood%20Hazard%20Mapping%20Partners%20Appendix%20G-Guidance%20for%20Alluvial%20Fan%20Flooding%20Analyses%20and%20Mapping%20(Apr%202003).pdf, accessed July 20, 2015.

Federal Highway Administration, 2003, Checklist and guidelines for review of geotechnical reports and preliminary plans and specifications: Federal Highway Administration Publication No. FHWA ED-88-053, 38 p.

Fell, R., Corominas, J., Bonnard, C., Cascini, L., Leroi, E., and Savage, W.Z., 2008a, Guidelines for landslide susceptibility, hazard, and risk zoning for land-use planning: Engineering Geology, v. 102, p. 85–98.

Fell, R., Corominas, J., Bonnard, C., Cascini, L., Leroi, E., and Savage, W.Z., 2008b, Commentary—guidelines for landslide susceptibility, hazard, and risk zoning for land-use planning: Engineering Geology, v. 102, p. 99–111.

Florsheim, J.L., Keller, E.A., and Best, D.W., 1991, Fluvial sediment transport in response to moderate storm flows following chaparral wildfire, Ventura County, southern California: Geological Society of America Bulletin, v. 103, no. 4, p. 504–511.

Forman, S.L., editor, 1989, Dating methods applicable to Quaternary geologic studies in the western United States: Utah Geological and Mineral Survey Miscellaneous Publication 89-7, 80 p.

Forman, S.L., and Miller, G.H., 1989, Radiocarbon dating of terrestrial organic material, *in* Forman, S.L., editor, Dating methods applicable to Quaternary geologic studies in the western United States: Utah Geological and Mineral Survey Miscellaneous Publication 89-7, p. 2–9.

Forster, R.R., 2006, Land subsidence in southwest Utah from 1993 to 1998 measured with interferometric synthetic aperture radar (InSAR): Utah Geological Survey Miscellaneous Publication 06-5, 35 p.

Forster, R.R., 2012, Evaluation of interferometric synthetic aperture radar (InSAR) techniques for measuring land subsidence and calculated subsidence rates for the Escalante Valley, Utah, 1998 to 2006: Utah Geological Survey Open-File Report 589, 25 p.

Galloway, D., Jones, D.R., and Ingebritsen, S.E., editors, 1999, Land subsidence in the United States: U.S. Geological Survey Circular 1182, variously paginated.

Gartner, J.E., Cannon, S.H., Santi, P.M., and deWolfe, V.G., 2008, Empirical models to predict the volumes of debris flows generated by recently burned basins in the western U.S.: Geomorphology, v. 96, no. 3-4, p. 339–354.

Gath, E., 2015, Mitigating surface faulting—developing an earthquake fault zoning act for the new millennium, *in* Lund, W.R., editor, Proceedings Volume, Basin and Range Province Seismic Hazards Summit III: Utah Geological Survey Miscellaneous Publication 15-5, variously paginated, CD.

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

Giraud, R.E., 2005, Guidelines for the geologic evaluation of debris-flow hazards on alluvial fans in Utah: Utah Geological Survey Miscellaneous Publication 05-06, 16 p.

Giraud, R.E., 2010, Investigation of the 2005 Uinta Canyon snowmelt debris flows, Duchesne County, Utah, *in* Elliott, A.H., compiler, Technical Reports for 2002-2009, Geologic Hazards Program: Utah Geological Survey Report of Investigation 269, p. 118–133.

Giraud, R.E., and Christenson, G.E., 2010, Investigation of the May 15, 2005, 1550 East Provo rock fall, Provo, Utah, *in* Ashley, A.H., compiler, Technical Reports for 2002–2009, Geologic Hazards Program: Utah Geological Survey Report of Investigation 269, p. 35–43.

Giraud, R.E., Elliott, A.H., and Castleton, J.J., 2010, Investigation of the April 11, 2009, 1550 East Provo rock fall, Provo, *in* Elliott, A.H., compiler, Technical reports for 2002–2009, Geologic Hazards Program: Utah Geological Survey Report of Investigation 269, p. 207–219.

Giraud, R.E., and Lund, W.R., 2010, Investigation of the June 3, 2005, landslide-generated Black Mountain debris flow, Iron County, Utah, *in* Elliott, A.H., compiler, Technical reports for 2002–2009, Geologic Hazards Program: Utah Geological Survey Report of Investigation 269, p. 143–163.

Giraud, R.E., and McDonald, G.N., 2007, The 2000–2004 fire-related debris flows in northern Utah, *in* Schaefer, V.R., Schuster, R.L., and Turner, A.K., editors, Conference presentations, 1st North American Landslide Conference, Vail, Colorado: Association of Environmental and Engineering Geologists Special Publication no. 23, p. 1522–1531.

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

Godsey, H.S., Currey, D.R., and Chan, M.A., 2005, New evidence for an extended occupation of the Provo shoreline and implications for regional climate change, Pleistocene Lake Bonneville, Utah, USA: Quaternary Research, v. 63, no. 2, p. 212–223.

Godsey, H.S., Oviatt, C.G., Miller, D.M., and Chan, M.A., 2011, Stratigraphy and chronology of offshore to nearshore deposits associated with the Provo shoreline, Pleistocene Lake Bonneville, Utah: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 310, no. 3–4, p. 442–450 (doi: 10.1016/j.palaeo.2011.08.005).

Gori, P.L., 1993, U.S. Geological Survey program, Assessment of Regional Earthquake Hazards and Risk along the Wasatch Front, Utah: U.S. Geological Survey Professional Paper 1519, variously paginated.

Gray, H.J., Mahan, S.A., Rittenour, T., and Nelson, M.S., 2015, Guide to luminescence dating techniques and their application for paleoseismic research, *in* Lund, W.R., editor, Proceedings Volume, Basin and Range Province Seismic Hazards Summit III: Utah Geological Survey Miscellaneous Publication 15-5, variously paginated, CD.

Hall, D.E., Long, M.T., and Remboldt, M.D., 1994, Slope stability reference guide for national forests in the United States: Washington, D.C., U.S. Forest Service Publication EM-7170-13, 3 volumes, 1091 p.

Hanks, T.C., and Andrews, D.J., 1989, Effect of far-field slope on morphological dating of scarplike landforms: Journal of Geophysical Research, v. 94, p. 565–573.

Hanson, K.L., Kelson, K.I., Angell, M.A., and Lettis, W.R., 1999, Techniques for identifying faults and determining their origins: Washington, D.C., U.S. Nuclear Regulatory Commission NUREG/CR-5503, variously paginated.

Harris, J., 2001, Relocation project has mixed results: The View Neighborhood Newspapers, Wednesday, July 11, 2001, online [no longer available].

Harris-Galveston Subsidence District, 2010, Web page: Online, http://www.hgsubsidence.org/, accessed March 31, 2010.

Hart, M.W., Shaller, P.J., and Farrand, G.T., 2012, When landslides are misinterpreted as faults—case studies from the western United States: Environmental and Engineering Geoscience, v. 18, no. 4, p. 313–325.

Harty, K.M., 1991, Landslide map of Utah: Utah Geological and Mineral Survey Map 133, 28 p. pamphlet, scale 1:500,000.

Harty, K.M., and Lowe, M., 2003, Geologic evaluation and hazard potential of liquefaction-induced landslides along the Wasatch Front: Utah Geological Survey Special Study 104, 40 p.

Harty, K.M., and McKean, A.P., 2015, Surface fault rupture hazard map of the Honeyville quadrangle, Box Elder and Cache Counties, Utah: Utah Geological Survey Open-File Report 638, 1 plate, scale 1:24,000, CD.

Harty, K.M., Mulvey, W.E., and Machette, M.N., 1997, Surficial geologic map of the Nephi segment of the Wasatch fault zone, eastern Juab County, Utah: Utah Geological Survey Map 170, scale 1:50,000.

Harvey, A.M., 1989, The occurrence and role of arid zone alluvial fans, *in* Thomas, D.S.G., editor, Arid zone geomorphology: New York, Halsted Press, p. 13−58.

Hatheway, A.W., and Leighton, F.B., 1979, Trenching as an exploratory tool, *in* Hatheway, A.W., and McClure, C.R., Jr., editors, Geology in the siting of nuclear power plants: Geological Society of America Reviews in Engineering Geology, Volume IV, p. 169–195.

Hecker, S., Abrahamson, N.A., and Woodell, K.E., 2013, Variability of displacement at a point—implications for earthquake-size distribution and rupture hazards on faults: Bulletin of the Seismological Society of America, v. 103, no. 2A, p. 651–674 (doi: 10.1785/0120120159).

Hereford, R., Thompson, K.S., Burke, K.J., and Fairley, H.C., 1996, Tributary debris fans and the late Holocene alluvial chronology of the Colorado River, eastern Grand Canyon, Arizona: Geological Society of America Bulletin, v. 108, no. 1, p. 3−19.

Higgins, J.D., and Andrew, R.D., 2012a, Chapter 2—rockfall types and causes, *in* Turner, A.K., and Schuster, R.L., editors, Rockfall characterization and control: Washington, D.C., Transportation Research Board of the National Academies, p. 21–55.

Higgins, J.D., and Andrew, R.D., 2012b, Chapter 6—site characterization, *in* Turner, A.K., and Schuster, R.L., editors, Rockfall characterization and control: Washington, D.C., Transportation Research Board of the National Academies, p. 177–211.

Highland, L.M., 2004, Landslide types and processes: U.S. Geological Survey Fact Sheet 2004-3072: Online, http://pubs.usgs.gov/fs/2004/3072/pdf/fs2004-3072.pdf.

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

Highland, L.M., and Schuster, R.L., 2000, Significant landslide events in the United States: U.S. Geological Survey: Online, http://landslides.usgs.gov/docs/faq/significantls_508.pdf, accessed July 20, 2015.

Hiscock, A.I., and Hylland, M.D., 2015, Surface-fault-rupture-hazard maps of the Levan and Fayette segments of the Wasatch fault zone, Juab and Sanpete Counties, Utah: Utah Geological Survey Open-File Report 640, 7 plates, scale 1:24,000.

Hoek, E., Carter, T.G., and Diederichs, M.S., 2013, Quantification of the Geological Strength Index chart: 47th U.S. Rock Mechanics/Geomechanics Symposium Proceedings, San Francisco, variously paginated: Online, http://www.rocscience.com/library/rocnews/fall2013/Quantification-GSI-Chart-Hoek-Carter-Diederichs.pdf.

Holtz, R.D., and Schuster, R.L., 1996, Stabilization of soil slopes, *in* Turner, A.K., and Shuster, R.L., editors, Landslides—investigation and mitigation: Washington, D.C., National

Academy Press, National Research Council, Transportation Research Board Special Report 247, p. 439–473.

Hoopes, J.C., McBride, J.H., Christiansen, E.H., and Kowallis, B.J., 2014, Characterizing a landslide along the Wasatch mountain front (Utah): Environmental and Engineering Geoscience, v. 20, no. 1, p. 1–24.

Huebl, J., and Fiebiger, G., 2005, Debris-flow mitigation measures, *in* Jakob, M., and Hungr, O., editors, Debris-flow hazards and related phenomena: Heidelberg, Springer-Praxis, p. 444−487.

Hungr, O., 2000, Analysis of debris flow surges using the theory of uniformly progressive flow: Earth Surface Process and Landforms, v. 25, p. 483−495.

Hungr, O., McDougall, S., and Bovis, M., 2005, Entrainment of material by debris flows, *in* Jakob, M., and Hungr, O., editors, Debris-flow hazards and related phenomena: Heidelberg, Springer-Praxis, p. 135−158.

Hungr, O., Morgan, G.C., and Kellerhals, R., 1984, Quantitative analysis of debris torrent hazards for design of remedial measures: Canadian Geotechnical Journal, v. 21, p. 663−677.

Hungr, O., Morgan, G.C., VanDine, D.F., and Lister, D.R., 1987, Debris flow defenses in British Columbia, *in* Costa, J.E., and Wieczorek, G.F., editors, Debris flows/avalanches: Geological Society of America Reviews in Engineering Geology, Volume VII, p. 201−222.

Hylland, M.D., 1995, Fatal Big Cottonwood Canyon rock fall prompts UGS emergency response: Utah Geological Survey, Survey Notes, v. 27, no. 3, p. 13.

Hylland, M.D., editor, 1996, Guidelines for evaluating landslide hazards in Utah: Utah Geological Survey Circular 92, 16 p.

Hylland, M.D., 2007, Spatial and temporal patterns of surface faulting on the Levan and Fayette segments of the Wasatch fault zone, central Utah, from surficial geologic mapping and scarp-profile data, *in* Willis, G.C., Hylland, M.D., Clark, D.L., and Chidsey, T.C., Jr., editors, Central Utah—diverse geology of a dynamic landscape: Utah Geological Association Publication 36, p. 255–271.

Hylland, M.D., DuRoss, C.B., McDonald, G.N., Olig, S.S., Oviatt, C.G., Mahan, S.A., Crone, A.J., and Personius, S.F., 2012, Basin-floor Lake Bonneville stratigraphic section as revealed in paleoseismic trenches at the Baileys Lake site, West Valley fault zone, Utah, *in* Hylland, M.D., and Harty, K.M., editors, Selected topics in engineering and environmental geology in Utah: Utah Geological Association Publication 41, p. 175–193, DVD.

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

Hylland, M.D., and Lowe, M., 1998, Characteristics, timing, and hazard potential of liquefaction-induced landsliding in the Farmington Siding landslide complex, Davis County, Utah: Utah Geological Survey Special Study 95, 38 p.

Ingebritsen, S.E., and Jones, D.R., 1999, Santa Clara Valley, California—a case of arrested subsidence, *in* Galloway, D., Jones, D.R., and Ingebritsen, S.E., editors, Land subsidence in the United States: U.S. Geological Survey Circular 1182, variously paginated.

International Code Council, 2014a, International building code: Country Club Hills, Illinois, 700 p.

International Code Council, 2014b, International residential code—for one and two story dwellings: Country Club Hills, Illinois, 902 p.

International Commission on Stratigraphy, 2009, International Stratigraphic Chart: International Commission on Stratigraphy and International Union of Geological Sciences: Online, http://www.stratigraphy.org/ICSchart/StratChart2009.pdf.

Iron County, 2011, Iron County, Utah Code of Ordinances, Title 17 Zoning—Chapter 17.59 Geologic conditions: Online, https://www.municode.com/library/ut/iron_county/codes/code_of_ordinances?nodeId=TIT17ZO_CH17.59GECO.

Iverson, R.M., 2003, The debris-flow rheology myth, *in* Rickenmann, D., and Chen, C.L., editors, Proceedings of the Third International Conference on Debris-Flow Hazards Mitigation—Mechanics, Prediction, and Assessment, September 10–12, 2003, Davos, Switzerland: Rotterdam, Millpress, p. 303−314.

Jackson, L.E., Jr., 1987, Debris flow hazard in the Canadian Rocky Mountains: Geological Survey of Canada Paper 86-11, 20 p.

Jackson, L.E., Jr., Kostaschuk, R.A., and MacDonald, G.M., 1987, Identification of debris flow hazard on alluvial fans in the Canadian Rocky Mountains, *in* Costa, J.E., and Wieczorek, G.F., editors, Debris flows/avalanches: Geological Society of America Reviews in Engineering Geology, Volume VII, p. 115−124.

Jakob, M., 2005, Debris-flow hazard analysis, *in* Jakob, M., and Hungr, O., editors, Debris-flow hazards and related phenomena: Heidelberg, Springer-Praxis, p. 411−443.

Jakob, M., and Hungr, O., 2005, Debris-flow hazards and related phenomena: Heidelberg, Springer-Praxis, 739 p.

Jakob, M., and Weatherly, H., 2005, Debris flow hazard and risk assessment, Jones Creek, Washington, *in* Hungr, O., Fell, R., Couture, R., and Eberhardt, E., editors, Landslide risk management: New York, A.A. Balkema, p. 533−541.

Janda, R.J., Scott, K.M., Nolan, K.M., and Martinson, H.A., 1981, Lahar movement, effects, and deposits, *in* Lipman, P.W., and Mullineaux, D.R., editors, The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 461−478.

Janecke, S.U., and Oaks, R.Q., Jr., 2011, Reinterpreted history of latest Pleistocene Lake Bonneville—geologic setting of threshold failure, Bonneville flood, deltas of the Bear River, and outlets for two Provo shorelines, southeastern Idaho, USA, *in* Lee, J., and Evans, J.P., editors, Geologic field trips to the Basin and Range, Rocky Mountains, Snake River Plain, and terrains of the U.S. Cordillera: Geological Society of America Field Guide 21, p. 195–222 (doi:10.1130/2011.0021[09]).

Jibson, R.W., 2011, Methods for assessing the stability of slopes during earthquakes—a retrospective: Engineering Geology, v. 122, p. 43–50.

Jibson, R.W., and Harp, E.L., 1995, The Springdale landslide, *in* Christenson, G.E., editor, The September 2, 1992 M_L 5.8 St. George earthquake, Washington County, Utah: Utah Geological Survey Circular 88, p. 21–30.

Jibson, R.W., and Jibson, M.W., 2003, Java programs for using Newmark's method and simplified decoupled analysis to model slope performance during earthquakes: U.S. Geological Survey Open-File Report 03-005, CD.

Johnson, A.M., and Rodine, J.R., 1984, Debris flow, *in* Brunsden, D., and Prior, D.B., editors, Slope instability: New York, John Wiley & Sons, p. 257−361.

Jones, C.L., Higgins, J.D., and Andrew, R.D., 2000, Colorado rock fall simulation program, version 4.0: Report prepared for the Colorado Department of Transportation, 127 p.

Kaliser, B.N., 1978, Ground surface subsidence in Cedar City, Utah: Utah Geological Survey Report of Investigation 124, 22 p., 1 plate, scale 1:24,000.

Katzenstein, K., 2013, InSAR analysis of ground surface deformation in Cedar Valley, Iron County, Utah: Utah Geological Survey Miscellaneous Publication 13-5, 43 p., CD.

Keate, N.S., 1991, Debris flows in southern Davis County, Utah: Salt Lake City, University of Utah, M.S. thesis, 174 p.

Keaton, J.R., 1984, Genesis-lithology-qualifier (GLQ) system of engineering geology mapping symbols: Bulletin of the Association of Engineering Geologists, v. XXI, no. 3, p. 355–364.

Keaton, J.R., 1986, Potential consequences of tectonic deformation along the Wasatch fault: Utah State University, Final Technical Report to the U.S. Geological Survey for the National Earthquake Hazards Reduction Program, Grant 14-08-0001-G0074, 23 p.

Keaton, J.R., 1988, A probabilistic model for hazards related to sedimentation processes on alluvial fans in Davis County, Utah: College Station, Texas A&M University, Ph.D. dissertation, 441 p.

Keaton, J.R., 1990, Predicting alluvial-fan sediment-water slurry characteristics and behavior from sedimentology and stratigraphy of past deposits, *in* French, R.H., editor, Proceedings, Hydraulics/Hydrology of Arid Lands, July 30–August 3, 1990, San Diego, California: American Society of Civil Engineers, p. 608−613.

Keaton, J.R., Anderson, L.R., and Mathewson, C.C., 1991, Assessing debris flow hazards on alluvial fans in Davis County, Utah: Utah Geological Survey Contract Report 91-11, 166 p., 7 appendices.

Keaton, J.R., Anderson, L.R., Topham, D.E., and Rathbun, D.J., 1987a, Earthquake-induced landslide potential in and development of a seismic slope stability map of the urban corridor of Davis and Salt Lake Counties, Utah, *in* McCalpin, J., editor, Proceedings of the 23rd Annual Symposium on Engineering Geology and Soils Engineering: Logan, Utah State University, April 6–8, 1987, p. 57–80.

Keaton, J.R., Currey, D.R., and Olig, S.J., 1987b, Paleoseismicity and earthquake hazards evaluation of the West Valley fault zone, Salt Lake City urban area, Utah: Salt Lake City, Dames & Moore and University of Utah Department of Geography, Final Technical Report prepared for U.S. Geological Survey, contract no. 14-08-0001-22048, 55 p. + 33 p. appendix. (Subsequently published in 1993 as Utah Geological Survey Contract Report 93-8.)

Keaton, J.R., and DeGraff, J.V., 1996, Surface observation and geologic mapping, *in* Turner, A.K., and Shuster, R.L., editors, Landslides—investigation and mitigation: Washington, D.C., National Academy Press, National Research Council, Transportation Research Board Special Report 247, p. 178–230.

Keaton, J.R., and Lowe, M., 1998, Evaluating debris-flow hazards in Davis County, Utah—engineering versus geological approaches, *in* Welby, C.W., and Gowan, M.E., editors, A paradox of power—voices of warning and reason in the geosciences: Geological Society of America Reviews in Engineering Geology, Volume XII, p. 97−121.

Keaton, J.R., and Rinne, R., 2002, Engineering-geology mapping of slopes and landslides, *in* Bobrowsky, P.T., editor, Geoenvironmental Mapping—methods, theory, and practice: Leiden, The Netherlands, Taylor and Francis/Balkema, p. 9–28.

Keaton, J.R., Wartman, J., Anderson, S., Denoit, J., deLaChapelle, J., Gilber, R., and Montgomery, D.R., 2014, The 22 March 2014 Oso landslide, Snohomish County, Washington: Geotechnical Extreme Events Reconnaissance, 172 p.

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

Kelson, K.I., Kang, K.-H., Page, W.D., Lee, C.-T., and Cluff, L.S., 2001, Representative styles of deformation along the Chelungpu fault from the 1999 Chi-Chi (Taiwan) earthquake—geomorphic characteristics and responses of man-made structures: Bulletin of the Seismological Society of America, v. 91, no. 5, p. 930–952 (doi: 10.1785/0120000741).

Kerr, J., Nathan, S., Van Dissen, R., Webb, P., Brunsdon, D., and King, A., 2003, Planning for development of land on or close to active faults—a guide to assist resource management in New Zealand: Prepared for the Ministry of the Environment, Wellington, New Zealand, by the Institute of Geological and Nuclear Sciences, client report 2002/124, 71 p.

Kirkham, R.M., Parise, M., and Cannon, S.H., 2000, Geology of the 1994 South Canyon fire area, and a geomorphic analysis of the September 1, 1994, debris flows, South Flank Storm King Mountain, Glenwood Springs, Colorado: Colorado Geological Survey Special Publication 46, 39 p., 1 appendix, 1 plate, scale 1:5,000.

Knudsen, T.R., 2011, Investigation of the February 10, 2010, rock fall at 274 Main Street, and preliminary assessment of rock-fall hazard, Rockville, Washington County, Utah: Utah Geological Survey Report of Investigation 270, 17 p.

Knudsen, T., Inkenbrandt, P., and Lund, W., 2012, Investigation of land subsidence and earth fissures in Cedar Valley, Iron County, Utah: Utah Geological Survey contract deliverable report to the Central Iron County Water Conservancy District, variously paginated.

Knudsen, T., Inkenbrandt, P., Lund, W., Lowe, M., and Bowman, S., 2014, Investigation of land subsidence and earth fissures in Cedar Valley, Iron County, Utah: Utah Geological Survey Special Study 150, 84 p., 8 appendices, CD.

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

Kockelman, W.J., 1986, Some techniques for reducing landslide hazards: Bulletin of the Association of Engineering Geologists, v. 23, no. 1, p. 29–52.

KSL, 2015, Deal struck—North Salt Lake, developers and gas company ready to fix landslide: KSL.com: Online, http://www.ksl.com/?sid=34936682&nid=148, accessed September 28, 2015.

Larson, R.A., 1992, A philosophy of regulatory review, *in* Stout, M., editor, Proceedings of the 35th Annual Meeting of the Association of Engineering Geologists: Association of Engineering Geologists, October 2–9, Long Beach, California, p. 224–226.

Larson, R.A., 2015, Reviewing fault surface-rupture and earthquake-hazard mitigation reports for regulatory compliance, *in* Lund, W.R., editor, Proceedings Volume, Basin and Range Province Seismic Hazards Summit III: Utah Geological Survey Miscellaneous Publication 15-5, variously paginated, CD.

Leake, S.A., 2004, Land subsidence from ground-water pumping: U.S. Geological Survey: Online, http://geochange.er.usgs.gov/sw/changes/anthropogenic/subside, accessed March 29, 2010.

Lettis, W.R., and Kelson, K.I., 2000, Applying geochronology in paleoseismology, *in* Noller, J.S., Sowers, J.M., and Lettis, W.R., editors, Quaternary geochronology: Washington, D.C., American Geophysical Union Reference Shelf 4, p. 479–495.

Lienkaemper, J.J., and Bronk Ramsey, C., 2009, OxCal—versatile tool for developing paleoearthquake chronologies—a primer: Seismological Research Letters, v. 80, no. 3, p. 431–434 (doi: 10.1785/gssrl.80.3.431).

Lin, Z., Huili, G., Lingling, J., Yaoming, S., Xiaojaun, L., and Jun, J., 2009, Research on evolution of land subsidence induced by nature and human activity by utilizing remote sensing technology: Urban Remote Sensing Event, Shanghai, 5 p. (doi 10.1109/URS.2009.5137693).

Lips, E.W., 1985, Landslides and debris flows east of Mount Pleasant, Utah, 1983 and 1984: U.S. Geological Survey Open-File Report 85-382, 12 p., scale 1:24,000.

Lips, E.W., 1993, Characteristics of debris flows in central Utah, 1983: Utah Geological Survey Contract Report 93-3, 66 p.

Lund, W.R., 2002a, Professional contributions—Large boulder damages Rockville home: Association of Engineering Geologists AEG News, v. 45, no. 2, p. 25.

Lund, W.R., 2002b, Large boulder damages Rockville home: Utah Geological Survey, Survey Notes, v. 34, no. 1, p. 9–10.

Lund, W.R., 2005, Consensus preferred recurrence-interval and vertical slip-rate estimates—review of Utah paleoseismic-trenching data by the Utah Quaternary Fault Parameters Working Group: Utah Geological Survey Bulletin 134, 109 p.

Lund, W.R., editor, 2012, Basin and Range Province Earthquake Working Group II—recommendations to the U.S. Geological Survey National Seismic Hazard Mapping Program for the 2014 update of the National Seismic Hazard Maps: Utah Geological Survey Open-File Report 591, 17 p.

Lund, W.R., 2013, Rock fall—an increasing hazard in urbanizing southwestern Utah: Utah Geological Survey, Survey Notes, v. 45, no. 3, p. 4–5.

Lund, W.R., 2014, Hazus loss estimation software earthquake model revised Utah fault database—updated through 2013, prepared for the Utah Division of Emergency Management: Utah Geological Survey Open-File Report 631, 11 p., CD.

Lund, W.R., 2015, Current strategies for mitigating surface faulting in the Basin and Range Province, *in* Lund, W.R., editor, Proceedings Volume, Basin and Range Province Seismic Hazards Summit III: Utah Geological Survey Miscellaneous Publication 15-5, variously paginated, CD.

Lund, W.R., Bowman, S.D., and Piety, L.A., 2011, Compilation of U.S. Bureau of Reclamation seismotectonic studies in Utah, 1982–1999—Paleoseismology of Utah, Volume 20: Utah Geological Survey Miscellaneous Publication 11-2, 4 p.

Lund, W.R., DuRoss, C.B., Kirby, S.M., McDonald, G.N., Hunt, G., and Vice, G.S., 2005, The origin and extent of earth fissures in Escalante Valley, southern Escalante Desert, Iron County, Utah: Utah Geological Survey Special Study 115, 30 p., CD.

Lund, W.R., Knudsen, T.R., and Bowman, S.D., 2014, Investigation of the December 12, 2013, fatal rock fall at 368 West Main Street, Rockville, Utah: Utah Geological Survey Report of Investigation 273, 21 p., CD.

Lund, W.R., Knudsen, T.R., and Brown, K.E., 2009a, Large rock fall closes highway near Cedar City, Utah: Association of Environmental and Engineering Geologists AEG News, v. 52, no. 2, p. 21–22.

Lund, W.R., Knudsen, T.R., and Brown, K.E., 2009b, January 5, 2009, State Route 14 milepost 8 rock fall, Cedar Canyon, Iron County, Utah [abs.]: Geological Society of America Abstracts with Programs, Rocky Mountain Section, GSA Abstracts with Programs, v. 41, no. 6, p. 46.

Lund, W.R., Knudsen, T.R., DuRoss, C.B., and McDonald, G.N., 2015, Utah Geological Survey Dutchman Draw site paleoseismic investigation, Fort Pearce section, Washington fault zone, Mohave County, Arizona, *in* Lund, W.R., editor, Geologic mapping and paleoseismic investigations of the Washington fault zone, Washington County, Utah, and Mohave County, Arizona—Paleoseismology of Utah, Volume 27: Utah Geological Survey Miscellaneous Publication 15-6, p. 43–86, 1 plate, CD.

Lund, W.R., Knudsen, T.R., and Sharrow, D.L., 2010, Geologic hazards of the Zion National Park Geologic-Hazard Study area, Washington and Kane Counties, Utah: Utah Geological Survey Special Study 133, 97 p., 12 plates, scale 1:24,000, DVD.

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

Lund, W.R., Schwartz, D.P., Mulvey, W.E., Budding, K.E., and Black, B.D, 1991, Fault behavior and earthquake recurrence on the Provo segment of the Wasatch fault zone at Mapleton, Utah County, Utah—Paleoseismology of Utah, Volume 1: Utah Geological Survey Special Study 75, 41 p.

Machette, M.N., 1989, Slope-morphologic dating, *in* Forman, S.L., editor, Dating methods applicable to Quaternary geologic studies in the western United States: Utah Geological and Mineral Survey Miscellaneous Publication 89-7, p. 30–42.

Major, J.J., 1997, Depositional processes in large-scale debris-flow experiments: Journal of Geology, v. 105, p. 345−366.

Marinos, P., and Hoek, E., 2000, GSI—a geologically friendly tool for rock mass strength estimation: Proceedings of the GeoEng2000 Conference, Melbourne, p. 1422–1442.

Marinos, V., Marinos, P., and Hoek, E., 2005, The geological strength index—applications and limitations: Bulletin of Engineering Geology and the Environment, v. 64, p. 55–65.

Marsell, R.E., 1972, Cloudburst and snowmelt floods, *in* Hilpert, L.S., editor, Environmental geology of the Wasatch Front, 1971: Utah Geological Association Publication 1, p. N1−N18.

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

Mathewson, C.C., Keaton, J.R., and Santi, P.M., 1990, Role of bedrock ground water in the initiation of debris flows and sustained post-flow stream discharge: Bulletin of the Association of Engineering Geologists, v. 27, no. 1, p. 73−83.

McCalpin, J., 1984, Preliminary age classification of landslides for inventory mapping, *in* Hardcastle, J.H., editor, Proceedings of the Twenty-First Annual Engineering Geology and Soils Engineering Symposium: Moscow, University of Idaho, p. 99–111.

McCalpin, J.P., 1987, Recommended setbacks from active normal faults, *in* McCalpin J.P., editor, Proceedings of the 23rd Annual Symposium on Engineering Geology and Soils Engineering: Logan, Utah State University, April 6–8, 1987, p. 35–56.

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

McCalpin, J.P., and Nelson, A.R., 2009, Introduction to paleoseismology, *in* McCalpin, J.P., editor, Paleoseismology (second edition): Burlington, Massachusetts, Academic Press (Elsevier), p. 1–27.

McDonald, G.N., and Giraud, R.E., 2010, September 12, 2002, fire-related debris flows east of Santaquin and Spring Lake, Utah County, Utah, *in* Elliott, A.H., compiler, Technical Reports for 2002–2009, Geologic Hazards Program: Utah Geological Survey Report of Investigation 269, p. 2−16.

McGuffey, V.C., Modeer, V.A., Jr., and Turner, A.K., 1996, Subsurface exploration, *in* Turner, A.K., and Schuster, R.L., editors., Landslides—investigation and mitigation: Washington, D.C., National Academy Press, National Research Council, Transportation Research Board Special Report 247, p. 278–316.

McKean, A., and Kirby, S., 2014, Newly discovered Holocene-active basin floor fault in Goshen Valley, Utah County, Utah: Utah Geological Survey, Utah Quaternary Fault Parameters Working Group 2014 Proceedings: Online, http://geology.utah.gov/ghp/workgroups/pdf/uqfpwg/UQFPWG-2014_Presentations.pdf.

Mears, A.I., 1992, Snow-avalanche hazard analysis for land-use planning and engineering: Colorado Geological Survey Bulletin 49, 55 p.

Meyer, G.A., and Wells, S.G., 1997, Fire-related sedimentation events on alluvial fans, Yellowstone National Park, U.S.A.: Journal of Sedimentary Research, v. 67, no. 5, p. 776−791.

Meyer, G.A., Wells, S.G., and Jull, A.J.T., 1995, Fire and alluvial chronology in Yellowstone National Park—climatic and intrinsic controls on Holocene geomorphic processes: Geological Society of America Bulletin, v. 107, no. 10, p. 1211−1230.

Mikulich, M.J., and Smith, R.B., 1974, Seismic-reflection and aeromagnetic surveys of the Great Salt Lake, Utah: Geological Society of America Bulletin, v. 85, no. 6, p. 991–1002, 1 plate.

Miller, B., 1965, Laser altimeter may aid photo mapping: Aviation Week & Space Technology, v. 88, no. 13, p. 60–65.

Miller, D.M., Oviatt, C.G., and McGeehin, J.P., 2013, Stratigraphy and chronology of Provo shoreline deposits and lake-level implications, late Pleistocene Lake Bonneville, eastern Great Basin, USA: Boreas, v. 42, no. 2, p. 342–361. [Article first published online October 25, 2012, doi: 10.1111/j.1502-3885.2012.00297.x.]

Milsom, J.J., and Eriksen, A., 2011, Field geophysics (fourth edition): Chichester, United Kingdom, John Willey and Sons, 304 p.

Mohapatra, G.K., and Johnson, R.A., 1998, Localization of listric faults at thrust ramps beneath the Great Salt Lake basin, Utah—evidence from seismic imaging and finite element modeling: Journal of Geophysical Research, v. 103, p. 10,047–10,063.

Monmonier, M., 2002, Aerial photography at the Agricultural Adjustment Administration—acreage controls, conservation benefits, and overhead surveillance in the 1930s: Photogrammetric Engineering & Remote Sensing, v. 68, no. 12, p. 1257–1261.

Morgan County, 2006, County Ordinance CO-06-22—an ordinance of Morgan County enacting regulations and standards for review of the issuance of building permits for certain subdivisions in Morgan County, and establishing an effective date: Online, http://www.planning.utah.gov/Index_files/PDFs/morganCO.6.22.pdf, 5 p.

Mulvey, W.E., 1993, Debris-flood and debris-flow hazard from Lone Pine Canyon near Centerville, Davis County, Utah: Utah Geological Survey Report of Investigation 223, 40 p.

Mulvey, W.E., and Lowe, M., 1992, Cameron Cove subdivision debris flow, North Ogden, Utah, *in* Mayes, B.H., compiler, Technical reports for 1990–1991, Applied Geology Program: Utah Geological Survey Report of Investigation 222, p. 186−191.

National Highway Institute, 2002, Subsurface investigations—geotechnical site characterization: Federal Highway Administration Publication No. FWHA NHI-01-031, variously paginated.

National Oceanic and Atmospheric Administration, 2008, Lidar 101—an introduction to LiDAR technology, data, and applications: Charleston, South Carolina, National Oceanic and Atmospheric Administration Coastal Services Center, 62 p.

National Research Council, 1996, Alluvial fan flooding: Washington, D.C., National Academies Press, Committee on Alluvial Fan Flooding, 182 p.

National Weather Service, Salt Lake City Forecast Office, 2015a, Avalanche deaths in Utah 1958–Present: Online, http://www.wrh.noaa.gov/slc/projects/disasters/avalanche_deaths.php, accessed September 24, 2015.

National Weather Service, Salt Lake City Forecast Office, 2015b, Flash flood & flood deaths in Utah prior to 1950: Online, http://www.wrh.noaa.gov/slc/projects/disasters/flood_stats/flood_deaths.php, accessed September 24, 2015.

Nelson, C.V., and Lund W.R., 1990, Geologic hazards and constraints, *in* Lund, W.R., editor, Engineering geology of the Salt Lake City metropolitan area, Utah: Utah Geological and Mineral Survey Bulletin 126, p. 25–35.

Nelson, A.R., Lowe, M., Personius, S., Bradley, L.A., Forman, S.L., Klauk, R., and Garr, J., 2006, Holocene earthquake history of the northern Weber segment of the Wasatch Fault Zone, Utah—Paleoseismology of Utah, Volume 13: Utah Geological Survey Miscellaneous Publication 05-8, 39 p., 2 plates.

Nelson, C.V, and Christenson, G.E., 1992, Establishing guidelines for surface fault rupture hazard investigations—Salt Lake County, Utah [abs.]: Proceedings of the Association of Engineering Geologists, 35th Annual Meeting, p. 242–249.

Neuendorf, K.K.E., Mehl, J.P., Jr., and Jackson, J.A., editors, 2011, Glossary of geology (5th edition, revised): Alexandria, Virginia, American Geosciences Institute, 800 p.

Newmark, N.M., 1965, Effects of earthquakes on dams and embankments: Geotechnique 15, p. 139–159.

Noller, J.S., Sowers, J.M., and Lettis, W.R., editors, 2000, Quaternary geochronology, methods and applications: Washington, D.C., American Geophysical Union, AGU Reference Shelf 4, 582 p.

North American Commission on Stratigraphic Nomenclature, 2005, North American stratigraphic code: American Association of Petroleum Geologists Bulletin, v. 89, no. 11, p. 1547–1591. [Reproduced by the U.S. Geological Survey: Online, http://ngmdb.usgs.gov/Info/NACSN/Code2/code2.html.]

O'Brien, J.S., and Julien, P.Y., 1997, On the importance of mudflow routing, *in* Chen, C.L., editor, Debris-flow hazards mitigation, Proceedings of First International Conference, San Francisco, California: American Society of Civil Engineers, p. 667−686.

Occupational Safety and Health Administration, 2011, OSHA Fact Sheet, trenching and excavation safety: Occupational Safety and Health Administration, 2 p.

Olig, S.S., 2011, Extending the paleoseismic record of the Provo segment of the Wasatch fault zone, Utah: Oakland, California, URS Corporation, unpublished Final Technical Report for the U.S. Geological Survey National Earthquake Hazards Reduction Program, award no. 02HQGR0109, variously paginated.

Olig, S.S., Gorton, A.E., Black, B.D., and Forman, S.L., 2000, Evidence for young, large earthquakes on the Mercur fault—implications for segmentation and evolution of the Oquirrh–East Great Salt Lake fault zone, Wasatch Front, Utah [abs.]: Geological Society of America Abstracts with Programs, v. 32, no. 7, p. A–120.

Olig, S.S., Gorton, A.E., Black, B.D., and Forman, S.L., 2001, Paleoseismology of the Mercur fault and segmentation of the Oquirrh–East Great Salt Lake fault zone, Utah: Oakland, California, URS Corporation, unpublished technical report to the U.S. Geological Survey National Earthquake Hazards Reduction Program, award no. 98HQGR1036, variously paginated.

Olig, S.S., Gorton, A.E., and Chadwell, L., 1999, Mapping and Quaternary fault scarp analysis of the Mercur and West Eagle Hill faults, Wasatch Front, Utah: Oakland, California, URS Greiner Woodward Clyde, unpublished technical report to the U.S. Geological Survey National Earthquake Hazards Reduction Program, award no. 1434-HQ-97-GR-03154, variously paginated.

Oviatt, C.G., 2015, Chronology of Lake Bonneville, 30,000 to 10,000 yr B.P.: Quaternary Science Reviews, v. 110, p. 166–171.

Oviatt, C.G., Currey, D.R., and Sack, D., 1992, Radiocarbon chronology of Lake Bonneville, eastern Great Basin, USA: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 99, p. 225–241.

Pack, R.T., 1985, Multivariate analysis of relative landslide susceptibility in Davis County, Utah: Logan, Utah State University, Ph.D. dissertation, 233 p.

Paul, J.H., and Baker, F.S., 1923, The floods in northern Utah: University of Utah Bulletin, v. 15, no. 3, 20 p.

Pavelko, M.T., Woods, D.B., and Laczniak, R.J., 1999, Las Vegas, Nevada—gambling with water in the desert, in Galloway, D., Jones, D.R., and Ingebritsen, S.E., editors, Land subsidence in the United States: U.S. Geological Survey Circular 1182, variously paginated.

Pearthree, P.A., 1990, Geomorphic analysis of young faulting and fault behavior in central Nevada: Tucson, University of Arizona, Ph.D. dissertation, 212 p.

Personius, S.F., and Scott, W.E., 1992, Surficial geologic map of the Salt Lake City segment and parts of adjoining segments of the Wasatch fault zone, Davis, Salt Lake, and Utah Counties, Utah: U.S. Geological Survey Miscellaneous Investigations Series Map I-2106, scale 1:50,000; also Utah Geological Survey Map 243DM (2009 digital release).

Peterson, F.F., 1981, Landforms of the Basin and Range Province defined for soil survey: Nevada Agricultural Experiment Station Technical Bulletin 28, 52 p.

Pierson, T.C., 1985, Effects of slurry composition on debris flow dynamics, Rudd Canyon, Utah, *in* Bowles, D.S., editor, Delineation of landslide, flash flood, and debris-flow hazards in Utah: Logan, Utah State University, Utah Water Research Publication G-85/03, p. 132−152.

Pierson, T.C., 2005a, Distinguishing between debris flows and floods from field evidence in small watersheds: U.S. Geological Survey Fact Sheet 2004-3142, 4 p.

Pierson, T.C., 2005b, Hyperconcentrated flow—transitional processes between water flow and debris flow, *in* Jakob, M., and Hungr, O., editors, Debris-flow hazards and related phenomena: Heidelberg, Springer-Praxis, p. 159−202.

Pierson, T.C., and Costa, J.E., 1987, A rheologic classification of subaerial sediment-water flows, *in* Costa, J.E., and Wieczorek, G.F., editors, Debris flows/avalanches: Geological Society of America Reviews in Engineering Geology, Volume VII, p. 1−12.

Price, J.G., 1998, Guidelines for evaluating potential surface fault rupture/land subsidence hazards in Nevada (Revision 1): Nevada Bureau of Mines and Geology, 9 p.

Price, J.G., Bell, J.W., and Helm, D.C., 1992, Subsidence in Las Vegas Valley: Nevada Bureau of Mines and Geology Quarterly Newsletter, Fall 1992, 2 p.

Prochaska, A.B., Santi, P.M., and Higgins, J.D., 2008, Debris basin and deflection berm design for fire-related debris-flow mitigation: Environmental and Engineering Geoscience, v. 14, no. 4, p. 297–313.

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

Reynolds, J.M., 2011, An introduction to applied and environmental geophysics (second edition): Chichester, United Kingdom, John Wiley and Sons, 712 p.

Robichaud, P.R., Beyers, J.L., and Neary, D.G., 2000, Evaluating the effectiveness of postfire rehabilitation treatments: U.S. Department of Agriculture, Forest Service, General Technical Report RMRS-GTR-63, 85 p.

Robison, R.M., 1993, Surface-fault rupture—a guide for land use planning, Utah and Juab Counties, Utah, *in* Gori, P.L., editor, Applications of research from the U.S. Geological Survey program, Assessment of Regional Earthquake Hazards and Risk along the Wasatch Front, Utah: U.S. Geological Survey Professional Paper 1519, p. 121–128.

RocScience, 2011, RocFall 4.0: Online, https://www.rocscience.com/products/12/RocFall, accessed June 2014.

Rogers, J.D., 1992, Recent developments in landslide mitigation techniques, *in* Slosson, J.E., Deene, A.G., and Johnson, J.A., editors, Landslides/landslide mitigation: Geological Society of America Reviews in Engineering Geology, Volume IX, p. 95–118.

Rowley, P.D., Hamilton, W.L., Lund, W.R., and Sharrow, D., 2002, Rock-fall and landslide hazards of the canyons of the upper Virgin River basin near Rockville and Springdale, Utah [abs.]: Geological Society of America 2002 Abstracts with Programs, Rocky Mountain Section, v. 34, no. 4, p. P–39.

Saines, M., Bell, J.W., Ball, S., and Hendrick, C., 2006, Formation of earth fissures over the past half century at the Las Vegas Earth Fissure Preserve, Las Vegas, Nevada [abs.], Seminar on Environmental Impacts of Growth, and Mitigation Measures in Southern Nevada, Las Vegas, Nevada, May 24–25, 2006: Las Vegas, Air and Waste Management Association, 1 p.

Salt Lake City, 2014, Chapter 18—Site development requirements: Salt Lake City: Online, http://www.sterlingcodifiers.com/codebook/index.php?book_id=672, accessed July 28, 2015.

Salt Lake County, 2002a, Geological hazards ordinance: Salt Lake County Planning and Development Services Division, Chapter 19.75: Online, https://www.municode.com/library/ut/salt_lake_county/codes/code_of_ordinances?searchRequest={%22searchText%22:%22geologic%22,%22pageNum%22:1,%22resultsPerPage%22:25,%22booleanSearch%22:false,%22stemming%22:true,%22fuzzy%22:false,%22synonym%22:false,%22contentTypes%22:[%22CODES%22],%22productIds%22:[]}&nodeId=TIT19ZO_CH19.75GEHAORFONAHAAR_19.75.060GEHAENGERE, accessed July 28, 2015.

Salt Lake County, 2002b, Minimum standards for surface fault rupture hazard studies: Salt Lake County Planning and Development Services Division, Geologic Hazards Ordinance, Chapter 19.75, appendix A, 9 p.: Online, http://slco.org/pwpds/zoning/pdf/geologichazards/AppAfaultReportMinStds.pdf, accessed July 28, 2015.

Santi, P.M., 1988, The kinematics of debris flow transport down a canyon: College Station, Texas A&M University, M.S. thesis, 85 p.

Santi, P.M., 2014, Precision and accuracy in debris-flow volume measurement: Environmental and Engineering Geoscience, v. 20, no. 4, p. 349–359.

Santi, P.M., deWolfe, V.G., Higgins, J.D., Cannon, S.H., and Gartner, J.E., 2008, Sources of debris flow material in burned areas: Geomorphology, v. 96, p. 310–321.

Schwartz, D.P., and Coppersmith, K.J., 1984, Fault behavior and characteristic earthquakes—examples from the Wasatch and San Andreas fault zones: Journal of Geophysical Research, v. 89, no. B7, p. 5681–5698.

Seed, R.B., Cetin, K.O., Moss, R.E.S., Kammerer, A.M., Wu, J.P., Pestana, J.M., Riemer, M.F., Sancio, R.B., Bray, J.D., Kayen, R.E., and Faris, A., 2003, Recent advances in soil liquefaction engineering—a unified and consistent framework: Berkeley, University of California, Earthquake Engineering Research Center Report 2003-06, 71 p.

Shan, J., and Toth, C.K., 2009, Topographic laser ranging and scanning, principals and processing: Boca Raton, Florida, CRC Press, 590 p.

Sharma, P.V., 1998, Environmental and engineering geophysics: New York, Cambridge University Press, 499 p.

Shepherd, E.C., 1965, Laser to watch height: New Scientist, v. 26, no. 437, p. 33.

Shlemon, R.J., 2004, Fissure impact on the built environment, *in* Shlemon Specialty Conference—Earth Fissures, El Paso, Texas, April 1–3, 2004, conference materials: The Association of Engineering Geologists and Engineering Geology Foundation, unpaginated, CD.

Shlemon, R.J., 2010, A proposed mid-Holocene age definition for hazardous faults in California: Environmental and Engineering Geoscience, v. XVI, no. 1, p. 55–64.

Shlemon, R.J., 2015, Acceptable risk for surface-fault rupture in the Basin and Range Province, *in* Lund, W.R., editor, Proceedings Volume, Basin and Range Province Seismic Hazards Summit III: Utah Geological Survey Miscellaneous Publication 15-5, variously paginated, CD.

Simon, D.B., Black, D.R., Hanson, J.R., and Rowley, P.D., 2015, Surface-fault-rupture-hazard investigation for a portion of the Southern Parkway Northern Extension (State Route 7), Fort Pearce section, Washington fault zone, Washington County, Utah, *in* Lund, W.R., editor, Geologic mapping and paleoseismic investigations of the Washington fault zone, Washington County, Utah and Mohave County, Arizona—Paleoseismology of Utah, Volume 27: Utah Geological Survey Miscellaneous Publication 15-6, p. 107–175.

Slemmons, D.B., 1969, New methods for studying regional seismicity and surface faulting: American Geophysical Union Transactions, EOS, v. 50, p. 397–398.

Slemmons, D.B., and dePolo, C.M., 1992, Evaluation of active faulting and associated hazards, *in* Studies in geophysics—active tectonics: Washington, D.C., National Research Council, p. 45–62.

Slosson, J.E., 1984, Genesis and evolution of guidelines for geologic reports: Bulletin of the Association of Engineering Geologists, v. XXI, no. 3, p. 295–316.

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

Soeters, R., and van Westen, C.J., 1996, Slope instability recognition, analysis, and zonation, *in* Turner, A.K., and Schuster, R.L., editors, Landslides—investigation and mitigation: Washington, D.C., National Academy Press, National Research Council, Transportation Research Board Special Report 247, p. 129–177.

Solomon, B.J., Storey, N., Wong, I., Silva, W., Gregor, N., Wright, D., and McDonald, G., 2004, Earthquake-hazards scenario for a M7 earthquake on the Salt Lake City segment of the Wasatch fault zone, Utah: Utah Geological Survey Special Study 111DM, 59 p.

Stock, G.M., Luco, N., Collins, B.D., Harp, E.L., Reichenbach, P., and Frankel, K.L., 2012a, Quantitative rock-fall hazard and risk assessment for Yosemite Valley, Yosemite National Park, California: National Park Service, 96 p.

Stock, G.M., Luco, N., Harp, E.L., Collins, B.D., Reichenbach, P., Frankel, K., Matasci, B., Carrea, D., Jaboyedoff, M., and Oppikofer, T., 2012b, Quantitative rock fall hazard and risk assessment in Yosemite Valley, California, USA, *in* Eberhardt, E., Froese, C., Turner, K., and Leroueil, S., editors, Landslides and engineered slopes—protecting society through improved understanding: London, CRC Press, p. 1119–1125.

Suter, M., 2006, Contemporary studies of the 3 May 1887 M_W 7.5 Sonora, Mexico (Basin and Range Province) earthquake: Seismological Research Letters, v. 77, no. 2, p. 134–147.

Swan, F.H., III, Hanson, K.L., Schwartz, D.P., and Black, J.H., 1981a, Study of earthquake recurrence intervals on the Wasatch fault at the Little Cottonwood Canyon site, Utah: U.S. Geological Survey Open-File Report 81-450, 30 p.

Swan, F.H., III, Schwartz, D.P., and Cluff, L.S., 1980, Recurrence of moderate to large magnitude earthquakes produced by surface faulting on the Wasatch fault zone, Utah: Bulletin of the Seismological Society of America, v. 70, p. 1431–1462.

Swan, F.H., III, Schwartz, D.P., Hanson, K.L., Kneupfer, P.L., and Cluff, L.S., 1981b, Study of earthquake recurrence intervals on the Wasatch fault at the Kaysville site, Utah: U.S. Geological Survey Open-File Report 81-228, 30 p.

Taylor, C.L., and Cluff, L.S., 1973, Fault activity and its significance assessed by exploratory excavation, *in* Proceedings of the Conference on Tectonic Problems of the San Andreas Fault System: Stanford University Publication, Geological Sciences, v. XIII, September 1973, p. 239–247.

Telford, W.M., Geldart, L.P., and Sherriff, R.E., 1990, Applied geophysics (second edition): Cambridge, United Kingdom, Cambridge University Press, 790 p.

Tepel, R.E., 2010, Faulting and public policy in California—the evolution of the Alquist-Priolo Earthquake Fault Zoning Act: Environmental and Engineering Geoscience, v. XVI, no. 1, p. 3–6.

Terzhagi, K., 1950, Mechanism of landslides, *in* Application of geology to engineering practice: Geological Society of America, Berkley Volume, p. 83–123.

Trandafir, A.C., Ertugrul, O.L., Giraud, R.E., and McDonald, G.N., 2015, Geomechanics of a snowmelt-induced slope failure in glacial till: Environmental Earth Sciences, v. 73, no. 7, p. 3709−3716.

Treiman, J.A., 2010, Fault rupture and surface displacement—defining the hazard: Environmental and Engineering Geoscience, v. XVI, no. 1, p. 19–30.

Turner, A.K., 2012, Chapter 5—Rockfall risk assessment and risk management, *in* Turner, A.K., and Schuster, R.L., editors, Rockfall characterization and control: Washington, D.C., Transportation Research Board of the National Academies, p. 113–174.

Turner, A.K., and Duffy, J.D., 2012, Chapter 9—Modeling and prediction of rockfall, *in* Turner, A.K., and Schuster, R.L., editors, Rockfall characterization and control: Washington, D.C., Transportation Research Board of the National Academies, p. 334–406.

Turner, A.K., and Jayaprakash, G.P., 2012, Chapter 1—Introduction, *in* Turner, A.K., and Schuster, R.L., editors, Rockfall characterization and control: Washington, D.C., Transportation Research Board of the National Academies, p. 3–20.

Turner, A.K., and Schuster, R.L., editors, 1996, Landslides—investigation and mitigation: Washington, D.C., National Academy Press, National Research Council, Transportation Research Board Special Report 247, 673 p.

Turner, A.K., and Schuster, R.L., editors, 2012, Rockfall characterization and control: Washington, D.C., Transportation Research Board of the National Academies, 658 p., CD supplement.

U.S. Bureau of Reclamation, 1998a, Earth manual—part 1 (third edition): U.S. Bureau of Reclamation, Earth Sciences and Research Laboratory, 311 p.

U.S. Bureau of Reclamation, 1998b, Engineering geology field manual (2nd edition)—Volume I: U.S. Department of the Interior, Bureau of Reclamation, Washington, D.C., 478 p.

U.S. Bureau of Reclamation, 2001, Engineering geology field manual (2nd edition)—Volume II: U.S. Department of the Interior, Bureau of Reclamation, Washington, D.C., 535 p.

U.S. Department of Defense, 2004, Unified Facilities Criteria (UFC), Soils and geology procedures for foundation design of building and other structures (except hydraulic structures): U.S. Department of Defense Publication UFC 3-220-03FA, variously paginated.

U.S. Department of Transportation, 2014, Guidance on the treatment of the economic value of a statistical life (VSL) in U.S. Department of Transportation analyses—2014 adjustment: U.S. Department of Transportation memorandum: Online, https://www.transportation.gov/sites/dot.gov/files/docs/VSL_Guidance_2014.pdf, accessed September 28, 2015.

U.S. Geological Survey, 2015, Quaternary fault and fold database of the United States: U.S. Geological Survey Earthquake Hazards Program: Online, http://earthquake.usgs.gov/hazards/qfaults/.

U.S. Nuclear Regulatory Commission, 2011, Practical implementation guidelines for SSHAC Level 3 and 4 hazard studies: U.S. Nuclear Regulatory Commission Regulatory Guide 2117, 227 p.

Utah Automated Geographic Reference Center, 2006a, 2006 NAIP 1 meter color orthophotography: Online, http://gis.utah.gov/data/aerial-photography/2006-naip-1-meter-color-orthophotography/, accessed November 18, 2010.

Utah Automated Geographic Reference Center, 2006b, 2 meter LiDAR: Online, http://gis.utah.gov/elevation-terrain-data/2-meter-lidar, accessed November 18, 2010.

Utah Automated Geographic Reference Center, 2009, 2009 HRO 1 foot color orthophotography: Online, http://gis.utah.gov/aerial-photography/2009-hro-1-foot-color-orthophotography, accessed December 8, 2010.

Utah Automated Geographic Reference Center, 2011, 1 meter LiDAR elevation data (2011): Online, http://gis.utah.gov/data/elevation-terrain-data/2011-lidar/, accessed November 18, 2010.

Utah Avalanche Center, 2015, Avalanche fatalities, 2015: Online, https://utahavalanchecenter.org/avalanches/fatalities, accessed September 24, 2015.

Utah Code, 2011, 58-76-10 – Title. Professional Geologists Licensing Act: Online, http://le.utah.gov/xcode/Title58/Chapter76/C58-76_1800010118000101.pdf.

Utah Department of Transportation, 2011, Geotechnical manual of instruction: Utah Department of Transportation, 70 p.: Online, http://udot.utah.gov/main/uconowner.gf?n=3959503745590753, accessed September 30, 2015.

Utah Department of Transportation, 2014, Pavement design manual of instruction: Utah Department of Transportation, 258 p.: Online, http://www.udot.utah.gov/main/uconowner.gf?n=20339215312776663, accessed September 30, 2015.

Utah Division of Emergency Management, 2014, State of Utah hazard mitigation plan: Utah Department of Emergency Management, variously paginated: Online, https://sites.google.com/a/utah.gov/utah/, accessed September 28, 2015.

Utah Environmental Public Health Tracking Network, 2015, Radon in Utah: Utah Department of Health, Bureau of Epidemiology, Environmental Epidemiology Program and Bureau of Health Promotion, Utah Cancer Control Program, 15 p.: Online, http://www.health.utah.gov/enviroepi/healthyhomes/epht/Radon_in_Utah.pdf, accessed September 29, 2015.

Utah Geological Survey, 2011, LiDAR elevation data, Cedar and Parowan Valleys: Utah Geological Survey: Online, http://geology.utah.gov/resources/data-databases/lidar-elevation-data/.

Utah Geological Survey, 2016, Utah Quaternary fault and fold database: Online, http://geology.utah.gov/resources/data-databases/qfaults/.

Utah Quaternary Fault Parameters Working Group, 2013, Summary—Utah Quaternary Fault Parameters Working Group meeting, Tuesday, February 5, 2013: Utah Geological Survey: Online, http://geology.utah.gov/ghp/workgroups/pdf/uqfpwg/UQFPWG-2013_Summary.pdf, 6 p.

Utah Section of the Association of Engineering Geologists, 1986, Guidelines for preparing engineering geologic reports in Utah: Utah Geological and Mineral Survey Miscellaneous Publication M, 2 p.

Utah State University Luminescence Laboratory, 2014, Instructions for sample collection and submittal: Online, http://www.usu.edu/geo/luminlab/submit.html.

Van Westen, C.J., Castellanos, E., and Kuriakose, S.L., 2008, Spatial data for landslide susceptibility, hazard, and vulnerability assessment—an overview: Engineering Geology, v. 102, p. 112–131.

VanDine, D.F., 1985, Debris flows and debris torrents in the southern Canadian Cordillera: Canadian Geotechnical Journal, v. 22, p. 44−68.

VanDine, D.F., 1996, Debris flow control structures for forest engineering: British Columbia Ministry of Forests Research Program, Working Paper 22, 68 p.

VanDine, D.F., Hungr, O., Lister, D.R., and Chatwin, S.C., 1997, Channelized debris flow mitigative structures in British Columbia, Canada, *in* Chen, C.L., editor, Debris-flow hazards mitigation, Proceedings of First International Conference, San Francisco, California: American Society of Civil Engineers, p. 606−615.

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

Viets, V.F., Vaughan, C.K., and Harding, R.C., 1979, Environmental and economic effects of subsidence: Berkeley, California, Lawrence Berkeley Laboratory Geothermal Subsidence Research Management Program, 251 p.

Viveiros, J.J., 1986, Cenozoic tectonics of Great Salt Lake from seismic-reflection data: Salt Lake City, University of Utah, unpublished M.S. thesis, 81 p.

Walker, J.D., and Cohen, H.A., 2006, The geoscience handbook—AGI data sheets (4th edition): American Geological Institute, 302 p.

Walter, H.G., 1934, Hansel Valley, Utah, earthquake: The Compass of Sigma Gamma Epsilon, v. 14, no. 4, p. 178–181.

Watters, R.J., and Delahaut, W.D., 1995, Effect of argillic alteration on rock mass stability, *in* Haneberg, W.C., and Anderson, S.A., editors, Clay and shale slope instability: Geological Society of America Reviews in Engineering Geology, Volume X, p. 139–150.

Webb, R.H., Melis, T.S., Griffiths, P.G., Elliott, J.G., Cerling, T.E., Poreda, R.J., Wise, T.W., and Pizzuto, J.E., 1999, Lava Falls rapid in the Grand Canyon—effects of late Holocene debris flows on the Colorado River: U.S. Geological Survey Professional Paper 1591, 90 p., 1 plate, scale 1:1,000.

Wells, S.G., and Harvey, A.M., 1987, Sedimentologic and geomorphic variations in storm-generated alluvial fans, Howgill Fells, northwest England: Geological Society of America Bulletin, v. 98, no. 2, p. 182−198.

Wells, W.G., II, 1987, The effects of fire on the generation of debris flows in southern California, *in* Costa, J.E., and Wieczorek, G.F., editors, Debris flows/avalanches: Geological Society of America Reviews in Engineering Geology, Volume VII, p. 105−114.

Wesnousky, S.G., 2008, Displacement and geometrical characteristics of earthquake surface ruptures—issues and implications for seismic-hazard analysis and the process of earthquake rupture: Bulletin of the Seismological Society of America, v. 98, no. 4, p. 1609–1632 and online electronic supplement.

Western States Seismic Policy Council, 2011, Policy Recommendation 11-2—Definition of fault activity for the Basin and Range Province: Western States Seismic Policy Council, 5 p.

Whipple, K.X., and Dunne, T., 1992, The influence of debris-flow rheology on fan morphology, Owens Valley, California: Geological Society of America Bulletin, v. 104, no. 7, p. 887−900.

Wieczorek, G.F., 1984, Preparing a detailed landslide-inventory map for hazard evaluation and reduction: Bulletin of the Association of Engineering Geologists, v. 21, no. 3, p. 337–324.

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

Wieczorek, G.F., Ellen, S., Lips, E.W., Cannon, S.H., and Short, D.N., 1983, Potential for debris flow and debris flood along the Wasatch Front between Salt Lake City and Willard, Utah, and measures for their mitigation: U.S. Geological Survey Open-File Report 83-635, 45 p.

Wieczorek, G.F., Lips, E.W., and Ellen, S., 1989, Debris flows and hyperconcentrated floods along the Wasatch Front, Utah, 1983 and 1984: Bulletin of the Association of Engineering Geologists, v. 26, no. 2, p. 191−208.

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

Williams, S.R., and Lowe, M., 1990, Process-based debris-flow prediction method, *in* French, R.H., editor, Proceedings, Hydraulics/Hydrology of Arid Lands, July 30–August 3, 1990, San Diego, California: American Society of Civil Engineers, p. 66−71.

Williamson, D.A., 1984, Unified rock classification system: Bulletin of the Association of Engineering Geologists, v. XXI, no. 3, p. 345–354.

Williamson, D.A., Neal, K.G., and Larson, D.A., 1991, The field-developed cross-section—a systematic method of portraying dimensional subsurface information and modeling for geotechnical interpretation and analysis [abs.]: Chicago, Illinois, Association of Engineering Geologists, 34th Annual Meeting, Proceedings, p. 719–738.

Woolley, R.R., 1946, Cloudburst floods in Utah, 1850–1938: U.S. Geological Survey Water Supply Paper 994, 128 p., 23 plates.

Working Group on Utah Earthquake Probabilities, 2016, Earthquake probabilities for the Wasatch Front region in Utah, Idaho, and Wyoming: Utah Geological Survey Miscellaneous Publication 16-3, variously paginated.

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

Youd, T.L., Hansen, C.M., and Bartlett, S.F., 1999, Revised MLR equations for predicting lateral spread displacement, Proceedings, 7th U.S.-Japan Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures against Liquefaction: Seattle, Washington, Multidisciplinary Center for Earthquake Engineering Research Technical Report MCEER-99-0019, p. 99–114.

Youd, T.L., Idriss, I.M., Andrus, R.D., Arango, I., Castro, G., Christian, J.T., Dobry, R., Liam Finn, W.D., Harder, L.F., Jr., Hynes, M.E., Ishihara, K., Koester, J.P., Liao, S.S.C., Macuson, W.F., III, Martin, G.R., Mitchell, J.K., Moriwaki, Y., Power, M.S., Robertson, P.K., Seed, R.B., and Stokoe, K.H., II, 2001, Liquefaction resistance of soils—summary report from the 1996 NCEER and 1998 NCEER/NSF workshops on Evaluation of Liquefaction Resistance of Soils: American Society of Civil Engineers Journal of Geotechnical and Geoenvironmental Engineering, v. 127, no. 10, p. 817–833.

Zebker, H.A., and Goldstein, R.M., 1986, Topographic mapping from interferometric synthetic aperture radar observations: Journal of Geophysical Research, v. 91, p. 4993–4999.

Zebker, H.A., Rosen, P.A., Goldstein, R.M., Gabriel, A., and Werner, C.L., 1994, On the derivation of coseismic displacement fields using differential radar interferometry—the Landers earthquake: Journal of Geophysical Research, v. 99, no. B10, p. 19,617–19,634.

Zilkoski, D.B., Carlson, E.E., and Smith, C.L., 2008, Guidelines for establishing GPS-derived orthometric heights, version 1.5: Silver Spring, Maryland, National Geodetic Survey, 15 p.

Zilkoski, D.B., D'Onofrio, J.D., and Frakes, S.J., 1997, Guidelines for establishing GPS-derived ellipsoid heights (Standards: 2 cm and 5 cm), version 4.3: Silver Spring, Maryland, National Geodetic Survey, 10 p.

APPENDICES

APPENDIX A
REPORT REVIEW CHECKLISTS

The Wasatch fault zone at the mouths of Little Cottonwood and Bells Canyons, Salt Lake Valley, Utah.

This appendix contains recommended report review checklists for combined geologic-hazard/engineering-geology reports (including school sites) and reports specific to a single hazard (surface fault rupture, landslides, debris flows, rockfall, and land subsidence and earth fissures) as described in this publication. These checklists are intended to promote uniformity in report preparation and review, and to provide a minimum acceptable level of geologic-hazard investigation. Digital fill-in versions of these checklists are also available at http://geology.utah.gov/about-us/geologic-programs/geologic-hazards-program/for-consultants-and-design-professionals/recommended-report-guidelines/.

ENGINEERING-GEOLOGY REPORT REVIEW CHECKLIST

For additional information, see chapter 2 of: Bowman, S.D., and Lund, W.R., editors, 2016, Guidelines for investigating geologic hazards and preparing engineering-geology reports, with a suggested approach to geologic-hazard ordinances in Utah: Utah Geological Survey Circular 122, p. 15–30.

Report and Review Information

Report Title:				
Report Type: _ Reconnaissance _ Preliminary _ Final _ Combined Engineering Geology/Geotechnical _ Other				
Author:		Project #:	**Adequately Documented**	**Additional Information Needed**
Location:		County:		
Reviewing Organization:		File #:		
Reviewed By:		Utah PG License #:		
First Review:	Review # ___:	Final Approval:		

1. Investigation/Report Purpose and Scope

Are the purpose and scope of the engineering-geology investigation appropriate and adequate for the proposed project?		
Review Comments:		

2. Project Description and Location

Is the description of the size, type of construction, intended foundation system, grade/floor elevations, building area (square feet), and International Building Code (IBC) risk category (Table 1604.5) appropriate and adequate for the proposed project? Reports should provide a marked location on an index map using a 7-1/2 minute U.S. Geological Survey (USGS) topographic map or equivalent base map; parcel number; provide the site latitude and longitude to four decimal places with datum; and a site development map adequate to show site boundaries, existing and proposed structures, other infrastructure, and relevant site topography. The scale of site development maps will vary depending on the size of the site and area of investigation; recommended scale is 1 inch = 200 feet (1:2400) or larger, as necessary		
Review Comments:		

3. Literature Review

Is the engineering-geology-investigation literature review appropriate and adequate for the proposed project? Are references properly cited in the report and reference list?		
Review Comments:		

4. Analysis of Aerial Photographs and Other Remote-Sensing Data

Is the analysis of aerial photography and other remote-sensing data (as available) appropriate and adequate for the proposed project? Are aerial photographs and remote-sensing data properly documented and referenced?		
Review Comments:		

5. Regional Geology and Geologic/Fault Maps

Are the description and analysis of the regional geology and geologic/Quaternary fault maps appropriate and adequate for the proposed project? Reports should provide a regional-scale (1:24,000 to 1:50,000) map showing the geology and location of all mapped or known Quaternary faults, including fault orientation (trend of surface trace, sense of displacement, etc.) and fault activity class (age category) within 10 miles of the site.		
Review Comments:		

6. Site-Specific Geology and Geologic Maps

Are the description and analysis of the site-specific geology, geologic maps, and cross sections appropriate and adequate for the proposed project? Reports should describe site geology according to Guidelines for Conducting Engineering-Geology Investigations and Preparing Engineering-Geology Reports in Utah (Chapter 2), and provide a site-scale geologic map(s) showing geologic and soil units, Quaternary and other faults, seeps or springs, slope failures, lineaments investigated for evidence of faulting, and other geologic features existing on and near the project site. Maps should show locations of trenches, test pits, boreholes, geoprobe holes, cone penetration test (CPT) soundings, and geophysical lines. Scale of site geologic maps will vary depending on the size of the site and area of investigation; recommended scale is 1 inch = 200 feet (1:2400) or larger, as necessary. Site geologic cross sections should be included as needed to illustrate three-dimensional geologic relations. The degree of detail and scale of site geologic mapping should be compatible with the geologic complexity of the site, type of building, and layout. For hillside sites, describe geology of both the site and adjacent properties, including any known or mapped landslides		
Review Comments:		

7. Surface-Fault-Rupture

Are the description and analysis of the potential for surface-fault rupture, and building setbacks appropriate and adequate for the proposed project? Reports should evaluate the surface-faulting hazard for any faults on the site having Quaternary displacement. If the fault age (activity class) is unknown, the fault should be considered Holocene, unless data are adequate to determine otherwise. If on-site investigations reveal the presence of a Quaternary fault, and fault avoidance is the surface-faulting-mitigation method chosen, an appropriate fault setback should be established following the method described in Guidelines for Evaluating Surface-Fault-Rupture Hazards in Utah (Chapter 3, this volume), and shown on either the site-specific geologic map or on a separate surface-faulting-hazard map depending on site scale and complexity. The degree of confidence in and limitations of data and conclusions must be clearly stated and documented in the report.		
Review Comments:		

8. Subsurface Investigation

Are the description and analysis of the subsurface investigation appropriate and adequate for the proposed project? Reports should provide subsurface engineering-geology and geotechnical information, including a site-specific plan view map showing exploration sites (borings, test pits, trenches, etc.), existing groundwater levels, and areas of existing and planned cuts and fills. Logs are required for all boreholes, standard penetration tests (SPT), and CPT soundings. Logs should include the geologic interpretation of deposit genesis for all layers. Because boreholes are typically multipurpose, borehole logs may also contain geotechnical, geologic, and groundwater data. All logs should include the identity of the person who made the log		
Review Comments:		

9. Seismic Ground Shaking and Design Parameters

Are the description and analysis of seismic ground shaking and seismic design parameters appropriate and adequate for the proposed project? Reports should include an evaluation of the seismic ground-shaking hazard and provide seismic-design parameters (site coefficients, mapped spectral accelerations, and design spectral response acceleration parameters) according to IBC Section 1613.5 or International Residential Code (IRC) Section 301.2.2. Characterize the upper 100 feet of the building site profile to determine the site class as outlined in IBC Table 1613.5.2. If the building site profile is Site Class F, site-specific evaluation is required by the IBC and outlined in ASCE Standard 7.		
Review Comments:		

10. Liquefaction

Are the description and analysis of liquefaction appropriate and adequate for the proposed project?

Reports should include an evaluation of the liquefaction hazard at the site. IBC Section 1803.5.11 requires a liquefaction evaluation if the structure is determined to be in Seismic Design Category C. IBC Section 1803.5.12 requires a liquefaction evaluation and an assessment of potential consequences of any liquefaction and mitigation measures if the structure is in Seismic Design Categories D, E, or F. See IRC Section 401.4 for residential structures. The evaluation should address the possibility of local perched groundwater and the raising of groundwater levels by seasonal or longer term climatic fluctuations, landscape irrigation, and soil absorption systems (septic systems, infiltration basins, etc.).

A minimum boring depth of 50 feet below the existing ground surface is recommended for evaluating liquefaction hazard. From site borings, report SPT blow counts using the current ASTM D1586 standard (ASTM, 2011). CPT data according to the current ASTM D5778 standard (ASTM, 2012b) may be used, but only concurrent with SPT data for reliable correlation. Include complete liquefaction analysis information, including all calculations. Minimum acceptable safety factors for liquefaction generally range from 1.15 to 1.3. The final choice of an acceptable safety factor depends on many factors, such as the ground-motion parameters used, site conditions, likely ground-failure mode (settlement, lateral spread, etc.), and the critical nature of the structure or facility. Lower safety factors may be justified for large, infrequent earthquakes (e.g., the maximum credible earthquake (MCE) or the 2% probability of exceedance in 50-year event), less damaging failure modes, and non-essential facilities. Determine the likely ground-failure mode, amount of displacement, and acceptable safety factor, and evaluate cost-effective liquefaction mitigation. As this review of liquefaction is from a geologic standpoint, additional engineering review by a Utah-licensed Professional Engineer will be necessary.

Review Comments:

11. Seismically Induced Settlement or Ground Failure

Are the description and analysis of seismically induced settlement or ground failure appropriate and adequate for the proposed project?

Reports should include an evaluation of the potential for seismically induced settlement or ground failure (other than liquefaction), such as from sensitive clays or loose, granular soils, and tectonic subsidence accompanying surface faulting. For Seismic Design Category C, IBC Section 1803.5.11 requires an assessment of surface displacement due to faulting or lateral spreading. For Seismic Design Categories D, E, and F, IBC Section 1803.5.12 requires an assessment of potential consequences of soil strength loss, including estimating differential settlement, lateral movement, and reduction in foundation soil bearing capacity, and addressing mitigation measures. See IRC Section 401.4 for residential structures. As this review of seismically induced settlement or ground failure is from a geologic standpoint, additional engineering review by a Utah-licensed Professional Engineer is necessary.

Review Comments:

12. Problem Soil and Rock and Shallow Groundwater

Are the description and analysis of problem soil and rock and shallow groundwater appropriate and adequate for the proposed project?

Reports should include an evaluation of the potential for problem soil and/or rock and shallow groundwater. The evaluation should consider collapsible, expansive, soluble, organic, erosion, piping, and corrosive soil and/or rock. If collapsible soils are present, the site should be classified as Site Class F according to IBC Table 1613.5.2, and a site-specific geotechnical evaluation is required. IBC Section 1803.5.3 outlines site soil classification and additional criteria for expansive soils. See IRC Section 401.4 for residential structures. The evaluation should also consider non-engineered fill, mine- and groundwater-induced subsidence, shallow bedrock, karst, breccia pipes, sinkholes, caliche, and active sand dunes, as applicable. The evaluation should address the possibility of local perched groundwater and the raising of groundwater levels by seasonal or longer term climatic fluctuations, landscape irrigation, and soil absorption systems (septic systems, infiltration basins, etc.).

Review Comments:

13. Soil and Rock Slope Stability, Debris Flows, and Rockfall

Are the description and analysis of slope stability, debris flows, and rockfall appropriate and adequate for the proposed project?

Reports should provide an evaluation of the potential for slope failure in accordance with the Guidelines for Evaluating Landslide Hazards in Utah (Chapter 4), debris flows in accordance with the Guidelines for the Geologic Evaluation of Debris-Flow Hazards on Alluvial Fans in Utah (Chapter 5), and rockfall in accordance with Guidelines for Evaluation of Rockfall Hazards in Utah (Chapter 7). The slope stability evaluation must consider immediately adjacent property, constructed cut and fill slopes, existing landslides, appropriate seismic ground-shaking levels (pseudo-static coefficients), and development- and climatic-induced groundwater conditions. The evaluation must also consider snow avalanche hazards, where appropriate. IBC Section 1808.7 outlines building setbacks from slopes and IBC Appendix J outlines grading provisions for cuts and fills, drainage, slope benching, and erosion control.

Review Comments:

14. Flooding

Are the description and analysis of flooding appropriate and adequate for the proposed project? Reports should provide an evaluation of the potential for flooding and erosion on alluvial fans and from streams, lakes, dam failures, canals, and ditches. Determine the Federal Emergency Management Agency flood zone on a current, official flood map (http://msc.fema.gov). IBC Appendix G outlines flood-resistant construction guidelines.		
Review Comments:		

15. Seiches, Tsunamis, and Other Earthquake- or Landslide-Induced Flooding

Are the description and analysis of seiches, tsunamis, and other earthquake- or landslide-induced flooding appropriate and adequate for the proposed project? Reports should provide an evaluation of the potential for seiches and other earthquake- or landslide-induced flooding if the site is near a lake or reservoir.		
Review Comments:		

16. Radon

Are the description and analysis of radon hazards appropriate and adequate for the proposed project? Reports should provide an evaluation of the potential for naturally occurring radon gas at the site.		
Review Comments:		

17. Geologic-Hazard Zones, Maps, and Ordinances

Are the description and application of applicable geologic-hazard zones, maps, and ordinances appropriate and adequate for the proposed project? Review and cite applicable geologic-hazard zones, maps, ordinances, and zoning and building regulations required by the permitting jurisdiction.		
Review Comments:		

18. Conclusions

Are the report conclusions, including the description, analysis, and statement of geologic hazards supported with geologic evidence and appropriate reasoning? Are the conclusions appropriate and adequate for the proposed project? The degree of confidence in and limitations of data and conclusions must be clearly stated and documented in the report.		
Review Comments:		

19. Recommendations

Are the report recommendations for geologic-hazard mitigation supported by the investigation data and report conclusions? Any limitations on the investigation and recommendations for additional investigation must be clearly stated and documented in the report.		
Review Comments:		

20. Utah-Licensed Professional Geologist/Engineer Seal

Is the report stamped by a Utah-licensed Professional Geologist (PG), and if the report contains engineering analysis and/or recommendations, by a Utah-licensed Professional Engineer (PE), in responsible charge of the project? The engineering-geology report must be stamped and signed by the engineering geologist who conducted the investigation (Utah Code 58-76-602). The geologist must be licensed to practice geology in Utah. The Utah Division of Occupational and Professional Licensing (DOPL) defines a PG as a person licensed to engage in the practice of geology before the public, but does not define or license geologic specialists, such as engineering geologists. The UGS considers an engineering geologist to be a person who through education, training, and experience is able to assure that geologic factors affecting engineering works are recognized, adequately interpreted, and presented for use in engineering practice and/or the protection of the public; this person shall have a Bachelor's degree in geology or engineering geology from an accredited university and at least five full years of experience in a responsible charge engineering-geology position. If a geotechnical report or other engineering analysis and/or recommendations are included with the engineering-geology report, a PE licensed in Utah must also stamp and sign the report or pertinent sections. For more information, see http://dopl.utah.gov/.		
Review Comments:		

Review Summary, Notes, and Reviewer Professional Geologist (PG) Stamp

Review Comments:	Reviewer's Utah PG Stamp

SURFACE-FAULT-RUPTURE-HAZARD REPORT REVIEW CHECKLIST

For additional information, see chapters 2 and 3 of: Bowman, S.D., and Lund, W.R., editors, 2016, Guidelines for investigating geologic hazards and preparing engineering-geology reports, with a suggested approach to geologic-hazard ordinances in Utah: Utah Geological Survey Circular 122, p. 15–58.

Report and Review Information

Report Title:				
Report Type: _ Reconnaissance _ Preliminary _ Final _ Combined Engineering Geology/Geotechnical _ Other				
Author:		Project #:	**Adequately Documented**	**Additional Information Needed**
Location:		County:		
Reviewing Organization:		File #:		
Reviewed By:		Utah PG License #:		
First Review:	Review # ___:	Final Approval:		

1. Investigation/Report Purpose and Scope

Are the purpose and scope of the surface-faulting investigation appropriate and adequate for the proposed project?		
Review Comments:		

2. Project Description and Location

Is the description of the size, type of construction, intended foundation system, grade/floor elevations, building area (square feet), and International Building Code (IBC) risk category (Table 1604.5) appropriate and adequate for the proposed project? Reports should provide a marked location on an index map using a 7-1/2 minute U.S. Geological Survey (USGS) topographic map or equivalent base map; parcel number; provide the site latitude and longitude to four decimal places with datum; and a site development map adequate to show site boundaries, existing and proposed structures, other infrastructure, and relevant site topography. The scale of site development maps will vary depending on the size of the site and area of investigation; recommended scale is 1 inch = 200 feet (1:2400) or larger, as necessary.		
Review Comments:		

3. Literature Review

Is the surface-fault-rupture-hazard investigation literature review appropriate and adequate for the proposed project? Are references properly cited in the report and reference list?		
Review Comments:		

4. Analysis of Aerial Photographs and Other Remote-Sensing Data

Is the analysis of aerial photography and other remote-sensing data (as available) appropriate and adequate for the proposed project? Are aerial photographs and remote-sensing data properly documented and referenced? Report should list the source; project code; roll, line, and frame numbers; date; and scale for aerial photography used.		
Review Comments:		

5. Regional Geology and Geologic/Fault Maps

Are the description and analysis of the regional geology and geologic/Quaternary fault maps appropriate and adequate for the proposed project? Reports should provide a regional-scale (1:24,000 to 1:50,000) map showing the geology and location of all mapped or known Quaternary and other faults, including fault orientation (trend of surface trace, sense of displacement, etc.) and fault activity class (age category) (Chapter 3) within 10 miles of the site.		
Review Comments:		

6. Site-Specific Geology and Geologic Maps

Are the description and analysis of the site-specific geology, geologic maps, and cross-sections appropriate and adequate for the proposed project? Reports should describe site geology according to Guidelines for Conducting Engineering-Geology Investigations and Preparing Engineering-Geology Reports in Utah (Chapter 2), and provide a site-scale geologic map(s) showing geologic and soil units, Quaternary and other faults, seeps or springs, slope failures, lineaments investigated for evidence of faulting, and other geologic features existing on and near the project site. Maps should show locations of trenches, test pits, boreholes, geoprobe holes, cone penetrometer test (CPT) soundings, and geophysical lines. Scale of site geologic maps will vary depending on the size of the site and area of investigation; recommended scale is 1 inch = 200 feet (1:2400) or larger as necessary. Site geologic cross sections should be included as needed to illustrate three-dimensional geologic relations. The degree of detail and scale of site geologic mapping should be compatible with the geologic complexity of the site, type of building, and layout. For hillside sites, describe geology of both the site and adjacent properties, including any known or mapped landslides. If on-site investigations reveal the presence of a hazardous Quaternary fault, and fault avoidance is the surface-faulting-mitigation method chosen, a fault setback should be established following the method described in the Guidelines for Evaluating Surface-Fault-Rupture Hazards in Utah (Chapter 3). The fault setback should be shown on either the site-specific geologic map or on a separate surface-faulting-hazard map depending on site scale and complexity		
Review Comments:		

7. Trench and Test Pit Logs

Are trench and test pit logs appropriate and adequate for the proposed project? Reports should include logs for each trench and test pit excavated as part of the investigation whether faults are encountered or not. Logs should show details of geologic units and structures. Logs should be to scale and not generalized or diagrammatic, and may be on a rectified photomosaic base. The scale (horizontal and vertical) should be 1 inch = 5 feet (1:60) or larger as necessary with no vertical exaggeration. Logs should be prepared in the field and accurately reflect the features observed in the excavation. Photographs are not a substitute for trench logs. All logs should include the identity of the person who made the log.		
Review Comments:		

8. Borehole and CPT Logs

Are boreholes and CPT soundings appropriately located and interpreted for the proposed project? Reports should include logs for all boreholes and CPT soundings. Logs should include the geologic interpretation of deposit genesis for all layers and whether or not evidence of faulting was encountered. Because boreholes are typically multipurpose, borehole logs may also contain geotechnical, geologic, and groundwater data. All logs should include the identity of the person who made the log.		
Review Comments:		

9. Geophysical Interpretations

Are geophysical lines (if any) appropriately located on the site-specific geology map and adequately interpreted for the proposed project? Reports should include complete geophysical logs and accompanying data and field/geophysical interpretation reports.		
Review Comments:		

10. Conclusions

Are the report conclusions, including the description, analysis, and statement of relative surface-faulting hazard, supported with geologic evidence and appropriate reasoning? Are the conclusions appropriate and adequate for the proposed project? The report should evaluate the surface-faulting hazard present at the site and state the relation to existing or proposed infrastructure. The report should include a statement of relative risk and address the potential for future surface faulting. The degree of confidence in and limitations of data and conclusions must be clearly stated and documented in the report.		
Review Comments:		

11. Recommendations

Are the report recommendations for surface-faulting mitigation supported by the investigation data and report conclusions? If the investigation reveals the presence of a hazardous Quaternary fault(s), and fault avoidance is the surface-faulting- mitigation method chosen, an appropriate fault setback should be established following the method described in Guidelines for Evaluating Surface-Fault-Rupture Hazards in Utah (Chapter 3) and shown on either the site-specific geologic map or on a separate surface-faulting-hazard map depending on site scale and complexity. If engineering-design mitigation of surface faulting is proposed, the recommendation must be based on adequate data to characterize the faults past displacement history sufficient for engineering-design purposes (recommend three closed seismic cycles – four paleoearthquakes; see Guidelines for Evaluating Surface-Fault-Rupture Hazards in Utah [Chapter 3). Any limitations on the investigation and recommendations for additional investigation must be clearly stated and documented in the report.		
Review Comments:		

12. Utah-Licensed Professional Geologist/Engineer Seal

Is the report stamped by a Utah-licensed Professional Geologist (PG), and if the report contains engineering analysis and/or recommendations, by a Utah-licensed Professional Engineer (PE) in responsible charge of the project? The engineering-geology report must be stamped and signed by the engineering geologist who conducted the investigation (Utah Code 58-76-602). The geologist must be licensed to practice geology in Utah. The Utah Division of Occupational and Professional Licensing (DOPL) defines a PG as a person licensed to engage in the practice of geology before the public, but does not define or license geologic specialists, such as engineering geologists. The UGS considers an engineering geologist to be a person who through education, training, and experience is able to assure that geologic factors affecting engineering works are recognized, adequately interpreted, and presented for use in engineering practice and/or the protection of the public; this person shall have a Bachelor's degree in geology, engineering geology, or a closely related field from an accredited university and at least five full years of experience in a responsible engineering-geology position. If a geotechnical report or other engineering analysis and/or recommendations (including liquefaction analysis) are included with the engineering-geology report, a PE licensed in Utah must also stamp and sign the report or pertinent sections. For more information, see http://dopl.utah.gov/.		
Review Comments:		

Review Summary, Notes, and Reviewer Professional Geologist (PG) Stamp

Review Comments:	Reviewer's Utah PG Stamp

LANDSLIDE-HAZARD REPORT REVIEW CHECKLIST

For additional information, see chapters 2 and 4 of: Bowman, S.D., and Lund, W.R., editors, 2016, Guidelines for investigating geologic hazards and preparing engineering-geology reports, with a suggested approach to geologic-hazard ordinances in Utah: Utah Geological Survey Circular 122, p. 15–30, 59–73.

Report and Review Information

Report Title:				
Report Type: _ Reconnaissance _ Preliminary _ Final _ Combined Engineering Geology/Geotechnical _ Other				
Author:		Project #:	Adequately Documented	Additional Information Needed
Location:		County:		
Reviewing Organization:		File #:		
Reviewed By:		Utah PG License #:		
First Review:	Review # ___:	Final Approval:		

1. Investigation/Report Purpose and Scope

Are the purpose and scope of the landslide-hazards investigation appropriate and adequate for the proposed project?		
Review Comments:		

2. Project Description and Location

Is the description of the size, type of construction, intended foundation system, grade/floor elevations, building area (square feet), and International Building Code (IBC) risk category (Table 1604.5) appropriate and adequate for the proposed project? Reports should provide a marked location on an index map using a 7-1/2 minute U.S. Geological Survey topographic map or equivalent base map; parcel number; provide the site latitude and longitude to four decimal places with datum; and a site development map adequate to show site boundaries, existing and proposed structures, other infrastructure, and relevant site topography. The scale of site development maps will vary depending on the size of the site and area of investigation; recommended scale is 1 inch = 200 feet (1:2400) or larger, as necessary.		
Review Comments:		

3. Literature Review

Is the landslide-hazard-investigation literature review appropriate and adequate for the proposed project? Are references properly cited in the report and reference list?		
Review Comments:		

4. Analysis of Aerial Photographs and Other Remote Sensing Data

Is the analysis of aerial photography and other remote sensing data (as available) appropriate and adequate for the proposed project? Are aerial photographs and remote-sensing data properly documented and referenced? Report should list the source; project code; roll, line, and frame numbers; date; and scale for aerial photography used.		
Review Comments:		

5. Regional Geology and Geologic/Fault Maps

Are the description and analysis of the regional geology and geologic/Quaternary fault maps appropriate and adequate for the proposed project? Reports should provide a regional-scale (1:24,000 to 1:50,000) map showing the geology and location of all mapped or known Quaternary and other faults, including fault orientation (trend of surface trace, sense of displacement, etc.) and fault activity class (age category) within 10 miles of the site.		
Review Comments:		

6. Site-Specific Geology and Geologic Maps

Are the description and analysis of the site-specific geology, geologic maps, and cross-sections appropriate and adequate for the proposed project? Reports should describe site geology according to Guidelines for Conducting Engineering-Geology Investigations and Preparing Engineering-Geology Reports in Utah (Chapter 2), and provide a site-scale geologic map(s) showing geologic and soil units, Quaternary and other faults, seeps or springs, slope failures, lineaments investigated for evidence of faulting, and other geologic features existing on and near the project site. Maps should show locations of trenches, test pits, boreholes, geoprobe holes, cone penetrometer test (CPT) soundings, and geophysical lines. Scale of site geologic maps will vary depending on the size of the site and area of investigation; recommended scale is 1 inch = 200 feet (1:2400) or larger as necessary. Site geologic cross sections should be included as needed to illustrate three-dimensional geologic relations. The degree of detail and scale of site geologic mapping should be compatible with the geologic complexity of the site, type of building, and layout, and should describe the geology of both the site and adjacent properties, including any known or mapped landslides.		
Review Comments:		

7. Landslide Hazard Map

Is the map showing landslide-hazard-zone boundaries and additional recommended setbacks (if any) appropriate and adequate for the proposed project? If on-site investigations reveal the presence of a landslide hazard, the boundary of the hazard zone with an appropriate building setback should be shown on either the site-specific geologic map or on a separate landslide-hazard map depending on site scale and complexity, and include a statement on uncertainty.		
Review Comments:		

8. Subsurface Investigation

Is the description and analysis of the subsurface investigation, including piezometers and/or slope instrumentation (if any), appropriate and adequate for the proposed project? Reports should provide subsurface engineering-geology and geotechnical information, including a site-specific plan view map showing exploration sites (borings, test pits, trenches, etc.), existing groundwater levels, and areas of existing and planned cuts and fills. Logs are required for all boreholes, standard penetration tests (SPT), and CPT soundings. Logs should include the geologic interpretation of deposit genesis for all layers. Because boreholes are typically multipurpose, borehole logs may also include geotechnical, geologic, and groundwater data. All logs should include the identity of the person who made the log.		
Review Comments:		

9. Geophysical Interpretations

Are geophysical lines (if any) appropriately located on the site-specific geology map and adequately interpreted for the proposed project? Reports should include complete geophysical logs and accompanying data and field/geophysical interpretation reports.		
Review Comments:		

10. Conclusions

Are the report conclusions, including the description, analysis, and statement of landslide hazards supported with geologic evidence and appropriate reasoning? Are the conclusions appropriate and adequate for the proposed project? The report should evaluate the landslide hazard present at or adjacent to the site and state the relation to existing or proposed infrastructure. The report should include a statement of relative risk and address the potential for future landslides. Boundaries of landslide hazard zones must be defined and include a statement/measure of boundary uncertainty. The degree of confidence in and limitations of data and conclusions must be clearly stated and documented in the report.		
Review Comments:		

11. Recommendations

Are the report recommendations for landslide-hazard mitigation supported by the investigation data and report conclusions? If a landslide hazard is present on site, the report should provide and justify building setbacks or other mitigation recommendations to control landslides and reduce risk. Any limitations on the investigation and recommendations for additional investigation must be clearly stated and documented in the report.		
Review Comments:		

12. Utah-Licensed Professional Geologist/Engineer Seal

Is the report stamped by a Utah-licensed Professional Geologist (PG), and if the report contains engineering analysis and/or recommendations, by a Utah-licensed Professional Engineer (PE) in responsible charge of the project? The engineering-geology report must be stamped and signed by the engineering geologist who conducted the investigation (Utah Code 58-76-602). The geologist must be licensed to practice geology in Utah. The Utah Division of Occupational and Professional Licensing (DOPL) defines a PG as a person licensed to engage in the practice of geology before the public, but does not define or license geologic specialists, such as engineering geologists. The UGS considers an engineering geologist to be a person who through education, training, and experience is able to assure that geologic factors affecting engineering works are recognized, adequately interpreted, and presented for use in engineering practice and/or the protection of the public; this person shall have a Bachelor's degree in geology, engineering geology, or a closely related field from an accredited university and at least five full years of experience in a responsible engineering-geology position. If a geotechnical report or other engineering analysis and/or recommendations (including liquefaction analysis) are included with the engineering-geology report, a PE licensed in Utah must also stamp and sign the report or pertinent sections. For more information, see http://dopl.utah.gov/.		
Review Comments:		

Review Summary, Notes, and Reviewer Professional Geologist (PG) Stamp

Review Comments:	Reviewer's Utah PG Stamp

DEBRIS-FLOW-HAZARD REPORT REVIEW CHECKLIST

For additional information, see chapters 2 and 5 of: Bowman, S.D., and Lund, W.R., editors, 2016, Guidelines for investigating geologic hazards and preparing engineering-geology reports, with a suggested approach to geologic-hazard ordinances in Utah: Utah Geological Survey Circular 122, p. 15–30, 75–91.

Report and Review Information

Report Title:				
Report Type: _ Reconnaissance _ Preliminary _ Final _ Combined Engineering Geology/Geotechnical _ Other				
Author:		Project #:	**Adequately Documented**	**Additional Information Needed**
Location:		County:		
Reviewing Organization:		File #:		
Reviewed By:		Utah PG License #:		
First Review:	Review # ___:	Final Approval:		

1. Investigation/Report Purpose and Scope

Are the purpose and scope of the debris-flow-hazard investigation appropriate and adequate for the proposed project?		
Review Comments:		

2. Project Description and Location

Is the description of the size, type of construction, intended foundation system, grade/floor elevations, building area (square feet), and International Building Code (IBC) risk category (Table 1604.5) appropriate and adequate for the proposed project? Reports should provide a marked location on an index map using a 7-1/2 minute U.S. Geological Survey (USGS) topographic map or equivalent base map; parcel number; provide the site latitude and longitude to four decimal places with datum; and a site development map adequate to show site boundaries, existing and proposed structures, other infrastructure, and relevant site topography. The scale of site development maps will vary depending on the size of the site and area of investigation; recommended scale is 1 inch = 200 feet (1:2400) or larger, as necessary.		
Review Comments:		

3. Literature Review

Is the debris-flow-hazard-investigation literature review appropriate and adequate for the proposed project? Are references properly cited in the report and reference list?		
Review Comments:		

4. Analysis of Aerial Photographs and Other Remote-Sensing Data

Is the analysis of aerial photography and other remote-sensing data (as available) appropriate and adequate for the proposed project? Are aerial photographs and remote-sensing data properly documented and referenced? Report should list the source; project code; roll, line, and frame numbers; date; and scale for aerial photography used.		
Review Comments:		

5. Regional Geology and Geologic/Fault Maps

Are the description and analysis of the regional geology and geologic/Quaternary fault maps appropriate and adequate for the proposed project? Reports should provide a regional-scale (1:24,000 to 1:50,000) map showing the geology and location of all mapped or known Quaternary and other faults, including fault orientation (trend of surface trace, sense of displacement, etc.) and fault activity class (age category) within 10 miles of the site.		
Review Comments:		

6. Site-Specific Geology and Geologic Maps

Are the description and analysis of the site-specific geology, geologic maps, and cross-sections appropriate and adequate for the proposed project? Reports should describe site geology according to Guidelines for Conducting Engineering-Geology Investigations and Preparing Engineering-Geology Reports in Utah (Chapter 2, this volume), and provide a site-scale geologic map(s) showing geologic and soil units, Quaternary and other faults, seeps or springs, slope failures, lineaments investigated for evidence of faulting, and other geologic features existing on and near the project site. Maps should show locations of trenches, test pits, boreholes, geoprobe holes, cone penetrometer test soundings, and geophysical lines. Scale of site geologic maps will vary depending on the size of the site and area of investigation; recommended scale is 1 inch = 200 feet (1:2400) or larger as necessary. Site geologic cross sections should be included as needed to illustrate three-dimensional geologic relations. The degree of detail and scale of site geologic mapping should be compatible with the geologic complexity of the site, type of building, and layout. For hillside sites, describe geology of both the site and adjacent properties, including any known or mapped landslides.		
Review Comments:		

7. Alluvial-Fan Evaluation

Is the alluvial-fan evaluation appropriate and adequate for the proposed project? Report should provide a site-scale surficial geologic map of the alluvial fan showing debris flow and alluvial deposits. The map should be provided at an appropriate scale for the fan investigated. The fan evaluation should provide basis for design flow-volume estimates (deposit thickness and area estimates). The fan evaluation should also state the anticipated probability of occurrence and volume, flow type(s), flow depth, deposition area, runout, gradation of debris, flow impact forces, stream-flow inundation and sediment burial depths, and age estimates or other evidence used to estimate the frequency of past debris flows.		
Review Comments:		

8. Drainage-Basin and Channel Evaluation

Is the drainage-basin and channel evaluation adequate for the proposed project? Report should provide a site-scale geologic map of the drainage basin showing surficial and bedrock geology at an appropriate scale for the drainage basin investigated. The evaluation should include an estimate of the susceptibility of the drainage basin to shallow landsliding, likely landslide volume(s), and volume of historical landslides, if present. A longitudinal channel profile, showing gradients from headwaters to the alluvial fan should be provided along with cross-channel profiles and a map showing their locations. The evaluation should include a basis for channel volume estimates including initial debris slides, total feeder channel length, length of channel lined by bedrock, and estimated volume of channel sediment available for sediment bulking, including estimated bulking rate(s) in cubic yards per linear foot of channel.		
Review Comments:		

9. Frequency and Magnitude Considerations for Risk Reduction

Are the debris-flow frequency and magnitude estimates of geologic parameters for engineering design appropriate for proposed risk-reduction measures? Investigators must state how the frequency and magnitude were determined and why they are appropriate for use in design of risk-reduction measures.		
Review Comments:		

10. Estimated Geologic Parameters for Engineering Design

Are the estimates of geologic parameters for engineering design appropriate for proposed risk-reduction structures? Many debris-flow design-parameter estimates have high levels of uncertainty; investigators must clearly state the limitations of the evaluation methods employed and the uncertainties associated with design-parameter estimates.		
Review Comments:		

11. Conclusions

Are the report conclusions, including the description, analysis, and statement of debris-flow hazards supported with geologic evidence and appropriate reasoning? Are the conclusions appropriate and adequate for the proposed project? Report should evaluate the debris-flow hazard present at or adjacent to the site and state the hazards relation to existing or proposed infrastructure. The report should include a statement of relative risk or quantified risk, address future debris-flow potential, and address the potential impacts from future debris flows. The limitations and uncertainty of data and conclusions must be clearly stated and documented in the report.		
Review Comments:		

12. Recommendations

Are the report recommendations for debris-flow hazard mitigation supported by the investigation data and report conclusions? Any limitations on the investigation and recommendations for additional investigation must be clearly stated and documented in the report.		
Review Comments:		

13. Utah-Licensed Professional Geologist/Engineer Seal

Is the report stamped by a Utah-licensed Professional Geologist (PG), and if the report contains engineering analysis and/or recommendations, by a Utah-licensed Professional Engineer (PE) in responsible charge of the project? The engineering-geology report must be stamped and signed by the engineering geologist who conducted the investigation (Utah Code 58-76-602). The geologist must be licensed to practice geology in Utah. The Utah Division of Occupational and Professional Licensing (DOPL) defines a PG as a person licensed to engage in the practice of geology before the public, but does not define or license geologic specialists, such as engineering geologists. The UGS considers an engineering geologist to be a person who through education, training, and experience is able to assure that geologic factors affecting engineering works are recognized, adequately interpreted, and presented for use in engineering practice and/or the protection of the public; this person shall have a Bachelor's degree in geology, engineering geology, or a closely related field from an accredited university and at least five full years of experience in a responsible engineering-geology position. If a geotechnical report or other engineering analysis and/or recommendations (including liquefaction analysis) are included with the engineering-geology report, a PE licensed in Utah must also stamp and sign the report or pertinent sections. For more information, see http://dopl.utah.gov/.		
Review Comments:		

Review Summary, Notes, and Reviewer Professional Geologist (PG) Stamp

Review Comments:	Reviewer's Utah PG Stamp

LAND-SUBSIDENCE AND EARTH-FISSURE-HAZARD REPORT REVIEW CHECKLIST

For additional information, see chapters 2 and 6 of: Bowman, S.D., and Lund, W.R., editors, 2016, Guidelines for investigating geologic hazards and preparing engineering-geology reports, with a suggested approach to geologic-hazard ordinances in Utah: Utah Geological Survey Circular 122, p. 15–30, 93–110.

Report and Review Information

Report Title:				
Report Type: _ Reconnaissance _ Preliminary _ Final _ Combined Engineering Geology/Geotechnical _ Other				
Author:		Project #:	**Adequately Documented**	**Additional Information Needed**
Location:		County:		
Reviewing Organization:		File #:		
Reviewed By:		Utah PG License #:		
First Review:	Review # ___:	Final Approval:		

1. Investigation/Report Purpose and Scope

Are the purpose and scope of the land-subsidence and earth-fissure-hazard investigation appropriate and adequate for the proposed project?		
Review Comments:		

2. Project Description and Location

Is the description of the size, type of construction, intended foundation system, grade/floor elevations, building area (square feet), and International Building Code (IBC) risk category (Table 1604.5) appropriate and adequate for the proposed project? Reports should provide a marked location on an index map using a 7-1/2 minute U.S. Geological Survey (USGS) topographic map or equivalent base map; parcel number; provide the site latitude and longitude to four decimal places with datum; and a site development map adequate to show site boundaries, existing and proposed structures, other infrastructure, and relevant site topography. The scale of site development maps will vary depending on the size of the site and area of investigation; recommended scale is 1 inch = 200 feet (1:2400) or larger, as necessary.		
Review Comments:		

3. Literature Review

Is the land-subsidence and earth-fissure-hazard investigation literature review appropriate and adequate for the proposed project? Are references properly cited in the report and reference list?		
Review Comments:		

4. Analysis of Aerial Photographs and Other Remote-Sensing Data

Is the analysis of aerial photography and other remote-sensing data (as available) appropriate and adequate for the proposed project? Are aerial photographs and remote-sensing data properly documented and referenced? Report should list the source; project code; roll, line, and frame numbers; date; and scale for aerial photography used.		
Review Comments:		

5. Regional Geology and Geologic/Fault/Subsidence Maps

Is the description and analysis of the regional geology and geologic/Quaternary fault/subsidence maps appropriate and adequate for the proposed project? Reports should provide a regional-scale (1:24,000 to 1:50,000) map showing the geology and location of all mapped or known Quaternary and other faults, including fault orientation (trend of surface trace, sense of displacement, etc.) and fault activity class (age category) within 10 miles of the site.		
Review Comments:		

6. Site-Specific Geology and Geologic Maps

Are the description and analysis of the site-specific geology, geologic maps, and cross-sections appropriate and adequate for the proposed project? Reports should describe site geology according to Guidelines for Conducting Engineering-Geology Investigations and Preparing Engineering-Geology Reports in Utah (Chapter 2, this volume), this volume and provide a site-scale geologic map(s) showing geologic and soil units, Quaternary and other faults, seeps or springs, slope failures, lineaments investigated for evidence of faulting, and other geologic features existing on and near the project site. Maps should show locations of trenches, test pits, boreholes, geoprobe holes, cone penetrometer test (CPT) soundings, and geophysical lines. Scale of site geologic maps will vary depending on the size of the site and area of investigation; recommended scale is 1 inch = 200 feet (1:2400) or larger as necessary. Site geologic cross sections should be included as needed to illustrate three-dimensional geologic relations. The degree of detail and scale of site geologic mapping should be compatible with the geologic complexity of the site, type of building, and layout. For hillside sites, describe geology of both the site and adjacent properties, including any known or mapped landslides.		
Review Comments:		

7. Subsurface Investigation

Are the description and analysis of the subsurface investigation, including wells, piezometers, and instrumentation (if any), appropriate and adequate for the proposed project? Reports should provide subsurface engineering-geology and geotechnical information, including a site-specific plan view map showing exploration sites (borings, CPT soundings, test pits, trenches, etc.), existing groundwater levels, and areas of existing and planned cuts and fills. Logs are required for all boreholes, Standard Penetration Tests (SPT), and CPT soundings. Logs should include the geologic interpretation of deposit genesis for all layers. Because boreholes are typically multipurpose, borehole logs may also include geotechnical, geologic, and groundwater data. All logs should include the identity of the person who made the log.		
Review Comments:		

8. Benchmarks and Other Elevation Data

Are benchmarks and other elevation data appropriately located on the regional and site-specific geology maps and adequately interpreted for the proposed project? Reports should include background data on elevation data used for the project, including surveying reports.		
Review Comments:		

9. Geophysical Interpretations

Are geophysical lines (if any) appropriately located on the site-specific geology map and adequately interpreted for the proposed project? Reports should include complete geophysical logs and accompanying data and field/geophysical interpretation reports.		
Review Comments:		

10. Conclusions

Are the report conclusions, including the description, analysis, and statement of land subsidence and earth fissures supported with geologic evidence and appropriate reasoning? Are the conclusions appropriate and adequate for the proposed project? The report should evaluate the land-subsidence and earth-fissure hazard present at or adjacent to the site and state the relation to existing or proposed infrastructure. The report should include a statement of relative risk and address the potential for future land subsidence or earth fissure formation. The degree of confidence in and limitations of data and conclusions must be clearly stated and documented in the report.		
Review Comments:		

11. Recommendations

Are the report recommendations for land-subsidence and earth-fissure-hazard mitigation supported by the investigation data and report conclusions? If a land subsidence and/or earth-fissure hazard is present on site, the report must provide and justify earth-fissure setbacks and/or other land-subsidence or earth-fissure mitigation recommendations to reduce risk. Any limitations on the investigation and recommendations for additional investigation must be clearly stated and documented in the report.		
Review Comments:		

13. Utah-Licensed Professional Geologist/Engineer Seal

Is the report stamped by a Utah-licensed Professional Geologist (PG), and if the report contains engineering analysis and/or recommendations, by a Utah-licensed Professional Engineer (PE) in responsible charge of the project? The engineering-geology report must be stamped and signed by the engineering geologist who conducted the investigation (Utah Code 58-76-602). The geologist must be licensed to practice geology in Utah. The Utah Division of Occupational and Professional Licensing (DOPL) defines a PG as a person licensed to engage in the practice of geology before the public, but does not define or license geologic specialists, such as engineering geologists. The UGS considers an engineering geologist to be a person who through education, training, and experience is able to assure that geologic factors affecting engineering works are recognized, adequately interpreted, and presented for use in engineering practice and/or the protection of the public; this person shall have a Bachelor's degree in geology, engineering geology, or a closely related field from an accredited university and at least five full years of experience in a responsible engineering-geology position. If a geotechnical report or other engineering analysis and/or recommendations (including liquefaction analysis) are included with the engineering-geology report, a PE licensed in Utah must also stamp and sign the report or pertinent sections. For more information, see http://dopl.utah.gov/.		
Review Comments:		

Review Summary, Notes, and Reviewer Professional Geologist (PG) Stamp

Review Comments:	Reviewer's Utah PG Stamp

ROCKFALL-HAZARD REPORT REVIEW CHECKLIST

For additional information, see chapters 2 and 7 of: Bowman, S.D., and Lund, W.R., editors, 2016, Guidelines for investigating geologic hazards and preparing engineering-geology reports, with a suggested approach to geologic-hazard ordinances in Utah: Utah Geological Survey Circular 122, p. 15–30, 111–123.

Report and Review Information

Report Title:				
Report Type: _ Reconnaissance _ Preliminary _ Final _ Combined Engineering Geology/Geotechnical _ Other				
Author:		Project #:	**Adequately Documented**	**Additional Information Needed**
Location:		County:		
Reviewing Organization:		File #:		
Reviewed By:		Utah PG License #:		
First Review:	Review # ___:	Final Approval:		

1. Investigation/Report Purpose and Scope

Are the purpose and scope of the rockfall-hazard investigation appropriate and adequate for the proposed project?		
Review Comments:		

2. Project Description and Location

Is the description of the size, type of construction, intended foundation system, grade/floor elevations, building area (square feet), and International Building Code (IBC) risk category (Table 1604.5) appropriate and adequate for the proposed project? Reports should provide a marked location on an index map using a 7-1/2 minute U.S. Geological Survey (USGS) topographic map or equivalent base map; parcel number; provide the site latitude and longitude to four decimal places with datum; and a site development map adequate to show site boundaries, existing and proposed structures, other infrastructure, and relevant site topography. The scale of site development maps will vary depending on the size of the site and area of investigation; recommended scale is 1 inch = 200 feet (1:2400) or larger, as necessary.		
Review Comments:		

3. Literature Review

Is the rockfall-hazard-investigation literature review appropriate and adequate for the proposed project? Are references properly cited in the report and reference list?		
Review Comments:		

4. Analysis of Aerial Photographs and Other Remote Sensing Data

Is the analysis of aerial photography and other remote-sensing data (as available) appropriate and adequate for the proposed project? Are aerial photographs and remote-sensing data properly documented and referenced? Report should list the source; project code; roll, line, and frame numbers; date; and scale for aerial photography used.		
Review Comments:		

4. Regional Geology and Geologic/Fault Maps

Is the description and analysis of the regional geology and geologic/Quaternary fault maps appropriate and adequate for the proposed project? Reports should provide a regional-scale (1:24,000 to 1:50,000) map showing the geology and location of all mapped or known Quaternary and other faults, including fault orientation (trend of surface trace, sense of displacement, etc.) and fault activity class (age category) within 10 miles of the site.		
Review Comments:		

5. Site-Specific Geology and Geologic Maps

Is the description and analysis of the site-specific geology, geologic maps, and cross-sections appropriate and adequate for the proposed project? Reports should describe site geology according to Guidelines for Conducting Engineering-Geology Investigations and Preparing Engineering-Geology Reports in Utah (Chapter 2, this volume), and provide a site-scale geologic map(s) showing geologic and soil units, Quaternary and other faults, seeps or springs, slope failures, lineaments investigated for evidence of faulting, and other geologic features existing on and near the project site. Maps should show locations of trenches, test pits, boreholes, geoprobe holes, cone penetrometer test (CPT) soundings, and geophysical lines. Scale of site geologic maps will vary depending on the size of the site and area of investigation; recommended scale is 1 inch = 200 feet (1:2400) or larger as necessary. Site geologic cross sections should be included as needed to illustrate three-dimensional geologic relations. The degree of detail and scale of site geologic mapping should be compatible with the geologic complexity of the site, type of building, and layout. For hillside sites, describe geology of both the site and adjacent properties, including any known or mapped landslides and rockfall source areas.		
Review Comments:		

6. Rockfall-Hazard Map

Is the map showing rockfall runout zone boundaries and additional recommended setbacks (if any) appropriate and adequate for the proposed project? If on-site investigations reveal the presence of a rockfall hazard, the boundary of the rockfall runout zone with an appropriate building setback (if any) should be shown with a statement/measure of runout zone boundary uncertainty. In general, the greater the uncertainty in the runout zone boundary, the greater the setback distance.		
Review Comments:		

7. Boreholes/Piezometers/Slope Monitoring Instrumentation Logs

Are boreholes, piezometers, and slope instrumentation (if any) locations appropriately located, documented, and interpreted for the proposed project? The report should provide surface and subsurface engineering-geology and geotechnical information, including a site-specific plan view map showing exploration sites (borings, CPT soundings, test pits, trenches, etc.), existing groundwater levels, and areas of existing and planned cuts and fills. Logs are required for all boreholes and CPT soundings, and should include the geologic interpretation of deposit genesis, weathering, fracturing, and other data relevant to rockfall genesis. Because boreholes are typically multipurpose, borehole logs may also include geotechnical, geologic, and groundwater data. All logs should include the identity of the person who made the log.		
Review Comments:		

8. Scanline and Geophysical Interpretations

Are scanlines and geophysical lines (if any) appropriately located on the site-specific geology map and adequately interpreted for the proposed project? Reports should include complete geophysical logs and accompanying data and field/geophysical interpretation reports.		
Review Comments:		

9. Conclusions

Are the report conclusions, including the description, analysis, and statement of relative rockfall hazard supported with geologic evidence and appropriate reasoning? Are the conclusions appropriate and adequate for the proposed project? Report must evaluate the rockfall hazard present at or adjacent to the site and state the hazards relation to existing or proposed infrastructure. The report should include a statement of relative risk and address the potential for future rockfalls. Boundaries of rockfall runout zones must be defined and include a statement/measure of boundary uncertainty. The degree of confidence in and limitations of data and conclusions must be clearly stated and documented in the report.		
Review Comments:		

10. Recommendations

Are the report recommendations for rockfall-hazard mitigation supported by the investigation data and report conclusions? If a rockfall hazard is present on site, the report must provide and justify runout zones and building setbacks or other mitigation recommendations to control rockfalls and reduce risk. Any limitations on the investigation and recommendations for additional investigation must be clearly stated and documented in the report.		
Review Comments:		

11. Utah-Licensed Professional Geologist/Engineer Seal

Is the report stamped by a Utah-licensed Professional Geologist (PG), and if the report contains engineering analysis and/or recommendations, by a Utah-licensed Professional Engineer (PE) in responsible charge of the project? The engineering-geology report must be stamped and signed by the engineering geologist who conducted the investigation (Utah Code 58-76-602). The geologist must be licensed to practice geology in Utah. The Utah Division of Occupational and Professional Licensing (DOPL) defines a PG as a person licensed to engage in the practice of geology before the public, but does not define or license geologic specialists, such as engineering geologists. The UGS considers an engineering geologist to be a person who through education, training, and experience is able to assure that geologic factors affecting engineering works are recognized, adequately interpreted, and presented for use in engineering practice and/or the protection of the public; this person shall have a Bachelor's degree in geology, engineering geology, or a closely related field from an accredited university and at least five full years of experience in a responsible engineering-geology position. If a geotechnical report or other engineering analysis and/or recommendations (including liquefaction analysis) are included with the engineering-geology report, a PE licensed in Utah must also stamp and sign the report or pertinent sections. For more information, see http://dopl.utah.gov/.		
Review Comments:		

Review Summary, Notes, and Reviewer Professional Geologist (PG) Stamp

Review Comments:	Reviewer's Utah PG Stamp

APPENDIX B
GLOSSARY OF GEOLOGIC-HAZARD AND OTHER TERMS

The Organ, typical Entrada Sandstone monolith in Arches National Park. The Three Gossips can be seen in the background. Photo credit: Gregg Beukelman, May 5, 2014.

GLOSSARY OF GEOLOGIC-HAZARD AND OTHER TERMS

Abandoned landslide – Inactive landslide which is no longer affected by its original causes. An example would be of a landslide whose movement is caused by stream erosion at its toe. The stream then changes course and the movement stops.

Acceptable and reasonable risk – A level of risk at which it is expected that there will be no loss of life or significant injury to occupants, no release of hazardous or toxic substances, and no more than minimal structural damage (i.e., physically and economically reasonable to repair) to critical infrastructure, critical facilities, or to structures designed for human occupancy, in the event that the anticipated geologic hazard were to occur.

Active landslide – Landslide that is currently moving; first-time movement or reactivated.

Active sand dunes – Shifting sand moved by wind. May present a hazard to existing structures (burial) or roadways (burial, poor visibility).

Activity class (of a fault) – The level of activity as defined by WSSPC (2011) of a fault based on the time of most recent rupture of the ground surface. Holocene activity class means movement of a fault that has broken the ground surface in approximately the past 11,700 years, shown as "<15,000 years" on the Quaternary Fault and Fold Database of the United States); Late Quaternary activity class means movement of a fault that has broken the ground surface in approximately the past 130,000 years; and, Quaternary activity class means movement of a fault that has broken the ground surface in approximately the past 2.6 million years. Depending on local conditions, faults in any activity class may be buried or concealed.

Alluvial fan – A generally low, cone-shaped deposit formed by deposition from a stream issuing from mountains as it flows onto a lowland.

Alluvial-fan flooding – Flooding of an alluvial-fan surface by overland (sheet) flow or flow in channels (stream flow, debris flow) branching outward from a canyon mouth. See also, alluvial fan.

Alluvial-fan surface, active – An alluvial-fan surface where the fan-building processes of flooding, debris flow, sediment deposition, and erosion are active or potentially active during storm or snowmelt events. Active portions of the fan have generally shallow stream channels, often braiding into several channels that distribute alluvium broadly across the fan surface. Active alluvial-fan surfaces receiving periodic sedimentation are typically rough (numerous boulders and cobbles at the surface) and support sparse vegetation.

Alluvial-fan surface, inactive – An alluvial-fan surface where the fan-building processes are no longer active. Inactive fan surfaces are stable and usually marked by well-developed soil and plant succession. Stream channels are generally single strand, incised below the inactive fan surface, and associated with a flat, low floodplain terrace. Floods along channels on inactive alluvial-fan surfaces behave as normal riverine floods.

Avalanche (snow) – A large mass of snow or ice that moves rapidly down a mountain slope.

Buildable area – That portion of a site, lot, or parcel that is entitled to contain the proposed improvement (for example, complies with zoning and building setbacks); and, either will not be impacted by a geologic hazard, or has all identified geologic hazards mitigated to an acceptable and reasonable risk. Any mitigation necessary to deem a geologically hazardous area as "buildable" must be based on an approved geologic-hazard report and engineered methods.

Canal/ditch flooding – Flooding due to overtopping or breaching of canals or ditches.

Collapsible soil – Soil that has considerable strength in its dry, natural state, but that settles significantly due to hydrocompaction when wetted; usually associated with young alluvial fans, debris flows, and loess.

Complex landslide – Landslide activity where a landslide exhibits at least two types of movement (fall, topple, slide, spread, or flow) in sequence.

Composite landslide – Landslide activity where a landslide exhibits at least two types of movement (fall, topple, slide, spread, or flow) in different parts of the displaced mass at the same time.

Creep – (a) Deformation that continues under constant stress. (b) A very slow to extremely slow rate of movement; not a recommended term, use very slow or extremely slow instead.

Crown – Non-displaced ground adjacent to the highest part of the main scarp of a landslide.

Dam-failure flooding – Flooding downstream from a dam caused by an unintentional release of water due to a partial or complete dam failure.

Debris – Any surficial accumulation of loose material that contains a significant proportion of coarse material; 20% to 80% of inorganic particles are larger than 2 mm (the upper limit of sand-size particles).

Debris flow – Slurry of rock, soil, organic matter, and water (generally >60% sediment by volume) that flows down channels and onto alluvial fans. May be initiated by erosion during a cloudburst storm or by a shallow (slip surface generally less than 10 feet deep) slope failure on a steep mountain slope. Debris flows can quickly travel long distances from their source areas, presenting hazards to life and property along stream channels and on or near downstream alluvial fans.

Development – For purposes of these guidelines, development includes the installation and construction of roads, utility lines/conveyances, subdivision improvements, buildings, structures, and physical improvements accessory to any of these uses.

Displaced material – Material moved from its original position by a landslide; includes both the depleted and accumulated masses (depletion and accumulation).

Dormant landslide – Inactive landslide that can be reactivated by its original or other causes.

Dormant-historic landslide – Slopes with evidence of previous landslide activity that have undergone most recent movement within preceding 100 years.

Dormant-young landslide – slopes with evidence of previous landslide activity that have undergone most recent movement during an estimated period of 100–5000 years before present.

Dormant-mature landslide – Slopes with evidence of previous landslide activity that have undergone most recent movement during an estimated period of 5000–10,000 years before present.

Dormant-old landslide – Slopes with evidence of previous landslide activity that have undergone most recent movement during an estimated period greater than 10,000 years before present.

Earth – Unconsolidated material that contains 80% or more of inorganic particles smaller than 2 mm (the upper limit of sand-size particles).

Earth fissure – A linear tension crack in the ground that extends upward from the groundwater table and is a direct result of land subsidence caused by groundwater depletion. The surface expression of earth fissures may range from less than a yard to several miles long and from less than half an inch to tens of feet wide. Earth fissures change runoff/flood patterns, break buried pipes and utilities, cause infrastructure to collapse, provide a direct conduit to the groundwater table for contaminants, and may pose a life-safety hazard. Earth fissures can quickly erode into sinkholes/gullies when washed out by surface runoff, and some can experience vertical offset.

Earthquake – A sudden motion or trembling of the Earth as stored elastic strain energy is released by fracture and movement of rocks along a fault.

Earthquake-induced flooding – Flooding caused by a seiche, tectonic subsidence, increase in spring discharge, rise in the water table, or disruption of streams and canals caused by an earthquake. See also, seiche, tectonic subsidence.

Engineering Geologist – A Utah-licensed geologist, who through education, training, and experience practices in the field of engineering geology. The term "Geologist" as used in this publication, specifically refers to an Engineering Geologist qualified to study the specific geologic hazard(s) identified. The engineering geologist in principal charge of investigations should have a minimum of five years of experience in a responsible position in the field of engineering geology either in Utah or in a state with similar geologic hazards.

Engineering geology – The application of the geological sciences to engineering practice for the purpose of assuring that the geologic factors affecting the location, design, construction, operation, and maintenance of engineering works are recognized and adequately provided for in the interest of the public health, safety, and welfare.

Erosion – Removal and transport of soil or rock from a land surface, usually through chemical or mechanical means.

Essential facilities –Infrastructure and facilities intended to remain operational in the event of an adverse geologic event or natural disaster. They include, but are not limited to, those uses listed under Risk Category IV as defined in the International Building Code (IBC, table 1604.5, p. 336; International Code Council, 2014a).

Expansive soil and/or rock – Soil or rock that swells when wetted and shrinks when dried. Typically associated with high clay content, particularly sodium-rich clay.

Fall – Landslide movement that starts with the detachment of soil or rock from a steep slope along a surface on which little or no shear displacement takes place.

Fault – A fracture in the Earth's crust forming a boundary between rock or soil masses that have moved relative to each other, due to tectonic forces. When the fracture extends to the Earth's surface, it is known as a surface-fault rupture, or fault trace.

Fault scarp – A steep slope or cliff formed by movement along a fault.

Fault setback – A specified distance on either side of a fault within which essential facilities and other structures designed for human occupancy are not permitted.

Fault trace, or surface-fault rupture – The intersection of a fault plane with the ground surface, often present as a fault scarp, or detected as a lineament.

Fault zone – A corridor of variable width along one or more fault traces, within which deformation has occurred.

Flank – Non-displaced material adjacent to the sides of the rupture surface of a landslide; compass directions are preferable in describing the flanks, but "left" and "right" can be used looking downslope.

Flow – A spatially continuous movement in which surfaces of shear are short-lived, closely spaced, and usually not preserved. The distribution of velocities in the displaced mass resembles that of a viscous liquid.

Geologic evaluation – The review of a geologic study area to determine the hazard potential relative to the proposed development, and to verify the need for geologic studies and reports. Geologic evaluations are performed by engineering geologists, or geotechnical engineers with input from engineering geologists

Geologic study area – A potential geologically hazardous area, within which geologic-hazard investigations are required prior to development.

Geologically hazardous area – An area that, because of its susceptibility to a geologic hazard, is not suitable for the siting of structures designed for human occupancy or critical facilities, consistent with public health or safety concerns, unless the hazard is mitigated to an acceptable and reasonable level.

Geotechnical Engineer: A professional, Utah-licensed engineer who, through education, training and experience, is competent in the field of geotechnical engineering and should have either (1) a graduate degree in civil engineering, with an emphasis in geotechnical engineering; or a B.S. degree in civil engineering with 12 semester hours of post-B.S. credit in geotechnical engineering, or course content closely related to evaluation of geologic hazards, from an accredited college or university; or (2) five full years of experience in a responsible position in the field of geotechnical engineering in Utah, or in a state with similar geologic hazards and regulatory environment, and experience demonstrating knowledge and application of appropriate techniques in geologic-hazards investigations.

Geotechnical engineering: The investigation and engineering evaluation of earth materials including soil, rock, and man-made materials and their interaction with earth retention systems, foundations, and other civil engineering works. The practice involves the fields of soil mechanics, rock mechanics, and earth sciences and requires knowledge of engineering laws, formulas, construction techniques, and performance evaluation of engineering.

Ground shaking – The shaking or vibration of the ground during an earthquake.

Hazard mitigation – An action taken to avoid, minimize, or compensate for the risk to human life and public and private property from identified hazards.

Holocene – The period of time between about 11,700 years ago and the present (Holocene Epoch). Also the geologic deposits that formed during that time (Holocene Series). See also, Quaternary.

Hydrocompaction – Where the ground subsides due to unconsolidated soils becoming saturated with water and losing their structural strength (soil bonds being dissolved by water), and the ground compacting under the weight above.

Hyperconcentrated flow – Slurry of rock, soil, organic matter, and water (generally 20%–60% sediment by volume) that flows down channels and onto alluvial fans. May be initiated by erosion during a cloudburst storm or by a shallow (slip surface generally less than 10 feet deep) slope failure on a steep mountain slope. Hyperconcentrated flows can travel long distances from their source areas, presenting hazards to life and property along stream channels and on or near downstream alluvial fans.

Lake flooding – Flooding around a lake caused by a rise in lake level.

Landslide – General term referring to a wide variety of mass-movement landforms and processes involving the downslope transport, under gravitational influence, of soil and rock materials

Liquefaction – Sudden, large decrease in shear strength of a saturated, cohesionless soil (generally sand, silt) caused by a collapse of soil structure and temporary increase in pore water pressure during earthquake ground shaking. Liquefaction may induce ground failure, including lateral spreads and flow-type landslides.

Main scarp – Steep surface of undisturbed material at the upslope extent of a landslide; caused by movement of the displaced material away from the undisturbed ground; the visible part of the surface of rupture.

Mine subsidence – Subsidence of the ground surface due to the collapse of underground mines; may also cause earth fissures.

Minor scarp – Steep surface on the displaced material of a landslide produced by differential movements within the displaced material.

Non-buildable area – An area that contains a geologic hazard that presents an unreasonable and unacceptable risk, such that the siting of structures designed for human occupancy, critical facilities, and other specified development improvements are prohibited in that area by permitting agencies.

Non-engineered fill – Soil, rock, or other fill material placed by humans without engineering specification, observation, and testing. Such fill may be uncompacted, contain voids and/or oversize, low-strength, and/or decomposable material; may be subject to differential subsidence; and may have a low bearing capacity and/or poor stability characteristics.

Organic deposits (peat) – An unconsolidated surface deposit of semi-carbonized plant remains in a water-saturated environment, such as a bog or swamp. May also occur as thin interbeds in soil or in a dried-out condition. Organic deposits are highly compressible, have a high water-holding capacity, can oxidize and shrink rapidly when drained, and may combust under certain circumstances.

Piping – Subsurface erosion of soil or rock by groundwater flow, forming narrow voids. Pipes can remove support of overlying soil and rock, resulting in collapse.

Problem soil and rock – Geologic materials having characteristics that make them susceptible to volumetric changes, collapse, subsidence, or other engineering geologic problems.

Quaternary – The period of time between 2.6 million years ago and the present (Quaternary Period). Also the geologic deposits that formed during that time (Quaternary System). The Quaternary comprises the Holocene and Pleistocene Epochs/Series. See also, Holocene.

Radon – A radioactive gas that occurs naturally through the decay of uranium and radium. Radon can be present in high concentrations in soil derived from rock such as granite, shale, phosphate, and certain metamorphic rocks. Exposure to elevated levels of radon can cause an increased risk of lung cancer.

Reactivated landslide – Landslide that is again active after being inactive.

Relic landslide – Landslide that clearly developed under different geomorphic conditions, perhaps thousands of years ago.

Rockfall – The relatively free falling or precipitous movement of rock from a slope by rolling, falling, toppling, or bouncing. The rockfall runout zone encompasses the area at risk from falling rocks below a rockfall source.

Rotational slide – Landslide in which the surface of rupture is curved concave upward and movement is roughly rotational about an axis parallel to the ground surface and transverse across the landslide.

Rupture surface – Surface that forms, or has formed, the lower boundary of the displaced material of a landslide below the original ground surface.

Sediment bulking – Erosion and incorporation of channel sediment by a debris flow.

Sensitive clay – Clay soil that experiences a particularly large loss of strength when disturbed, and therefore is subject to failure during earthquake ground shaking.

Setback, geologic hazard – An area subject to risk from a geologic hazard, within which construction of critical facilities and structures designed for human occupancy are not permitted.

Shallow bedrock – Bedrock at depths sufficiently shallow to be encountered in construction excavations.

Shallow groundwater – Groundwater at depths sufficiently shallow to be encountered in construction excavations, typically within 10 feet of the ground surface or less. A rising water table can cause flooding of basements, crawlspaces, and septic drain fields.

Slide – A downslope movement of a soil or rock mass occurring dominantly on surfaces of rupture or on relatively thin zones of intense shear strain.

Slope failure – Downslope movement of soil or rock by falling, toppling, sliding, or flowing. See also, landslide.

Slope stability analysis – Analysis of static and dynamic stability of engineered and natural slopes of soil and rock.

Soil – Aggregate of solid, typically inorganic particles that either was transported or was formed in situ by weathering of rock; subdivided into earth and debris.

Soluble soil or rock (karst) – Soil or rock containing minerals that are soluble in water, such as calcium carbonate (principal component of limestone), dolomite, and gypsum. Dissolution of minerals and rocks can cause subsidence and formation of sinkholes.

Spread – An extension of a cohesive soil or rock mass combined with a general subsidence of the fractured mas of cohesive material into softer underlying material.

Stabilized landslide – Landslide that has stopped moving after mitigation measures have been applied.

Stream flooding – Overbank flooding of floodplains along streams; area subject to flooding generally indicated by extent of floodplain or calculated extent of the 100- or 500-year flood.

Structure designed for human occupancy – Any building or structure containing a habitable space, or classified as an assembly, business, educational, factory and industrial, institutional, mercantile, or residential occupancy classification under the adopted International Building Code.

Subsidence – Permanent lowering of the normal level of the ground surface by hydrocompaction, piping, karst, collapse of underground mines, loading, decomposition or oxidation of organic soil, faulting, groundwater mining, or settlement of non-engineered fill.

Surface faulting (surface fault rupture) – Propagation of an earthquake-generating fault rupture to the ground surface, displacing the surface and forming a scarp.

Suspended landslide – Landslide that have moved within the last annual cycle of seasons but that are not moving at present.

Talus – Accumulated rock fragments lying at the base of a cliff or a steep rocky slope.

Tectonic subsidence – Lowering and tilting of a basin floor on the downdropped side of a fault during an earthquake.

Toe – Lower, usually curved, margin of the displaced material of a landslide, the most distant from the top of a landslide.

Topple – A forward rotation out of the slope of a mass of soil or rock about a point or axis below the center of gravity of the displaced mass

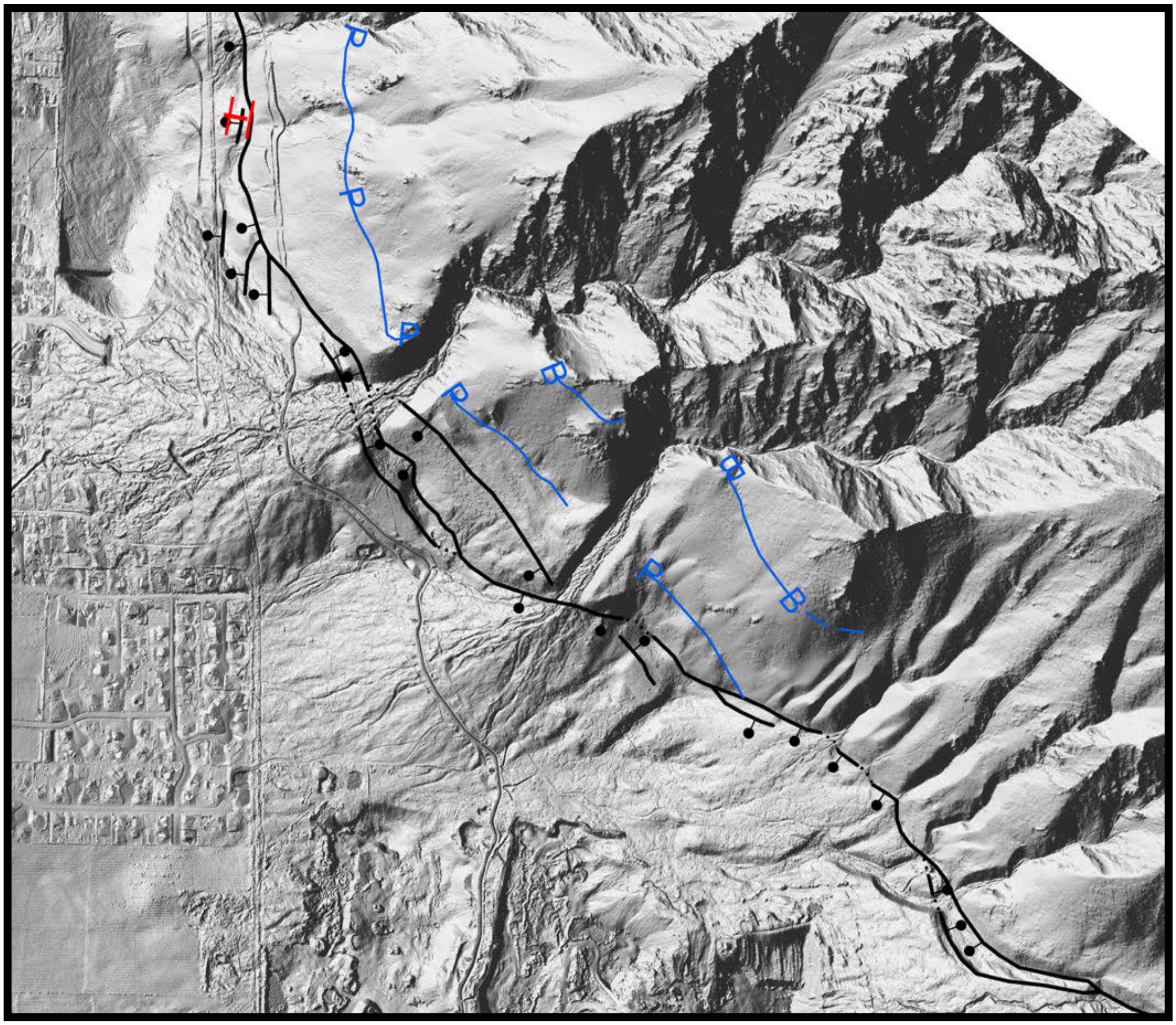
Translational – Type of landslide that moves along a roughly planar surface with little rotation or backward tilting.

Trigger – Cause that puts a slope into a marginal state of activity leading to a landslide.

Zone of accumulation – Portion of a landslide within which the displaced material lies above the original ground surface.

Zone of depletion – Portion of a landslide within which the displaced material lies below the original ground surface.

APPENDIX C
LIGHT DETECTION AND RANGING (LIDAR) BACKGROUND AND APPLICATION



Bare-earth lidar DEM showing the Bonneville and Provo shorelines of Pleistocene Lake Bonneville and the trace of the Wasatch fault zone. Image credit: Adam McKean.

Suggested citation: Bowman, S.D., 2016, Light detection and ranging (lidar) background and application, *in* Bowman, S.D., and Lund, W.R., editors, Guidelines for investigating geologic hazards and preparing engineering-geology reports, with a suggested approach to geologic-hazard ordinances in Utah: Utah Geological Survey Circular 122, appendix C, p. 189–196.

LIGHT DETECTION AND RANGING (LIDAR) BACKGROUND AND APPLICATION

by Steve D. Bowman, Ph.D., P.E., P.G.

INTRODUCTION

Light detection and ranging (lidar) technology uses transmitted and reflected laser pulses to measure the distance to an object. Lidar transmitted from an airborne platform (fixed-wing aircraft or helicopter) is commonly used to determine ground surface elevations to create highly accurate, bare-earth digital elevation models (DEM). A lidar instrument can send many thousands of laser pulses at a rapid rate, which allows a high point spacing density, much greater than is possible using traditional surveying methods. Landslides (figure C1), fault scarps (figure C2), earth fissures (figure C3), and other features that are difficult or not possible to detect visually because of vegetation, access, or other issues, may often be clearly shown in lidar data.

Unlike radar interferometry (InSAR), most lidar data are acquired by private aerial imaging and mapping firms. In 1996, only one vendor was selling commercial lidar systems (Baltsavias, 1999); today there are numerous commercial vendors producing lidar scanning systems including Leica Geosystems, Toposys (now Trimble), Optech, and Riegl, along with numerous aerial imaging and mapping firms employing the technology. Most of these systems are small and light enough to be installed and operated in small, single-engine aircraft, and more recently, in remotely operated, unmanned aircraft.

LIDAR BACKGROUND AND ACQUISITION

First developed in the 1960s with early laser components (Miller, 1965; Shepherd, 1965), lidar has evolved from simple electronic distance measurement systems used in surveying (Shan and Toth, 2009) into a sophisticated surface mapping technique on multiple platforms, including terrestrial, airborne, or spaceborne. Lidar may be applied using one of two general methods: profiling or scanning. Profiling involves acquiring elevation data along a single flight path of the platform. Scanning involves acquiring elevation data along a swath parallel to the flight path of the platform, or in the case of terrestrial scanners, along a path parallel to the angular rotation path of the stationary scanner. In addition, the reflected light backscatter, intensity, and other parameters can be measured for additional applications. Lidar can measure the ground surface with accuracies of a few inches horizontally and a few tenths of inches vertically (Carter and others, 2001) and can penetrate thick vegetation canopies as shown on figure C1 from the Snowbasin, Utah, area. For more detailed information than provided here, Renslow (2012) provides a comprehensive review of airborne lidar systems and processing.

Lidar may be acquired from three different platforms: terrestrial, airborne, and spaceborne. The most common acquisition platform is airborne, with the lidar unit mounted in the floor of an airplane or helicopter (figure C4). Terrestrial lidar is commonly used to map steep slopes, such as cut or mine slopes, and fault or landslide scarps.

Due to the long path length of emitted and reflected laser light, spaceborne lidar systems require high-power lasers with high electrical input requirements. Consequently, few spaceborne lidar systems are in use, with the exception of profiling systems, which typically are employed for atmospheric and/or ocean monitoring and research, such as the NASA ICESat satellite (NASA, 2010).

Lidar systems typically use either a neodymium-doped yttrium aluminum garnet (Nd:YAG) or gallium arsenide (GaAs) laser (Shan and Toth, 2009) driven by a power source and sophisticated electronics, and for aircraft acquisition, are coupled with a GPS or more recently, a Global Navigation Satellite System (GNSS) inertial measurement unit (IMU) to determine precise three-dimensional position information. Figure C5 shows a Leica ALS70 instrument mounted in an aircraft used for the 2011 State of Utah acquisition. The position information is used during processing raw sensor data to point cloud and to bare-earth data to correct for aircraft flight path drift (yaw, pitch, and roll) and other irregularities. During acquisition of terrestrial lidar, each instrument location is measured with GPS or GNSS, which is used for subsequent processing to a three-dimensional model.

While scanning systems generally comprise a laser aimed at a rotating mirror, various manufacturers use different methods, including standard rotating mirrors (Optech and Leica Geosystems ALS scanners); rotating optical polygon scanners (Reigl scanners); Palmer scanning with a wobbling mirror (NASA Airborne Topographic Mapper [ATM] and Airborne Oceanographic Lidar [AOL] scanners; and tilted, rotating mirrors with a fiber optic array (Toposys scanners) (Leica Geosystems, 2008a; National Oceanic and Atmospheric Administration, 2008; Shan and Toth, 2009).

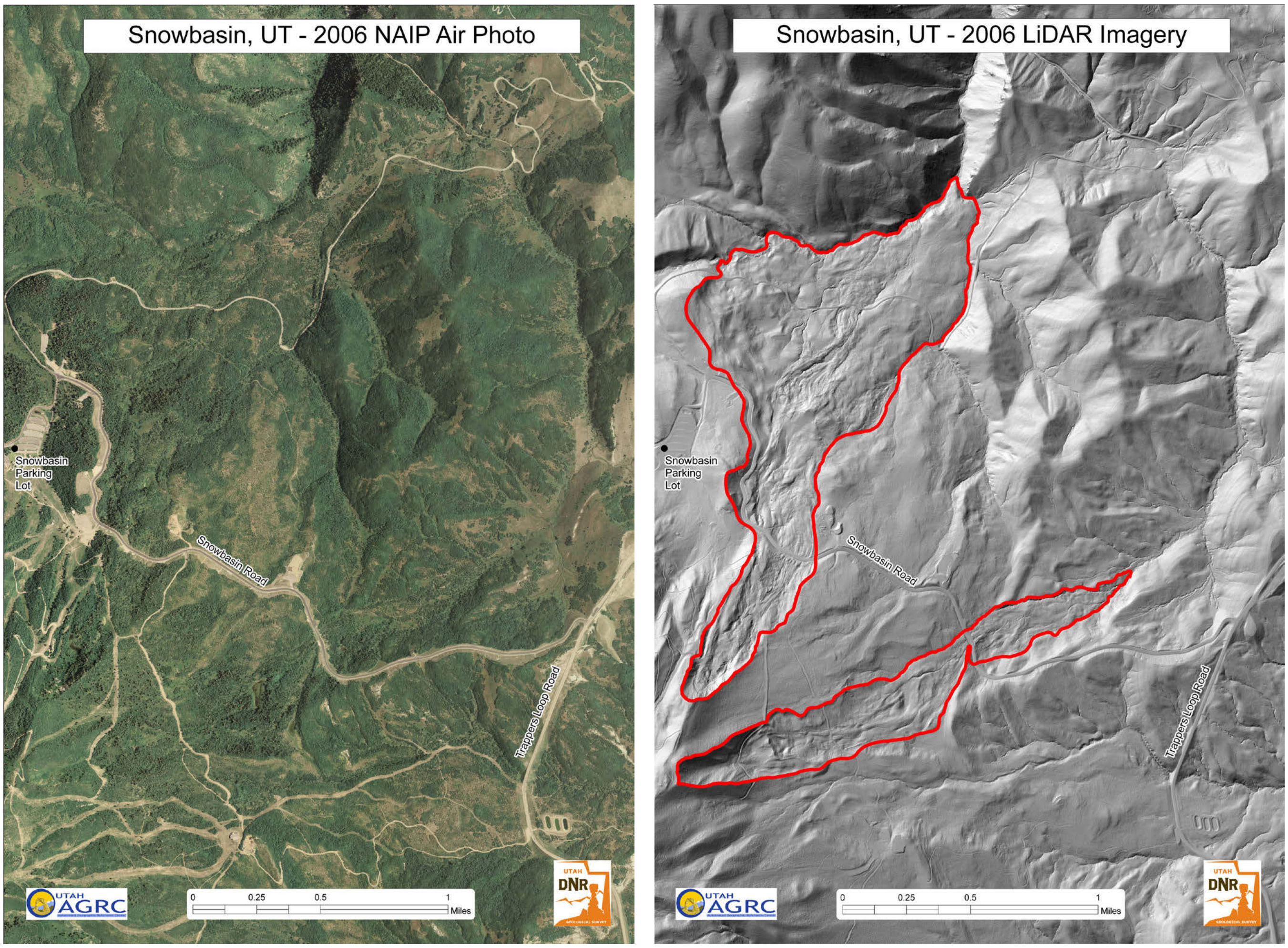


Figure C1. *Comparison of 2006 National Agriculture Imagery Program (NAIP) 1-meter color orthophoto imagery (left) and 2006 2-meter airborne lidar imagery (right) in the Snowbasin area, Weber County, Utah. Red lines outline the Green Pond and Bear Wallow landslides that are clearly visible in the lidar imagery, but barely visible to undetectable in the NAIP imagery. Data from the Utah Automated Geographic Reference Center (AGRC) (2006a, 2006b), and graphics generated by the Utah Geological Survey, Geologic Hazards Program, undated.*

Lidar data acquired from the reflected laser pulses (figures C6 and C7) are converted to raw point cloud data—a collection of range measurements (straight-line distance from platform system to the imaged ground surface) and sensor orientation parameters (Fernandez and others, 2007) in the lidar system. The intensity of returned laser pulses can also be used to determine general surface texture, although ground surface classification can be difficult.

For use in elevation and most geologic studies, the point cloud data must first be converted to bare-earth data that have vegetation and other non-native features (buildings, etc.) removed, and then be georeferenced to a coordinate system. The point cloud data are converted by using the range and orientation of each laser shot (pulse) to place the shot in a three-dimensional reference frame (Fernandez and others, 2007). Bare-earth lidar data may then be processed by a variety of remote sensing image software to develop DEMs, shaded-relief hillshade and slopeshade images at various sun (illumination) angles, or a combination of these image types. Hillshade images show the ground surface illuminated from a particular angle, in a line-of-sight style. Slopeshade images show the ground surface slope angle with steep slopes shaded and shallow slopes illuminated so topography is not masked by illumination shadow. Digital surface models (DSM) can also be produced that retain vegetation and non-native features, representing the highest return of the imaged surface. Often, numerous shaded-relief images with different illumination angles are needed for interpretation of fault scarps, landslides, and other geologic features, due to different feature aspect angles and will vary with each project and the feature(s) of interest.

Lidar Data Acquisition and Specifications

Acquisition of new lidar data should follow specifications matching the specific project for which it is acquired. The U.S. Geological Survey (USGS), in partnership with several other organizations, developed a comprehensive lidar acquisition, processing, and handling specification (Heidemann, 2014; http://pubs.usgs.gov/tm/11b4/) suitable for most geologic projects and is widely used. In addition, the Federal Emergency Management Agency (FEMA) developed standards for li-

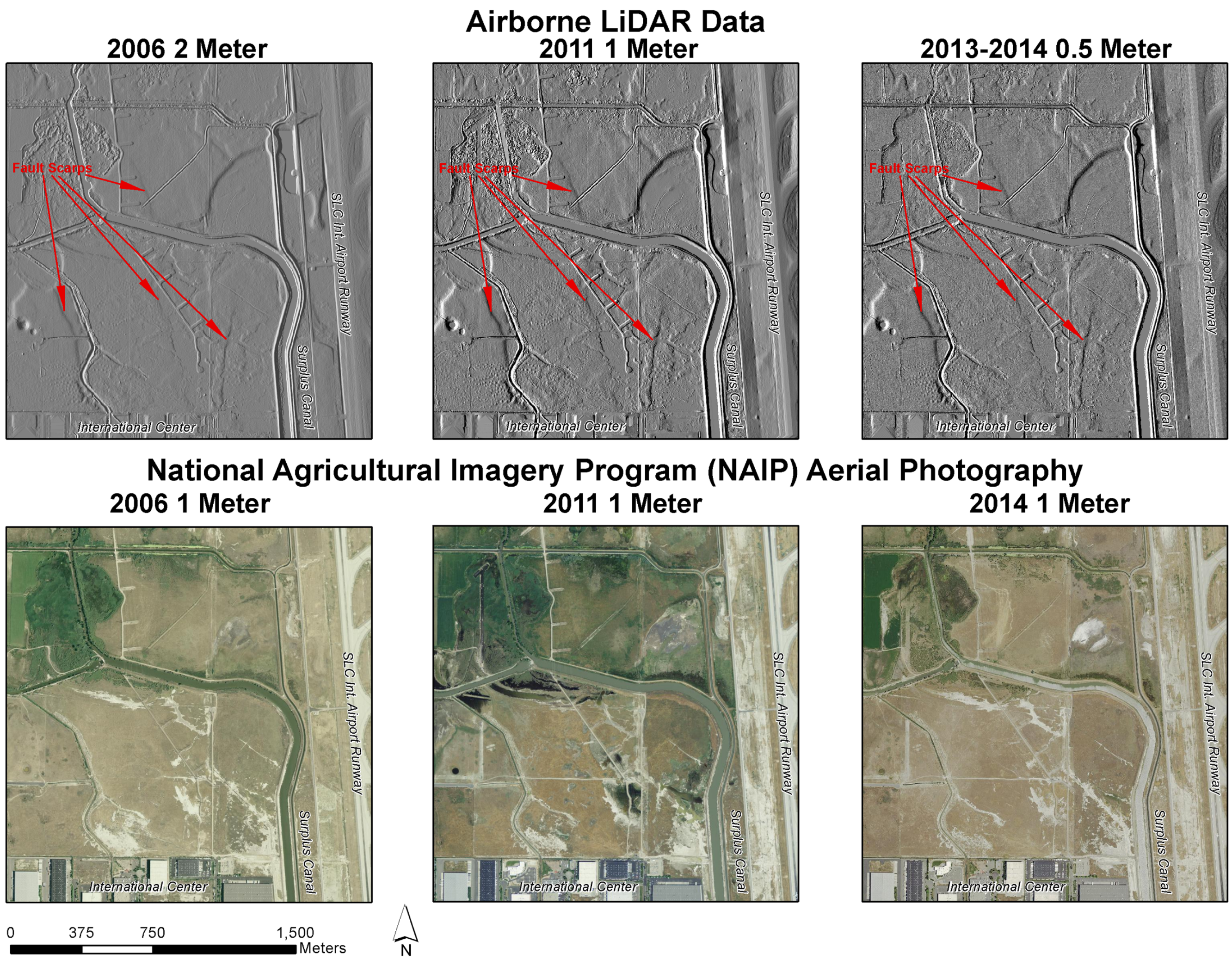


Figure C2. *Comparison of 2006 (2 meter), 2011 (1 meter), and 2013–2014 (0.5 meter) airborne lidar imagery (top row) to 2006, 2011, and 2014 (1 meter, bottom row) National Agriculture Imagery Program (NAIP) imagery in the International Center area, Salt Lake City, Utah. Fault scarps indicated by red arrows show traces of the Granger fault, West Valley fault zone, that are clearly visible in the lidar imagery, but barely visible to undetectable in the NAIP imagery. Salt Lake International Airport visible to the right on each image. Data from the AGRC (2006b, 2009).*

dar data used in flood mapping analyses included in RiskMap (Bellomo, 2010) that integrate with the USGS specification. One-meter or better ground cell size data is often needed for detailed landslide, fault, and other geologic investigations as shown on figure C2.

The Utah Geological Survey (UGS) and Utah Automated Geographic Reference Center (AGRC) partners with other governmental agencies to acquire lidar data in Utah, and collectively has acquired over 3254 square miles of 0.5- and 1-meter data. If lidar data is acquired for a specific project, we suggest consider donating the data to AGRC for public distribution (contact information available at http://gis.utah.gov/about/contact/) once the project is complete.

Issues with Lidar Acquisition and Processing

Variable vegetation and tree canopy cover density and thickness and/or steep, mountainous terrain can result in difficult post-acquisition processing of the raw lidar data to bare-earth data. Vegetation-related issues can introduce additional height error and may cause additional scattering of the transmitted laser pulse, resulting in less laser energy reflected back to the receiving sensor. Various laser backscatter methods may be used to resolve canopy height issues. Increased flight line overlap may be needed in steep, mountainous areas to ensure adequate ground point density and to minimize potential shadow areas. These issues can be reduced with good project specifications, should be addressed by the data acquisition vendor prior to data delivery, and should be checked during a quality control process by the data purchaser before final data acceptance.

LIDAR DATA AVAILABILITY AND ANALYSIS

Lidar coverage in Utah is mainly limited to urban areas, and has predominantly been collected for FEMA RiskMap flood map-

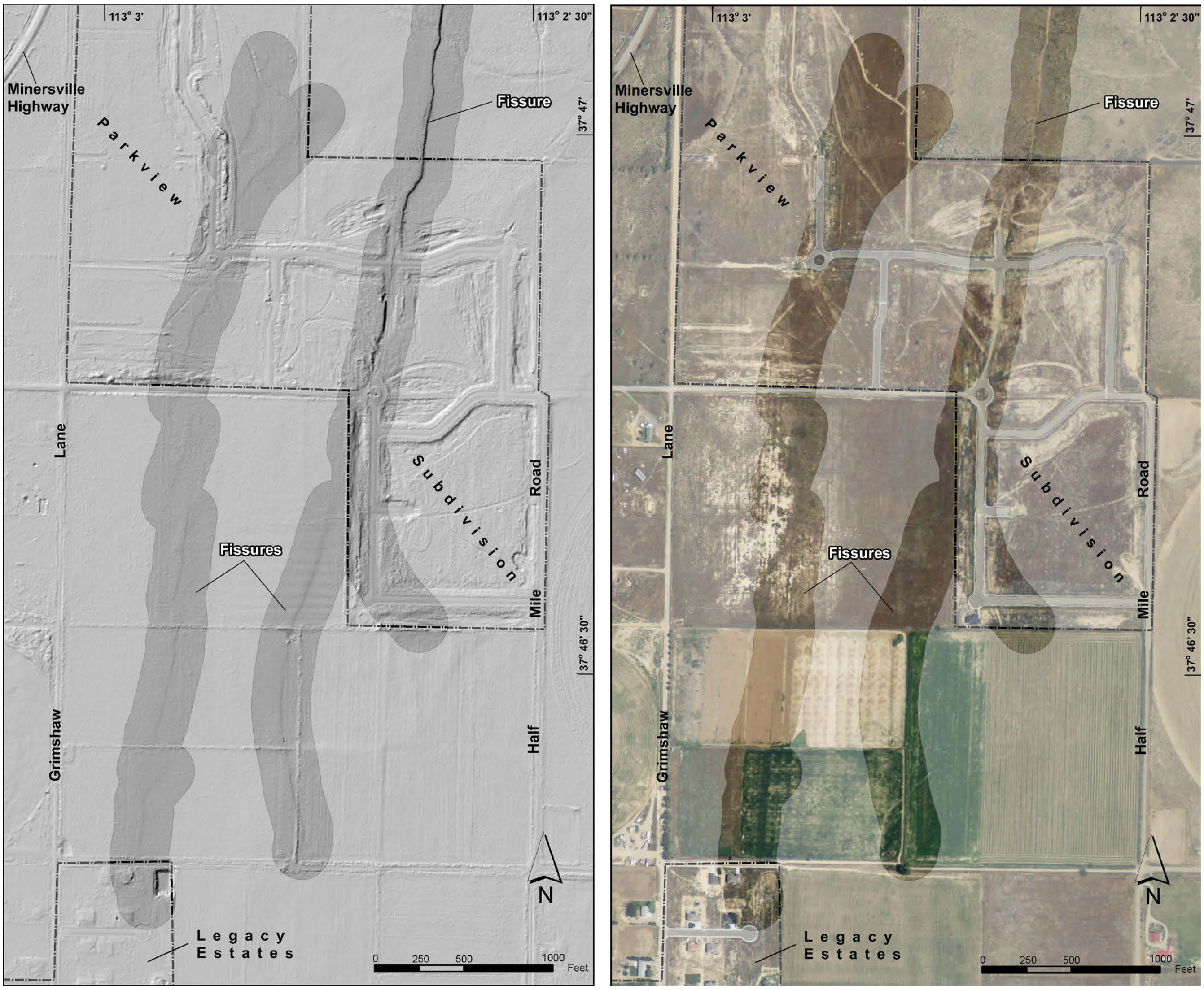


Figure C3. *Comparison of 2011 bare-earth lidar image (left; Knudsen and others, 2014, data from UGS, 2011) and 2011 National Agriculture Imagery Program (NAIP; AGRC, 2011) 1-meter color orthophoto imagery (right) showing where Enoch-graben-west fissures intersect the Parkview and Legacy Estates subdivisions. Fissures that are clearly identifiable in the lidar image are barely visible to undetectable in the NAIP imagery, particularly in the southern half of the image. Shading added to highlight fissure traces. Graphics generated by Tyler Knudsen, Utah Geological Survey, Geologic Hazards Program, 2014.*

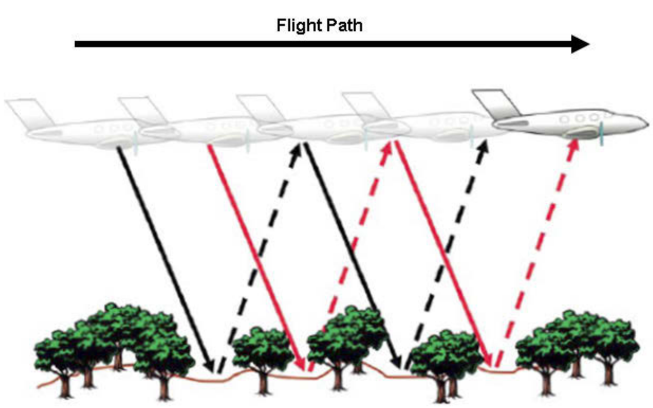


Figure C4. *General imaging geometry of an airborne lidar instrument. Dashed lines indicate reflected laser pulses that may be detected if sensor crosses the reflected path (modified from Leica Geosystems, 2008b).*

ping projects, land-use planning, and fault trace mapping. Available data is generally 1- to 2-meter ground cell size in bare-earth, digital elevation model format. However, high-quality 0.5-meter data acquired in 2013–2014 by the UGS, AGRC, and other partners, is now available for Salt Lake and Utah Valleys, and along the entire Wasatch and West Valley fault zones. Raw point cloud data for some areas may be available. Available data coverage can be searched using the AGRC Raster Data Discovery Application (http://mapserv.utah.gov/raster/) or ftp://ftp.agrc.utah.gov/LiDAR/, and OpenTopography (http://www.opentopography.org), a National Science Foundation-supported portal to high-resolution topography data and analysis tools.

Lidar data are not directly viewable without suitable software, such as Global Mapper (http://www.bluemarblegeo.com/products/global-mapper.php), Fusion (http://forsys.cfr.wash-

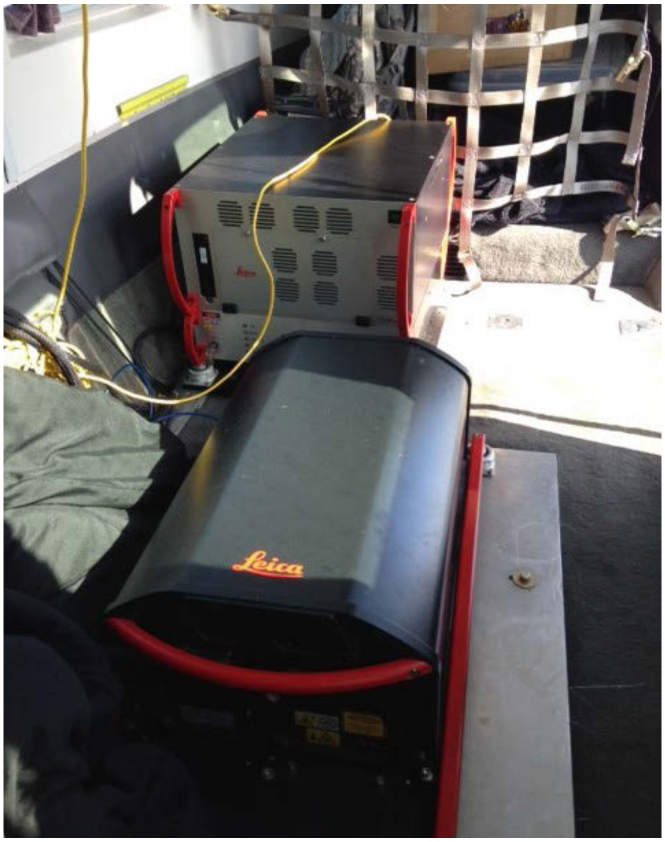


Figure C5. *Leica ALS70 lidar instrument mounted in a Piper Navajo aircraft used for the 2013 Utah acquisition by the Utah Geological Survey and partners (photo credit: Watershed Sciences, Inc.)*

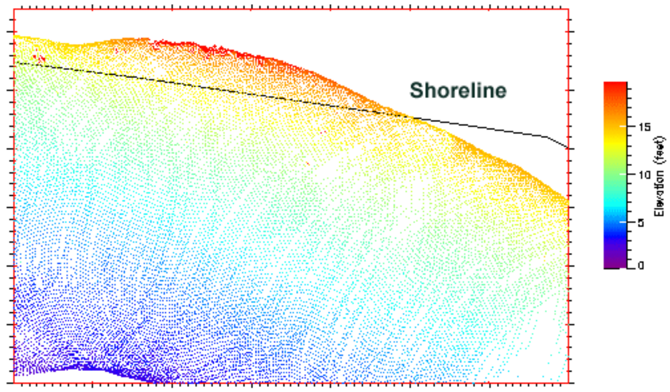


Figure C6. *Scanning swath from the ATM-2 lidar scanner showing oscillating scanning motion (modified from National Oceanic and Atmospheric Administration, 2008). Individual laser data points are shown as colored dots.*

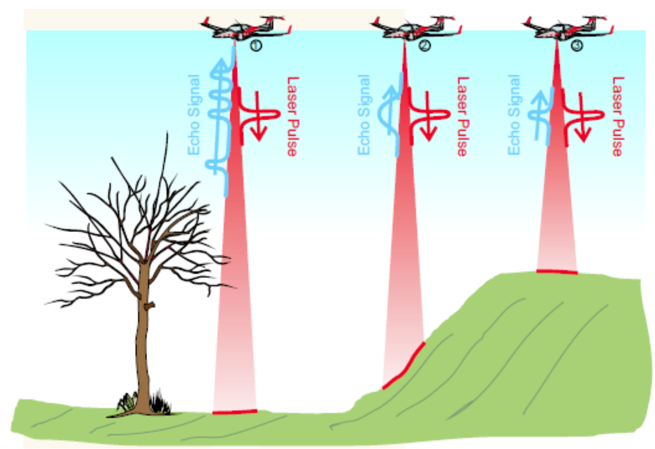


Figure C7. *Typical lidar transmitted and received pulses for flat, but partially obscured; sloping; and flat, smooth terrain from left to right (modified from Riegl Laser Measurement Systems GmbH, 2010).*

ington.edu/fusion/fusionlatest.html), FugroViewer (http://www.fugroviewer.com/), and ESRI ArcGIS. Data from OpenTopography may be processed online to Google Earth KMZ files using user-selected parameters (such as hillshade altitude and azimuth), and is generally the easiest way to access the data for most users without the use of specialized software.

UGS Lidar Data

The UGS acquires lidar data with its partners in support of various geologic mapping and research projects. In 2011, approximately 1902 square miles (4927 km^2) of 1-meter lidar data was acquired for the Cedar and Parowan Valleys, Great Salt Lake shoreline/wetland areas, Hurricane fault zone, Lowry Water area, Ogden Valley, and North Ogden, Utah. The 2011 lidar acquisition was performed by Utah State University, LASSI Service Center through a partnership with AGRC and the Utah Division of Emergency Management (UDEM).

In late 2013, the UGS and its partners acquired 0.5-meter lidar of Salt Lake and Utah Valleys, the West Valley fault zone, and along the entire length of the Wasatch fault zone from north of Malad City, Idaho, south to Fayette, Utah. The 2013 lidar acquisition was performed by Watershed Sciences, Inc. through a partnership with AGRC, USGS, Salt Lake County Surveyors Office, and UDEM.

The 2011 datasets include raw LAS (industry standard lidar format), LAS, DEM, DSM, and metadata (XML metadata, project tile indexes, and area completion reports) files. This lidar data is available from the AGRC Raster Data Discovery Application (DEM data and metadata only, http://mapserv.utah.gov/raster), is included in the USGS National Elevation Dataset (http://ned.usgs.gov/) that is part of The National Map (DEM data and metadata only, http://nationalmap.gov/viewer.html), and OpenTopography (all data and metadata, http://www.opentopography.org/id/OTLAS.042013.26912.1).

The datasets acquired by the UGS and its partners are in the public domain and can be freely distributed with proper credit to the UGS and its partners. For more information about UGS lidar acquisitions and data, see http://geology.utah.gov/resources/data-databases/lidar-elevation-data/.

Data Analysis

Bare-earth lidar data can be used to create DEMs (often supplied by the vendor), and subsequently to determine ground subsidence and for ground surface modeling, and/or hillshade and slopeshade images that can be used for geologic feature mapping, such as landslides (figure C1), faults (figure C2), scarps (figures C1 and C2), shorelines, etc. Often, numerous shaded-relief (hillshade and slopeshade) images with different illumination angles are needed for interpretation of fault scarps, landslides, and other geologic features, due to different feature aspect angles and will vary with each project and the feature(s) of interest. Use of GIS software will assist with geologic mapping, by allowing various data sets, such as aerial orthoimagery, to be overlain on the lidar data.

Landslides

Landslides may be difficult to detect using aerial photography in vegetated areas, as illustrated on figure C1. Bare-earth DEMs with hillshade and/or slopeshade illumination methods are often used to delineate landslides and internal landslide features. McDonald and Giraud (in preparation) used 1-meter lidar data in the Lowry Water area of the Wasatch Plateau to map and inventory landslides at a scale of 1:12,000 in a densely vegetated (conifer forest and brush) area.

Faults

Traditionally, faults have been mapped using a combination of low-sun-angle (preferably stereoscopic) aerial photography and field reconnaissance. Additional information on aerial photography is available in chapter 2 of this publication. However, small fault scarps may not be visible on aerial photography, and/or barely visible in the field. A lidar-derived slopeshade image with a slope gradient from 0 to 45 degrees (white to black) is often useful in mapping. McKean and Hylland (2013) used 1-meter lidar data near Great Salt Lake for mapping subtle fault scarps that were not apparent on aerial photography, and were very difficult to recognize in the field, as a part of geologic mapping of the Baileys Lake quadrangle. Starting in 2014, the UGS mapped traces of the Wasatch fault zone at a scale of 1:10,000 using 0.5-meter lidar data (Harty and McKean, 2015; Hiscock and Hylland, 2015). Fault trace mapping at this level of detail and scale would not be possible without high-quality lidar data.

Earth Fissures

Lidar is often invaluable for mapping earth fissures. While larger earth fissures with significant vertical and/or horizontal displacement are often visible on aerial photography, smaller to “hairline” earth fissures are often not visible on aerial photography, due to little or no vertical displacement and/or contrast change across the fissure. Knudsen and others (2014) used 1-meter lidar data of Cedar Valley to map over 8.3 miles of earth fissures, while previous aerial-photography-based mapping only revealed 3.9 miles of fissures.

Ground Subsidence

For determining ground subsidence, at least one repeat data acquisition is required to determine the magnitude using lidar data. However, several repeat acquisitions would be necessary to determine the ongoing rate of ground subsidence over a specified time period. These acquisitions must be timed correctly to avoid snow cover and to have similar vegetation coverage conditions to ensure similar data processing of each lidar acquisition. Once two or more DEMs are available over an area, they can be subtracted from each other to determine the change in elevation over a given time period. By using three or more DEMs and the corresponding elevation differences, an estimate of the rate of change in elevation can be determined.

The rate of change may also be influenced by seasonal changes in groundwater levels and ground temperature that may overprint ground subsidence changes, as soil material volume changes result in an inflation or deflation signal. The major drawbacks to this method are the relatively high cost of lidar data when used in a repeat acquisition application and the variable vertical accuracy of the data, which can be significant if data acquisition is not carefully controlled.

CONCLUSIONS

Lidar is a valuable new tool for detecting, mapping, and understanding geologic hazards, particularly in areas that are difficult to access and/or visually observe, and is often critical to use in highly vegetated areas. Lidar has allowed the mapping of many geologic hazards at unprecedented levels of detail that was not possible previously using traditional methods. Geologic hazard investigations should utilize lidar data whenever possible, and on large and/or complex projects where data does not currently exist, lidar data acquisition should be seriously considered with data donated to the public domain where possible.

REFERENCES

Baltsavias, E.P., 1999, Airborne laser scanning—existing systems and firms and other resources: ISPRS Journal of Photogrammetry & Remote Sensing, v. 54, p. 164–198.

Bellono, D.A., 2010, Procedure Memorandum No. 61—Standards for LiDAR and other high quality digital topography: Federal Emergency Management Agency Procedure Memorandum No. 61, 26 p.

Carter, W., Shrestha, R., Tuell, G., Bloomquist, D., and Sartori, M., 2001, Airborne laser swath mapping shines new light on Earth’s topography: EOS, Transactions, v. 82, no. 46, p. 549–555.

Fernandez, J.C., Singhania, A., Caceres, J., Slatton, K.C., Starek, M., and Kumar, R., 2007, An overview of LiDAR point cloud processing software: Geosensing Engineering and Mapping, Civil and Coastal Engineering Department, University of Florida, 27 p.

Harty, K.M., and McKean, A.P., 2015, Surface fault rupture hazard map of the Honeyville quadrangle, Box Elder and Cache Counties, Utah: Utah Geological Survey Open-File Report 638, 1 plate, scale 1:24,000, CD.

Heidemann, H.K., 2014, LiDAR base specification version 1.2: U.S. Geological Survey Techniques and Methods, book 11, chapter B4, 67 p.

Hiscock, A.I., and Hylland, M.D., 2015, Surface-fault-rupture-hazard maps of the Levan and Fayette segments of the Wasatch fault zone, Juab and Sanpete Counties, Utah: Utah Geological Survey Open-File Report 640, 7 plates, scale 1:24,000.

Knudsen, T., Inkenbrandt, P., Lund, W., Lowe, M., and Bowman, S., 2014, Investigation of land subsidence and earth fissures in Cedar Valley, Iron County, Utah: Utah Geological Survey Special Study 150, 84 p., 8 appendices, CD.

Leica Geosystems, 2008a, Leica ALS60 airborne laser scanner: Online, http://www.leica-geosystems.com/common/shared/downloads/inc/downloader.asp?id=10325, accessed November 18, 2010.

Leica Geosystems, 2008b, Leica ALS Corridor Mapper, Airborne laser corridor mapper product specifications: Online, http://www.leica-geosystems.com/common/shared/downloads/inc/downloader.asp?id=9035, accessed November 18, 2010.

McKean, A.P., and Hylland, M.D., 2013, Interim geologic map of the Baileys Lake quadrangle, Salt Lake and Davis Counties, Utah: Utah Geological Survey Open-File Report 624, scale 1:24,000, 18 p. booklet.

Miller, B., 1965, Laser altimeter may aid photo mapping: Aviation Week & Space Technology, v. 88, no. 13, p. 60–65.

National Aeronautics and Space Administration, 2010, ICESat & ICESat-2, Cryospheric Sciences Branch, Code 614.1: Online, http://icesat.gsfc.nasa.gov/, accessed November 18, 2010.

National Oceanic and Atmospheric Administration, 2008, Topographic LiDAR—an emerging beach management tool, data collection animations: Online, http://www.csc.noaa.gov/beachmap/html/animate.html, accessed November 18, 2010.

Riegl Laser Measurement Systems GmbH, 2010, Long-range airborne scanner for full waveform analysis, LMS-Q680i: Online, http://www.riegl.com/uploads/tx_pxpriegldownloads/10_DataSheet_LMS-Q680i_20-09-2010.pdf, accessed November 18, 2010.

Renslow, M., editor, 2012, Airborne topographic LiDAR manual: Bethesda, Maryland, American Society for Photogrammetry and Remote Sensing, 528 p.

Shan, J., and Toth, C.K., 2009, Topographic laser ranging and scanning, principles and processing: Boca Raton, Florida, CRC Press, 590 p.

Shepherd, E.C., 1965, Laser to watch height: New Scientist, v. 26, no. 437, p. 33.

Utah Automated Geographic Reference Center, 2006a, 2006 NAIP 1 meter color orthophotography: Online, http://gis.utah.gov/naip2006, accessed November 18, 2010.

Utah Automated Geographic Reference Center, 2006b, 2 meter LiDAR: Online, http://gis.utah.gov/elevation-terrain-data/2-meter-lidar, accessed November 18, 2010.

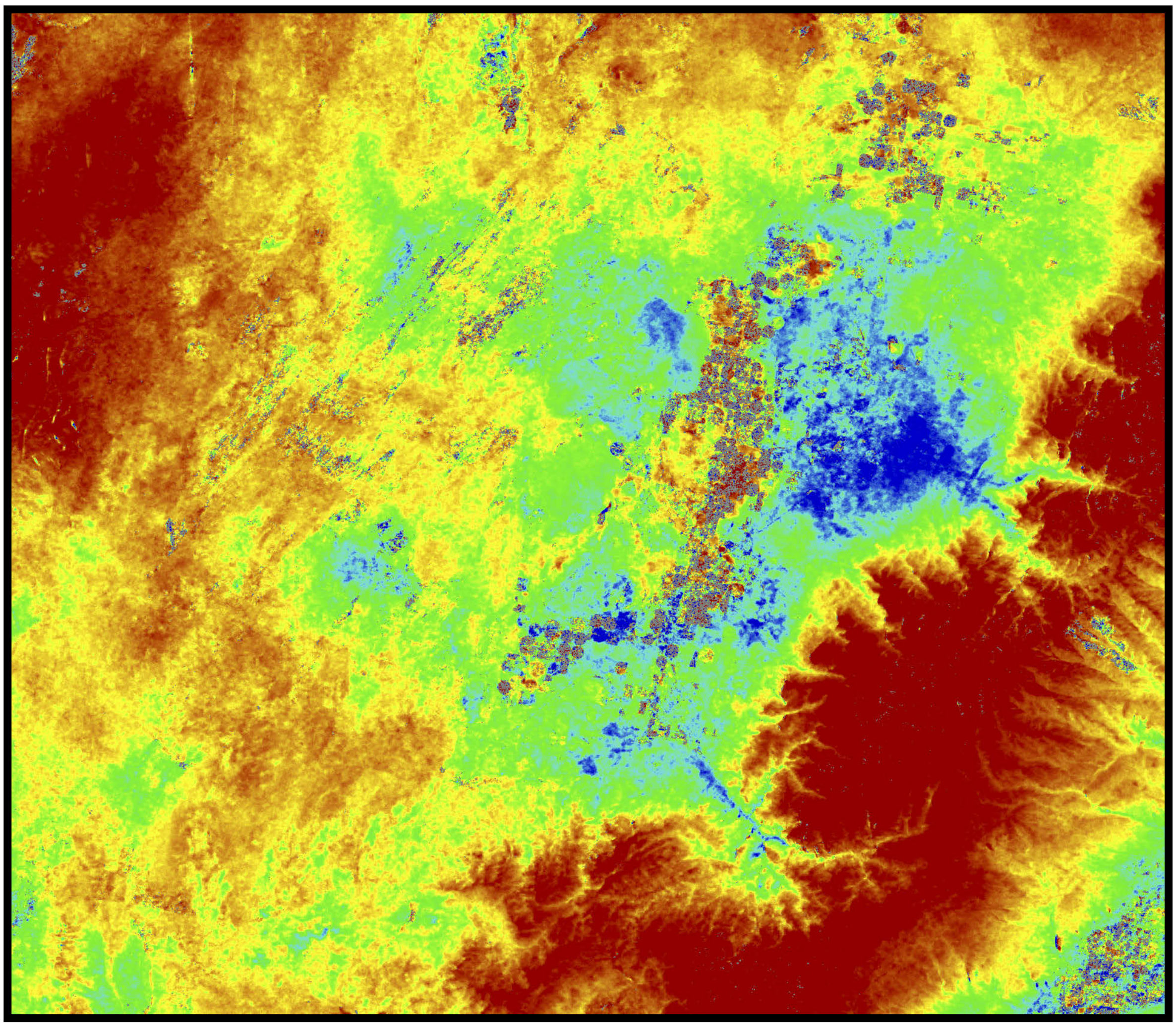
Utah Automated Geographic Reference Center, 2009, 2009 HRO 1 foot color orthophotography: Online, http://gis.utah.gov/aerial-photography/2009-hro-1-foot-color-orthophotography, accessed December 8, 2010.

Utah Automated Geographic Reference Center, 2011, 2011 NAIP 1 meter orthophotography: Online, http://gis.utah.gov/data/aerial-photography/2011-naip-1-meter-orthophotography/, accessed April 22, 2014.

Utah Automated Geographic Reference Center, 2013, 1 meter LiDAR elevation data (2011): Online, http://gis.utah.gov/data/elevation-terrain-data/2011-lidar/, accessed September 3, 2013.

Utah Geological Survey, 2011, LiDAR elevation data: Online http://geology.utah.gov/databases/lidar/lidar.htm, accessed September 3, 2013.

APPENDIX D
INTERFEROMETRIC SYNTHETIC APERTURE RADAR (INSAR) BACKGROUND AND APPLICATION



InSAR interferogram of Cedar Valley, Utah, and vicinity.

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INTERFEROMETRIC SYNTHETIC APERTURE RADAR (INSAR) BACKGROUND AND APPLICATION

by Steve D. Bowman, Ph.D., P.E., P.G.

INTRODUCTION

Radar interferometry is a process of using phase differences between two or more correlated radar images over the same area to measure surface displacements or topography. Interferometric synthetic aperture radar (InSAR) may now be applied worldwide, due to the availability of high-quality interferometric datasets from various spaceborne (ERS-1, ERS-2, JERS-1, ALOS, ALOS-2, Radarsat-1, Radarsat-2, ENVISAT, SRTM, SIR-C, TerraSAR-X, TanDEM-X, and COSMO-SKYMED) and airborne platforms. Only ALOS-2, Radarsat-2, Sentinel-1, TerraSAR-X, TanDEM-X, and COSMO-SKYMED satellites are still operational; ERS-1, ERS-2, ENVISAT, Radarsat-1, ALOS, and JERS-1 have failed.

InSAR Spaceborne Acquisition Platforms

The United States does not have operating synthetic aperture radar (SAR) satellites and relies on research and academic data access agreements with the European Space Agency (ESA), the Canadian Space Agency (CSA), and others. Commercial users must purchase all SAR data. However, the United States (National Aeronautics and Space Administration [NASA]) operated the Shuttle Radar Topographic Mission (SRTM) during 11 days in February 2000, and the Shuttle Imaging Radar (SIR-C) mission during 11 days in April 1994, and again in September–October 1994, that flew aboard the Space Shuttle (Jet Propulsion Laboratory, 2010a, 2010b), along with several other radar satellite platforms that are no longer operational. NASA is currently investigating developing the L- and S-band NISAR radar satellite in a joint mission with the Indian Space Research Organization.

The ESA has a long history of SAR satellites, beginning with the launch of ERS-1 in July 1991, followed by a second edition of the satellite, the ERS-2, in April 1995 (ESA, 2008). During 1995 to 1996, the ERS-1 and ERS-2 satellite tandem mission was developed where the satellite space orbits were adjusted to support InSAR between ERS-1/2 image pairs. The ERS-1 and ERS-2 satellites failed in March 2000 (ESA, 2008) and September 2011 (ESA, 2012b), respectively. ESA launched the next-generation radar satellite ENVISAT (which also included other sensors) in March 2002 (ESA, 2010), that failed on April 8, 2012 (ESA, 2012a).

Japan, through their Japan Aerospace Exploration Agency (JAXA), developed the JERS-1 satellite that was launched on February 11, 1992, and ended operation on October 12, 1998 (JAXA, 2010a). JAXA launched the next-generation radar satellite ALOS on January 24, 2006, and ended operation in May 2011 (JAXA, 2010b). JAXA launched ALOS-2, the successor to ALOS, in May 2014 (JAXA, undated). Canada, through the CSA and a partnership with a private company, developed the Radarsat-1 and Radarsat-2 satellites with launches in November 1995 and December 2007, respectively (CSA, 2010). Radarsat-1 failed on March 29, 2013 (CSA, 2013). Germany, through the German Aerospace Center (DLR) and a partnership with a private company, developed the TerraSAR-X satellite that was launched on June 15, 2007 (DLR, 2009), and a tandem, almost identical satellite, TanDEM-X that was launched on June 21, 2010 (DLR, 2010).

InSAR BACKGROUND AND PROCESSING TECHNIQUES

First developed by Richman (1971) and Graham (1974) with very limited datasets, InSAR for mapping surface displacements and topography was later investigated by Zebker and Goldstein (1986), Gabriel and others (1989), Goldstein and others (1993), and many others who contributed new processing techniques. The mapping of coseismic displacements resulting from the 1992 Landers earthquake (Zebker and others, 1994) was one of the early applications of InSAR. Later applications included glacier monitoring, volcano deformation monitoring, landslide detection, subsidence monitoring, and other applications. Hanssen (2001) used InSAR to map the displacement field of the Cerro Prieto geothermal field in Mexico, and documented about 8 cm/year (3.1 inches/year) of subsidence resulting from the extraction of water and steam for geothermal power production. Rosen and others (2000) gave an in-depth review and discussion of InSAR concepts, theory, and applications.

Use of InSAR requires an interferometric dataset, a suitable temporal and spatial baseline, and images that correlate together (matching similar locations in each image). InSAR may be applied in one of two methods: differential or topographic interferometry. Differential InSAR measures small-scale ground displacements due to subsidence, earthquakes, glacier movements, landslides, and other ground movement with the effects of topography removed. Topographic InSAR measures ground topography with no ground displacement, resulting in a digital elevation model (DEM). A DEM can be thought of as a three-dimensional topographic map. Differential InSAR can measure displacements to sub-centimeter accuracy and topographic InSAR can measure topography to tens of meters, depending on sensor and platform characteristics. As shown on figure D1, two satellite image acquisitions with slightly different satellite locations (defined as Orbit 1 and Orbit 2 locations) are needed for InSAR.

InSAR Theory

Radar interferometry works by measuring the phase differences of two complex-format radar images or images that retain phase information (real and imaginary electrical components of the reflected radar signal). Standard radar images do not retain phase information and cannot be used in InSAR processing and analysis. The interferometric phase, ϕ is defined as:

$$\phi = \varphi_1 - \varphi_2 = \frac{4\pi}{\lambda} \quad (\rho_2 - \rho_1)$$

where $\varphi 1$ = phase of Image #1, φ_2 = phase of Image #2, λ = radar wavelength, ρ_1 = range of Image #1, and ρ_2 = range of Image #2 (Rosen and others, 2000). Figure D2 shows the imaging geometry of a radar satellite during data acquisition, including the range direction.

The two complex-format radar images typically have short temporal and spatial baselines—the time between the two image acquisitions and the distance between the imaging locations (satellite three-dimensional position) of the two images, respectively. The two images must also cover nearly the same area on the ground surface. The critical baseline, B_c or maximum baseline distance that can be processed, is defined as:

$$B_c = \frac{\lambda r}{2 * R \cos\theta}$$

where λ = radar wavelength, r = radar path length, R = ground range resolution, and θ = local incidence angle (Hanssen, 2001). Table D1 shows the common spaceborne radar platforms and operating radar bands. For C-band systems, $B_c \sim$ 1100 m; L-band systems, $B_c \sim$ 4500 m; and X-band systems, $B_c \sim$ 100 m. The actual usable baseline for ERS-1/2 and Radarsat-1/2 (C-band platforms) is typically 500–600 m or less. Two radar images that generally match the above characteristics can form an interferometric pair.

InSAR data processing generally begins with raw sensor data, or single-look complex (SLC) data, and involves raw data processing and co-registering two or more images. The second image (and others if used) must be precisely aligned with the first image with sub-pixel accuracy; otherwise, additional

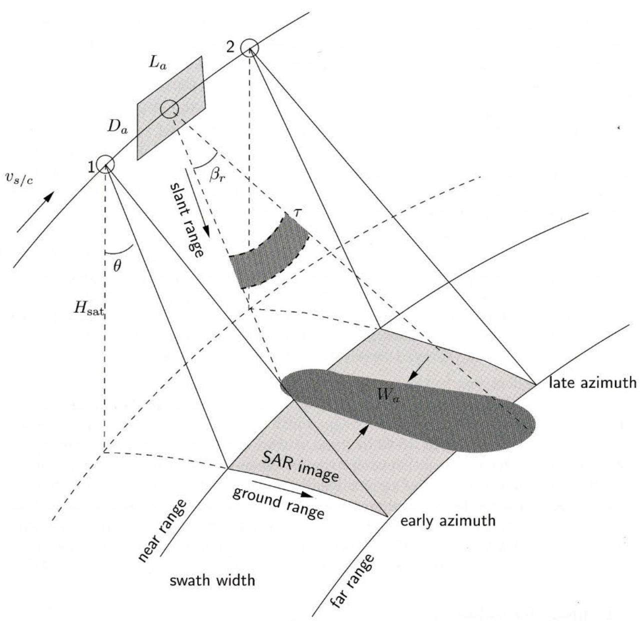

Figure D2. *Imaging geometry of a radar satellite. As the satellite moves in a forward direction (to the upper right in the figure), the satellite images the light gray swath on the ground surface. The dark gray area on the ground surface indicates the area covered by a single radar pulse (modified from Hanssen, 2001).*

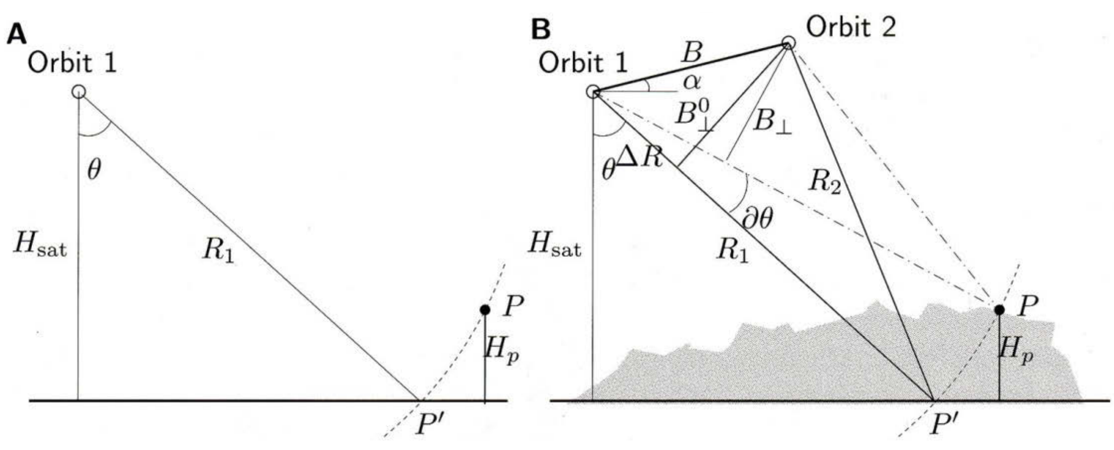

Figure D1. *Satellite geometry for single-pass (A) and interferometric (B) radar acquisition. Using two different satellite space positions allows for the height difference, H_p to be determined (modified from Hanssen, 2001).*

__Table D1.__ Radar bands, wavelengths, and InSAR spaceborne platforms showing year date ranges of operation and launch/operating country.

Radar Band	Wavelength Range (cm)	Civilian Space InSAR Platforms[1,2]	
		Non-Operational	**Operating**
X	2.4 – 3.8	X-SAR (SIR-C, 1994, USA) STRM (2000, USA)	TerraSAR-X (2007+, Germany/EU) TanDEM-X (2010+, Germany/EU) COSMO-SkyMed 1 (2007+, Italy/EU) COSMO-SkyMed 2 (2007+, Italy/EU) COSMO-SkyMed 3 (2008+, Italy/EU) COSMO-SkyMed 4 (2010+, Italy/EU) KOMPSAT-5 (2013+, South Korea)
C	3.8 – 7.5	ERS-1 (1991-2000, EU) ERS-2 (1995-2011, EU) SIR-C (1994, USA) ENVISAT (2002-2012, EU) Radarsat-1 (1995-2013, Canada)	Radarsat-2 (2007+, Canada) Sentinel-1 (2014+, EU)
S	8 – 15	--	Proposed: NISAR (USA/India)
L	15 – 30	Seasat[3] (1978, USA) JERS-1 (1992-1998, Japan) SIR-C (1994, USA) ALOS (2006-2011, Japan)	ALOS-2 (2014+, Japan) Proposed: NISAR (USA/India)

[1] EU – European Union, USA – United States of America.
[2] All systems are satellite-based, with the exception of SIR-C and SRTM, which were flown on the now-defunct Space Shuttle.
[3] The USA's only civilian radar satellite, Seasat, operated for 105 days in 1978 (JPL, 1998). Seasat data has been used in some InSAR analysis; however, the data was never intended to be used for InSAR, custom processing software is required, and products are relatively poor when compared to more modern data products.

error is introduced into the process and later processing steps will fail. After co-registration, the complex phase information of the first image is multiplied by the conjugate (inverse) phase of the second image to generate an interferogram or interference image.

The interferogram contains topographic and ground displacement information with each cycle of phase (or phase change of 0 to 2π radians) representing a specific quantity of change. At this point in the processing chain, the interferogram is in radar coordinates, which later must be registered to ground coordinates (such as latitude/longitude, Universal Transverse Mercator [UTM], or other coordinate system).

Phase Unwrapping

One of the most difficult steps in InSAR processing is the phase unwrapping process. This process utilizes the phase information from the interferogram to determine the magnitude of surface displacements or topography (depending on the analysis method) present in the image. Phase unwrapping may use branch-cut, least squares, and error minimization criteria methods (Rosen and others, 2000). Branch-cut methods utilize phase differences and integrating that difference. The phase-unwrapped solution should be independent of the path of integration (Madsen and Zebker, 1998); however, this may not always be the case. Phase residues may result from this process, across which phase unwrapping is not possible. If an area is enclosed by these errors, the area will not be unwrapped, and no information will be obtained. Many of the branch-cut algorithms are automated and do not require user intervention during processing. An existing DEM, which must cover all of the ground area covered in the radar image, is often used to generate seed points to help in automatic guiding of the phase unwrapping process. Least squares phase unwrapping follows the general procedures of the branch-cut methods, but with least-squares estimation.

Figure D3 shows a final, unwrapped, geocoded interferogram from Envisat data of Cedar Valley (Iron County) and the surrounding region. Specific color fringes in the Beryl-Enterprise area, Quichipa Lake, and Enoch graben show vertical displacement directly related to ground subsidence. The variable colors in the rest of the image are the result of incomplete removal of topography and/or atmospheric noise in the data.

After phase unwrapping of the interferogram and depending on the analysis method used, a displacement map may be generated if the effects of topography are removed using an existing DEM, or a DEM may be created if the interferogram contains little to no surface displacements.

Issues With InSAR Processing

Problems associated with InSAR are chiefly (1) shadowing present in the original radar data from topographic relief (particularly when applied to mapping mountainous areas where steep mountains block the inclined radar signal), and (2) decorrelation caused by changes in the imaged area. These changes may be due to freezing, thawing, precipitation, vegetation,

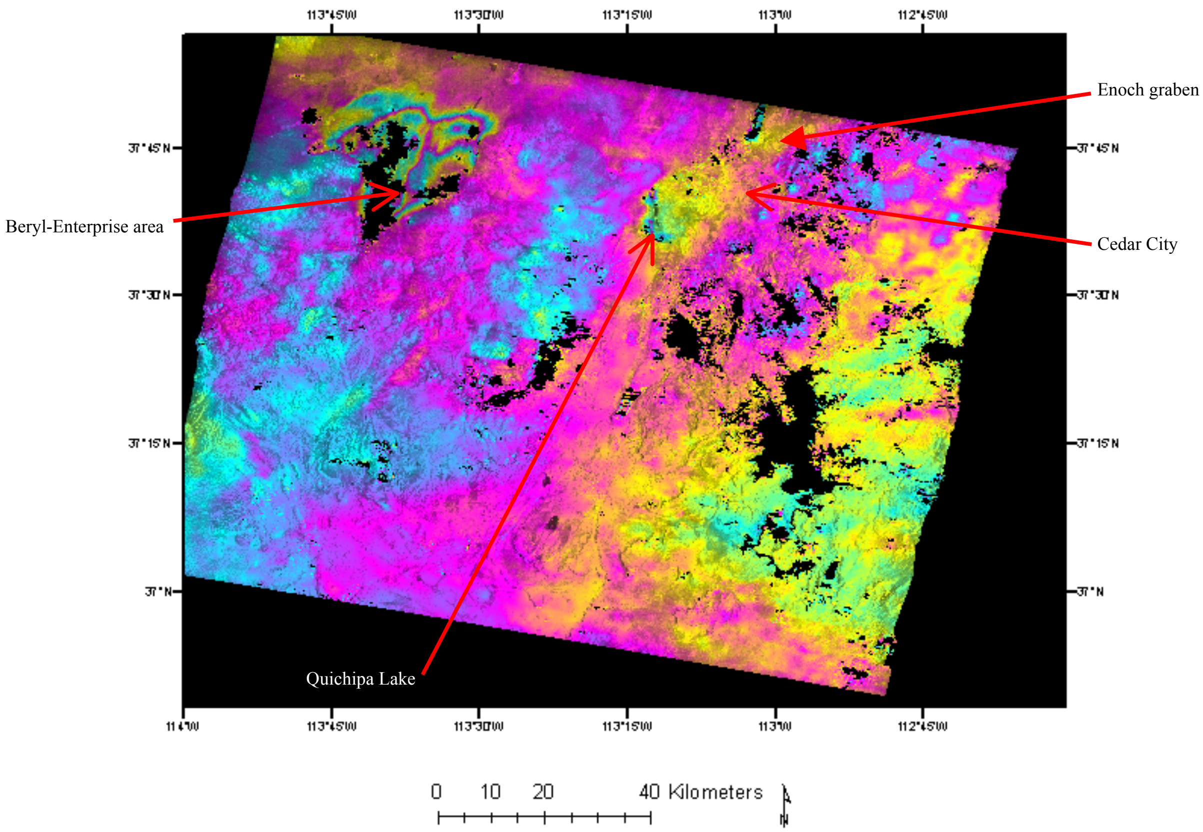

Figure D3. *Unwrapped interferogram of an entire Envisat frame, processed by the UGS, covering the time period of August 11, 2009, to August 31, 2010, showing significant subsidence near Quichapa Lake, Enoch graben, and the Beryl-Enterprise area resulting from groundwater withdrawal. Each specific color cycle represents 3 cm of deformation; the variable colors in the rest of the image are the result of incomplete removal of topography and/or atmospheric noise in the data. Area outside the Envisat frame shown in black on the edges; black areas within interferogram denote areas of no data from shadowing or from no correlation between the two images used to create the interferogram. Envisat data ©2009, 2010 European Space Agency.*

wind, motion of water, and human-induced changes, such as changes in land use. Agricultural fields are constantly changing due to vegetation (crop) changes in height and size, and from tilling of fields that may cause significant decorrelation. Vegetated areas may also exhibit decorrelation, due to wind moving vegetation, such as in forests.

Increased time between two radar image acquisitions will result in increased temporal decorrelation and is directly related to ground surface parameters. Zebker and Villasenor (1992) found that increasing the time between acquisitions decreased correlation significantly for lava flows and forests in Oregon; however, the Death Valley, California, valley floor did not experience this correlation decrease. Some geographic areas typically have low temporal decorrelation, including many desert and low-vegetation-density areas; high-temporal-decorrelation areas include many moderately to highly vegetated and/or forested areas, active agricultural lands, and other areas subject to surface disturbance. Persistent scatterers, a relatively new technique utilizing point scatterers (Hooper and others, 2004), may be used to match common points between radar images, such as the centers of pivoting agricultural sprinklers, reflective metallic objects that may act as near-corner reflectors, or other stationary reflective objects.

SAR DATA AVAILABILITY AND PROCESSING

SAR data suitable for use in differential interferometric processing is available for many areas in Utah from ESA (ERS-1, ERS-2, and ENVISAT) and Japanese (ALOS and ALOS-2) satellites. InSAR satellites have commonly been designed, launched, and managed by joint government-commercial funding and operation agreements, and as such, two cost levels of data exist. Academic and government researchers typically acquire data through governmental agreements and partnerships, with data access proposals often required. All other use requires commercial purchase from private vendors, and all data is typically subject to third-party data transfer restrictions. Commercial purchases of ERS-1, ERS-2, and ENVISAT data in the existing ESA data archive cost approximately $560 per scene (2013).

Due to the large amount of data generated by a radar system, available satellite on-board data storage, and high power (electrical) use of a radar system, radar data is not continuously acquired as in other imaging satellites, such as the Landsat series (1-7). Rather, specific, pre-determined areas of the Earth's surface are imaged on each path of the satellite within the power and data storage capabilities of the satellite. These pre-determined areas are based on requirements of the satellite program, scientific investigator requests, and commercial purchases. In many cases, radar data are downlinked to ground stations within radio receiving range (ground station mask), so additional data may be acquired beyond the limits of on-board data storage, or are transmitted to a satellite communications network that in turn transmits to ground stations. This pre-planning and equipment adds additional cost to new data acquisitions, which is reflected in the higher cost of new acquisitions to the end-user.

Data Analysis and Applications

Due to the complexities of processing InSAR data, and that most InSAR processing software is generally expensive (commercial versions) or difficult to obtain (due to licensing and/or export restrictions), prospective users of InSAR should seek out a competent remote sensing researcher familiar with InSAR data and processing.

InSAR is particularly suited to detecting and monitoring ground deformation, such as that caused by seismic deformation and groundwater-withdrawal- or mining-induced land subsidence. Prior to the widespread use of lidar, InSAR was used to create DEMs, and is still used to create DEMs of large areas today, such as in Alaska and Antarctica, although with lower resolution (larger ground cell size) than lidar.

Seismic Deformation

Detecting and monitoring seismic deformation was one of the early applications of InSAR, including the 1999 M_w 7.1 Hector Mine, California, earthquake (Simons and others, 2002). However, InSAR has yet to be applied in Utah for seismic deformation as no active faults in the state are known to creep, and a surface rupturing earthquake has not occurred in Utah since InSAR data have become available.

Ground Subsidence

InSAR has been applied to detecting and monitoring ground subsidence throughout the Intermountain West, including for groundwater-withdrawal-induced subsidence in Utah (Forester, 2006, 2012; Knudsen and others, 2014), Nevada (Katzenstein, 2008), and Arizona (Arizona Department of Water Resources, undated). Interferograms and derivative ground deformation maps can be used to show areas and magnitudes of ground deformation that can assist with developing detailed ground deformation monitoring and groundwater management programs.

CONCLUSIONS

InSAR is a valuable, evolving tool for detecting, mapping, and understanding geologic hazards, particularly related to ground deformation, such as that caused by seismic deformation and groundwater-withdrawal- or mining-induced land subsidence. Large surface areas can be covered with repeat coverages, allowing time-series analysis of deformation. InSAR has allowed the mapping of ground deformation at unprecedented levels of detail over large regional areas that was not possible previously using traditional methods.

REFERENCES

Arizona Department of Water Resources, undated, Fact Sheet—Monitoring the state's water resources, InSAR—ADWR's satellite based land subsidence monitoring program: Arizona Department of Water Resources, 2 p.

Avery, T.E., and Berlin, G.L., 1992, Fundamentals of remote sensing and airphoto interpretation, fifth edition: New York, Macmillan Publishing Company, 472 p.

Canadian Space Agency, 2010, Satellites—earth-observation satellites: Online, http://www.asc-csa.gc.ca/eng/satellites/, accessed October 18, 2010.

Canadian Space Agency, 2013, RADARSAT—seventeen years of technological success: Online, http://www.asc-csa.gc.ca/eng/media/news_releases/2013/0509.asp, accessed September 3, 2013, no longer available.

European Space Agency, 2008, ERS overview: Online, http://www.esa.int/esaEO/SEMGWH2VQUD_index_0_m.html, accessed October 18, 2010.

European Space Agency, 2010, ENVISAT history: Online, http://earth.esa.int/category/index.cfm?fcategoryid=87, accessed October 18, 2010.

European Space Agency, 2012a, ESA declares end of mission for Envisat: Online, https://earth.esa.int/web/guest/news/-/asset_publisher/G2mU/content/good-bye-envisat-and-thank-you, accessed September 3, 2013.

European Space Agency, 2012b, ERS satellite missions complete after 20 years: Online, https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/ers/news/-/asset_publisher/T7aX/content/ers-satellite-missions-complete-after-20-years-7895?p_r_p_564233524_assetIdentifier=ers-satellite-missions-complete-after-20-years-7895&redirect=%2Fc%2Fportal%2Flayout%3Fp_l_id%3D66101, accessed March 15, 2012.

Forster, R.R., 2006, Land subsidence in southwest Utah from 1993 to 1998 measured with interferometric synthetic aperture radar (InSAR): Utah Geological Survey Miscellaneous Publication 06-5, 30 p.

Forster, R.R., 2012, Evaluation of interferometric synthetic aperture radar (InSAR) techniques for measuring land subsidence and calculated subsidence rates for the Escalante Valley, Utah, 1998 to 2006: Utah Geological Survey Open-File Report 589, 25 p., CD.

Gabriel, A.K., Goldstein, R.M., and Zebker, H.A., 1989, Mapping small elevation changes over large areas—differential radar interferometry: Journal of Geophysical Research, v. 94, p. 9183–9191.

German Aerospace Center, 2009, TerraSAR-X—Germany's radar eye in space: Online, http://www.dlr.de/eo/en/desktopdefault.aspx/tabid-5725/9296_read-15979/, accessed March 15, 2012.

German Aerospace Center, 2010, TanDEM-X—a new high resolution interferometric SAR mission: Online, http://www.dlr.de/hr/desktopdefault.aspx/tabid-2317/3669_read-5488/, accessed September 3, 2013.

Goldstein, R., Englehardt, H., Kamb, B., and Frohlich, R.M., 1993, Satellite radar interferometry for monitoring ice sheet motion—application to an Antarctic ice stream: Science, v. 262, p. 525–1530.

Graham, L.C., 1974, Synthetic interferometer radar for topographic mapping: Institute of Electrical and Electronics Engineers, Proceedings of the IEEE, v. 62, no. 6, p. 763–768.

Hanssen, R.F., 2001, Radar interferometry—data interpretation and error analysis: Dordrecht, The Netherlands, Kluwer Academic Publishers, 308 p.

Hooper, A., Zebker, H., Segall, P., Kampes, B., 2004, A new methods for measuring deformation on volcanoes and other natural terrians using InSAR persistent scatterers: Geophysical Research Letters, v. 31, p. 1–5.

Japan Aerospace Exploration Agency, 2010a, Japanese earth resources satellite “FUYO-1” (JERS-1): Online, http://www.jaxa.jp/projects/sat/jers1/index_e.html, accessed October 18, 2010.

Japan Aerospace Exploration Agency, 2010b, Advanced land observing satellite “DAICHI”: Online, http://www.alos-restec.jp/en/staticpages/index.php/aboutalos, accessed October 25, 2010.

Japan Aerospace Exploration Agency, undated, ALOS-2-the advanced land observing satellite-2 “DAICHI-2”: Online, http://global.jaxa.jp/activity/pr/brochure/files/sat29.pdf, accessed September 3, 2013.

Jet Propulsion Laboratory, 1998, SEASAT 1978: Online, http://southport.jpl.nasa.gov/ scienceapps/seasat.html, accessed May 22, 2014.

Jet Propulsion Laboratory, 2010a, Shuttle Radar Topography Mission—the mission to map the world: Online, http://www2.jpl.nasa.gov/srtm/, accessed October 18, 2010.

Jet Propulsion Laboratory, 2010b, SIR-C/X-SAR flight 1 statistics: Online, http://southport.jpl.nasa.gov/sir-c/html/mission.html, accessed October 18, 2010.

Katzenstein, K.W., 2008, Mechanics of InSAR-identified bedrock subsidence associated with mine-dewatering in north-central Nevada: Reno, University of Nevada, Reno, Ph.D. dissertation, 300 p.

Knudsen, T., Inkenbrandt, P., Lund, W., Lowe, M., and Bowman, S., 2014, Investigation of land subsidence and earth fissures in Cedar Valley, Iron County, Utah: Utah Geological Survey Special Study 150, 84 p., 8 appendices, CD.

Madsen, S.N., and Zebker, H.A., 1998, Imaging radar interferometry, *in* Henderson, F.M., and Lewis, A.J., editors, Principals & applications of imaging radar, third edition, volume 2: New York, John Wiley & Sons, p. 359–380.

Richman, D., 1971, Three dimensional azimuth-correcting mapping radar: United Technologies Corporation, variously paginated.

Rosen, P.A., Hensley, S., Joughin, I.R., Li, F., Madsen, S.N., Rodriquez, E., and Goldstein, R.M., 2000, Synthetic aperture radar interferometry: Institute of Electrical and Electronics Engineers, Proceedings of the IEEE, v. 88, no. 3.

Simons, M., Fialko, Y., and Rivera, L., 2002, Coseismic deformation from the 1999 M_w 7.1 Hector Mine, California, earthquake as inferred from InSAR and GPS observations: Bulletin of the Seismological Society of America, v. 92, no. 4, p. 1390–1402.

Zebker, H.A., and Goldstein, R.M., 1986, Topographic mapping from interferometric synthetic aperture radar observations: Journal of Geophysical Research, v. 91, p. 4993–4999.

Zebker, H.A., Rosen, P.A., Goldstein, R.M., Gabriel, A., and Werner, C.L., 1994, On the derivation of coseismic displacement fields using differential radar interferometry—the Landers earthquake: Journal of Geophysical Research, v. 99, no. B10, p. 19,617–19,634.

Zebker, H.A., and Villasenor, J., 1992, Decorrelation in interferometric radar echoes: IEEE Transactions on Geoscience and Remote Sensing, v. 30, no. 5, p 950–959.