GEOLOGIC HAZARDS OF MONROE CITY, SEVIER COUNTY, UTAH

by
Richard E. Giraud

SPECIAL STUDY 110
UTAH GEOLOGICAL SURVEY
a division of
Utah Department of Natural Resources
2004

UTAH GEOLOGICAL SURVEY

GIRAUD

GEOLOGIC HAZARDS OF MONROE CITY, SEVIER COUNTY, UTAH

UGS SS 110

ISBN 1-55791-703-5

GEOLOGIC HAZARDS OF MONROE CITY, SEVIER COUNTY, UTAH

by
Richard E. Giraud

Digital compilation by Justin P. Johnson

Cover photo: Southwest view of the southern part of Monroe and Sevier Valley, principal hazards in the area include earthquake ground shaking, debris-flows, alluvial-fan flooding, collapsible soils, and radon gas. The snow-capped Tushar Mountains are in the distance.

ISBN 1-55791-703-5

SPECIAL STUDY 110
UTAH GEOLOGICAL SURVEY
a division of
Utah Department of Natural Resources
2004

UTAH GEOLOGICAL SURVEY

STATE OF UTAH
Olene S. Walker, Governor

DEPARTMENT OF NATURAL RESOURCES
Robert L. Morgan, Executive Director

UTAH GEOLOGICAL SURVEY
Richard G. Allis, Director

PUBLICATIONS
contact
Natural Resources Map/Bookstore
1594 W. North Temple
telephone: 801-537-3320
toll-free: 1-888-UTAH MAP
website: http://mapstore.utah.gov
email: geostore@utah.gov

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

1/04

CONTENTS

TABLES

FIGURES

PLATES (on CD in pocket)

GIS FILES (on CD in pocket)

GEOLOGIC HAZARDS OF MONROE CITY, SEVIER COUNTY, UTAH

by
Richard E. Giraud

Digital compilation by
Justin P. Johnson

ABSTRACT

Geologic hazards are naturally occurring processes that present a risk to life and property. This report provides information for the Monroe City area, in Utah's central Sevier Valley, to reduce losses from geologic hazards.

Surficial-geologic mapping provides the basis on which individual geologic hazards are identified and mapped. Alluvial-fan and basin-fill deposits cover most of the map area. Other deposits consist of colluvium, artificial fill, spring travertine, and volcanic bedrock.

Areas of potential geologic hazards are shown on plates 2-4, which include recommendations for site-specific studies to identify hazards. Planners may use these stand-alone maps separately from the report for land-use planning. Details supporting the geologic hazard analysis and specific recommendations, and expanded map unit designations, are given in the text. Mapped geologic hazards include alluvial-fan flooding and debris flows, problem soil and rock, earthquakes and related hazards, and radon gas. Alluvial-fan flooding and debris-flow hazards are greatest near the mountain front, but alluvial-fan-flooding may also occur on alluvial fans and basin-fill areas downslope, particularly on the Monroe Creek alluvial fan. The Utah Geological Survey recommends a request be made to the Federal Emergency Management Agency to update and remap flood zones on Monroe Creek alluvial fan and consider the mapping results of the U.S. Army Corps of Engineers flood study. Collapsible soils are present in alluvial fans and the hazard potential is widespread since alluvial fans cover a large part of the map area. Earthquake ground shaking is the most widespread and potentially damaging earthquake hazard. All of Monroe is in *International Building Code* seismic design category D, regardless of site class or seismic use groups, and in *International Residential Code* seismic design category D1. Large to moderate earthquakes have the potential to generate rock falls from volcanic bedrock outcrops east and southeast of Monroe. The Sevier fault is mapped as a buried fault along the eastern map boundary and a surface-fault rupture special-study area is outlined for construction of critical facilities. Both high and moderate radon-hazard-potential areas are mapped within the study area. No areas of low radon-hazard potential were identified. Other hazards such as landslides, earthquake-induced liquefaction, shallow ground water, and expansive soils and other problem soils are generally not present.

The geologic hazards maps show where hazards may exist. The maps should be used to inform citizens and developers of potential risks and for local government officials to make prudent land-use planning decisions. The maps are general, and site-specific studies are needed to demonstrate site suitability prior to development. Typical risk-reduction methods for these geologic hazards generally include avoidance or engineering design to reduce the risk to an acceptable level.

INTRODUCTION

The Monroe City study area lies along the eastern side of central Sevier Valley in central Utah. Near Monroe, Sevier Valley is bounded by the Sevier Plateau on the east and the Pahvant Range on the west (figure 1). The Sevier River flows to the northeast through the relatively flat valley northwest of the study area (figure 1). Alluvial fans and the valley floor slope northwest away from the mountain flank east of Monroe. The climate of the valley is semiarid; Richfield, 10 miles (16 km) north of Monroe (figure 1), receives an annual average precipitation of 8.12 inches (206 mm) (Western Regional Climate Center, 2003). Summer precipitation typically consists of brief intense thunderstorms of short duration, whereas winter precipitation consists of longer duration rainfall and snowfall. Topographic elevations in the area range from 5,300 feet (1,616 m) north of Monroe to 11,227 feet (3,423 m) on Monroe Peak 6 miles (9.7 km) southeast of Monroe.

Within the study-area boundaries (figure 1), elevations range from 5,320 to 6,200 feet (1,623-1,890 m). The area of study is 6.1 square miles (15.8 km^2). The majority of land within the study area north, west, and south of Monroe is used for agriculture.

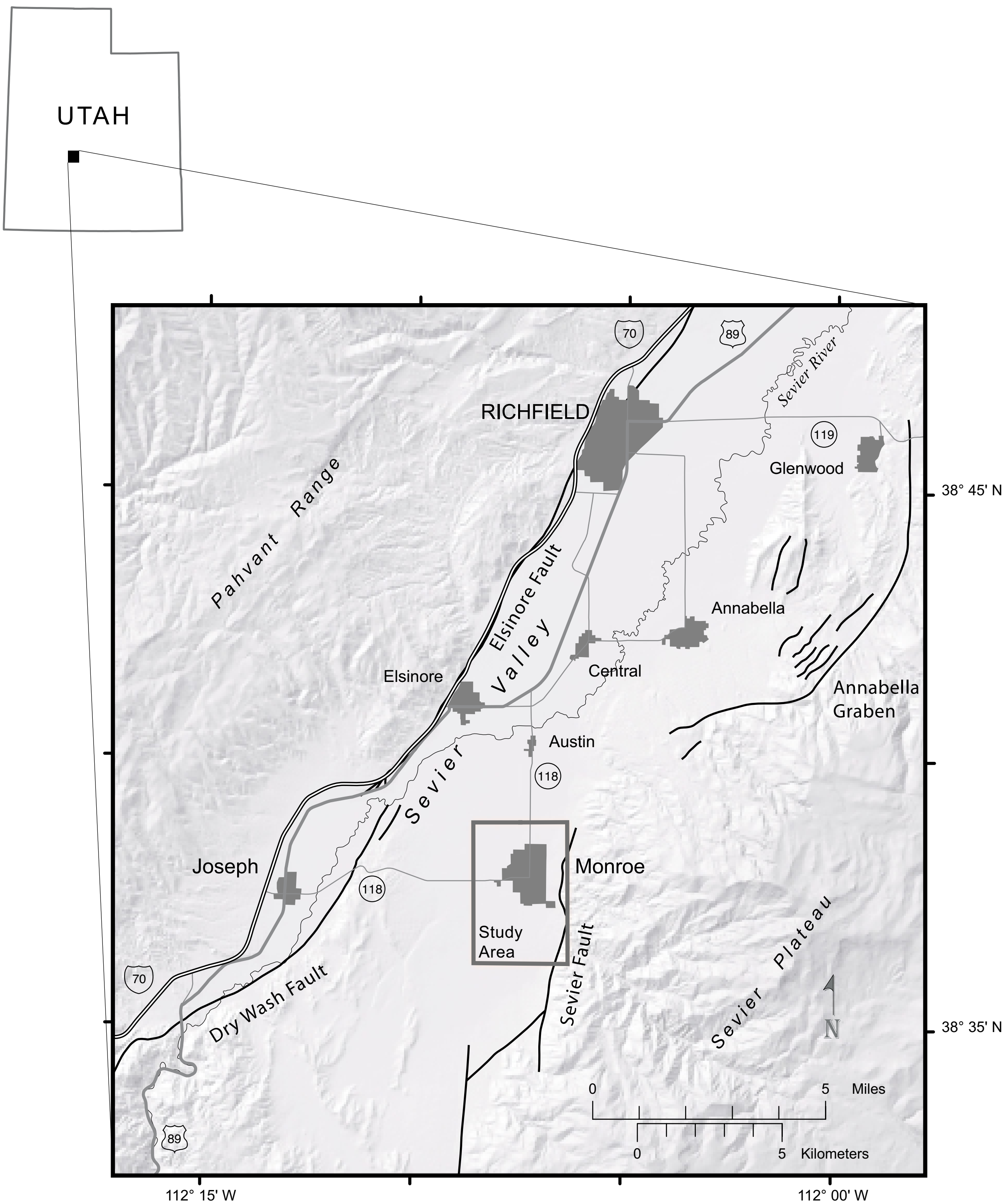


Figure 1. *Location of the Monroe City geologic-hazard study area in Sevier Valley, Utah. Base from U.S. Geological Survey (USGS) 7.5-minute Digital Elevation Model (DEM) quadrangles and Utah Automated Geographic Refrence Center (AGRC) data sources.*

Many of the geologic processes that shaped the landscape in and around Monroe in the geologic past are still active today and are potentially hazardous to property and life. Principal geologic hazards in the area are: (1) alluvial-fan flooding and debris flows, (2) problem soils and rock, (3) earthquakes and related hazards, and (4) radon gas.

Where development takes place in geologically hazardous areas, geologic input is most important early in the planning and development process; redesigning subdivisions and other development around geologic problems or repairing damage caused by a geologic hazard is costly and often impractical. For Monroe area homeowners, government officials, and developers this report provides maps and other information concerning geologic hazards that may affect development in the Monroe area.

The hazard maps included with this report (plates 2-4) are derived primarily from the surficial geologic map (plate 1) and are based on relationships among hazards and the origins of the different geologic units. The key sources for flooding and debris flows include the Federal Emergency Management Agency (FEMA) national flood insurance rate maps (1979a, 1979b) and compilations and reports from Woolley (1946, 1947), Keetch (1971), U.S. Soil Conservation Service (SCS) (1971), Butler and Marsell (1972), Utah Division of Comprehensive Emergency Management (1981), and U.S. Forest Service (1983, 1984). The main sources for problem soil and rock hazards include the SCS (1976) investigation for the proposed Bertlesen Canyon debris basin; the SCS (1984, 1986), Smith and Deal (1988), and URS Greiner Woodward Clyde (1999) investigations at the Sand H debris basin; and the SCS (1991) unpublished soil mapping. The main sources for earthquake hazards include the neotectonic framework of the central Sevier Valley report (Anderson and Barnhard, 1992), the University of Utah Seismograph Stations earthquake catalog (Arabasz and McKee, 1979), and procedures outlined in the *International Building Code* and the *International Residential Code* (International Code Council, 2000a, 2000b). The Utah Geological Survey (UGS) study of the radon-hazard potential of central Sevier Valley is the primary source of indoor-radon-hazard information. Geologic hazards data were compiled onto 1:10,000-scale hazards maps. The areal extent of most of the geologic hazards is based on mapping of surficial and bedrock deposits.

The scope of work for this hazard mapping included meeting with local-government officials and residents, reviewing pertinent literature, interpreting aerial photographs, field mapping, excavation and logging of test pits, geotechnical laboratory testing of soil samples, and preparing a geotechnical soils database. The report presents a detailed discussion of geologic hazards specific to the Monroe area and addresses possible hazards, application of the maps to land-use planning, and possible risk-reduction measures.

GEOLOGY

Setting

Central Sevier Valley is a graben bounded by the Elsinore fault on the west and the Sevier fault on the east (figure 1) (Anderson and Barnhard, 1992). Both faults coincide with the valley margins where unconsolidated basin-fill deposits are in contact with bedrock. Historically, central Sevier Valley has experienced earthquakes as large as about magnitude 6 $^1/_2$ and is one of the most active parts of the Intermountain seismic belt in Utah (Anderson and Barnhard, 1992). Monroe hot springs on the eastern edge of Monroe (figure 2) discharge from the Sevier fault zone and have a relatively constant temperature of 169° Fahrenheit (76°C) (Mase and others, 1978). Monroe Creek has perennial flow but other drainages to the east and south are ephemeral (figure 2).

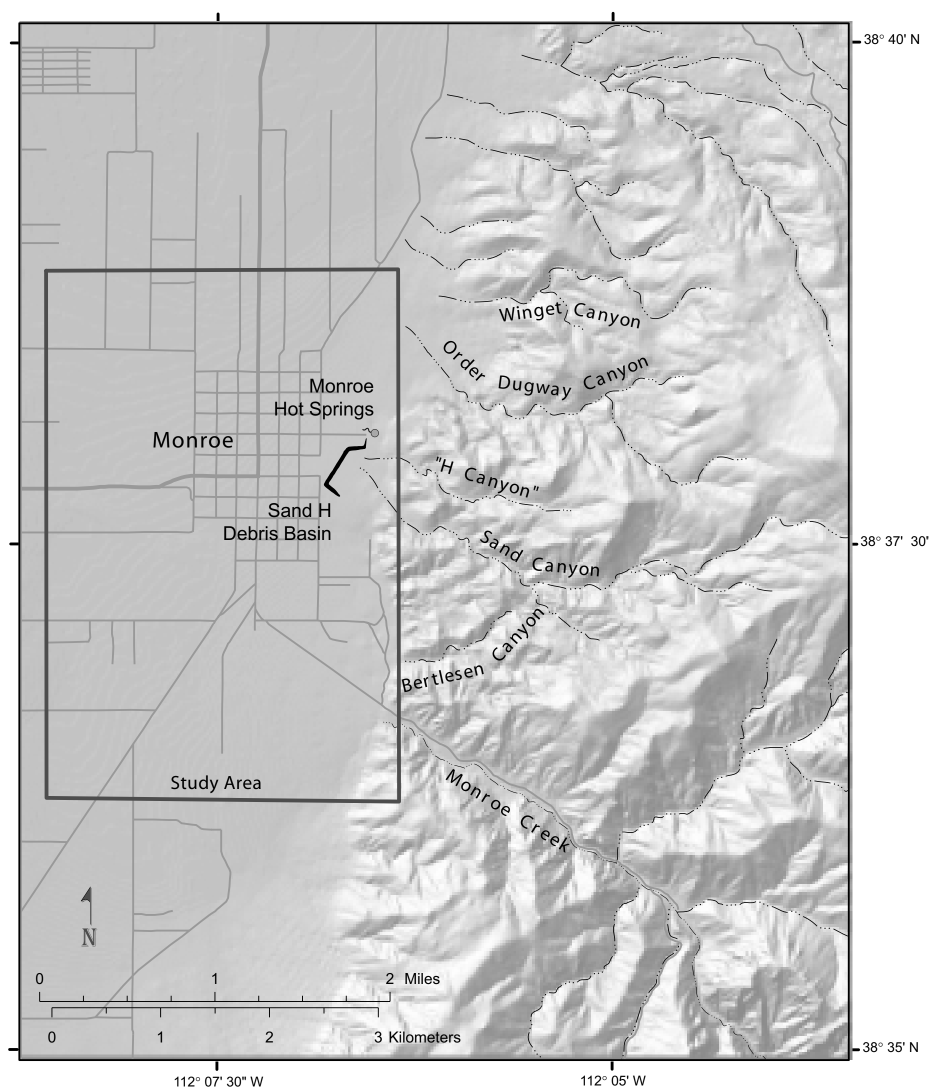


Figure 2. *Canyons and drainage basins east of Monroe. Base from USGS 7.5-minute DEM quadrangles and AGRC data sources.*

Most of the study area lies on unconsolidated basin-fill or fan alluvium that fills Sevier Valley. The unconsolidated deposits are derived from Tertiary volcanic rocks east of the study area. The volcanic rock units consist of dacite lava flows of the Bullion Canyon Volcanics (Miocene and Oligocene), quartz latite ash-flow tuff of the Needles Range Formation (Oligocene), and volcanic conglomerate, sandstone, and mudflow and minor lava flows and flow breccias of the volcanic rocks of Cliff Canyon alluvial facies (Oligocene) (Rowley and others, 1981a, 1981b).

Description of Map Units

Geologic mapping provides basic information from which geologic hazards can be identified and addressed. Plate 1, the surficial geologic map, shows geology of the study area a scale of 1:10,000. I mapped the geology on 1:24,000-scale aerial photographs and 1:10,000-scale orthophotographs, then transferred to the 1:10,000-scale topographic map.

The map units are shown on plate 1. Map-unit descriptions are grouped by genesis (mode of formation) and age. Genetic divisions include alluvial, spring, colluvial, and artificial deposits. For this map, many of the age categories are based on geomorphic expression, the degree of soil development, desert varnish, historical sedimentation and flooding events, and the degree of secondary calcium carbonate development.

Alluvial Deposits

The alluvial deposits consist of variable amounts of cobble gravel, pebble gravel, sand, silt, and clay, deposited by perennial and ephemeral streams as stream flows, sheetfloods, and debris flows. The map units are subdivided into four deposit types: stream alluvium, fan alluvium of two different ages (Qaf_1 and Qaf_2), and basin-fill alluvium.

Stream deposits are mapped in the channel and along the narrow terraces of Monroe Creek in Monroe Canyon. These deposits are differentiated based on sorting, grain size, morphological expression, and association with modern streams.

Alluvial-fan deposits are present on the piedmont (alluvial apron at the mountain front). These deposits are differentiated by: (1) their position relative to basin-fill alluvium and other fan deposits, (2) the degree of soil development, (3) the degree of desert varnish on cobbles, (4) geomorphic expression, and (5) historical flood and sedimentation events. The alluvial-fan deposits are poorly to well sorted and are both matrix supported (that is, consist of pebbles and cobbles that are suspended in a fine-grained matrix of sand, silt, and clay) and clast supported. The Monroe Creek alluvial fan has a relatively gentle average fan slope of 2° and was deposited largely by stream flows. The alluvial fans at the mouths of Winget, Order Dugway, Sand, and Bertlesen Canyons, and other small unnamed canyons, have average fan slopes greater than 3° and were formed from both debris flows and stream flows.

Basin-fill alluvium is mapped downslope of alluvial fans. The basin-fill deposits are differentiated from other alluvium based on sorting, grain size, morphology, and position relative to alluvial fans.

Stream alluvium (Qal): I mapped stream alluvium in and along Monroe Creek, a perennial stream. This deposit forms the narrow creek bed and terraces along the creek in Monroe Canyon. The unit grades downslope into alluvial-fan deposits on the Monroe Creek alluvial fan (unit Qaf_1). The unit consists of pebble, cobble, and boulder gravel, gravelly sand, silty sand, and minor clay. The alluvium is moderately sorted, thin to medium bedded, and clasts are subangular to well rounded. The unit is probably less than 15 feet (5 m) thick and is late Holocene in age.

Fan alluvium, unit 1 (Qaf_1): Unit 1 is fan alluvium deposited on the Monroe Creek alluvial fan and on coalescing fan complexes at the base of the mountain front at the mouths of Winget, Order Dugway, Sand, and Bertlesen Canyons, and other small unnamed drainages. On the Monroe Creek alluvial fan the deposits consist of poorly to well-sorted coarse- and fine-grained alluvium deposited largely by stream flows. The Monroe Creek fan surface is dominated by boulder and cobble gravel. On the other alluvial fans the deposits consist of poorly sorted coarse- and fine-grained alluvium deposited by both stream flows and debris flows. The other alluvial fans also have a relatively smooth surface compared to the cobble-rich Monroe Creek fan surface. The unit probably ranges up to 40 feet (12 m) thick and is late Holocene in age.

Fan alluvium, unit 2 (Qaf_2): Unit 2 is older fan alluvium deposited on the Monroe Creek alluvial fan. The unit forms the older and largest portion of the Monroe Creek alluvial fan. The deposits consist of poorly to well-sorted coarse- and fine-grained alluvium deposited largely by stream flows. The fan surface is dominated by boulder and cobble gravel. The unit probably ranges up to 50 feet (15 m) thick and is early Holocene to late Pleistocene age.

Basin-fill alluvium (Qab): I mapped basin-fill alluvium downslope of alluvial fans. This fine-grained alluvium is deposited by stream flows and sheetflows off the distal ends of alluvial fans. Based on water-well logs, the unit is greater than 320 feet (98 m) thick, and is Holocene and Pleistocene in age.

Colluvial Deposits

Colluvial deposits (Qc) are composed of hillslope colluvium derived from weathered volcanic bedrock. The colluvium is deposited by slope-wash and mass-wasting processes on steep (20° to 35°) slopes along the mountain front and in steep-sided canyons. The deposits consist of pebble, cobble, and boulder gravel, gravelly sand, silty sand, sandy silt, and minor clay and are generally clast supported, unsorted, and poorly stratified. The clasts are generally angular to subangular owing to short transport distances from weathered rock sources. The deposits are moderately hard when cemented by calcium carbonate. The colluvial cover ranges up to about 20 feet (6 m) thick and is Holocene and Pleistocene in age.

Spring Deposits

The spring deposits consist of travertine (Qst) deposited around Monroe hot springs. The travertine is composed largely of calcium carbonate (limestone), and is massive, finely crystalline, and tan to brown. The deposit forms an arc-shaped travertine terrace deposited on Tertiary volcanic rocks. The travertine ranges up to about 20 feet (6 m) thick and is Holocene to late Pleistocene in age. Shallow ground water and hot springs are present within this unit.

Artificial-Fill Deposits

Artificial-fill deposits (Qf) consist of historically placed engineered fill and non-engineered fill. Engineered fill consists of selected earth materials that have been placed and compacted for construction of the Sand H debris basin and dikes, and the underground and surface-water reservoir at the mouth of Monroe Creek. Non-engineered fill consists of locally derived surficial deposits of variable grain size used for construction of small ponds and the flood-control dikes on the Monroe Creek alluvial fan. Non-engineered fill consisting of organic material, concrete, and minor building demolition material is also present in the barrow pit at the east end of 580 South Street. The organic material in the fill when completely buried may generate methane gas. The artificial fill may also undergo settlement. The unit ranges in thickness from 3 to 20 feet (1-6 m).

Bedrock

Bedrock deposits (Tv) consist of Tertiary volcanic rocks of Miocene and Oligocene age. The volcanic rocks include the Bullion Canyon Volcanics (dacite lava flows), Needles Range Formation (quartz latite ash-flow tuff), and volcanic rocks of Cliff Canyon alluvial facies (volcanic conglomerate, sandstone, and mudflows). Bedrock units are not shown in detail on plate 1. The outcrop patterns of these units provide generalized information about source rocks for alluvial and colluvial units. For more information, consult the 1:24,000-scale bedrock geologic maps by Rowley and others (1981a, 1981b).

ALLUVIAL-FAN-FLOODING AND DEBRIS-FLOW HAZARDS

From a historical perspective, alluvial-fan-flooding and debris-flow hazards are the most frequent and destructive geologic hazards affecting Monroe. Since settlement in 1863, Monroe has had an extensive history of flooding and debris flows. The flooding and debris-flow hazards result from snowmelt and rainfall runoff from the steep, rugged drainage basins east and southeast of Monroe. Development in the eastern and southern parts of Monroe on active alluvial fans results in significant exposure to alluvial-fan-flooding and debris-flow hazards. FEMA (1979a, 1979b) mapped the 100-year flood (flood with a 1 percent probability of occurring in any given year) associated with Monroe Creek and areas of minimal flooding in the Monroe area. The U.S. Army Corps of Engineers (1995) performed a study of flooding potential on the Monroe Creek alluvial fan using the FLO-2D flood routing computer model and considering the existing flood-control dikes. Even though floods are primarily water, records indicate significant sediment transport and deposition by floodwaters, perhaps in some cases associated with debris-flow events. Construction of the Sand H debris basin in Monroe by the SCS (presently U.S. Natural Resources Conservation Service) provides flood and debris-flow protection from Sand Canyon and “H Canyon” (figure 2) (H Canyon is an unnamed canyon north of Sand Canyon; SCS, 1984). Flood-control dikes are present on the Monroe Creek alluvial fan to divert and control flood waters. The adequacy of the existing debris basin and flood-control structures was not assessed in preparation of these hazard maps. However, these structures will limit the extent of sediment deposition and flooding from Sand and H Canyons and Monroe Creek.

Alluvial-fan flooding consists of a continuum of flow types, from stream flows to debris flows, based on the proportion of sediment to water. Stream flows and debris flows are often related and can result from the same precipitation event. As floodwaters travel down a drainage they can erode and incorporate sediment to form debris flows, which again become stream flows downfan as sediment is deposited. Beverage and Culbertson (1964) described the following flow types based on sediment-water proportions: stream flow (less than 20 percent sediment by volume), hyperconcentrated flow (20 to 60 percent sediment by volume), and debris flow (greater than 60 percent sediment by volume). For the hazard map (plate 2), the term debris flow is not used in the strict sediment-water-concentration sense, but is used in a general way to include all flows within the hyperconcentrated- and debris-flow sediment-water concentration range (greater than 20 percent sediment). The term alluvial-fan flooding includes stream flows and debris flows, although stream-flow and debris-flow hazards may be managed differently in terms of land-use planning and protective measures. However, because steps taken to reduce debris-flow hazards can also reduce associated stream-flow hazards, evaluating both the debris-flow and stream-flow phases of alluvial-fan flooding concurrently is usually beneficial.

Because of their topographic location, alluvial fans are subject to flash floods in response to thunderstorm precipitation with little warning time for evacuation and emergency actions to protect property. Alluvial-fan floods are characterized by great flow-path uncertainty as channels shift, and by abrupt sediment erosion and subsequent deposition as flows lose their competence to carry material eroded from steeper upstream source areas (FEMA, 1999). Floods from snowmelt or prolonged rainfall can also occur and are of longer duration and are more predictable than flash floods from intense thunderstorm rainfall.

The alluvial fans in Monroe are relatively flat to moderately sloping fan-shaped landforms composed of loose to weakly consolidated sediment deposited at the mountain front. Alluvial-fan deposits grade from coarser to finer toward the valley as fan-surface gradients decrease. The distal portions of alluvial fans grade into the basin-fill sediments of Sevier Valley. The Monroe Creek alluvial fan has a relatively gentle average fan slope of 2° and was deposited largely by stream-flow processes characteristic of alluvial fans having average slopes of 2° or less (Blair and McPherson, 1994). Even though stream-flow processes dominate on the Monroe Creek alluvial fan, significant amounts of sediment have been transported in historical flood events (Keetch, 1971).

The alluvial fans east of Monroe at the mouths of Winget, Order Dugway, Sand, and Bertlesen Canyons (figure 2) have average fan slopes of 3° to 5.4°. These fans are steeper and smaller than the Monroe Creek alluvial fan and were constructed from both debris flows and stream flows.

Alluvial-Fan Flooding Descriptions

Stream Flow

Monroe has a long history of flooding events (table 1) caused by snowmelt, prolonged rainfall, and intense thunderstorm rainfall (flash flooding). Damaging effects from flooding include ground saturation, erosion, deposition of sediment, and the force of the water itself, which can damage property and take lives (Stauffer, 1992). Stream flooding on alluvial fans can have velocities as high as 15 to 30 feet per second (5-9 m/s) (10 to 21 miles per hour [16-34 km/hr]) (FEMA, 1989b). Water velocities of 10 feet per second (3 m/s) (7 miles per hour [11 km/hr]) or more can undermine pilings and slab foundations (FEMA, 1987). The potential for flooding and flooding damages can be significantly increased by human activities such as placing structures in flood paths, developing on alluvial fans without adequate flood protection, and poor watershed management. Wildfires that burn drainage-basin vegetation create conditions that promote runoff and erosion, increasing the potential for alluvial-fan flooding, particularly debris flows.

Alluvial-fan flooding generally begins at the highest point on the fan where flow is last confined, often at the mountain front or canyon mouth, and then spreads out as a sheet flood or debris slurry of varying sediment concentration in multiple channels along uncertain flow paths (National Research Council, 1996). Both stream and sheet flows have caused damage on alluvial fans in Monroe. The streamflow phase of alluvial-fan flooding refers to flows having less than 20 percent sediment confined to a network of broad, shallow, shifting channels. Sheet flooding refers to a broad expanse of moving unconfined water that spreads as a thin, continuous, relatively uniform sheet over a large area and is

Table 1. *Principal floods, Monroe, Utah, 1896-1984. Compiled from Woolley (1946, 1947), Keetch (1971), U.S. Soil Conservation Service (1971), Butler and Marsell (1972), Utah Division of Comprehensive Emergency Management (1981), and U.S. Forest Service (1983, 1984).*

Year	Date	Drainage	Peak Discharge cfs	Damage (- indicates no data)
1896	July14-17	Monroe	-	Farms, orchards, roads, and bridges
1917		Monroe	-	-
1922	June 30	Monroe	-	Mud deposited 8-10 inches deep
1922	June 30	Bertlesen	400	$910
1922	June	Sand	350	
1925	July 24	Monroe	600	$920
1930	August13	Bertlesen	350	-
1930	August 13	Sand	450	-
1932		Sand	600	-
1933	July 30	Monroe	-	Road, water pipeline, and powerhouse dam
1934	August 6	Monroe	500	Several thousand dollars; culinary water and power system; fields covered with rocks and debris
1934	August 14	Monroe	-	Water pipeline, road, and fields
1934	August 14	Sand	300	-
1935	-	Sand	800	-
1935	-	Bertlesen	500	-
1937	-	Monroe	-	$1,080
1937	-	Sand	500	-
1938	-	Sand	400	-
1939	-	Monroe	1,400	-
1939	-	Bertlesen	700	-
1939	-	Sand	1,190	-
1943	July 31	Monroe	2,380	-
1943	-	Bertlesen	155	-
1943	-	Sand	650	-
1947	-	Monroe	-	-
1953	-	Sand	-	High school and canal
1954	-	Monroe	-	Diversion canal
1957	-	Monroe	-	Power plant water supply, culinary water supply, canals, road, and farm fields
1960	-	Bertlesen	400	-
1960	-	Sand	100	-
1960	-	Order Dugway	60	-
1971	July 20	Order Dugway	-	3 inches of sediment deposited in Monroe cemetery
1971	-	Sand	-	Sediment and trash plugging of outlet structures in Sand H debris basin (Monroe protected by debris basin)
1971	-	Bertlesen	-	Sediment deposited in Monroe but no significant damage
1971	August 25	Monroe	-	Road damage
1983	May 28-29	Monroe	650	-
1984	-	Monroe	-	-

not concentrated in well-defined channels. Sheet floods generally travel short distances and last only minutes to hours. Although often lacking the depth and velocity to cause significant damage to structures, sheet floods can cause localized inundation, especially where conditions allow for ponding or entrance into a basement or other below-ground facility. Sheet flooding can also deposit considerable fine-grained sediment. Sheet flooding is generally the end product of alluvial-fan flooding after the floodwaters emerge from shallow channels and begin to slow down and spread laterally across the alluvial fan. Stream and sheet flooding can also occur before or after debris flows as secondary flows from the drainage basin. Sheet flooding can also occur from purely locally derived runoff from intense rainfall on alluvial-fan and other surfaces.

The FEMA Flood Insurance Rate Maps (FIRMs) (FEMA, 1979a, 1979b) show Monroe Creek, the Monroe Creek alluvial fan, basin-fill areas downslope of the alluvial fan, and the area behind the Sand H debris basin as zone A. Zone A is an area of 100-year flooding where the base flood elevations and flood-hazard factors have not been determined. The area outside of zone A, which includes most of Monroe, is mapped as zone C. Zone C is considered an area of minimal flooding by FEMA. Even though the FIRMs show zone C for most of Monroe, the eastern part of Monroe has experienced localized alluvial-fan flooding near the mountain front (plate 2) from thunderstorm rainfall. Mandatory flood insurance purchase requirements apply in zone A (FEMA, 1989a). In zone C, flood insurance is available in participating communities but is not required by regulation (FEMA, 1989a).

The first recorded flooding in Monroe was in 1896 (Woolley, 1946). Records continue only through 1984 (U.S. Forest Service, 1984). A total of 37 historic flood events are documented in Monroe since 1896 (table 1). I list these here under stream-flow floods on alluvial fans, but some probably include debris flows. Historically, Monroe Creek floods most frequently (16 floods), followed by Sand Canyon (12 floods), Bertlesen Canyon (7 floods), and Order Dugway (2 floods). No floods are recorded from Winget Canyon. In addition to the large drainages listed in table 1, homeowners along the east side of Monroe indicate that flooding from small drainage basins has also occurred with intense thunderstorm precipitation. Floods from these small basins have transported sediment and caused property damage. The Sand H debris basin captures flood waters from Sand and H Canyons. Flooding from Winget, Order Dugway, and Bertlesen Canyons and the small drainages east of Monroe is largely uncontrolled. The runout distance of floodwaters from Order Dugway and Bertlesen Canyons has exceeded 4,000 feet (1,220 m) from the mouths of the canyons. The flood-control dikes constructed on the Monroe Creek alluvial fan help confine and divert the flows to a channel under Bohman road.

The information in table 1 documents the Monroe area flood frequency. On Monroe Creek, the longest time period between floods is 21 years and the shortest is 8 days. For the other large drainages east of Monroe (figure 2), the longest time period between floods is 17 years and the shortest is 1 year. The peak flood-flow estimates listed by Keetch (1971) should be considered in any flood-hazard-reduction measures.

Debris Flows

Debris flows are fast-moving slurries of rock, mud, organic matter, and water that flow down steep mountain channels and then spread out and come to rest on alluvial fans. Debris flows are generally triggered by rapid snowmelt or intense thunderstorm rainfall and often have associated stream-flow flooding. Debris flows triggered by snowmelt typically start as shallow debris slides on steep drainage-basin slopes that quickly transform into debris flows. Debris flows triggered by intense rainfall typically start as runoff that erodes soil from hillslopes and sediment from drainage channels, increasing the amount of sediment until the mixture becomes a debris flow. Stream-flow flooding generally occurs downfan from debris flows as floodwaters travel off the alluvial fan downslope onto basin-fill areas.

Debris flows pose a hazard very different from normal flooding due to their destructive power. Debris flows are life-threatening because they move rapidly and occur with little warning. Debris flows can also exert large impact pressures due to their density, flow thickness, and velocity. In addition to physical impact, debris flows can cause damage to buildings and infrastructure by sediment burial, erosion, and associated water flooding. Debris flows are capable of destroying buildings, roads, and bridges lying in their path and of depositing thick layers of mud and rock on the alluvial fan. The peak discharges of debris flows can be up to 40 times greater than those of extreme floods for small streams (VanDine, 1996). Observed velocities of debris flows range from 1 to 66 feet per second (0.3-20 m/s) (1 to 45 miles per hour [2-28 km/hr]) (Costa, 1984).

The volume and frequency of debris flows depend on several factors including the amount of sediment in a drainage available for erosion and transport, magnitude and frequency of storms, amount of vegetation, and soil conditions. The volcanic rocks east of Monroe weather rapidly, contributing an ample supply of easily eroded sediment to drainage channels. The study of historical debris flows in Utah indicates 80 to 90 percent of the debris-flow volume is eroded from the channel (Croft, 1967; Keaton and Lowe, 1998). Therefore, sediment-supply conditions in canyons east of Monroe are favorable for future debris flows.

Debris flows can be deposited anywhere on the active alluvial fan. The active-fan area includes those areas where modern deposition, erosion, and alluvial-fan flooding may occur. In general, sites of sediment deposition during Holocene time (the past 10,000 years) are considered active unless proven otherwise. Detailed assessment of the debris-flow hazard can broadly define hazard zones on the active fan (Hungr and others, 1987). In general, the upper part of the active alluvial fan has a higher debris-flow hazard due to greater velocities, impact pressures, thicknesses, burial depths, and frequency than distal alluvial-fan areas.

On July 20, 1971, an intense thunderstorm caused flooding in Order Dugway, Sand, H, and Bertlesen Canyons (table 1). Both floodwaters and debris flows from Sand and H Canyons transported boulders up to 5 to 6 feet (1.5-1.8 m) in diameter and filled the debris basin with an estimated 40,000 cubic yards (30,600 m^3) of sediment and water (SCS, 1971). The Sand H debris basin prevented major damage to Monroe City from this event and clearly demonstrated the benefit of risk reduction. The magnitude of this event should be considered in the design of any debris flow risk-reduction measures in similar-sized drainages. Alluvial fans at Winget, Order Dugway, and Bertlesen Canyons and all other small drainages east of Monroe are unprotected from debris-flow hazards.

Unintentional Water Release From Water-Retention Structures

An unintentional release of water due to the failure of a water-retention or conveyance structure may occur with little warning. Flood damage depends largely on the depth of inundation, although damage potential also increases dramatically with increases in floodwater velocity. Dam-failure floods are generally not addressed in land use planning, but rather in emergency preparedness by developing evacuation plans based on dam-failure-inundation maps. The Utah Division of Water Rights, Dam Safety Section, is the agency regulating dam safety in Sevier County. Because the Sand H debris basin in Monroe is not designed to store water and rarely impounds water, dam-failure-flooding hazards are minimal as long as the dam is properly maintained and inspected. An emergency action plan (Monroe City, 1995) showing dam-failure-inundation maps is on file with the Utah Division of Water Rights, Dam Safety Section.

Sources of Data

The following sources of information were used to identify alluvial-fan-flooding-and debris-flow-hazard areas in Monroe: (1) FEMA (1979a, 1979b), (2) the distribution of young (Holocene) alluvial-fan deposits, including debris-flow deposits, shown on plate 1, and (3) published compilations and homeowner reports of historical flooding and damage.

Map Units

Based on Flood Insurance Rate Maps (FIRMs) and 1:10,000-scale geologic mapping, I identified seven flooding categories and show these as map units on plate 2; one category (map unit AF) contains both flooding and debris flows. The mapped categories are:

MCFP The active channel, flood plain, and low terraces along Monroe Creek (geologic unit Qal) in Monroe Canyon. The stream deposits used to define this flood category grade downslope into alluvial-fan deposits and correspond to zone A (100-year flood) on the FIRM. Flood flows in this area are still largely confined by terraces or canyon walls compared to flood flows downslope on the alluvial fan that are largely unconfined, except locally by dikes. Significant volumes of sediment have been transported and deposited at channel constrictions along Monroe Creek upstream of the map area (Keetch, 1971, page 88).

$MCAF_1$ The active part of the Monroe Creek alluvial fan (geologic unit Qaf1). Flooding in this category is within zone A on the FIRM and corresponds to the active alluvial-fan surface (unit Qaf_1). Flooding on the Monroe Creek alluvial fan occurs as stream flow in shallow alluvial-fan channels and as sheetfloods on the alluvial-fan surface. Dikes of non-engineered fill derived from the alluvial-fan surface have been constructed to constrict the flows on the alluvial fan and divert them into a culvert under Bhoman Road (plate 2). From Bhoman Road, water flows are routed to the Sevier River in a flood-control ditch (plate 2). The dikes bordering this flood-control ditch are not shown on the FIRM and are not recognized by FEMA as a protective flood structure. A flood study by the U.S. Army Corps of Engineers (USACE) (1995) shows that flood-control dikes, the culvert under Bhoman Road, and the flood-control ditch do not contain the 100-year flood.

$MCAF_2$ The area outside of the active part of the Monroe Creek alluvial fan (geologic unit Qaf_2). Predevelopment flooding on the Monroe Creek alluvial fan is confined to the active alluvial-fan surface (map category $MCAF_1$, geologic unit Qaf_1). However, breach of flood-control dikes in map category MCAF1 or failure of flood-irrigation diversion structures at the fan apex may result in flooding within category MCAF2 (geologic unit Qaf_2). The historical flood record indicates significant amounts of sediment have been transported and deposited (Keetch, 1971). Deposition of sediment could block the existing fan channel and breach flood-control dikes. This category is within zones A and C on the FIRM. As stated above, the USACE (1995) study shows that flood-control dikes, the culvert under Bhoman Road, and the flood-control ditch do not contain the 100-year flood and prevent flooding in areas of $MCAF_2$.

AF Alluvial fans (geologic unit Qaf_1) that are subject to both stream flow and debris flows. This category includes parts of Bertlesen, Order Dugway, and Winget Canyons and other small unnamed drainages east and southeast of Monroe that are normally dry, ephemeral stream channels. Part of the Bertlesen Canyon alluvial fan is mapped as zone A on the FIRMs, although most of the fan is mapped as zone C. Debris flows can occur anywhere on the alluvial fans but in general debris flows on the upper fan have greater velocities, impact pressures, thicknesses, burial depths, and frequency than on distal alluvial-fan areas. The small gravel pits at the mouths of unnamed drainages between Sand H and Bertlesen Canyons likely reduce the risk of floods and debris flows.

AFSH Alluvial fan (geologic unit Qaf_1) below the Sand H Debris basin. The risk of floods and debris flows from Sand and H Canyons is reduced by the Sand H debris basin.

AB Basin-fill alluvium (geologic unit Qab) downslope of the Monroe Creek and other alluvial fans. This category includes areas mapped as zone A and zone C on the FIRMs. Flooding occurs as distal stream flows and sheet flooding with relatively low velocity, shallow flow depths, and low sediment load. Local overbank flooding may occur along the Monroe Creek flood-control ditch if it is inadequate to contain flows.

HS Hillslopes (geologic units Qc and Tv) above alluvial fans. This category includes areas mapped as zone A and zone C on the FIRMs. Flooding occurs as the result of intense rainfall and runoff on moderate to steep slopes with possible concentration in small drainages, generally with relatively high velocity and shallow flow depths.

Using the Map

The mapped categories are shown on the alluvial-fan-flooding- and debris-flow- hazards map (plate 2). The boundaries between categories are approximate and gradational. Small, localized areas of higher or lower hazard are likely within any given map area, but their identification is precluded because of the limitations of the map scale and the detail required to further characterize the alluvial-fan-flooding- and debris-flow-hazard areas. Map unit $MCAF_2$ is shown as a potential flooding area even though the unit is outside the geologically defined active fan area (unit $MCAF_1$). Modification of the natural fan surface by irrigation diversions and flood-control dikes may change the flooding behavior; therefore, $MCAF_2$ is included as a potential flood-hazard area. Given the flood frequency and uncertainty of the ability of the flood-control dikes and ditch to adequately manage Monroe Creek flood flows, I recommend Monroe City request remapping of the flood hazard on the Monroe Creek alluvial fan and downstream by FEMA to update the FIRMs. Remapping the flood hazard should consider the USACE (1995) flood study and incorporate the mapping if appropriate. FEMA has a priority list of flood-hazard mapping for each state and Monroe Creek is currently not on the list.

FEMA flood zones A and C include mapped alluvial-fan-flooding and debris-flow categories on plate 2. Due to differences in scale and a lack of common registration points between the FIRMs and 1:24,000-scale topographic maps used as the base for this study, the FEMA 100-year flood boundaries shown on the accompanying map are only approximate. Where development is planned within the boundaries of a FEMA 100-year flood zone, the original FIRM should be consulted. Flood insurance is required in zone A and is optional in zone C on the FIRMs.

The 2000 *International Building Code* (IBC; International Code Council, 2000a), adopted statewide in 2002, states that 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) identified on the FIRMs by FEMA. Appendix G of the IBC outlines subdivision requirements, flood-resistant construction, and required permit information. Adoption and enforcement of IBC appendix G is left up to local jurisdictions. The Monroe City Ordinance Chapter 3 “Flood Damage Prevention” (Monroe City, 1989) also has requirements for new construction in flood-hazard areas (zone A). Similar to IBC appendix G, the ordinance outlines requirements for obtaining permits for proposed subdivisions and construction.

Plate 2 shows alluvial-fan-flooding- and debris-flow-hazards map units, the hazard types, the NFIP requirements in each map unit, and recommendations for site-specific studies. Flooding and/or debris-flow studies are recommended prior to development in all mapped categories with the exception of categories AFSH, AB, and HS. For the area protected by the Sand H debris basin (map unit AFSH), I used topographic contours to delineate the area where risks of flooding and debris flows are reduced by the Sand H debris basin and flood-control dikes. In units MCFP, $MCAF_1$, $MCAF_2$, and AF, the impacts of flooding and debris flows on existing and new development are poorly understood. Performing flood and debris-flow studies prior to development provides an understanding of the potential impacts and which risk-reduction measures are most feasible and cost effective.

The first consideration in alluvial-fan-flooding- and debris-flow-hazard reduction is proper identification of hazard areas through detailed mapping, and qualitative assessment of the hazard. The stream-flow component of the alluvial-fan-flooding-hazard assessment should determine the active flooding area, the frequency of past events, and the potential inundation and flow depths. The debris-flow-hazard assessment should determine active depositional areas, the frequency and volume of past events, and sediment burial depths. The level of detail for a hazard assessment depends on several factors including: the type, nature, and location of the proposed development; the geology and physical characteristics of the drainage basin, channel, and alluvial fan; the history of previous flooding and debris-flow events; the level of risk acceptable to property owners and land-use regulators; and proposed risk-reduction measures.

Where development is proposed in areas identified as having a potential alluvial-fan-flooding and/or debris-flow hazard, a geotechnical firm familiar with alluvial-fan-flooding hazards should be retained early in the project design phase to conduct a site-specific investigation of the proposed site. If a hazard is present, the geotechnical consultant should provide design or site preparation recommendations as necessary to reduce the hazard.

Hazard Reduction

Stream Flow

Avoiding areas subject to floods is the most effective means of flood-hazard reduction. However, avoidance may not always be a viable or cost-effective option. The main consideration in flood-hazard reduction is proper identification of hazard areas through detailed mapping, and quantitative assessment of the hazard. The National Research Council (1996) report *Alluvial-Fan Flooding* and the FEMA (1999) document *Guidelines for Determining Flood Hazards on Alluvial Fans* provide guidance for evaluating alluvial-fan-flooding hazards.

The principal goals of flood-hazard reduction on alluvial fans are to prevent acceleration or diversion of floodwater and increased erosion, and ensure that individual structures and infrastructure are adequately protected from high-velocity flows, inundation, sediment and debris burial, and erosion (FEMA, 1987). Structural flood-hazard reduction on alluvial fans is generally subdivided into whole-fan protection, localized protection, and single lot/structure protection (FEMA, 1989b). Whole-fan protection generally involves a large flood-control structure like the Sand H debris basin. Localized protection often consists of a flood-control dike to protect a group of houses. Single lot/structure protection generally involves elevating the lot and floodproofing the structure. FEMA (1987) provides guidance for flood protection based on different alluvial-fan hydraulic zones.

The most common method of reducing flood losses is flood insurance through the National Flood Insurance Program (NFIP). The NFIP is a federal program enabling property owners to purchase insurance protection against losses from flooding. Participation in the NFIP is based on an agreement between local communities and the Federal Government which states that if a community will implement and enforce measures to reduce future flood risks to new construction in special flood-hazard areas, the federal government will make flood insurance available within the community as a financial protection against flood losses (FEMA, 1989a). Flood Insurance Rate Maps are legal documents that govern the administration of the NFIP. In addition to NFIP requirements in zone A, IBC appendix G and Monroe City Flood Damage Prevention Ordinance requirements apply to new construction in zone A.

Debris Flows

Methods for reducing debris-flow hazards generally include avoidance, source-area modification, channel modification, and defensive structures on the alluvial fan. Avoidance strategies can include avoiding hazard areas permanently or at the time of imminent danger for life-safety purposes. Permanent avoidance is often not possible because some parts of a community are already built on active alluvial fans. Historical records of debris flows in Utah have shown the flows to be highly variable in terms of size, material properties, and travel and depositional behavior; a high level of precision for debris-flow-design parameters cannot yet be attained. Therefore, conservative designs must be used where risk reduction is necessary.

Debris flow hazard-reduction methods are either passive or active (VanDine, 1996). Passive methods involve avoidance, zoning regulations, public notification or education, and use of warning systems. Passive methods make no attempt to prevent, modify, or control the debris-flow hazard. Active methods involve construction of engineered protective structures in the debris-flow starting zone, transportation zone, and deposition zone to limit the amount of sediment produced or to reduce the damaging effects of debris flows. Where the debris-flow hazard cannot be avoided, protective structures as discussed above under stream-flow flooding are necessary.

Starting-zone modifications generally strive to limit the amount of hillslope material available for incorporation into a debris flow either by limiting erosion or reducing landslide potential. Structures in the starting zone include water-control structures to restrict runoff and resulting erosion, and slope stabilization. Slope stabilization is often impractical depending on the elements at risk. Transportation-zone modifications are generally designed to limit the volume of channel sediment incorporated into the flow and to control the flow downchannel. Check dams are constructed in unstable erosive channels to trap sediment and retard flow. Channel-flow control methods often involve improving the ability of the channel to pass debris-flow surges to designated runout and deposition areas or debris basins by lining the channel, removing vegetation and channel irregularities, and enlarging culverts. Structures that must cross debris-flow channels may be protected by bridging the channels to allow debris flows to pass under the structure or designing structures to withstand the debris-flow impact, burial, and subsequent re-excavation (Hungr and others, 1987).

Structures in the deposition zone generally consist of debris basins, barriers, or berms (VanDine, 1996; U.S. Army Corps of Engineers, 1993). These structures are designed to control the extent of deposition and prevent damage to houses or other structures on the alluvial fan. Debris basins generally offer the highest level of risk reduction if they are appropriately sized and designed. Debris berms, barriers, and terminal walls may be constructed to divert flows and encourage sediment deposition in designated areas on the alluvial fan to protect a portion of the fan. Smaller structures or house design can protect individual lots or houses. This protection may consist of deflection walls, elevated and reinforced foundation walls, eliminating ground floor or basement doors and windows within the runup and sediment burial zone, house floodproofing, and eliminating basements. Maintenance and removal of sediment is required for most retention and deflection structures.

Role of Government in Risk Reduction

To adequately reduce risks from alluvial-fan flooding, including debris flows, engineered flood- and debris-retention basins or other significant flood-control structures are often required. Although some cities and counties attempt to address these issues in the subdivision approval process, problems arise because these structures: (1) benefit the community as well as individual subdividers, (2) can be expensive, (3) require reliable maintenance and periodic sediment removal, (4) may divert flows and increase hazards in adjacent areas, and (5) must often be located in areas not owned or controlled by an individual subdivider. Because of this, reducing risks reduction from alluvial-fan flooding and debris flows may be considered a government public works responsibility. This is particularly true in urban settings where hazard areas encompass more than one subdivision and include pre-existing development already permitted by a city or county. Monroe City can use this map to consider its long-term approach to alluvial-fan flooding and debris flows.

PROBLEM SOIL AND ROCK HAZARDS

Soil and rock units having characteristics that make them susceptible to volumetric change, collapse, subsidence, or other engineering-geologic problems are classified as problem soils and rocks (Mulvey, 1992). Geologic parent material, climate, and depositional processes largely determine the type and extent of problem soils. Collapsible soils are the principal soil problem in the Monroe area. Collapsible soils are soils that consolidate and settle in response to the addition of water, a process called hydrocompaction. Shallow bedrock and soluble rock (spring-deposited travertine) are the only rock-related problems in the map area. Shallow bedrock can impede excavation and the proper functioning of soil-absorption wastewater disposal systems. The flow of water through subsurface fractures can dissolve soluble rock, resulting in settlement or collapse. I found no evidence of expansive soil and rock subject to shrink/swell when wetted or dried. The SCS (1991) mapped isolated areas of clay loam and silty clay loam soils having moderate shrink-swell potential in the northwest and southwest corners of the map area. I found no evidence of gypsum and gypsiferous soil susceptible to dissolution, active sand dunes, or soil containing sodium sulfate. Although I found no evidence of active erosion or piping (localized subsurface erosion), most soils in Monroe are susceptible under the right conditions. Within the study area the SCS classifies the soil erosion potential as ranging from slight to moderate for both wind and water erosion (SCS, 1991).

The definitions of soil and rock used in this report generally conform to those in general use by engineers and engineering geologists (Sowers and Sowers, 1970; U.S. Bureau of Reclamation, 1974, undated). Here I define soil as any generally nonindurated accumulation of solid particles produced by the physical and/or chemical disintegration of bedrock with gases or liquids between the particles and which may or may not contain organic matter. I use the term soil in the engineering rather than an agricultural context. Rock is defined as lithified or indurated crystalline or noncrystalline materials in which primary features of the rock mass, such as bedding, joints, or crystalline structure are still recognizable. By this definition, rock weathered in place, even though it can be excavated without blasting or ripping, would still be considered rock and not a residual soil if primary features of the rock unit are still recognizable and influence the engineering properties of the material.

Sources of Data

Sources of data used to evaluate problem soil and rock hazards in the Monroe area include: (1) SCS *Soil Survey of the Richfield Area, Utah* (Wilson and others, 1958); (2) SCS unpublished soil mapping (1991); (3) SCS (1984, 1986), URS Greiner Woodward Clyde (1999), and Smith and Deal (1988) investigations of cracking in the Sand H debris basin due to collapsible soils; (4) SCS (1976) investigation for the proposed Bertlesen Canyon debris basin; and (5) surficial geologic mapping and collapsible soils investigations conducted in this study. Elsewhere in Sevier Valley, collapsible soils have been reported on alluvial fans in Richfield subdivisions (Rollins and others, 1992) and along Interstate 70 (Vlam, 1987).

Geotechnical data are primarily from collapsible soil investigations at the Sand H debris basin and at the proposed Bertlesen Canyon debris basin (plate 3). Geotechnical data were collected in three areas during this study: in northeast Monroe (300 North 400 East), southeast of the Sand H debris basin, and in southeast Monroe (600 South 550 East). All of these sample areas are on young alluvial fans (unit Qaf_1, plate 1). No geotechnical data are available for the other geologic map units.

I compiled data from the soils reports and soils investigations into a geotechnical database (appendix A, included as a diskette). The database contains information from 74 test pits shown on plate 3. Where possible, I used these data to characterize geologic and soil units and to project their geotechnical properties to those parts of the study area lacking geotechnical information. The geologic test-pit logs for the collapsible soils investigations conducted in this study are included as appendix B.

Collapsible Soils

Description

Collapsible soils have considerable dry strength and stiffness in their dry natural state, but can settle dramatically when they become wet following deposition (Costa and Baker, 1981; Rollins and Rogers, 1994) causing damage to property and structures. Collapsible soils are common throughout the arid southwestern U.S. and are typically geologically young materials, chiefly debris-flow sediments in Holocene-age alluvial fans, and some wind-blown, lacustrine, and colluvial deposits (Owens and Rollins, 1990; Mulvey, 1992). Collapsible sediments typically have a high void ratio and corresponding low unit weight and a relatively low moisture content (< 15%; Owens and Rollins, 1990), all characteristics that result from the initial rapid deposition and drying of the sediments. Intergranular bonds form between the larger grains (sand and gravel) of a collapsible deposit; these bonds develop through capillary tension or a binding agent such as silt, clay, or salt. Later saturation of the soil results in a loss of capillary tension or the softening, weakening, or dissolving of the bonding agent allowing the larger particles to compact into a denser structure (Rollins and

Williams, 1991). The reorientation of particles causes a net volume decrease in the soil's mass that results in settlement and possible damage to buildings (figure 3). The amount of collapse or volume decrease usually depends on the amount of water and the overburden pressure or load on the soil.

In general, collapsible alluvial-fan soils are associated with drainage basins that are dominated by soft, clay-rich sedimentary rocks such as shale, mudstone, claystone, and siltstone (Bull, 1964; Owens and Rollins, 1990). All of the soils within the study area are derived from volcanic rocks that weather into clay, silt, sand, and volcanic rock fragments. Bull (1964) found that the maximum collapse of alluvial-fan soils in Fresno County, California, coincided with a clay content of approximately 12 percent. Alluvial-fan soils exhibiting dramatic collapse behavior in Nephi, Utah, typically contain 10 to 15 percent clay-size material (Rollins and Rogers, 1994). At clay contents greater than about 12 to 15 percent, the expansive nature of the clay begins to dominate and the soil is subject to swell rather than collapse. Characteristically, collapsible soils consist of silty sands, sandy silts, and clayey sands (Rollins and Williams, 1991), although Rollins and others (1994) identified collapse-prone gravels containing as little as 5 to 20 percent fines at several locations in the southwestern U.S. Smith and Deal (1988) found that cracking and damage of the Sand H debris basin dike was due to collapsible gravels.

Naturally occurring deep percolation of water into collapsible deposits is uncommon after deposition due to the arid conditions in which the deposits typically form and the steep gradient of many alluvial-fan surfaces. Therefore, soil collapse is usually triggered by human activity such as irrigation, urbanization, or disposal of wastewater. Kaliser (1978) reported significant damage (estimated $3 million) to public and private structures in Cedar City, Utah and Rollins and others (1994) documented more than $20 million in required remedial measures to a cement plant near Leamington, Utah.

Map Units

Review of the geotechnical reports and the soil investigation for this study were used to identify and map collapsible soil areas and generate the geotechnical soils database (appendix A). However, geotechnical data are only available for a small part of the study area. To map the collapse potential where geotechnical data are not available, I extrapolated soil conditions based on the characteristics of the geologic units in collapsible soil areas. Extrapolation is greatly aided by the 1:10,000-scale surficial geologic mapping and the unpublished 1:24,000-scale soil mapping completed by the SCS (1991) in the area. Depths to ground water in the study area exceed 30 feet (Lambert and others, 1995), and ground water has likely had little effect on saturating and consolidating collapsible soils.

The surficial geologic map (plate 1) classifies the unconsolidated geologic deposits into five different units. Soil collapse tests are available only for young fan alluvium (unit Qaf_1). The soil collapse tests have reported collapse values of ≥ 3 percent, the level at which soil collapse becomes a significant concern (Jennings and Knight, 1975). Borehole pressure-meter testing at the Sand H debris basin indicated collapsible soil to depths of 44 feet (13 m) (SCS, 1986). As

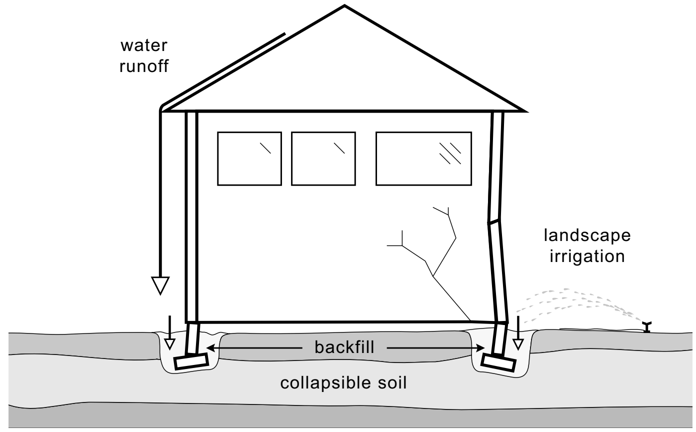


Figure 3. *Possible damage to foundation and house from soil collapse due to infiltration of roof runoff and landscape irrigation water.*

discussed above, soil collapse is closely associated with soil texture. A few percent difference in clay content can mean the difference between a deposit that will collapse and one that will swell when wetted. The unconsolidated geologic units shown on plate 1 are defined on the basis of landform, origin, and, to a lesser extent, texture. As a result, some unconsolidated geologic units can show considerable textural variation. Textural variations are recognized in soil descriptions (appendices A and B) within the young fan alluvium (Qaf_1). Therefore, while geology can be used as an indicator of collapse potential to outline hazard-map units, the geologic criteria are not an infallible guide and careful testing of individual deposits is required to confirm the collapse potential.

For this study, I grouped the unconsolidated geologic units in the Monroe area into four categories based on available information regarding their collapse potential (plate 3). The categories are as follows:

C_{AF} Young alluvial-fan deposits (geologic unit Qaf_1) with a high potential for collapse. Within this category, known areas of soil collapse and building damage exist. Geotechnical testing has identified soil collapse in both gravel and fine-grained soils. Soil-consolidation tests have collapse values of ≥ 3 percent. These alluvial fans have ephemeral stream drainages, slope gradients of 5 to 10 percent, and contain both irrigated and non-irrigated areas.

C_{MCAF} Alluvial-fan deposits (geologic units Qaf_1 and Qaf_2) on the Monroe Creek alluvial fan and Monroe Creek alluvium (geologic unit Qal). No geotechnical information or collapse data exist in this category but the origins of these deposits are permissive of collapse (chiefly geologically young alluvial-fan deposits). Monroe Creek is a perennial stream and the Monroe Canyon alluvial fan was constructed largely from stream-flow processes where natural wetting and collapse may have occurred. However, the extent of stream and flood flows saturating and consolidating alluvial-fan sediments is unknown. Few buildings are present on this unit, so little is known of building performance. This category has slopes of 5 percent or less and is mostly non-irrigated.

C_{AB} Alluvial basin-fill deposits (geologic unit Qab) in Sevier Valley. No geotechnical information or collapse data exist for this unit. Most of Monroe City is within this unit and no collapsible-soil building damage has been reported. This area is flat to gently sloping with slopes of 0 to 3 percent. Much of this category is irrigated either by landscape or agricultural irrigation.

C_C/R_B Hillslope colluvial deposits (geologic unit Qc) east and southeast of Monroe. No geotechnical information or collapse data exist for this unit but colluvium is typically a loose, mostly non-cohesive deposit that accumulates downslope bedrock outcrops. The loose, non-cohesive nature of colluvium indicates a potential for collapse. This unit occurs on slopes of 20 to 65 percent and is not irrigated. This category also includes areas of shallow bedrock (RB) that underlie the colluvium.

Figure 4. *Crack developed in the Sand H debris basin embankment due to soil collapse (from U.S. Soil Conservation Service, 1984).*

Investigation of Collapsible Soils

I completed a building survey to determine types of damage and spatial distribution of damage caused by collapsible soils. This survey also provided insight into the performance of soils under residential house loads. Smith and Deal (1988) reported on soil collapse under large structural loads at the Sand H debris basin (figure 4), but little is known about the effects of residential house loads on collapsible soils in Monroe. The survey focused on neighborhoods east of 300 East Street and southeast of the Sand H debris basin containing houses with suspected collapsible soil damage. Homeowners were interviewed when possible to profile the timing and cause of collapsible soil damage.

A total of 22 houses and properties were surveyed and eight showed some level of damage apparently related to soil collapse. The damages typically consist of cracked concrete foundation walls, brick walls, concrete driveways, and concrete sidewalks (figures 5 and 6). The survey focused specifically on significant cracks caused by soil collapse rather than minor cracks related to normal performance of building materials. Some houses with larger amounts of settlement also had interior damage to walls and floors. Ground cracks developed in one area where soil collapsed in response to tree irrigation. All of the observed house damage is on young alluvial fans (geologic unit Qaf_1).

Figure 5. *Typical crack in concrete foundation wall due to soil collapse on the Sand Canyon alluvial fan southeast of the Sand H debris basin.*

Figure 6. *Crack developed along mortar in brick wall due to soil collapse on the Sand Canyon alluvial fan southeast of the Sand H debris basin.*

The spatial pattern of collapsible-soil damage is variable. One house may have significant damage while adjacent houses have no damage. This may be due to textural variation of soils within the young fan alluvium or human-controlled factors such as the amount of water introduced into the soils. The presence of damage identifies collapse-prone areas, but the lack of damage does not necessarily indicate that collapsible soils are not present. Damage is usually dependent on the degree of soil saturation in and around the house foundation, generally caused by roof runoff or application of landscape irrigation water and the weight of the house on the underlying soil (figure 3). Some homeowners mentioned that foundation cracks developed shortly after landscape irrigation started, implying that landscape irrigation caused soil saturation and subsequent collapse. The most significant damage observed was higher on the young alluvial fans adjacent to the mountain front.

To gain a better understanding of collapsible soils, 10 test pits were excavated in three areas as part of this study. With the assistance of Monroe City I excavated, logged, and sampled five test pits (HSTP-1 through HSTP-5) in northeast Monroe (300 North 400 East), three test pits (CTP-1, CTP-2, CTP-3) southeast of the Sand H debris basin, and two test pits (PTP-1, PTP-2) in southeast Monroe (600 South 550 East) (plate 3). Soil descriptions and laboratory data for these test pits are included in the geotechnical database (appendix A), and the geologic test pit logs are included as appendix B. The soils were described and classified using the *Description and Identification of Soils* (American Society for Testing and Materials, 1993). The test pits were up to 9.5 feet (3 m) deep.

Simple field tests were conducted in three test pits to evaluate soil collapse in response to water saturation. The test pits (HSTP-5, CTP-1, and PTP-1) were excavated 3 to 4 feet (0.9-1.2 m) deep. Elevation control was established by surveying a stake in the test-pit floor and another stake outside the test pit. Once elevation control was established, the test pits were filled with water. The stakes were resurveyed for three consecutive days following saturation to measure settlement. The test pit southeast of the Sand H debris basin (CTP-1) showed no settlement. However, the test pits in the 300 North 400 East (HSTP-5) and 600 South 550 East (PTP-1) areas both settled 0.5 inch (1.3 cm). This demonstrates the soils collapsed following saturation even without an external load and the weight of the overlying soil removed.

Soil density and soil moisture were measured at different depths in the test pits using a nuclear moisture-density probe and the results are included in the geotechnical database (appendix A). Measurements were taken in test pits in the 300 North 400 East and 600 South 550 East areas. Cobbles and gravel prevented nuclear moisture-density probe testing in test pits east of the Sand H debris basin. The soil dry density ranged from 84 to 116 pounds per cubic foot (1,384-1,861 kg/m^3) and the moisture ranged from 4 to 13 percent. The low-density soils and low moisture contents are consistent with collapsible soils elsewhere in Utah (Owens and Rollins, 1990; Mulvey, 1992).

Fine-grained soil blocks from test pits HSTP-1 and HSTP-4 in the 300 North 400 East area underwent laboratory consolidation testing. Soil consolidation tests measure the amount a soil will collapse when saturated under a given load. Soil consolidation test results indicate that under loads of 1,000 to 5,000 pounds per square foot (4,891-24,455 kg/m^2) the soils collapsed 2 to 12.5 percent after water was added to the samples. These tests were completed on clayey sand and silty sand samples from depths of 2.2 to 4 feet (0.7-1.2 m). Tests having loads of 1,000 to 3,000 pounds per square foot (4,891-14,673 kg/m^2) (within the range of residential house loads) show collapse values of 2 to 9 percent. Since soil collapse values of $\geq$ 3 percent are a level for significant concern (Jennings and Knight, 1975), the laboratory testing indicates collapsible soils are present and therefore have the potential to damage buildings. The consolidation testing also shows a correlation of increasing collapse with increasing load or overburden pressure.

Shallow Bedrock and Soluble Rock

Description

The principal problem related to shallow bedrock is difficulty of excavation. Resistant, unweathered bedrock makes excavations for basements, foundations, underground utilities, and road cuts difficult. Shallow bedrock can also impact septic tank soil-absorption systems.

The travertine terrace at Monroe hot springs is composed largely of calcium carbonate, a soluble mineral which is subject to dissolution by surface and ground water. Activities that can cause problems in soluble rock include: (1) building structures that induce differential compaction of soils above an irregular soluble-rock surface, (2) building structures directly on unrecognized soluble-rock settlement or collapse features, and (3) impounding water above, or directing water into, an unrecognized dissolution feature that may lead to further dissolution and collapse or lead to ground-water pollution (Johnson, 1996, 1997). I observed one small subsidence depression along the west edge of the travertine terrace.

Map Units

Shallow bedrock typically underlies hillslope colluvium adjacent to bedrock outcrop areas. Most of these areas are on slopes greater than 30 percent where development is generally not permitted.

The Monroe hot springs travertine terrace can be dissolved by surface and ground water. The flow of waters through subsurface fractures or conduits can dissolve travertine until the overlying travertine collapses under its own weight. The addition of water from irrigation, onsite wastewater disposal systems, or by other human-induced means could locally cause dissolution of travertine resulting in subsidence.

I group areas having shallow bedrock and soluble rock into two categories:

R_B Hillslope outcrops of volcanic bedrock (geologic unit Tv). These are areas where bedrock crops out at or near the ground surface. The bedrock is generally hard and resistant when unweathered and may require blasting to excavate. Most of these areas are too steep for development.

R_S Spring travertine deposits (geologic unit Qst) at Monroe hot springs. The travertine may be dissolved by ground water creating a loss of internal structure and potential for subsidence. Shallow ground water may be present near the hot springs. Localized areas of volcanic rock altered to clay may underlie the travertine. In contrast to volcanic bedrock, the travertine is generally soft enough to excavate without ripping or blasting.

Using the Map

The mapped categories, hazard types, and recommendations for site specific studies are shown on the problem soil and rock hazards map (plate 3). The UGS recommends that standard geotechnical soil-foundation studies be performed for all new development in all areas. The intent of this map is to show where additional special studies are recommended to address specific problem soil and rock hazards. Performing special studies for these hazards prior to development provides an understanding of the potential impacts and which risk-reduction measures are most feasible and cost effective. The boundaries between map categories are approximate and gradational. Small, localized areas of higher or lower hazard are likely within any given map area, but their identification is precluded primarily because of the limitations of the map scale. Also, soil textural variations within young fan alluvium are known to influence the collapse potential of soils, and site-specific studies are needed to define these variations. Irrigation in some of the areas may have induced collapse and possibly modified or eliminated the hazard.

Specific types of laboratory soil testing and geotechnical investigations are recommended within the different map categories (plate 3). Map category C_{AF} is an area of high soil collapse potential based on geotechnical characteristics, soil-consolidation tests, and existing building damage due to collapsible soils. In addition to standard geotechnical soil-foundation investigations, laboratory soil-consolidation testing is necessary to evaluate the collapse potential and specify appropriate measures to eliminate or reduce the hazard within category C_{AF}. Map category C_{MCAF} covers the Monroe Creek alluvial fan where no geotechnical data exist and little development is present to evaluate the performance of buildings on the soils. Laboratory soil-consolidation tests are also recommended for new development within unit C_{MCAF}, primarily because the potential of soil collapse is unknown. If multiple soil tests within unit C_{MCAF} indicate collapsible soils are not present, then the recommendation for laboratory soil-consolidation tests should be eliminated. Although standard geotechnical soil-foundation investigations are recommended within map category C_{AB}, laboratory soil-consolidation tests are not considered necessary because irrigation may have reduced the collapse potential and no collapsible-soil building damage has been reported in this area. Standard geotechnical soil-foundation investigations and laboratory soil-consolidation tests are recommended within map category C_C/R_B to determine if the colluvium is prone to collapse, and if shallow bedrock is present. Geotechnical soil- and/or rock-foundation investigations with consideration of soluble rock are recommended in map unit R_S on the Monroe hot springs travertine terrace. Consideration of soluble rock includes investigations for sinkholes or subsidence features, transient spring discharge points, subsurface voids, and other indications of dissolution, ground-water, or drainage problems.

Where development is proposed in areas identified as having potential soil or rock problems, a geotechnical firm having practical experience with collapsible soil, shallow bedrock, and soluble rock should be retained early in the project design phase to conduct a site-specific investigation of the proposed site. If a hazard is present, the geotechnical consultant should provide design or site preparation recommendations as necessary to reduce the hazard.

Hazard Reduction

Collapsible Soil

Although potentially costly when not recognized and properly accommodated in project design, problems associated with collapsible soil are rarely life threatening. As with most geologic hazards, avoidance is the most effective way to reduce the hazard. However, collapsible soils are widespread on young alluvial fans east of Monroe and avoidance is generally not a viable or cost-effective hazard-reduction option. Engineering techniques are available to reduce the collapsible soil hazard. These typically consist of (1) ground modification (generally removal or consolidation by prewetting or mechanical compaction of collapsible soils), (2) structural reinforcement of buildings, and (3) deep foundations that transfer the building load to a deeper competent soil layer. Drainage and proper water management in and around foundations are important in preventing soil collapse.

Shallow Bedrock

Shallow bedrock typically presents problems to excavation of materials when unweathered bedrock is present.

Avoidance is the most effective way to reduce the shallow bedrock hazard. When avoidance is not possible, geotechnical investigations can identify shallow bedrock and make appropriate recommendations regarding excavation difficulty and foundation design.

Soluble Rock

As with the collapsible-soil and shallow-bedrock hazards, soluble rock is rarely life threatening but can be costly when not recognized. In general, early hazard recognition followed by avoidance is the most effective way to reduce hazards associated with soluble rock. However, when avoidance is not a viable option and development is planned in soluble-rock areas, a geotechnical engineering firm having practical experience with soluble rock should be retained to conduct investigations to identify problems and provide site-specific design recommendations to reduce the hazard.

EARTHQUAKE HAZARDS

Earthquakes occur without warning and can cause injury and death, major economic loss, and social disruption (Utah Seismic Safety Commission, 1995). An earthquake is the abrupt rapid shaking of the earth caused by sudden slippage of rocks deep beneath the earth's surface. The surface along which the rocks slip is called a fault. Earthquakes occur when accumulated strain exceeds the rock's strength. During an earthquake, seismic waves are generated and transmitted outward from the earthquake source, producing ground shaking.

Earthquakes cause a wide variety of geologic hazards including ground shaking, surface faulting, liquefaction and related ground failure, slope failure, regional subsidence, and various types of flooding (table 2). The principal earthquake hazard in Monroe is ground shaking, although rock falls, surface fault rupture, and flooding are also possible in the area.

Ground shaking is the most widespread and typically most damaging earthquake hazard. Strong ground shaking can last from several seconds to minutes, and can be amplified or deamplified (decreased) depending on local soil and rock conditions. Ground shaking is usually strongest near the earthquake epicenter and decreases away from that point. The type and quality of construction plays a large role in determining the extent of damage caused by ground shaking. Strong ground shaking can also generate rock falls on steep slopes. Large earthquakes (> M 6.5) are commonly accompanied by surface faulting. The rupture may affect a zone tens to hundreds of yards wide and many miles long. Flooding may also result during an earthquake due to damage to water storage or conveyance structures such as dams, pipelines, and canals.

I did not find evidence of the other earthquake hazards listed in table 2. Liquefaction occurs in areas of shallow ground water (less than 30 feet [9 m] deep) when water-saturated, cohesionless soils (sandy) are subjected to strong ground shaking (Seed, 1979). Because depths to ground water measured in water supply wells are 46 feet (14 m) or greater, liquefiable conditions are unlikely within Monroe.

Slope failures are common in steep terrain during moderate and large earthquakes. However, other than rock falls, landslides and earthquake-induced landslides are unlikely because no evidence of landsliding was identified within steep terrain along the eastern boundary of Monroe. Subsidence due to tilting of the downdropped block during a large surface-faulting earthquake can affect large areas extending miles from the surface trace of the fault. However, the main hazard related to subsidence is surface- and ground-water flooding in areas of shallow ground water. Because shallow ground water is not found in Monroe, the hazard is low.

A variety of magnitude scales are used to measure earthquake size (dePolo and Slemmons, 1990). The magnitude scale in most common use today is the Richter scale (Richter, 1938; Bolt, 1999), which measures earthquake magnitude based on the amount of earthquake-induced ground shaking

Table 2. *Principal earthquake hazards, expected effects, and hazard-reduction techniques (modified from Utah Seismic Safety Commission, 1995).*

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

recorded on a seismograph. The Richter scale is logarithmic, having no upper or lower bounds, and each one-unit increase represents a ten-fold increase in the amplitude of ground displacement at a given location. The Richter scale's relation to earthquake energy release is also logarithmic so that each one-unit increase on the scale represents about a 30-fold increase in energy release. Therefore, a Richter magnitude 6 earthquake is about 30 times more powerful than a magnitude 5 earthquake, and a magnitude 7 earthquake is about 900 times more powerful than a magnitude 5 event. Unless stated otherwise, all magnitudes reported here are Richter magnitudes. The human detection threshold for earthquakes is about magnitude 2 and significant damage begins to occur at about magnitude 5.5. In the Intermountain West, surface faulting is typically above about magnitude 6.5.

Sources of Data

The Anderson and Barnhard (1992) study of the neotectonic framework of the central Sevier Valley area was the principal information source used to evaluate earthquake hazards for this study. I also used four 1:24,000-scale geologic maps of the 7.5-minute topographic quadrangles of the Monroe area prepared by the U.S. Geological Survey (USGS) (Cunningham and Steven, 1979; Steven, 1979; Rowley and others [(1989a, 1981b]) and mapping by Miller (1976) to evaluate earthquake hazards. Information on potential location of the Sevier fault was obtained from geothermal studies at Monroe and Red Hill hot springs (Chapman and Harrison, 1978; Mase and others, 1978). Information on historical earthquakes in central Utah comes chiefly from the University of Utah Seismograph Stations earthquake catalog (Arabasz and McKee, 1979). For early historical earthquakes lacking instrumental recordings, Richter magnitude is estimated from the size of the felt area. In such cases, the magnitudes are listed as a whole number followed by a ± or a fraction rather than a decimal (University of Utah Seismograph Stations, 2002). Black and others (2003; updated from Hecker, 1993) have compiled a database of Utah's Quaternary faults, which includes estimates of the timing of their most recent surface faulting.

Earthquakes in Central Utah

In Utah, most earthquakes are associated with the Intermountain seismic belt (ISB) (Smith and Sbar, 1974; Smith and Arabasz, 1991), an approximately 100-mile-wide (160 km), north-south-trending zone of earthquake activity that extends from northern Montana to northwestern Arizona (figure 7). Central Sevier Valley is one of the most seismically active parts of the ISB in Utah. Since 1850, at least 16 earthquakes of magnitude 6.0 or greater have been recorded within the ISB in Utah (Smith and Arabasz, 1991). Included among those 16 events are Utah's two largest historical earthquakes, the 1901 Richfield earthquake with an estimated magnitude of $6\frac{1}{2}$ ±, and the 1934 Hansel Valley magnitude 6.6 earthquake, which produced Utah's only historical surface fault rupture. In an average year Utah experiences more than 700 earthquakes, but most are too small to be felt. Moderate-magnitude (5.5 – 6.5) earthquakes happen every several years on average, the most recent being the magnitude 5.8 St. George earthquake on September 2, 1992. Large-magnitude earthquakes (6.5 – 7.5) are much less frequent in Utah.

Fault-related surface rupture has not occurred in Monroe or the Sevier Valley historically, but the area does have a pronounced record of earthquakes. Figure 8 shows epicenters of earthquakes of magnitude 2 and greater from 1876 to 2002 in the greater Monroe area. The number and distribution of epicenters on figure 8 shows the seismic activity of the area. Epicenters of six earthquakes of magnitude 5 or greater have occurred within a 15-mile (24 km) radius of Monroe since 1901 (table 3). The largest event was the magnitude $6\frac{1}{2}$ ± Richfield earthquake in 1901. In 1921 several magnitude 5.7 to 6 ± earthquakes were centered under Elsinore. Both the Richfield and Elsinore earthquakes caused considerable building damage in Monroe. Newspaper articles, photo-

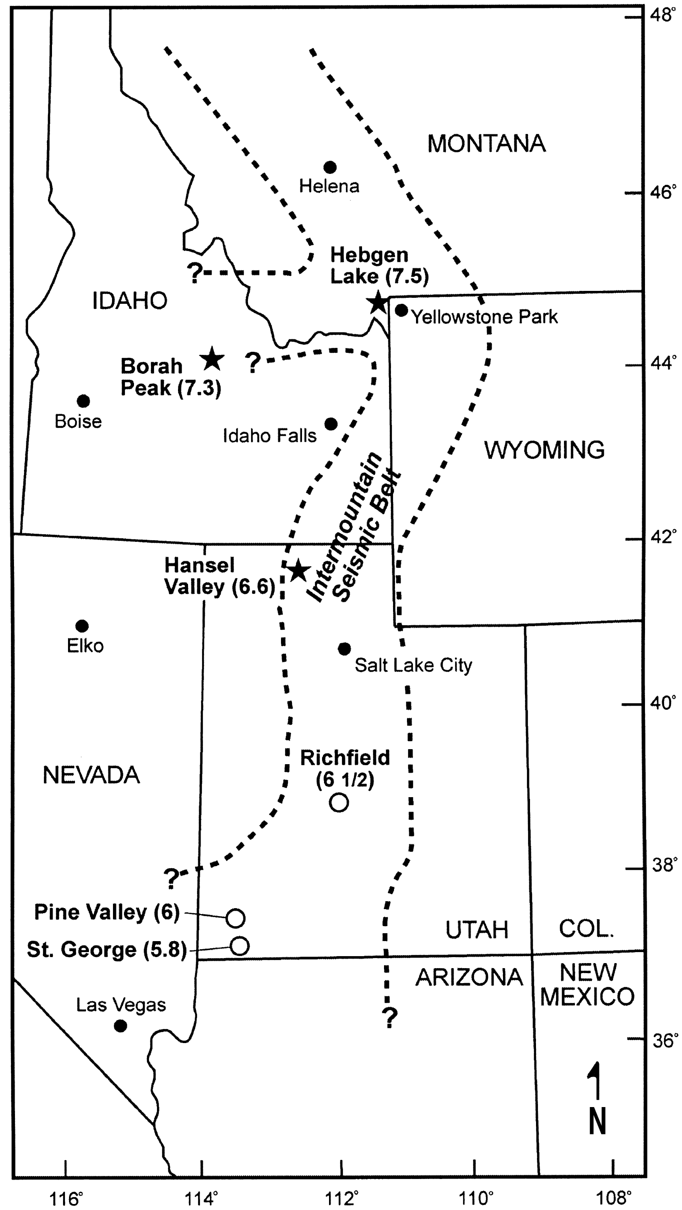


Figure 7. *The Intermountain seismic belt and major historical ISB earthquakes (magnitude). Modified from Arabasz and others (1992).*

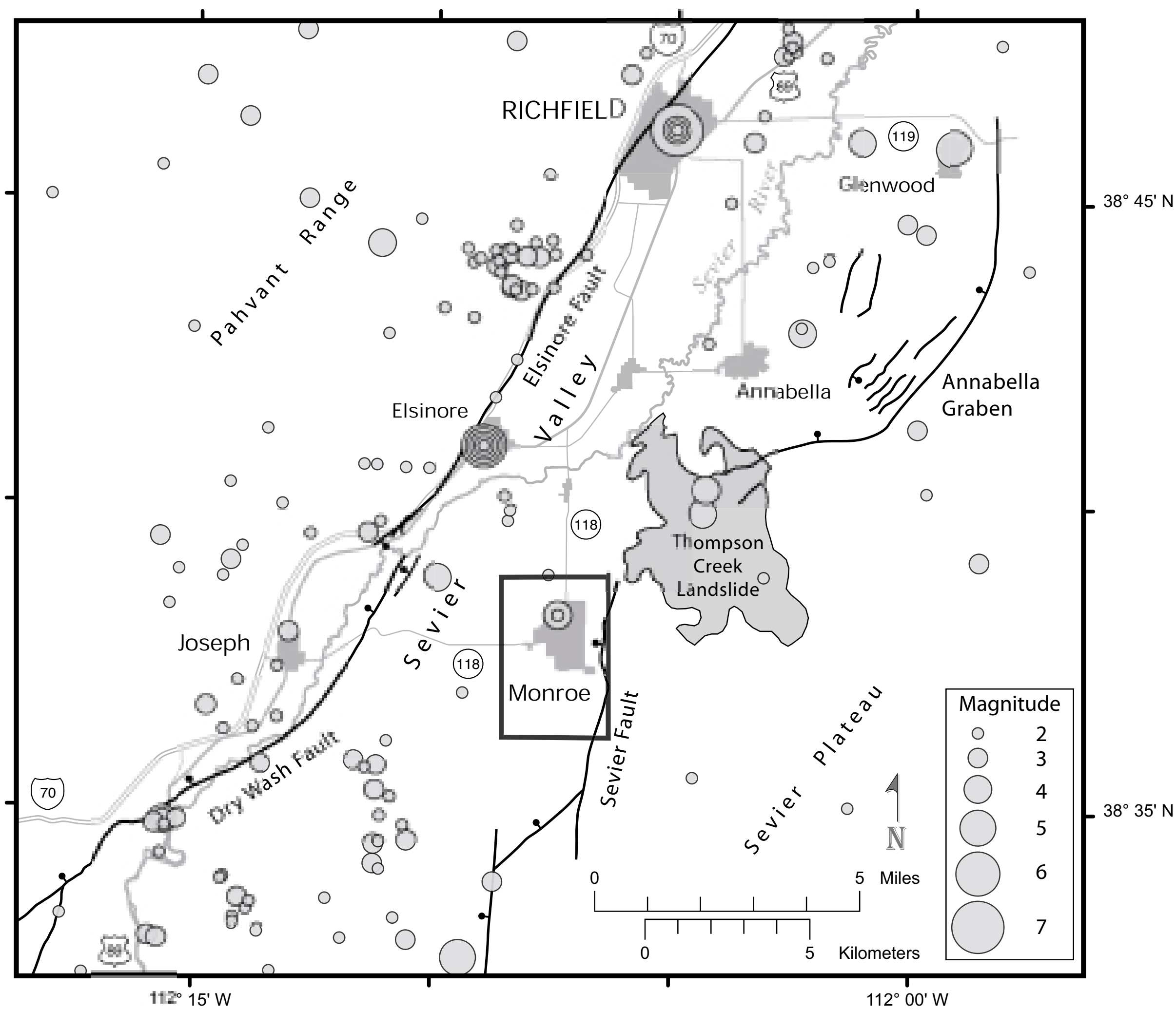


Figure 8. Map showing faults and earthquake epicenters of magnitude 2 and greater from 1876 to 2002 in the Monroe area. Historical earthquakes with the same magnitude that lack an instrumental recording are not apparent because the epicenters are assigned the same geographic coordinates and plot in the same location. For example, the three 1921 Elsinore earthquakes of magnitudes 6 ±, 5.7, and 6 ± (table 3) plot as one magnitude 6 epicenter circle on the map. Earthquake data are from the University of Utah Seismograph Stations. Fault locations compiled and modified from Cunningham and Steven (1979), Steven (1979), Rowley and others (1981a, 1981b), and Cunningham and others (1983). The bar and ball are on the downthrown side of the fault. Base from AGRC data sources.

Table 3. Historical earthquakes of magnitude 5 or greater in the central Sevier Valley.

Date	Nearest Town	Magnitude
November 13, 1901	Richfield	6 1/2 ±
January 10, 1910	Elsinore	5.0
September 29, 1921	Elsinore	6 ±
September 30, 1921	Elsinore	5.7
October 1, 1921	Elsinore	6 ±
November 17, 1945	Glenwood	5.0

graphs, and personal accounts of the 1901 Richfield and 1921 Elsinore earthquakes can be viewed on the University of Utah Seismograph Stations (2003) Web site. Photographs, geologic effects, and building damage of the 1921 Elsinore earthquakes are discussed by Eldredge and O'Brien (2001). No building damage in Monroe was reported for the 1910 Elsinore and 1945 Glenwood earthquakes (University of Utah Seismograph Stations, 2002).

Earthquake Ground Shaking

Description

Ground shaking is the most widespread and frequently occurring earthquake hazard. Ground shaking is caused by seismic waves that originate at the source of the earthquake and radiate outward in all directions. The extent of property damage and loss of life due to ground shaking, typically the most damaging of earthquake hazards, depends on factors such as (1) earthquake magnitude, (2) proximity of the earthquake to an affected location, (3) the strength, duration, and frequency of earthquake ground motions, (4) nature of the geologic materials through which the ground motions travel, and (5) the design and construction of engineered structures (Costa and Baker, 1981).

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

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

The *2000 International Building Code* (IBC; International Code Council, 2000a), adopted statewide in 2002, and the 2003 IBC (International Code Council 2002; scheduled for adoption in Utah in January 2004) describe a procedure to determine the amount of amplification at a specific site. The procedure starts by defining site classes based upon the site-specific geotechnical properties of soil and rock. I adapted the site-specific techniques of the IBC to map the regional distribution of site classes to estimate the response of near-surface geologic materials to strong earthquake ground shaking.

The site class is a key element in determining applicable design requirements, specified for most structures by the IBC and for one- and two-family dwellings and townhouses by the *International Residential Code* (IRC) (International Code Council, 2000b, 2003). Design requirements depend on the seismic design category of a structure. The IBC and IRC assign structures to a seismic design category based on their design spectral response acceleration and, for the IBC, seismic use group (IBC table 1616.3 and IRC table R301.2.2.1.1). Design spectral response accelerations depend on rock spectral response accelerations (mapped on IBC figure 1615) adjusted using site coefficients. Seismic use groups depend on the nature of occupancy for buildings and other structures (IBC table 1604.5). Site coefficients represent the degree of amplification and are associated with each IBC site class.

Because different structures are affected by different frequencies of ground shaking, the IBC presents two site coefficients appropriate for use with a wide range of building types. These site coefficients take into account the varying frequencies of ground shaking which, when matching the natural frequency of vibration of a structure (a function of building height and construction type), may cause resonance resulting in severe damage or collapse. One site coefficient is appropriate for use when evaluating the effect of short-period (high-frequency) ground motions, which typically affect short buildings (IBC table 1615.1.2[1]), and the other site coefficient is appropriate for use when evaluating the effect of long-period (low-frequency) ground motions, which typically affect tall buildings (IBC table 1615.1.2[2]).

Map Units

Figure 9 is a site-class map for the Monroe area, on which I show three dual site-class units (B-C, C-D, D-E). Each site-class letter corresponds to an individual IBC site class designated B through E, defined by the IBC using geotechnical properties in the upper 100 feet (30 m) of rock or soil (table 4). Each individual site class is associated with a soil profile name representing a qualitative description of the geologic materials. Soils having the characteristics defining IBC site class A are not shown on this map and are unlikely to exist within the map area.

The dual site-class approach accommodates the lateral change in sediment grain size in the alluvial-fan and basin-fill units. The dual site-class approach is also necessary because of the limited data available for defining site class. The objective of site-class mapping is to determine the response of near-surface geologic materials (<100 feet [30 m] deep) to strong earthquake ground shaking. The preferred data for defining individual site classes C, D, and E are shear-wave velocity, standard penetration tests in geotechnical boreholes, and measured undrained shear strength of soils. None of these data exist within the map area. Subsurface data (<100 feet [30 m] deep) are limited to water-well logs (obtained from well logs on the Utah Division of Water Rights [2003] Web site) and geothermal well logs (Mase and others, 1978). The most detailed area-wide information on near-surface geologic materials is the surficial geologic map. For site-class identification, I therefore relied primarily on the lithologic descriptions on the surficial geologic map, collapsible soils investigations conducted in this study, and geothermal and water-well logs.

The site-class unit boundaries on figure 9 correspond to contacts between selected geologic. Unit B-C (rock-soft rock) corresponds to volcanic bedrock and hillslope colluvium. Because the hillslope colluvium is relatively thin (about 20 feet [6 m] thick), this site-class unit is based on volcanic rock shear-wave-velocity values reported in the literature and elsewhere in Utah (Ashland and Rollins, 1999). Unit C-D (very dense soil-stiff soil) corresponds to alluvial-fan deposits. Based on information in the geothermal and water-well logs, this site-class unit includes coarse-grained alluvium at the head of the alluvial fans that grades to fine-grained alluvium at the fan toe. Unit D-E (stiff soil-soft soil) corresponds to basin fill. This site-class unit likely consists mostly of stiff soil, but some water-well logs indicate a significant percentage of clay in the upper 100 feet (30 m). Therefore, I included site class E (soft soil) in this unit. In general, the site-class units grade from the soft rock at the mountain front westward into stiff or possibly soft soils in the basin fill.

Unit C-D and parts of units B-C are shaded (figure 9), indicating the possibility of site class F if collapsible soils are

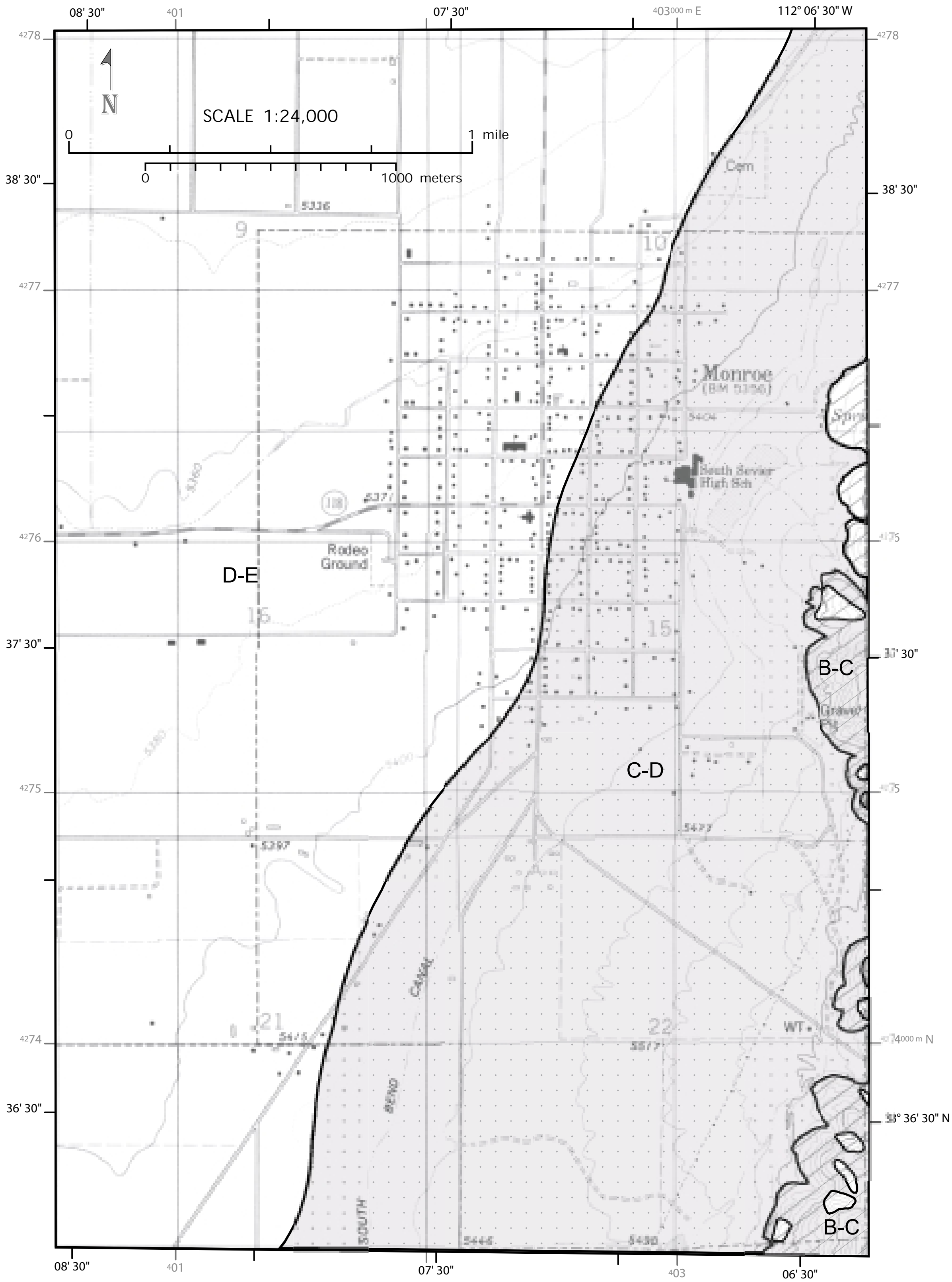


Figure 9. Earthquake site-class map of the Monroe area. Site-class map units: B-C, rock and soft rock; C-D, very dense soil and stiff soil; D-E, stiff soil and soft soil. The shading within map units B-C and C-D indicates the possibility of collapsible soils. If collapsible soils are present, the site is classified as site class F. See table 4 for individual International Building Code site-class definitions. Base from USGS 7.5-minute quadrangles.

Table 4. *IBC site-class definitions (modified from IBC table 1615.1.1).*

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

present (table 4). IBC section 1615.1.5.1 states if collapsible soils are identified, the site must be classified as site class F and a site-specific geotechnical evaluation is required. The potential for collapsible soils is based on observations and laboratory tests outlined in the Problem Soil and Rock Hazards section of this report. I found a high potential for collapse in young alluvial-fan deposits (geologic unit Qaf_1), possible collapsible soils in Monroe Creek alluvial-fan deposits (geologic units Qaf_1 and Qaf_2), and possible collapsible soils in hillslope colluvial deposits (geologic unit Qc).

Calculation of Design Accelerations

The IBC earthquake ground motions (available on the IBC *Earthquake Spectral Response Acceleration Map* CD) are only for site class B (rock), which is assigned an amplification factor of 1.0. Site coefficients (amplification factors) for other site classes are calculated relative to site class B. Site coefficients less than one indicate that ground motions will be less than those for site class B (deamplified). Coefficients greater than one indicate that ground motions will be greater than those for site class B. The coefficient for site class A (hard rock) for both short- and long-period ground motions is 0.8, indicating that ground shaking will be deamplified. The coefficients for site classes C, D, and E (very dense soil or soft rock, stiff soil, and soft soil, respectively) range from 0.9 to 3.0, indicating that ground shaking may either be amplified or deamplified, depending upon the period and strength of ground motions; amplification increases as the period of ground shaking increases and accelerations decrease.

The design spectral response ground accelerations are calculated at the four map corners according to the 2000 IBC and IRC (International Code Council, 2000a, 2000b) and are presented in table 5. I determined the mapped spectral response accelerations for each map corner for site class B using the IBC CD and then calculated the design spectral response accelerations. The spectral response accelerations are the same for all four map corners (table 5). Table 5 also shows the seismic design categories that are discussed later. Site classes are shown as individual site classes on table 5 rather than as the dual site classes shown on the site-class map. Even though site class A is not present on the site-class map, I have included it in table 5 for comparison purposes. The design spectral response accelerations for short-period ground motions in the map area range from 0.51 to 0.71 *g*. The design spectral response accelerations for long period ground motions in the map area range from 0.16 to 0.48 *g*. For short-period ground motions, site class E is deamplified slightly compared to site class D.

One of the objectives of calculating design accelerations is to evaluate if the different site classes change the IBC and IRC seismic design categories. Based on the calculated design spectral response accelerations, the IBC and IRC seismic design categories are D and D1, respectively. Table 5 shows that for the different seismic use groups, the different site classes do not change the seismic design category. Because the seismic design categories do not change with site class, the determination of site class for construction based solely on seismic design category is not needed except for areas with collapsible soils that classify as site class F.

Using the Map

Because the IBC and IRC seismic design categories are the same in Monroe regardless of site class (except site class F), this map (figure 9) is provided for information purposes only. However, if collapsible soils are identified in units B-

Table 5. *Seismic design categories in the Monroe area by site class and seismic use group. Categories are determined in the four corners of the study area in accordance with the 2000 editions of the IBC and IRC and are subject to change if requirements are revised in subsequent editions (equation identifier numbers change in the 2003 IBC).*

Site Class	Mapped Spectral Response Accelerations[1]		Site Coefficients[2]		Maximum Considered Spectral Response Accelerations[3]		Design Spectral Response Accelerations[4]		Seismic Design Category[5]				
									Seismic Use Group[6]				
									I		II	III	
	Short Period (S_s)	Long Period (S_1)	Short Period (F_a)	Long Period (F_v)	Short Period (S_{MS})	Long Period (S_{M1})	Short Period (S_{DS})	Long Period (S_{D1})	One- and Two-Family Dwellings and Townhouses (IRC)	All Other Buildings and Structures Except Those Listed in Groups II and III (IBC)	Buildings and Other Structures That Represent a Substantial Hazard to Human Life in the Event of Failure (IBC)	Buildings and Other Structures Designated as Essential Facilities (IBC)	Buildings and Other Structures That Represent a Low Hazard to Human Life in the Event of Failure (IBC)
Spectral response accelerations mapped at the northwest (latitude 38.65° longitude 112.14°), northeast (latitude 38.65° longitude 112.11°), southwest (latitude 38.6° longitude 112.14°) and southeast (latitude 38.6° longitude 112.11°) map corners.													
A	0.96	0.24	0.8	0.8	0.77	0.19	0.51	0.13	D_1	D	D	D	No IBC seismic design requirements
B			1.0	1.0	0.96	0.24	0.64	0.16	D_1	D	D	D	
C			1.0	1.6	0.96	0.38	0.64	0.25	D_1	D	D	D	
D			1.1	1.9	1.06	0.46	0.71	0.31	D_1	D	D	D	
E			0.9	3.0	0.86	0.72	0.57	0.48	D_1	D	D	D	
F			Site-specific geotechnical investigation and dynamic site-response analysis shall be performed to determine appropriate values and seismic design categories										

[1] Mapped spectral response accelerations with a 2 percent probability of exceedance in 50 years at 0.2-second (S_s) and 1.0-second (S_1) periods, determined from the IBC CD.

[2] Site coefficients defined in IBC table 1615.1.2.

[3] Maximum considered spectral response accelerations calculated using IBC equations 16-16 ($S_{MS} = F_a S_s$) and 16-17 ($S_{M1} = F_v S_1$).

[4] Design spectral response accelerations calculated using IBC equations 16-18 ($S_{DS} = \frac{2}{3} S_{MS}$) and 16-19 ($S_{D1} = \frac{2}{3} S_{M1}$).

[5] In accordance with IBC section 1616.3, the seismic design category is the most severe category specified in IBC table 1616.3, irrespective of the fundamental period of vibration of the structure. Seismic design categories are based on design spectral response accelerations (S_{DS} and S_{D1}), except for IBC seismic design categories E and F, which are based on mapped spectral response accelerations at a 1-second period (S_1).

[6] The three seismic use groups are those listed in the 2003 IBC (International Code Council, 2002) rather than the 2000 IBC, which incorrectly defines a seismic use group IV in table 1604.5. The 2003 IBC is scheduled for statewide adoption in January 2004.

C and C-D, the site must be classified as site class F and the IBC requires that site-specific geotechnical investigations and dynamic site-response analyses be performed to determine appropriate site coefficient values. The IBC does not provide specific guidance on how to conduct the site-specific evaluation for collapsible soils. Therefore, the methods and tests used to determine the soil characteristics in site-specific evaluation are the responsibility of the investigator. Although the IRC does not specifically mention collapsible soils, IRC section R401.4 (p. 57) leaves the need for soil tests up to the local building official in areas likely to have expansive, compressive, shifting, or other unknown soil characteristics. To aid building officials in applying IRC requirements, the UGS recommends site-specific studies for one- and two-family dwellings and townhouses (included in seismic use group I, table 5) where collapsible soils are identified. Addressing the collapsible-soil hazard as recommended in the Problem Soil and Rock section of this report and using mitigation techniques to reduce the collapsible soil hazard will likely eliminate the need for classifying the soils as site class F. This is probably a more logical and cost-effective hazard-reduction option than conducting a site class F site-specific investigation.

Builders desiring a higher performance level than that required under the IBC or IRC may be interested in the site class and may use the map to estimate the site class, although the site class should be confirmed in the field as outlined in the IBC. For construction in areas underlain by rock (site class B in unit B-C) subject to no amplification, site geologic studies are needed only to confirm the mapped site class based on rock type. For construction in areas underlain by soil site class C, D, and E in units B-C, C-D, or D-E, special studies are needed to geotechnically characterize site soil conditions.

Limitations on the Use of this Map

The earthquake site-class map (figure 9) is based on limited data and a dual site-class approach. Different mapping techniques may yield different spatial patterns of site classes. The map also depends on the quality of geologic information. Only generalized geologic information was used to derive the map, and more detailed geotechnical information is needed to separate the dual site classes into individual site classes and for site-specific studies. Because site-class boundaries are based on limited geologic data, the boundaries are approximate and subject to change with additional data. The class at any particular site may be different from that shown because of geological variations within a map unit, gradational and approximate map-unit boundaries, and the regional map scale. The map is intended only for use in general planning and does not preclude the need for site-specific studies.

When using this map, several important limitations must be noted:

- Geologic interpretations based on water-well logs are less precise than interpretations of geotechnical borehole logs. The use of water-well logs is appropriate only for regional studies in areas where geotechnical data are sparse or lacking. Water-well logs should not be relied on for site-specific investigations.

- The shaded areas of figure 9, indicating areas of potential site class F due to the presence of collapsible soils, are based on areas of collapsible soils identified in this study and areas where collapsible soils may exist. Collapsible soils may or may not be present in these shaded areas.

- Amplification by soft soils diminishes significantly as the strength of ground shaking increases (Building Seismic Safety Council, 1997). Consequently, amplification by soft soils may be minor during strong ground shaking generated by a nearby large earthquake, but could be significant for moderate ground shaking generated either by a more distant large earthquake or nearby moderate earthquake. Because moderate ground shaking is much more likely to occur, areas on this map assigned a high amplification factor (site coefficient) may be subjected to potentially damaging ground motion more often than areas assigned a low amplification factor.

- This map does not address amplification of ground motion near the fault causing the earthquake due to near-fault rupture directivity. Sites near surface traces of faults may be subject to ground motions greater than IBC or IRC design motions. This effect is particularly significant for structures, such as tall buildings, that are sensitive to long-period ground motions (Somerville and others, 1997; Somerville, 1998b).

- This map does not address amplification of ground motion due to topography, which can exceed amplification due to soil conditions in some cases. High amplification is commonly experienced on hills, ridges, and the tops of cliffs (Somerville, 1998a).

- This map does not address amplification of ground motion due to three-dimensional effects, such as the focusing of energy due to the structure of the earth's crust in the region, which can be as great as amplification due to soil conditions (Somerville, 1998a).

- Amplified ground-motion hazards on this map reflect variations due to soil conditions, which are applicable to most earthquakes that will affect the region. Near-fault, topographic, and three-dimensional effects are more dependent on the earthquake location and direction of seismic-energy propagation.

- Amplification factors in the IBC were determined from studies of worldwide earthquakes, where near-surface softer sediments (clays) were observed to amplify ground shaking. However, recent studies of Salt Lake Valley (Wong and Silva, 1993; Wong and others,

2002) indicate that significant amplification may also occur in shallow stiff (sandy and gravelly) soils; this amplification is not reflected in IBC site coefficients.

Ground-Shaking Hazard Reduction

Ground shaking cannot be avoided, but meeting requirements for earthquake-resistant design and construction can reduce loss of life and damage to structures. Earthquake-resistant design requirements for Utah are specified in seismic provisions of the IBC and IRC. Section 1614.1 of the IBC states, "Every structure, and portion thereof, shall as a minimum, 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 help accomplish this by assigning each structure, with some exceptions, to a seismic design category (IBC section 1616.3 and IRC section R301.2.2.1).

The seismic design categories appropriate for the Monroe area are shown in table 5 and discussed above. One- and two-family dwellings and townhouses in areas of site classes B-C, C-D, and D-E all fall within seismic design category D_1 as defined by the IRC. All other structures of seismic use groups I, II, and III fall within seismic design category D as defined by the IBC. Therefore, determination of site class for construction based solely on seismic design category is not needed except for areas having collapsible soils that classify as site class F.

Figure 9 provides an estimate of the regional distribution of IBC site classes, which are generally used to determine seismic design categories (although in Monroe seismic design categories do not change with site class). Figure 9 is suitable as a screening tool to indicate the likely scope of subsequent site-specific investigations should site class be important to a particular design. The investigation results should then be used to fulfill IBC and IRC requirements for earthquake-resistant design and construction to minimize loss of life and damage to structures.

Rock Fall

Rock fall is a possible hazard along most mountain fronts, and is the most common type of slope failure caused by earthquakes. Rock falls pose a hazard because a large boulder traveling at high speed can cause significant damage. Keefer (1984) indicates earthquakes as small as magnitude 4.0 can trigger rock falls. Historical earthquakes in Utah of magnitude 5 or greater have caused rock falls. Historical earthquakes in the Monroe area have generated rock falls in Monroe Canyon east of the map area. Slope modification such as cuts for roads and building pads for development can increase or create a local rock-fall hazard.

I found no evidence of rock-fall deposits in the map area. This is largely due to weathering of the volcanic rock outcrops by granular disintegration to gravel- and sand-sized material. The outcrops weather into rubble rather than breaking along joints to yield large rocks that could roll downslope. Even though I found no rock-fall deposits, I believe rock fall from rock outcrops (figure 10) is possible, particularly during moderate to large earthquakes. However, to evaluate this hazard, site-specific investigation of rock outcrops is required. Mapping individual outcrops is precluded here because of the limitations of map scale.

Map Unit

I recommend evaluating the rock-fall hazard where development is proposed below rock outcrops. The rock-fall hazard special-study area is shown on plate 4. The hazard areas shown include rock outcrop sources determined from surficial geologic mapping and downslope runout areas. The hazard areas were delineated using a 20° projection (shadow angle; Evans and Hungr, 1993) from the base of the source area (figure 11).

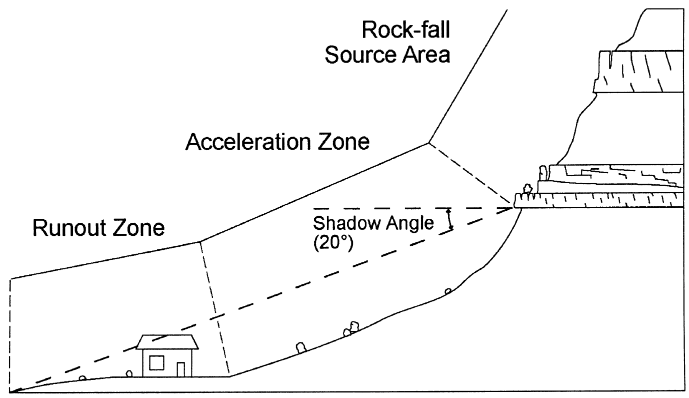


Figure 11. *Schematic illustration of rock-fall hazard areas. Hazard areas below source based on 20° shadow angle from the base of the source area.*

I recommend the following tasks be performed to evaluate the rock-fall potential:

1. Determine if a rock-fall hazard is present by evaluating individual outcrops and possible runout paths to determine if the proposed development could be impacted.

2. If a rock-fall hazard is present, make pertinent risk-reduction recommendations.

Rock-Fall Hazard Reduction

Engineered catchments or deflection structures such as 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. In areas where a site-specific evaluation indicates a rock-fall hazard is present but the hazard is low, disclosure of the hazard to landowners and residents may be an acceptable alternative to avoidance or costly hazard-reduction efforts. Disclosure ensures that buyers are informed of the hazard and are willing to accept the risks.

Quaternary Faults

From an earthquake-hazard standpoint, faults are classified as either active, likely to generate damaging earthquakes, or inactive, not likely to generate earthquakes, in some defined time period. The term "active fault" is fre-

Figure 10. *Rock outcrops on mountain slope east of Monroe possibly capable of generating rock fall induced by earthquake ground shaking.*

quently incorporated into regulations pertaining to earthquake hazards, and over time the term has been defined differently for different regulatory and legal purposes. In fact, faults possess a wide range of activity levels. Some, such as the San Andreas fault in California, produce repeated large earthquakes and associated surface faulting every few hundred years or less, while others, like many of the faults in the Basin and Range Province and adjoining areas such as Sevier Valley, generate large earthquakes and surface faulting every few thousand to tens or even hundreds of thousands of years or less. Therefore, depending on the area of interest or the intended purpose, the definition of "active fault" may change. The time period over which faulting activity is assessed is critical because it determines which faults are ultimately classified as hazardous and therefore of regulatory concern (National Research Council, 1986). In general, all faults that show have evidence for rupture during the Quaternary Period (1.6 million years to present) must be evaluated with respect to level of activity and potential to generate earthquakes.

Fault Activity Classes for Utah

In California, the Alquist-Priolo Earthquake Fault Zoning Act (Hart and Bryant, 1997), which regulates development along known active faults, defines an "active fault" as one that has had "surface displacement within Holocene time (about the last 11,000 years)." Because California has a well-recognized earthquake hazard and was the first state to implement regulations designed to reduce those hazards, the California "Holocene" standard is used in many regulations in other parts of the country, even in areas where the Holocene is not the best time frame against which to measure surface-faulting recurrence. dePolo and Slemmons (1998) argue that in the Basin and Range Province a time period longer than the Holocene is more appropriate for defining active faults because most faults in the province have surface-faulting recurrence intervals (average repeat times) that approach or exceed 10,000 years. They advocate a latest Pleistocene age criteria, specifically 130,000 years, to define active faults in the Basin and Range Province. They base their recommendation on the observation that six to eight (> 50%) of the 11 historical surface-faulting earthquakes in the Basin and Range Province occurred on faults that lacked evidence of Holocene activity, but which did have evidence of late Pleistocene activity.

Because of the difficulties in using a single "active" fault definition, Utah has adopted the fault activity classes defined by the Western States Seismic Safety Policy Council (WSSPC) for the Basin and Range Province (WSSPC Policy Recommendation 97-1 in Lund, 1998; WSSPC, 2002):

- Holocene fault – a fault that has moved within the past 10,000 years.

- Late Quaternary fault – a fault that has moved within the past 130,000 years.

- Quaternary fault – a fault that has moved within the past 1,600,000 years.

The WSSPC policy states “earthquakes occur along faults within the Basin and Range Province with a wide range of recurrence intervals, from hundreds of years to hundreds of thousands of years. Recurrence intervals of a few tens of thousands of years are typical.” Christenson and others (2003) recommended adopting the WSSPC fault activity class definitions in Utah and I follow that recommendation in this study.

Evaluating Fault Activity

Because both the instrumental and historical records of earthquakes in Utah are short (less than 200 years), geologists must use other means to evaluate the record of past surface fault rupture to assess fault activity levels. The study of prehistorical surface-faulting earthquakes is termed “paleoseismology” (Solonenko, 1973; Wallace, 1981). Paleoseismic studies can provide information on the timing of the most recent surface-faulting earthquake (MRE) and earlier events, the average recurrence interval between surface-faulting events, net displacement per event, slip rate (net displacement averaged over time), and other faulting-related parameters (Allen, 1986; McCalpin, 1996). Determining the timing of the MRE establishes the fault’s activity level (see above). Paleoseismic data can show if a fault ruptures as a single entity, or if it is subdivided into a series of smaller independent seismogenic segments each capable of generating earthquakes. Perhaps most importantly, paleoseismic studies can establish the relation between the elapsed time since the MRE and the average recurrence interval between surface-faulting events. Once that relation is known, the likelihood of surface fault rupture in a time frame of significance to most engineered structures can be evaluated.

Quaternary Faults in Sevier Valley

Monroe and Sevier Valley are located in the structural transition zone between the Basin and Range Province and Colorado Plateau. Three major faults in Sevier Valley are near Monroe: the Sevier, Dry Wash, and Elsinore faults (figure 8). Although primarily a fault, the Elsinore fault is also expressed as a monoclinal fold (Willis, 1988, 1994; Anderson and Barnhard, 1992). All of these faults are normal faults where the hanging wall appears to have moved downward relative to the footwall (figure 12). These faults have scarps that resulted from large earthquakes that ruptured the ground surface, and they have faults with the potential to generate large earthquakes in the Monroe area. No paleoseismic studies have been completed for these faults, therefore little is known about how frequently they generate large earthquakes and rupture the ground surface. Arabasz and Julander (1986) identify two areas of concentrated seismic activity, one northeast of Annabella and another southwest of Elsinore (figure 8). Both of these areas coincide with late Quaternary normal faults.

Sevier fault: The Sevier fault extends from near Annabella south about 35 miles (56 km) to near Kingston, Utah (Black and others, 2003). The Thompson Creek landslide (figure 8) obscures the trace of the fault between Annabella and the northeast corner of the study area. Within the map area, the Sevier fault lies near the base of the mountain front separating Sevier Valley from the uplifted Sevier Plateau to the east. The fault trends north through the map area and I map the fault as a concealed fault buried by alluvium (plate 1). Anderson and Barnhard (1992) state the uplift of the Sevier Plateau is probably distributed over a broad zone of faults collectively referred to as the Sevier fault. Based on the interpretation of geophysical and drill hole data at Monroe and Red Hill hot springs, Chapman and Harrison (1978) and Mase and others (1978) show the Sevier fault as a zone of

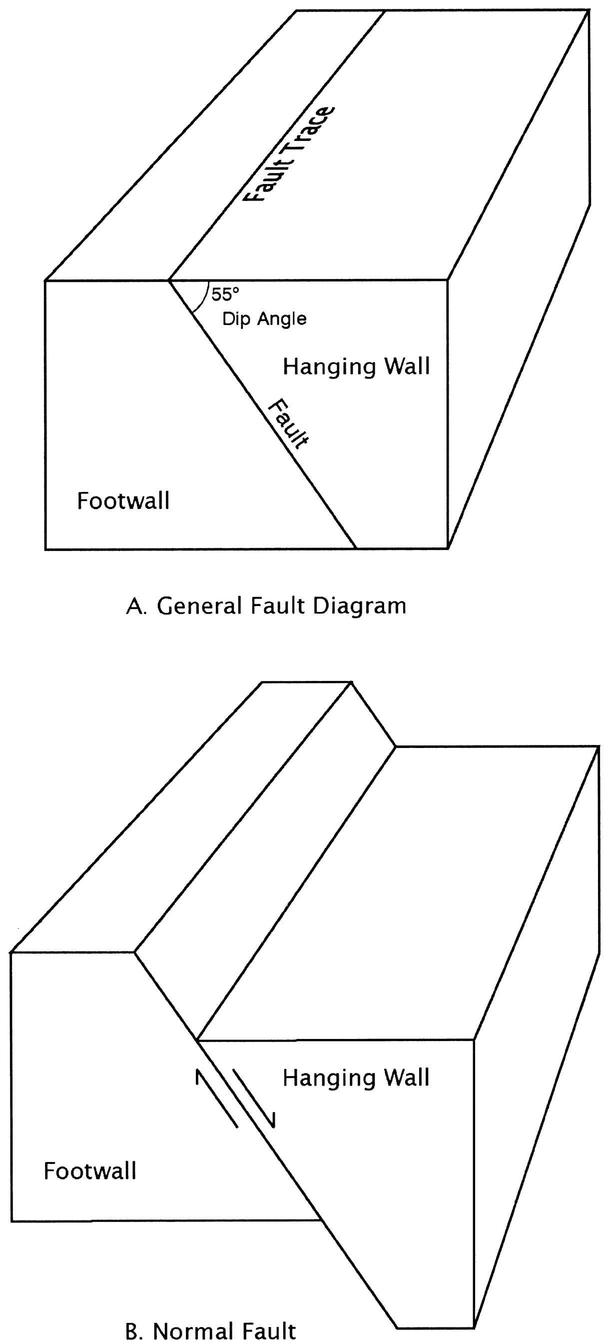


__Figure 12.__ Normal fault block diagrams.

several north-trending normal faults stepping down into Sevier Valley. Even though these authors discuss a broad zone of faults, they infer the trace of the Sevier fault at the base of the mountain front.

Anderson and Barnhard (1992) identified several late Quaternary fault scarps in the Annabella graben 8 miles (13 km) northeast of Monroe. The Annabella graben is in a structurally complex bend at the north end of the Sevier fault. Hecker (1993) indicates the age of most recent movement within the Annabella graben is latest Pleistocene to early Holocene and states the age and rate of deformation within the graben is likely not characteristic of deformation elsewhere along the Sevier fault, where larger, longer return-period earthquakes are likely.

Elsinore fault (fold): The Elsinore fault is 4 miles (6 km) northwest of Monroe. The Elsinore fault trends northeast and separates Sevier Valley from the uplifted Pahvant Range to the west. The origin of the Elsinore fault is controversial. Willis (1988, 1994) maps a fault bounding the Pahvant Range. Anderson and Barnhard (1992) describe both faulting and monoclinal folding along the range front and also found evidence for both normal and strike-slip movement. Hecker (1993) shows a buried Quaternary monocline along the north trace and a fault along on the south trace of the fault. Late Quaternary fault scarps with normal displacement are present at the south end of the Elsinore fault southwest of the town of Elsinore (figure 8) (Steven, 1979). These scarps provide evidence for previous large earthquakes near Monroe.

Dry Wash fault: The Dry Wash fault lies 3 miles (5 km) west of Monroe and lies at the base of the Antelope Range. At the northern end of the Dry Wash fault, Anderson and Barnhard (1992) identify eastward-tilted Quaternary Sevier River terraces associated with late Quaternary normal-displacement fault scarps.

Surface-Faulting Hazard

Among the potential effects of large earthquakes (magnitude ≥ 6.5) is surface faulting, which occurs when movement at depth on a fault during an earthquake propagates to the surface. The resulting displacement at the ground surface produces ground cracking and typically one or more "fault scarps" (figure 13). Immediately following an earthquake, fault scarps have near-vertical slopes and depending on the size of the earthquake, can range in height from a few feet or less to 10 feet (3 m) or more. Local ground tilting and graben formation by secondary (antithetic) faulting may accompany surface faulting, resulting in a zone of deformation along the fault trace tens to hundreds of feet wide (figure 13). Surface faulting, while of limited areal extent when compared to other earthquake-related hazards such as ground shaking and liquefaction, can have serious consequences for structures or other facilities that lie along the rupture path (Bonilla, 1970). Buildings, bridges, dams, tunnels, canals, and pipelines have all been severely damaged by surface faulting (Lawson, 1908; Ambrasey, 1960, 1963; Duke, 1960; Christenson and Bryant, 1998; U.S. Geological Survey, 2000).

The hazard due to surface faulting is directly related to the activity of the fault: that is, how often the fault ruptures the ground surface and how likely it is to rupture in the future (Christenson and Bryant, 1998). Because designing a structure to withstand surface faulting is generally considered impractical from an economic, engineering, and architectural standpoint for most structures (Hart and Bryant, 1997; Christenson and others, 2003), avoiding active fault traces is the recommended approach for reducing surface-faulting hazards. Effectively avoiding surface faulting requires conducting a site-specific investigation to: (1) identify all potential Quaternary faults at a site, (2) assess the level of activity of the faults, and (3) establish appropriate setback distances based on fault activity level(s).

Sevier Fault Special-Study Area

Plate 4 shows the Sevier fault and special-study area at a scale of 1:10,000. I show the Sevier fault as an inferred buried fault (plates 1 and 4). I have inferred the fault trace under alluvium near the mountain front based primarily on geomorphology and geothermal drilling information at Mon-

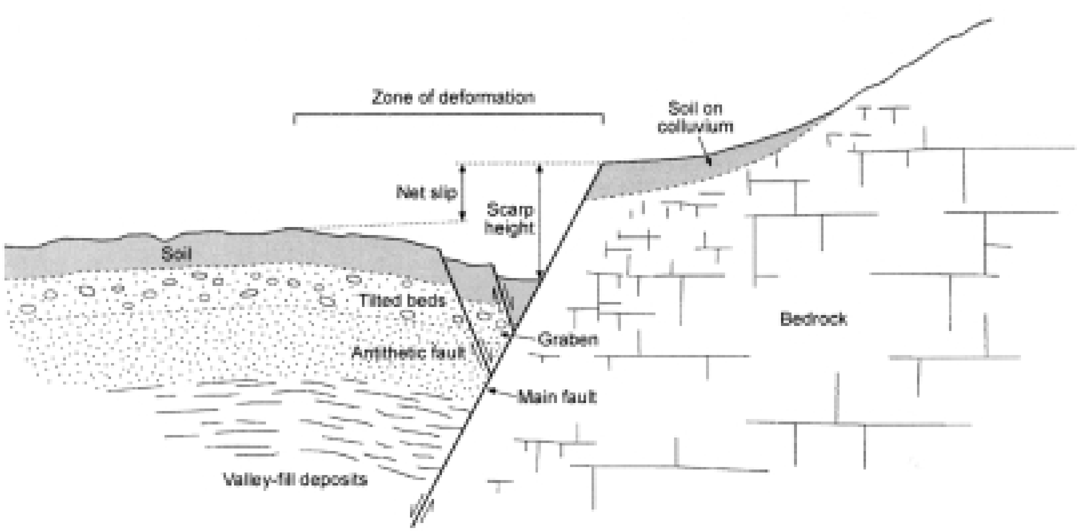


Figure 13. *Cross section of a typical normal-slip fault showing scarp formation and tilted beds and graben formation in the deformation zone associated with the fault. Modified from Robison (1993).*

roe hot springs (Chapman and Harrison, 1978; Mase and others, 1978). Geothermal drill hole MC-2 (plate 4) encountered bedrock at a depth of 610 feet (186 m)(Chapman and Harrison, 1978), 200 to 500 feet (61-152 m) west of travertine and volcanic bedrock outcrops at the mountain front. This suggests the fault lies between the mountain front and the down-dropped block and dips to the west 50º to 70º. Even though I infer the fault along the base of the mountain front, the mapped location is approximate, and the trace could be east or west of the inferred location on the map. My inferred trace of the fault is similar to that mapped by Miller (1976), Chapman and Harrison (1978), Mase and others (1978), and Rowley and others (1981a, 1981b).

I did not find any fault scarps in Quaternary deposits in Monroe. The reasons for the lack of fault scarps are varied, but are chiefly related to one of the following causes: (1) long earthquake recurrence intervals that allow evidence for the fault to be obscured by subsequent erosion and deposition, (2) rapid deposition in some areas that quickly obscures faults, even those with comparatively short recurrence intervals, (3) the fault generates earthquakes that produce relatively small scarps (< 3 feet [1 m]) that are quickly obscured, or (4) faulting occurs at or above the bedrock/alluvium contact in relatively steep, mostly bedrock terrain and is difficult to identify.

Although no scarps in alluvium are present, the Sevier fault may still pose a significant surface-fault-rupture hazard that should be evaluated prior to development in areas where the fault may rupture to the ground surface. Because the fault is buried and its location is uncertain, the surface-fault-rupture-hazard special-study area is broader than the area around a well-defined fault. Using the criteria outlined in Christenson and others (2003), I have outlined a surface-fault-rupture-hazard special-study area extending 1,000 feet (305 m) on either side of the buried trace of the fault (plate 4).

Fault Activity Class

Recommendations for surface-fault-rupture special studies are based on the fault activity class and the type of structure proposed, in accordance with the UGS *Guidelines for Evaluating Surface-Fault-Rupture Hazards in Utah* (Christenson and others, 2003). The fault activity class of the Sevier fault in the Monroe area is unknown because the fault is buried and no paleoseismic studies have been completed. However, I infer a late Quaternary activity class in part based on the lack of scarps in alluvium near Monroe. Also, Anderson and Bucknam (1992) estimate an age for the most recent surface-faulting event on the Annabella graben to the north as comparable to the Bonneville shoreline (~17,000 – 18,000 cal yr B.P.) based on scarp profiles. Hecker's (1993) statement that longer return-period earthquakes are likely elsewhere along the Sevier fault to the south outside the Annabella graben, where scarps are assigned a late Pleistocene to early Holocene age, supports a late Quaternary activity class. For late Quaternary faults, surface-fault-rupture-hazard studies are recommended for all critical facilities (Christenson and others, 2003). Critical facilities are Category II and III structures as defined in the 2000 IBC (table 1604.5, p. 297; International Code Council, 2000a) and category III and IV structures in the 2003 IBC (table 1604.5, p. 272, International Code Council, 2002), and include schools, hospitals, fire stations, high-occupancy buildings, water-treatment facilities, and facilities containing hazardous materials (IBC class E, H, and I structures). Studies for other structures for human occupancy remain prudent, but should be based on an assessment of whether risk-reduction measures are justified by weighing the probability of occurrence against the risk to lives and potential economic loss. Earthquake risk-assessment techniques are summarized in Reiter (1990) and Yeats and others (1997).

Surface-Fault-Rupture-Hazard Special-Study Parameters

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

Because buried faults, like the Sevier fault, lack a clearly identifiable surface trace, they are not amenable to trenching, which is the standard surface-fault-rupture hazard-evaluation technique used to study well-defined faults. Where critical facilities are planned within the special-study area (plate 4), I recommend that the following tasks be performed to better define the surface-fault-rupture hazard in those areas:

1. Review of published and unpublished maps, literature, and records concerning geologic units, faults, surface and ground water, previous subsurface investigations, and other relevant factors.

2. Stereoscopic interpretation of aerial photographs to detect any subtle fault-related features expressed in the site topography, vegetation or soil contrasts, and any lineaments of possible fault origin.

3. Field reconnaissance of the proposed site and surrounding area to observe pertinent surface evidence for faulting; map geologic units as necessary to define critical geologic relations; evaluate geomorphic features such as springs or seeps (aligned or not), sand blows or lateral spreads, or other evidence of earthquake-induced features; and excavate test pits to evaluate the age of the deposits on site to constrain the time of most recent surface faulting.

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

Surface-Fault-Rupture-Hazard Reduction

Because surface fault rupture is typically confined to relatively narrow, discrete zones along the surface trace of a fault, avoidance is the most effective strategy for reducing this hazard. Once the activity class of the fault is determined (see Fault Activity Classes for Utah above), I recommend that facilities be set back from the fault trace and any associated zone of deformation in accordance with Christenson and others (2003). In the absence of practical design techniques for reducing surface-fault-rupture hazards, the most reliable procedure for reducing damage and injury due to surface fault rupture includes carefully locating all potentially active fault traces on a site, assessing their level of activity and amount of displacement, and establishing an appropriate setback distance from the fault.

INDOOR-RADON HAZARD

Description

Radon is an odorless, tasteless, and colorless radioactive gas. The most common type of radon is a naturally occurring product of the radioactive decay of uranium found in small concentrations in nearly all soil and rock. Because radon is a gas, it is highly mobile and can enter buildings through small foundation cracks and other penetrations such as utility pipes. Although outdoor-radon concentrations never reach dangerous levels because air movement dissipates the gas, indoor-radon concentrations may reach hazardous levels because of poor air circulation in buildings. Breathing any level of radon over time increases a person's risk of lung cancer, but long-term exposure to low radon levels is generally considered a small health risk. Smoking increases the health risk due to radon. The U.S. Environmental Protection Agency (EPA) recommends that action be taken to reduce indoor-radon levels when they exceed 4 picocuries per liter of air (pCi/L).

Several geologic factors affect the indoor-radon hazard. A primary geologic prerequisite is that the building must be built on soil or rock that contains a source of radon. Granite, metamorphic rocks, some volcanic rocks and shale, and soils derived from these rocks are generally associated with high indoor-radon hazards. If a radon source is present, the ability of radon to move through the soil and into the overlying building is improved by high soil permeability. Saturation of the soil by ground water inhibits radon movement in soil gas by dissolving radon in the water and reducing its ability to migrate upward through the foundation soil. The Monroe area is underlain by uranium-bearing Quaternary alluvial-fan deposits derived from Tertiary volcanic rocks to the east. Both moderate soil permeability and a depth to ground water of 46 feet (14 m) or more enhance radon emanation and migration and increase the potential for elevated indoor-radon levels.

Geologic factors influence radon levels in soil gas, but a number of non-geologic factors also influence radon levels in a building. Although the influence of geologic factors can be estimated, the influence of non-geologic factors such as occupant lifestyle and home construction methods is more variable. As a result, indoor-radon levels fluctuate and must be measured in each building to determine if a problem exists. Testing is easy, inexpensive, and may often be conducted by the building occupant, but professional assistance is available.

Solomon (1996) studied the radon-hazard potential of the central Sevier Valley and found the average indoor-radon levels in the Sevier Valley considerably higher than average levels in Utah and the United States. The statewide average indoor-radon level is 2.7 pCi/L and the national average is 1.7 pCi/L (Solomon, 1996). The measured residential indoor-radon levels from the Monroe area range from 2 to 22 pCi/L (Solomon, 1996, table A-2). The long-term measurements reported in the Solomon (1996) study average 8.8 pCi/L, 120 percent above the EPA indoor-radon action level of 4 pCi/L. Recent short-term indoor measurements for Monroe obtained from the Utah Division of Radiation Control average 8.2 pCi/L, 105 percent above the action level. Both existing and new buildings in the Monroe area have the potential to exceed this level. The measured indoor-radon levels and the geologic factors responsible for producing high indoor-radon levels indicate the need for testing in existing buildings and incorporating radon-resistant techniques in new construction.

Sources of Data

I used the following sources of information to produce the indoor-radon-hazard map: the indoor-radon-hazard-potential map of central Sevier Valley (Solomon, 1996, figure 30), new residential radon measurements (John Hultquist, Utah Division of Radiation Control, verbal communication, January 6, 2003), and depths to ground water in recently drilled water wells (obtained from well logs on the Utah Division of Water Rights, 2003, Web site). The new radon measurements and depths to ground water support the hazard boundaries of Solomon (1996) with minor modifications using his hazard criteria outlined below. I extend the high-hazard-potential area to the south, beyond the boundary of the Solomon (1996) map, based primarily on depth to ground water.

Map Units

Solomon (1996) used geologic factors that influence indoor-radon levels to classify the relative hazard potential. The hazard-classification boundaries, independent of mapped geologic units, were compiled on the composite hazard map derived from overlays of rating factors. Numerical ratings from 1 to 3 were assigned to each of the three geologic factors used to evaluate probable indoor-radon concentrations: (1) uranium concentration, (2) soil permeability, and (3) ground-water depth. Higher ratings correspond to conditions favorable for elevated indoor-radon concentrations. Solomon (1996) mapped three radon-hazard-potential categories in Sevier Valley, each related to evaluated geologic factors: (1) high - areas with geologic factors generally conducive to elevated indoor-radon levels; (2) moderate - areas with geologic factors generally conducive to elevated indoor-radon levels but limited by one or two unfavorable geologic conditions; and (3) low - areas with geologic factors generally not conducive to indoor-radon levels.

My map of the radon-hazard potential of Monroe (plate 4) identifies two categories of indoor-radon-hazard potential: (1) high, areas where probable indoor concentrations are greater than 4 pCi/L, and (2) moderate, areas where probable indoor concentrations range from 2 - 4 pCi/L. These mapped categories correlate with indoor radon measurements. No areas of low hazard (probable indoor concentration < 2 pCi/L) are identified in Monroe, although Solomon (1996) mapped such areas elsewhere in Sevier Valley.

Using the Map

Geologic radon-hazard-potential maps cannot accurately characterize indoor-radon levels because indoor levels are also affected by non-geologic factors. A hazard–potential map does, however, provide an estimate of the underlying geologic basis for indoor-radon levels, which may be modified by non-geologic effects. The relative hazard potential can be used to prioritize the dissemination of public information on the indoor-radon hazard to indicate the need for radon testing in existing buildings, and to evaluate the need for radon-resistant new construction.

Although the radon-hazard map can be used to prioritize indoor testing by indicating where and the urgency with which it should be undertaken, ultimately all existing buildings should be tested. The radon-hazard map can be used to determine where radon-resistant construction techniques should be considered for new construction (see Hazard Reduction section below).

Site investigations addressing the potential for indoor-radon hazards in new construction are typically not cost-effective or recommended. Should such investigations be desired, however, Yokel and Tanner (1992) propose measurement methods and test procedures for the assessment of the radon-source potential of individual building sites and fill materials. The methods and procedures are based on repeatable measurement of invariant soil properties, with corrections for typical prevailing environmental conditions.

Protocols suggested by Yokel and Tanner (1992) may be unsuitable for some geologic materials, costly for certain types of development, and limited by equipment availability. The appropriate use of these or similar protocols will provide information for sites at scales beyond the resolution of this radon-hazard-potential map.

Cautions When Using This Map

The indoor-radon-hazard-potential categories on the radon-hazard-potential map are relative. This map should not be used to indicate absolute indoor-radon levels in specific buildings because a quantitative relationship between geologic factors and indoor-radon levels does not exist. Factors not considered can strongly affect indoor-radon levels.

The mapped boundaries between radon-hazard categories are approximate and gradational. Small, localized areas of higher or lower radon potential likely exist within any given map area, but their identification is precluded because of the effects of unconsidered factors, the limitations of the map scale, and the relatively sparse data. The use of imported fill for foundation material can also affect the radon potential in small areas because the imported material may have different geologic characteristics than native soil.

Hazard Reduction

Techniques for reducing indoor-radon levels in existing buildings are included in two categories: (1) preventing radon from entering the building, and (2) removing radon or its decay products from the building after entry. The specific technique chosen depends on the initial radon concentration, and building design and construction. Immediate actions to reduce indoor-radon levels can be done quickly with a minimum of expense, but they are not long-term solutions. Immediate actions include discouraging smoking inside a home, spending less time in areas of high radon concentration, and improving ventilation by opening windows and using fans. Permanent actions to reduce indoor-radon levels often require professional assistance to identify radon-entry routes and perform diagnostic testing to aid in the selection of the most effective radon-reducing technique (EPA, 1992). New buildings may incorporate methods to restrict radon entry, and features can also be incorporated during construction that facilitate radon removal after house completion if prevention methods are inadequate. If professional assistance is required to test for radon or reduce the indoor-radon hazard, choose a contractor who has been certified by the EPA; these contractors pass comprehensive exams and agree to follow rigorous standards of professional conduct.

For new construction, the EPA believes that the use of passive radon control systems in areas of high radon-hazard potential, and the activation of those systems if necessitated by follow-up testing, is the best approach to achieving both significant radon-risk reduction and cost-effectiveness in construction of new houses (for descriptions of these systems, see EPA, 1994). A passive system includes construction techniques that create physical barriers to radon entry, reduce the forces that draw radon into a building, and facilitate post-construction radon removal if the barrier techniques prove to be inadequate. Passive systems do not need the active participation of the occupant for operation or maintenance. Radon-resistant construction techniques are recommended in high radon-hazard potential areas, may be appropriate in moderate radon-hazard potential areas, and are generally not necessary in low radon-hazard potential areas.

For new construction, the IRC (International Code Council, 2000b) provides construction techniques that are intended to resist radon entry and prepare the building for post-construction radon reduction, if necessary. Appendix F, Radon Control Methods, of the IRC outlines requirements for new construction in jurisdictions where radon-resistant construction is required. Adoption and enforcement of IRC appendix F is left to local jurisdictions, and the need for adoption and enforcement can be determined through the use of locally available data such as plate 4 or zone 1 designation in IRC figure AF101. IRC figure AF101 was developed to assist building officials in deciding whether radon-resistant construction is applicable in new construction. IRC figure AF101, based on county-wide averages of radon-related factors, shows all of Sevier County (including Monroe) as zone 1 (high potential > 4 pCi/L). Plate 4 is more detailed and delineates the boundary between moderate (probable indoor concentration 2 - 4 pCi/L) and high (probable indoor concentration > 4 pCi/L) indoor-radon-hazard potential and should be used instead of IRC figure AF101 in Monroe.

Zone 1 on IRC figure AF101 is equivalent to the high indoor-radon-hazard potential area of plate 4 (probable indoor concentration > 4 pCi/L) and zone 2 is equivalent to the moderate indoor-radon hazard potential area (plate 4). The UGS recommends adoption and enforcement of construction techniques in IRC appendix F in the high areas, and appropriate disclosure of the potential hazard in moderate areas where radon-resistant construction can be used at the homeowner's discretion, but does not consider radon-resistant construction techniques necessary in low areas.

SUMMARY

Surficial geologic mapping provides the basis for identifying and delineating geologic hazards. The surficial geologic map of the Monroe area (plate 1) shows unconsolidated material consisting of alluvial-fan, basin-fill, colluvial, and artificial-fill deposits. The geologic map also shows spring travertine and volcanic bedrock. Most of the map area is covered by alluvial-fan and basin-fill deposits. Based on geologic mapping, derivative hazard maps were produced at the same scale as the geologic map (1:10,000) and at a smaller scale of 1:24,000. The hazard maps are general and only indicate potential hazards that may be encountered. The hazard maps are intended to inform citizens of their risk and provide a tool for land-use planning and development. The maps may be adopted in city ordinances to show areas where site-specific studies are required prior to development. These site-specific studies, in addition to evaluating the hazards, should include recommendations for hazard reduction.

The mapped geologic hazards include: (1) alluvial-fan flooding and debris flows, (2) problem soil and rock (3) earthquakes and related hazards, and (4) radon gas. The alluvial-fan-flooding and debris-flow hazards are shown on plate 2. Historically, alluvial-fan flooding and debris flows have been the most frequent and damaging geologic hazard in the Monroe area. The Sand H debris basin provides flood and debris-flow protection for part of Monroe, but other areas remain at risk.

The problem soil and rock hazards are shown on plate 3. The main hazard is collapsible soil that consolidates and settles in response to wetting. Settlement attributed to collapsible soils has damaged the Sand H debris-basin embankment and houses in the eastern part of Monroe. Field and laboratory tests confirm that collapsible soils are present and have the potential to damage buildings. The hazard potential is widespread because collapsible soils are present on alluvial fans and cover a large part of the eastern map area. The problem rock hazards are localized in comparison and consist of excavation difficulties in areas of shallow volcanic bedrock, and soluble travertine at Monroe hot springs.

The most widespread and potentially damaging earthquake hazard is earthquake ground shaking. I determined seismic design category is D for all IBC seismic use groups and seismic design category D1 for one- and two-family dwellings. In Monroe, the seismic design category is not affected by site class except for areas with collapsible soils that classify as site class F. Site-specific geotechnical evaluation is required in site class F. Rock fall from volcanic bedrock outcrops is possible during moderate to large earthquakes. A late Quaternary activity class is inferred for the buried Sevier fault, and surface-fault-rupture-hazard studies are recommended for critical facilities within the defined surface-fault-rupture special-study area (plate 4).

Areas of both high and moderate radon-hazard potential are mapped in the study area (plate 4). Radon-resistant construction techniques are recommended in high potential areas and appropriate disclosure is recommended in moderate potential areas where radon-resistant construction can be used at the homeowner's discretion.

In general, I found no evidence for landslide hazards other than rock falls and debris flows, and conditions are not susceptible to earthquake-induced liquefaction. Also, other hazards such as shallow ground water and problem soils such as expansive or compressible soils are not present.

Hazard-reduction methods generally include avoidance or engineering design to reduce risk. The engineering designs may include protection for an individual house or a group of houses. Large hazard-reduction structures like the Sand H debris basin have shown their ability to prevent damage and economic loss from floods and debris flows. Acceptance of a hazard is also an option where a low level of risk is present, although this method does not reduce the hazard.

ACKNOWLEDGMENTS

A Local Government Comprehensive Planning Project grant (contract no. 02-16-99) from the Utah Governor's Office of Planning and Budget obtained by the City of Monroe supported this study. I thank Tom Payne with the Monroe City Planning Commission who recommended the hazard study and Emalee Curtis (Monroe City Recorder) for obtained a grant and coordinated the study. Emalee Curtis and Doug Gadd (Monroe City Public Works Director) were valuable in focusing the collapsible-soils investigation and providing many suggestions. Monroe City provided a backhoe and water truck for the collapsible-soils investigation. Rod Wanless (Monroe City equipment operator) excavated test pits and assisted with collapsible-soils field tests. I thank Monroe homeowners for providing information on collapsible soils and building performance. Victor Parslow and Bob Rasely with the U.S. Natural Resources Conservation Service provided information on unpublished soil mapping and geotechnical investigations at the Sand H debris basin. Dale Deiter and Mike Smith with the Fish Lake National Forest provided aerial photographs and information on soils mapping and historical flooding. Pat Sizemore with the Utah Department of Transportation provided information on collapsible soils along highways. Dr. Kyle Rollins and Dr. Leslie Youd with Brigham Young University provided comments and suggestions on collapsible soils and IBC site class F classification. John Hultquist (Utah Division of Radiation Control) provided indoor-radon test information for the Monroe area. I worked cooperatively with Bill Lund, Barry Solomon, and Greg McDonald of the UGS Geologic Hazards Program to develop geologic hazards write-ups. Gary Christenson (Geologic Hazards Program Manager) provided technical assistance and critically reviewed the text and maps. Victor Parslow, Dale Deiter, and Dave Marble (Utah Division of Water Rights) provided outside peer reviews and constructive comments. Kent Brown, Mike Hylland, Greg McDonald, and Barry Solomon of the UGS also provided valuable review comments.

REFERENCES

Allen, C.R., 1986, Seismological and paleoseismological techniques of research in active tectonics, *in* Active tectonics: Washington, D.C., National Academy Press, p. 148-154.

Ambrasey, N.N., 1960, On the seismic behavior of earth dams: Proceedings of the Second World Conference on Earthquake Engineering, Tokyo and Kyoto, Japan, v. 1, p. 331-358.

—1963, The Buyin-Zara (Iran) fault earthquake of September 1962, a field report: Seismological Society of America Bulletin, v. 53, p. 705-740.

American Society for Testing Materials, 1993, Standard practice for description and identification of soils: American Society for Testing Materials International, Standard D2488-93, p. 75-85.

Anderson, R.E., and Barnhard, T.P., 1992, Neotectonic framework of the central Sevier Valley area, Utah, and its relationship to seismicity, *in* Gori, P.L., and Hays, W.W., editors, Assessment of regional earthquake hazards and risk along the Wasatch Front, Utah: U.S. Geological Survey Professional Paper 1500, p. F1-F47.

Arabasz, W.J., and Julander, D.R., 1986, Geometry of seismically active faults and crustal deformation within the Basin and Range-Colorado Plateau transition in Utah, *in* Mayer, Larry, editor, Extensional tectonics of the southwestern United States-a perspective on process and kinematics: Geological Society of America Special Paper 208, p. 43-74.

Arabasz, W.J., and McKee, M.E., 1979, Utah earthquake catalog 1850 – June 1962, *in* Arabasz, W.J., Smith R.B., and Richins, W.D., editors, Earthquake studies in Utah 1850 – 1978: Salt Lake City, University of Utah Seismograph Stations, Department of Geology and Geophysics, p. 119 – 251.

Arabasz, W.J., Pechmann, J.C., and Brown, E.D., 1992, Observational seismology and the evaluation of earthquake hazards and risk in the Wasatch Front area, Utah, *in* Gori, P.L., and Hays, W.W., editors, Assessment of regional earthquake hazards and risk along the Wasatch Front, Utah: U.S. Geological Survey Professional Paper 1500, p. D1-D36.

Ashland, F.X., and Rollins, Kyle, 1999, Seismic zonation using geotechnical site-response mapping, Salt Lake Valley, Utah: Utah Geological Survey unpublished Final Technical Report for the U.S. Geological Survey, National Earthquake Hazards Reduction Program Award No. 1434-HQ-97-GR-03126, 33 p.

Beverage, J.P., and Culberston, J.K., 1964, Hyperconcentrations of suspended sediment: American Society of Civil Engineers, Journal of the Hydraulics Division, v. 90, no. HY6, p. 117-126.

Black, B.D., Hecker, Suzanne, Hylland, M.D., Christenson, G.E., and McDonald, G.N., 2003, Quaternary fault and fold database and map of Utah: Utah Geological Survey Map 193DM, scale 1:500,000, CD-ROM.

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.

Bolt, B.A., 1999, Earthquakes (4th edition): New York, W.H. Freeman and Company, 366 p.

Bonilla, M.G., 1970, Surface faulting and related effects, *in* Wiegel, R.L., coordinating editor, Earthquake engineering: Englewood Cliffs, New Jersey, Prentice-Hall, Inc., p. 47-74.

Building Seismic Safety Council, 1997, NEHRP recommended provisions for seismic regulations for new buildings and other structures: Washington D.C., Federal Emergency Management Agency Publication 302, Part 1 - Provisions, 337 p.

Bull, W.B., 1964, Alluvial fans and near-surface subsidence in western Fresno County, California: U.S. Geological Survey Professional Paper 437-A, 70 p.

Butler, Elmer, 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.

Chapman, D.S., and Harrison, R., 1978, Monroe, Utah, hydrothermal system - Results from the drilling of test wells MC-1 and MC-2: Salt Lake City, University of Utah, Department of Geology and Geophysics Topical Report, DOE/DGE contract EY-76-S-07-1601, 26 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 hazard and land-use planning in Utah, *in* Lund, W.R., editor, Proceedings Volume, Basin and Range Province Seismic-Hazards Summit: Utah Geological Survey Miscellaneous Publication 98-2, p. 63-73.

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., and Baker, V.R., 1981, Surficial geology—Building with the Earth: New York, John Wiley and Sons, 498 p.

Croft, A.R., 1967, Rainstorm debris floods, a problem in public welfare: University of Arizona, Agricultural Experiment Station, Report 248, 35 p.

Cunningham, C.G., and Steven, T.A., 1979, Geologic map of the Monroe SW quadrangle, west-central Utah: U.S. Geological Survey Miscellaneous Field Studies Map MF-1140, scale 1:24,000.

Cunningham, C.G., Steven, T.A., Rowley, P.D., Glassgold, L.B., and Anderson, J.J., 1983, Geologic map of the Tushar Mountains and adjoining areas, Marysvale volcanic field, Utah: U.S. Geological Survey Miscellaneous Investigations Series Map I-1430-A, scale 1:50,000.

dePolo, C.M., and Slemmons, D.B., 1990, Estimation of earthquake size for seismic hazards, *in* Krinitzsky, E.L., and Slemmons, D.B., editors, Neotectonics in earthquake evaluation: Geological Society of America Reviews in Engineering Geology Volume VIII, p. 1-28.

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

Duke, C.M., 1960, Foundations and earth structures in earthquakes: Proceedings of the Second World Conference on Earthquake Engineering, Tokyo and Kyoto, Japan, v. 1, p. 435-455.

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

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

Federal Emergency Management Agency, 1979a, National Flood Insurance Program flood insurance rate map, town of Monroe, Utah, Sevier County: Federal Emergency Management Agency, Community-Panel Number 490129 001B, scale 1:7,200.

—1979b, National Flood Insurance Program flood insurance rate map, Sevier County, Utah (unincorporated areas): Federal Emergency Management Agency, Community-Panel Number 490121 0016C, scale 1:24,000.

—1987, Reducing losses in high risk flood hazard areas - a guidebook for local officials: Federal Emergency Management Agency Publication 116, 23 p.

—1989a, Answers to questions about the National Flood Insurance Program: Washington, D.C., Federal Emergency Management Agency, 48 p.

—1989b, Alluvial fans - hazards and management: Washington, D.C., Federal Emergency Management Agency, Federal Insurance Administration, Office of Loss Reduction, 13 p.

—1999, Guidelines for determining flood hazards on alluvial fans: Washington, D.C., Federal Emergency Management Agency, 23 p.

Hart, E.W., and Bryant, W.A., 1997, Fault-rupture hazard zones in California – Alquist-Priolo earthquake fault zoning act with index to earthquake fault zone maps: Online, California Division of Mines and Geology, <http://www.consrv.ca.gov/dmg/>, accessed May 22, 2003.

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

Hecker, Suzanne, 1993, Quaternary tectonics of Utah with emphasis on earthquake-hazard characterization: Utah Geological Survey Bulletin 127, 157 p., 2 plates.

Hungr, O., Morgan, G.C., VanDine, D.F., and Lister, D.R., 1987, Debris flow defenses in British Columbia, *in* Costa, J.E., and Wiezorek, G.F., editors, Debris flows/avalanches: Geological Society of America Reviews in Engineering Geology, v. VII, p. 201-222.

International Code Council, 2000a, International Building Code - 2000: Falls Church, Virginia, International Code Council, 756 p.

—2000b, International Residential Code for One- and Two-Family Dwellings - 2000: Falls Church, Virginia, International Code Council, 578 p.

—2002, International Building Code - 2003: Falls Church, Virginia, International Code Council, 656 p.

—2003, International Residential Code for One- and Two-Family Dwellings - 2003: Falls Church, Virginia, International Code Council, 604 p.

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

Johnson, K.S., 1996, Gypsum karst in the United States, *in* Klimchouk, A., Lowe, D., Cooper, A., and Sauro, U., editors, Gypsum karst of the world: International Journal of Speleology, v. 25 (3-4), p. 183-193.

—1997, Evaporite karst in the United States: Carbonates and Evaporites, v. 12, no. 1, p. 2-14.

Kaliser, B.N., 1978, Ground surface subsidence in Cedar City, Utah: Utah Geological and Mineral Survey Report of Investigation 124, 130 p.

Keaton, J.R., and Lowe, Mike, 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, v. XII, p. 97-121.

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

Keetch M.R., compiler, 1971, Sevier River basin floods 1852 – 1967: Salt Lake City, Utah, unpublished report by U.S. Department of Agriculture, Economic Research Service, Forest Service, and Soil Conservation Service, 113 p.

Lambert, P.M., Masson, J.L., and Puchta, R.W., 1995, Hydrology of the Sevier-Sigurd ground-water basin and other ground-water basins, central Sevier Valley, Utah: Utah Department of Natural Resources, Division of Water Rights Technical Publication No. 103, 181 p.

Lawson, A.C., editor, 1908, The California earthquake of April 18, 1906, Report of the state Earthquake Investigation Commission (Volume 1): Carnegie Institution of Washington Publication No. 87, v. 1, 254 p.

Lund, W.R., 1998, Proceedings volume, Basin and Range Province Seismic-Hazards Summit: Utah Geological Survey Miscellaneous Publication 98-2, p. 2.

Mase, C.W., Chapman, D.S., and Ward, S.H., 1978, Geophysical study of the Monroe-Red Hill geothermal system: Salt Lake City, University of Utah, Department of Geology and Geophysics Topical Report, DOE/DGE contract EY-76-S-07-1701, 99 p.

McCalpin, J.P., 1996, Paleoseismology: San Diego, Academic Press, 588 p.

Miller, C.D., 1976, Alteration and geochemistry of the Monroe known geothermal resource area: Salt Lake City, University of Utah, M.S. thesis, 121 p.

Monroe City, 1989, Monroe City Ordinance – Flood Damage Prevention Ordinance: Monroe, Utah, p. 89-99.

—1995, Emergency action plan for Sand H debris basin, Monroe City, Sevier County, Utah: Monroe, Utah, unpublished report by Monroe City, 42 p.

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

National Research Council, 1986, Active tectonics: Washington, D.C., National Academy Press, 266 p.

—1996, Alluvial fan flooding: Washington, D.C., National Academy Press, Committee on Alluvial Fan Flooding, 172 p.

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

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

Richter, C.F., 1938, An instrumental earthquake magnitude scale: Seismological Society of America Bulletin v. 25, p. 1-32.

—1958, Elementary seismology: San Francisco, W.H. Freeman and Co., 768 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.

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

Rollins, K.M., Rollins, R.L., Smith, T.D., and Beckwith, G.H., 1994, Identification and characterization of collapsible gravels: Journal of Geotechnical Engineering, v. 120, no. 3, p. 528-542.

Rollins, K.M., and Williams, Tonya, 1991, Collapsible soil hazard mapping for Cedar City, Utah, *in* McCalpin, J.P., editor, Proceedings of the 27th Symposium on Engineering Geology & Geotechnical Engineering: Pocatello, Idaho State University, p. 31-1 to 31-16.

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

Rowley, P.D., Cunningham, C.G., and Kaplan, A.M., 1981a, Geologic map of the Monroe SE quadrangle, Sevier County, Utah: U.S. Geological Survey Miscellaneous Field Studies Map MF-1331, scale 1:24,000.

Rowley, P.D., Steven, T.A., and Kaplan, A.M., 1981b, Geologic map of the Monroe NE quadrangle, Sevier County, Utah: U.S. Geological Survey Miscellaneous Field Studies Map MF-1330, scale 1:24,000.

Seed, H.B., 1979, Soil liquefaction and cyclic mobility evaluation for level ground during earthquakes: Journal of the Geotechnical Engineering Division, American Society of Civil Engineers, v. 102, p. 201-255.

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

Smith, R.B., and Sbar, M.L., 1974, Contemporary seismicity in the Intermountain seismic belt: Geological Society of America Bulletin, v. 85, p. 1205-1218.

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

Solomon, B.J., 1996, Radon-hazard potential of the central Sevier Valley, Sevier County, Utah: Utah Geological Survey Special Study 89, 37 p.

Solonenko, V.P., 1973, Paleoseismology: Izv. Academy of Science, USSR Physics Solid Earth, v. 9, p. 3-16 (in Russian).

Somerville, P.G., 1998a, Emerging art—earthquake ground motion, *in* Dakoulas, P., Yegian, M., and Holtz, R.D., editors, Geotechnical earthquake engineering and soil dynamics III: American Society of Civil Engineers, Geotechnical Special Publication 75, p. 1-38.

—1998b, The characteristics and quantification of near-fault ground motion, with implications for the Basin and Range Province, *in* Lund, W.R., editor, Proceedings volume, Basin and Range Province Seismic-Hazards Summit: Utah Geological Survey Miscellaneous Publication 98-2, p. 96-109.

Somerville, P.G., Smith, N.F., Graves, R.W., and Abrahamson, N.A., 1997, Modification of empirical strong ground motion attenuation relations to include the amplitude and duration effects of rupture directivity: Seismological Research Letters, v. 68, no. 1, p. 199-222.

Sowers, G.B., and Sowers, G.F., 1970, Introductory soil mechanics and foundations (3rd edition): New York City, The MacMillan Company, 556 p.

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

Steven, T.A., 1979, Geologic map of the Monroe NW quadrangle, west-central Utah: U.S. Geological Survey Miscellaneous Field Studies Map MF-1107, scale 1:24,000.

University of Utah Seismograph Stations, 2002, Personalizing the earthquake threat: Online, <http://www.quake.utah.edu/lqthreat/perseq.shtml>, accessed February and March 2003.

URS Greiner Woodward Clyde, 1999, Geotechnical study for Sand H debris basin dam, Sevier County, Utah: Salt Lake City, Utah, unpublished consultant's report, 10 p.

U.S. Army Corps of Engineers, 1993, Assessment of structural flood-control measures on alluvial fans: Davis, California, U.S. Army Corps of Engineers Hydrologic Engineering Center, 76 p.

—1995, Special flood hazard study, Monroe, Utah: Sacramento, unpublished report for City of Monroe, 5 p.

U.S. Bureau of Reclamation, 1974, Earth manual (2nd edition): Washington, D.C., United States Government Printing Office, 810 p.

—undated, Engineering geology field manual: U.S. Bureau of Reclamation, 599 p.

U.S. Environmental Protection Agency, 1992, Consumer's guide to radon reduction: U.S. Environmental Protection Agency, 402-K92-003, 12 p.

—1994, Model standards and techniques for control of radon in new residential buildings: U.S. Environmental Protection Agency, Office of Air and Radiation, EPA 402-R-94-009, 15 p.

U.S. Forest Service, 1983, Flood damage report - snowmelt runoff event spring 1983: Richfield, Utah, unpublished report by the Fishlake National Forest, 20 p.

—1984, Flood damage assessment report for the 1984 spring floods: Richfield, Utah, unpublished report by the Fishlake National Forest, 5 p.

U.S. Geological Survey, 2000, Implications for earthquake risk reduction in the United States from the Kocaeli, Turkey earthquake of August 17, 1999: U.S. Geological Survey Circular 1193, 64 p.

U.S. Soil Conservation Service, 1971, Flood investigation Annabella-Monroe watershed: Salt Lake City, Utah, unpublished report by Soil Conservation Service, 13 p.

—1976, Geologic report Bertlesen debris basin, Monroe-Annabella watershed, Sevier County, Utah: Portland, Oregon, unpublished report, 8 p., 9 attachments.

—1984, Engineering report – Investigation of longitudinal cracking on Sand H debris basin: Portland, Oregon, unpublished report, 20 p., 9 attachments.

—1986, Supplemental engineering investigation – Investigation of longitudinal cracking on Sand H debris basin: Portland, Oregon, unpublished report, 6 p., 3 appendices, 2 attachments.

—1991, Soil survey of Sevier County, Utah: Richfield, Utah, unpublished mapping, scale 1:24,000.

Utah Division of Comprehensive Emergency Management, 1981, History of Utah floods, 1847-1981: Floodplain Management Status Report, contract number EMW-K-0223, variously paginated.

Utah Division of Water Rights, 2003, Water well logs: Online, <http://www.waterrights.utah.gov/wellinfo/ugs.htm>, accessed February 26, 2003.

Utah Seismic Safety Commission, 1995, A strategic plan for earthquake safety in Utah: Salt Lake City, Utah Seismic Safety Commission, 64 p.

VanDine, D.F., 1996, Debris flow control structures for forest engineering: British Columbia Ministry of Forests Research Program, Working Paper 22, 68 p.

Vlam, Herber, 1987, Review of collapsible soil studies and summary of recommendations, Interstate 70 south Richfield to north Richfield: Salt Lake City, Utah, unpublished Utah Department of Transportation memorandum, 2 p.

Wallace, R.E., 1981, Active faults, paleoseismology, and earthquake hazards in the western United States, *in* Simpson, D.W., and Richards, P.G., editors, Earthquake prediction, an international review: American Geophysical Union Maurice Ewing Series, v. 4, p. 209-216.

Western Regional Climate Center, 2003, Utah climate summaries: Online, <http:// www.wrcc.dri.edu/summary/ climsmut.html>, accessed May 22, 2003.

Western States Seismic Policy Council, 2002, WSSPC policy recommendation 97-1 White Paper: Online, <htpp://www. wsspc.org/publicpolicy/policyrecs/policy971html>.

Willis, G.C., 1988, Geologic map of the Aurora quadrangle, Sevier County, Utah: Utah Geological Survey Map 112, scale 1:24,000, 21 p.

—1994, Interim geologic map of the Richfield quadrangle, Sevier County, Utah: Utah Geological Survey Open-File Report 309, scale 1:24,000, 82 p.

Wilson, Le Moyne, Jennings, D.S., Rikenback, R.G., Gourley, Rex, Neilson, J.E., Frost, R.L., Adair, J.S., and Rabe, F.S., 1958, Soil survey of the Richfield area, Utah: U.S. Soil Conservation Service, in cooperation with Utah Agricultural Experiment Station, series 1944, no. 9, 93 p., 4 sheets, scale 1:31,680.

Wong, I.G., and Silva, W.J., 1993, Site-specific strong ground motion estimates for the Salt Lake Valley, Utah: Utah Geological Survey Miscellaneous Publication 93-9, 34 p.

Wong, I., Silva, W., Olig, S., Thomas, P., Wright, D., Ashland, F., Gregor, N., Pechmann, J., Dober, M., Christenson, G., and Gerth, R., 2002, Earthquake scenario and probabilistic ground shaking maps for the Salt Lake City metropolitan area, Utah: Utah Geological Survey Miscellaneous Publication 02-05, 50 p., 9 plates, scale 1:75,000.

Woolley, R.R., 1946, Cloudburst floods in Utah, 1850-1938: U.S. Geological Survey Water-Supply Paper 994, 128 p.

—1947, Utilization of surface-water resources of Sevier Lake Basin, Utah: U.S. Geological Survey Water-Supply Paper 920, 393 p.

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

Yokel, F.Y., and Tanner, A.B., 1992, Site exploration for radon source potential: Gaithersburg, Maryland, Building and Fire Research Laboratory, National Institute of Standards and Technology, NIS-TIR 5135, 61 p.

GLOSSARY OF GEOLOGIC-HAZARDS TERMS

Active sand dunes - Shifting sand moved by wind. May present a hazard to existing structures (burial) or roadways (burial, poor visibility).

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.

Avalanche - A large mass of snow or ice that moves rapidly down a mountain slope.

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-flow deposits, and loess.

Dam-failure flooding - Flooding downstream from a dam caused by an unintentional release of water due to a partial or complete dam failure.

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 [3 m]deep) slope failure on a steep mountain slope. Debris flows can travel long distances from their source areas, presenting hazards to life and property on downstream alluvial fans.

Earthquake - A sudden motion or trembling in the earth as stored elastic strain energy is released by fracture and movement of rocks along a fault.

Erosion - Removal and transport of soil or rock from a land surface, usually through chemical or mechanical means.

Expansive soil/rock - Soil or rock that swells when wetted and contracts when dried. Associated with high clay content, particularly sodium-rich clay.

Flooding (earthquake) - Flooding caused by seiches, tectonic subsidence, increases in spring discharge or rises in water tables, disruption of streams and canals. See also, Seiche; Tectonic subsidence.

Ground shaking - The shaking or vibration of the ground during an earthquake.

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 [3 m] deep) slope failure on a steep mountain slope. Hyperconcentrated flows can travel long distances from their source areas, presenting hazards to life and property on downstream alluvial fans.

Lake flooding - Shoreline flooding around a lake caused by a rise in lake level.

Landslide - General term referring to any type of slope failure, but usage here refers chiefly to large-scale rotational slumps and slow-moving earth flows.

Liquefaction - Sudden large decrease in shear strength of a saturated, cohesionless soil (generally sand, silt) caused by 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.

Mine subsidence - Subsidence of the ground surface due to the collapse of underground mines.

Non-engineered fill - Soil, rock, or other fill material placed by humans without engineering specification. Such fill may be uncompacted, contain oversized and low-strength or decomposable material, and be subject to differential subsidence, and may have low bearing capacity and poor stability characteristics.

Organic deposits (Peat) - An unconsolidated surface deposit of semicarbonized plant remains in a water-saturated environment such as a bog or swamp. Organic deposits are highly compressible, and have a high water-holding capacity and can oxidize and shrink rapidly when drained.

Piping - Soil or rock subject to subsurface erosion through the development of subsurface tunnels or pipes. Pipes can remove support of overlying soil/rock and collapse.

Problem soils - Geologic materials having characteristics that make them susceptible to volumetric changes, collapse, subsidence, or other engineering-geologic problems.

Radon - A radioactive gas that occurs naturally through the decay of uranium. Radon can be found in high concentrations in soil or rock containing uranium, granite, shale, phosphate, and pitchblende. Exposure to elevated levels of radon can cause an increased risk of lung cancer.

Rock fall - The relatively free falling or precipitous movement of a rock from a slope by rolling, falling, toppling, or bouncing. The rock-fall runout zone is the area below a rock-fall source which is at risk from falling rocks.

Sensitive clay - Clay soil that experiences a particularly large loss of strength when disturbed and is subject to failure during earthquake ground shaking.

Shallow bedrock - Bedrock at depths sufficiently shallow to be encountered in foundation excavations.

Shallow ground water - Ground water within about 30 feet (10 m) of the ground surface. Rising ground-water tables can cause flooding of basements and septic drain fields. Shallow ground water is an aspect of liquefaction.

Slope failure - Downslope movement of soil or rock by falling, toppling, sliding, or flowing.

Soluble soil/rock (karst) - Soil or rock containing minerals that are soluble in water, such as calcium carbonate (principal constituent of limestone), dolomite, and gypsum. Dissolution of minerals and rocks can cause subsidence and formation of sinkholes. See also, Gypsiferous soil.

Stream flooding - Overbank flooding of flood plains along streams; area subject to flooding generally indicated by extent of flood plain or calculated extent of the 100- or 500-year flood.

Stream flow – Clear-water component (generally <20% sediment by volume) of alluvial-fan flooding.

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, 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.

Tectonic subsidence - Subsidence (downdropping) and tilting of a basin floor on the downdropped side of a fault during an earthquake.

APPENDIX A

GEOTECHNICAL SOILS DATABASE

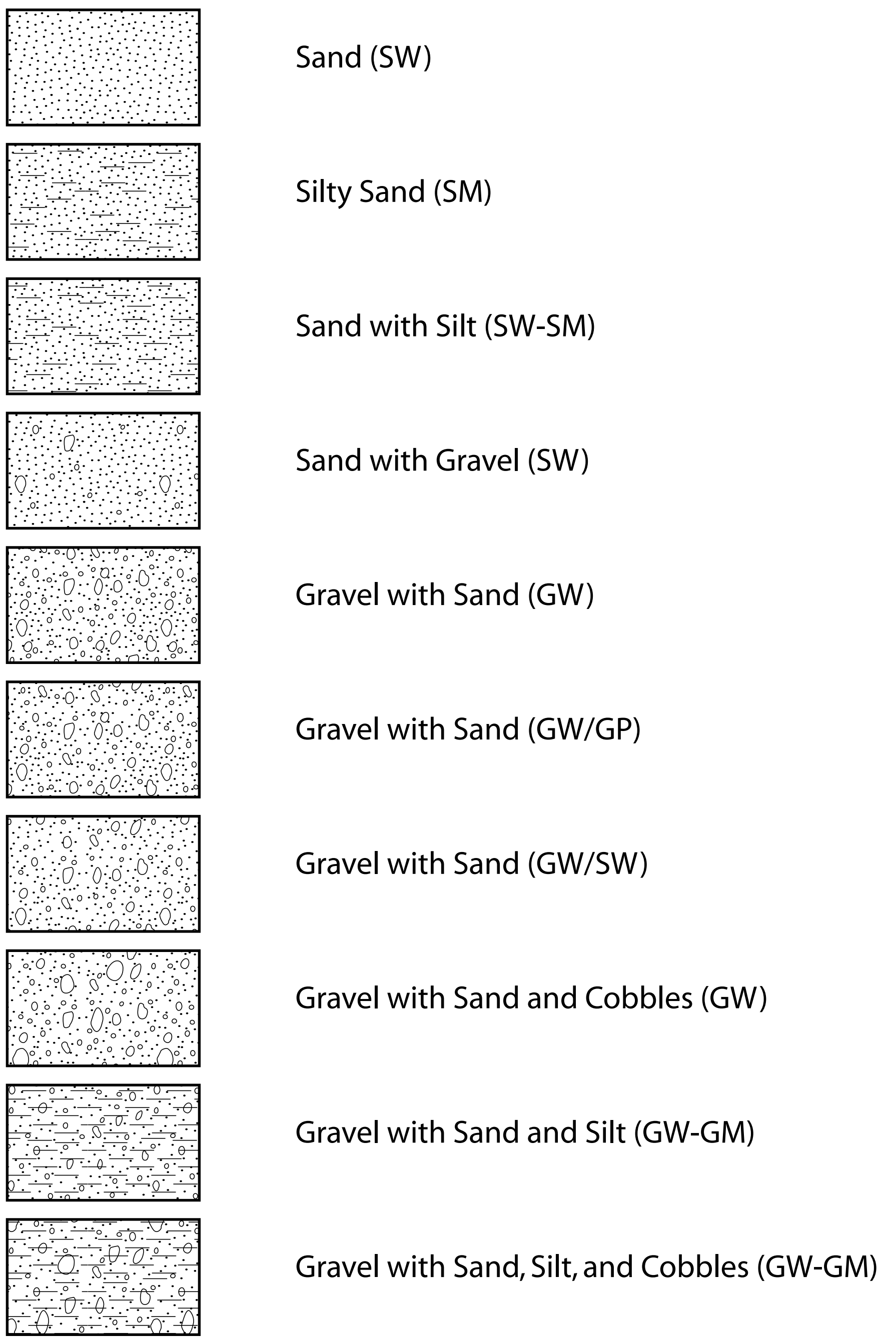
(on CD in pocket)

APPENDIX B

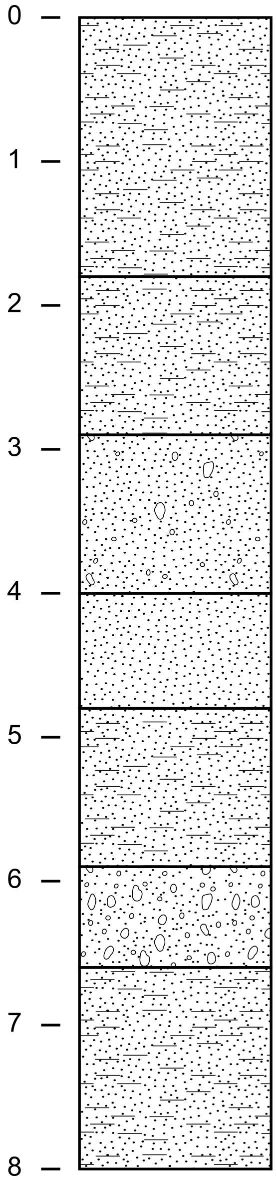
LOGS OF UTAH GEOLOGICAL SURVEY TEST PITS

(refer to plate 3 for test pit locations)

Explanation of Soil Units

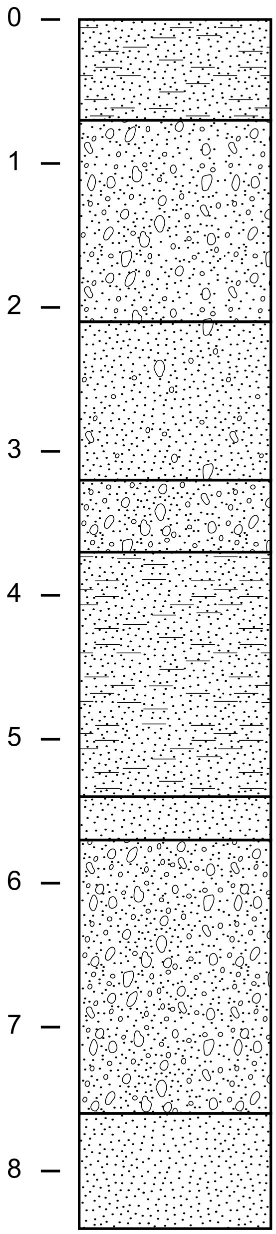


Test Pit HSTP1



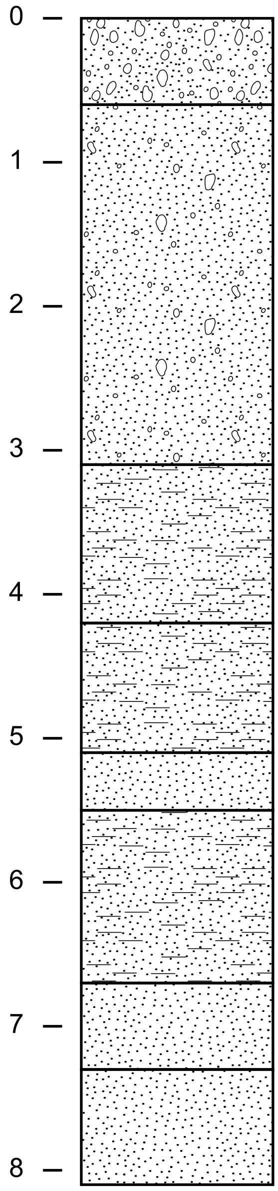
Depth (feet)	Description
0 - 1.8	Silty sand (SM); light brown; loose, nonplastic, dry; 5% gravel, 70% sand, 25% fines, maximum clast size 0.2 feet, angular to subrounded, poorly sorted, pinhole texture, reacts strongly to HCl; roots; graded surface; stream-flow deposit.
1.8 - 2.9	Silty sand (SM); light brown; loose, nonplastic, dry; 5% gravel, 70% sand, 25% fines, maximum clast size 0.2 feet, angular to subrounded, poorly sorted, pinhole texture, reacts strongly to HCl; stream-flow deposit. Soil block for laboratory testing collected from 2.2-2.6 feet depth, see results for HSTP1 in appendix A.
2.9 - 4.0	Sand with gravel (SW); brown; loose, nonplastic, dry; 15% gravel, 85% sand, maximum clast size 0.2 feet, angular to subrounded; poorly to moderately sorted; reacts strongly to HCl; stream-flow deposit.
4.0 - 4.8	Sand (SW); brown; loose, nonplastic, dry; 10% gravel, 90% sand, maximum clast size 0.1 feet, angular to subrounded; reacts strongly to HCl; stream-flow deposit.
4.8 - 5.9	Silty sand (SM); light brown; loose, nonplastic, dry; 5% gravel, 80% sand, 15% fines, maximum clast size 0.3 feet, angular to subrounded, pinhole texture; reacts strongly to HCl; charcoal at lower contact; stream-flow deposit.
5.9 - 6.6	Gravel with sand (GW/SW); brown; loose, nonplastic, dry; 50% gravel, 50% sand, maximum clast size 0.2 feet, angular to subrounded, poorly sorted; reacts strongly to HCl; stream-flow deposit.
6.6 - 8.0	Silty sand (SM); light brown; loose, nonplastic, dry; 10% gravel, 70% sand, 15% fines, maximum clast size 0.1 feet, angular to subrounded, poorly sorted; reacts strongly to HCl; stream-flow deposit.

Test Pit HSTP2



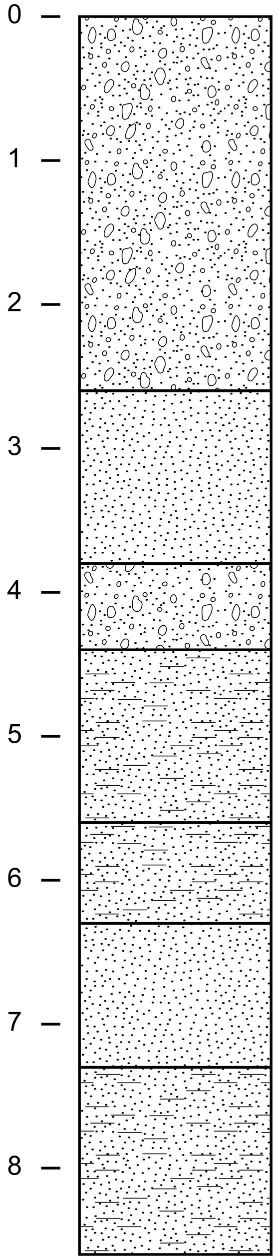
Depth (feet)	Description
0 - 0.7	Silty sand (SM); light brown; low density, nonplastic, dry; 2% gravel, 73% sand, 25% fines, maximum clast size 0.1 feet, angular to subrounded, poorly sorted, pinhole texture; reacts strongly to HCl; roots; graded surface; stream-flow deposit.
0.7 - 2.1	Gravel with sand (GW/SW); light brown; loose, nonplastic, dry; 50% gravel, 50% sand, maximum clast size 0.7 feet, angular to subrounded, poorly sorted; reacts strongly to HCl; stream-flow deposit.
2.1 - 3.2	Sand with gravel (SW); light brown; loose, nonplastic, dry; 15% gravel, 85% sand, maximum clast size 0.7 feet, angular to subrounded, moderately to poorly sorted; reacts strongly to HCl; weak iron oxide staining at upper contact; stream-flow deposit.
3.2 - 3.7	Gravel with sand (GW); light brown; loose, nonplastic, dry; 65% gravel, 35% sand, maximum clast size 0.2 feet, angular to subrounded, poorly sorted, clast supported; reacts strongly to HCl; stream-flow deposit.
3.7 - 5.4	Silty sand (SM); light brown; loose, nonplastic, dry; 80% sand, 20% fines, angular to subrounded, well stratified, pinhole texture; reacts strongly to HCl; stream-flow deposit.
5.4 - 5.7	Sand (SW); light brown; loose, nonplastic, dry; 10% gravel, 90% sand, maximum clast size 0.2 feet, angular to subrounded, moderately to poorly sorted; reacts strongly to HCl; stream-flow deposit.
5.7 - 7.7	Gravel with sand (GW); light brown; loose, nonplastic, dry; 75% gravel, 25% sand, maximum clast size 0.3 feet, angular to subrounded, moderately to poorly sorted, clast supported, large voids between grains; reacts strongly to HCl; stream-flow deposit.
7.7 - 8.4	Sand (SW); light brown; loose, nonplastic, dry; 100% sand, angular to subrounded, moderately to poorly sorted; reacts strongly to HCl; stream-flow deposit.

Test Pit HSTP4



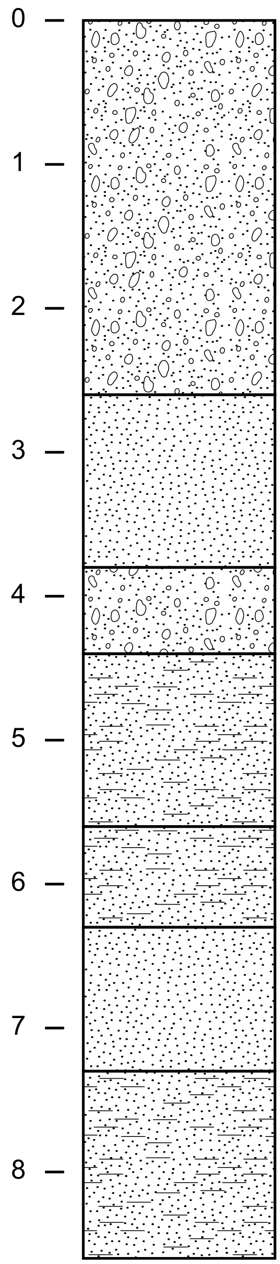
Depth (feet)	Description
0 - 0.6	Gravel with sand (GW/GP); light brown; loose, nonplastic, dry; 60% gravel, 40% sand, angular to subangular, maximum clast size 0.6 feet, poorly to well sorted, clast supported; reacts strongly to HCl; graded surface, calcium carbonate rinds on bottom of gravel clasts, stream-flow deposit.
0.6 - 3.1	Sand with gravel (SW); light brown; loose, nonplastic, dry; 15% gravel, 85% sand, angular to subrounded, maximum clast size 0.3 feet, poorly to moderately sorted, both matrix and clast supported, well bedded with 0.4-foot-thick beds, reacts strongly to HCl, gravel at basal contact; stream-flow deposit.
0.6 - 4.2	Silty sand (SM); light brown; loose, nonplastic, dry; 10% gravel, 75% sand, 15% fines, angular to subangular, maximum clast size 0.3 feet, moderately to well sorted, internally stratified, reacts strongly to HCl, charcoal sample collected at 4 foot depth; gravel at basal contact; stream-flow deposit. Soil blocks for laboratory testing collected from 3.4-3.8 and 3.6 - 4.0 feet depth, see results for HSTP4 in appendix A.
4.2 - 5.1	Silty sand (SM); light brown; loose, nonplastic, dry; 10% gravel, 75% sand, 15% fines, angular to subangular, maximum clast size 0.3 feet, moderately to well sorted, internally stratified, reacts strongly to HCl; stream-flow deposit.
5.1 - 5.5	Sand (SW); light brown; loose, nonplastic, dry; 95% sand, 5% fines, angular to subrounded, poorly to moderately sorted; reacts strongly to HCl; stream-flow deposit.
5.5 - 6.7	Silty sand (SM); light brown; loose, nonplastic, dry; 80% sand, 20% fines, angular to subrounded, poorly to moderately sorted, pinhole texture; reacts strongly to HCl; stream-flow deposit.
6.7 - 7.3	Sand (SW); light brown; loose, nonplastic, dry; 10% gravel, 85% sand, 5% fines, angular to subrounded, poorly to moderately sorted; reacts strongly to HCl; stream-flow deposit.
7.3 - 8.1	Sand (SW); light brown; loose, nonplastic, dry; 95% sand, 5% fines, angular to subrounded, poorly to moderately sorted; reacts strongly to HCl; stream-flow deposit.

Test Pit HSTP5



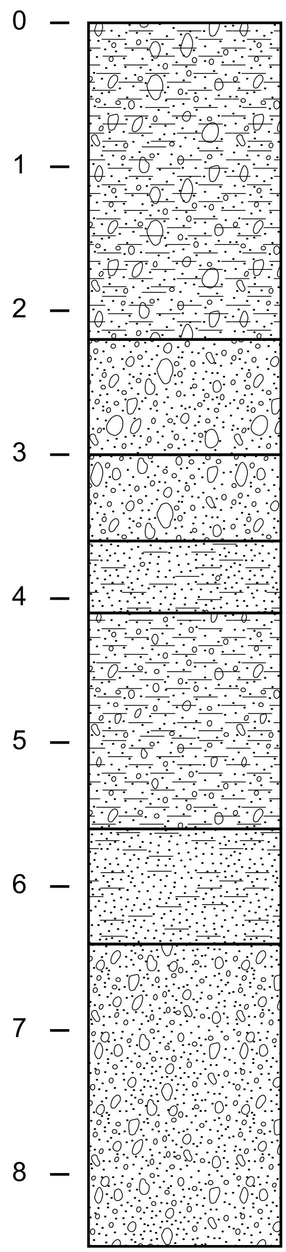
Depth (feet)	Description
0 - 2.6	Gravel with sand (GW/SW); light brown; loose, nonplastic, dry; 50% gravel, 50% sand, maximum clast size 0.7 feet, angular to subangular, poorly sorted, clast supported; reacts strongly to HCl, graded surface; basal cobble lag; stream-flow deposits with discrete gravel lenses up to 0.1 foot thick.
2.6 - 3.8	Sand (SW); light brown; loose, nonplastic, dry; 95% sand, 5% fines, angular to subangular, poorly to moderately sorted; reacts strongly to HCl; stream-flow deposit.
3.8 - 4.4	Gravel with sand (GW/SW); light brown; loose, nonplastic, dry; 50% gravel, 50% sand, maximum clast size 0.3 feet, angular to subangular, poorly sorted, clast supported; reacts strongly to HCl, graded surface; basal gravel bed; stream-flow deposit; hyperconcentrated-flow deposit.
4.4 - 5.6	Silty sand (SM); light brown; low density, nonplastic, dry; 85% sand, 15% fines, angular to subangular, poorly to moderately sorted, pinhole texture; reacts strongly to HCl; hyperconcentrated-flow deposit.
5.6 - 6.3	Silty sand (SM); light brown; low density, nonplastic, dry; 85% sand, 15% fines, angular to subangular, poorly to moderately sorted, prominent pinhole texture 5.1 to 6.1 foot depth; reacts strongly to HCl; hyperconcentrated-flow deposit.
6.3 - 7.3	Sand (SW); light brown; loose, nonplastic, dry; gravel 5%, 90% sand, 5% fines, angular to subangular, poorly to moderately sorted; reacts strongly to HCl; stream-flow deposit.
7.3 - 8.6	Silty sand (SM); light brown; loose, nonplastic, dry; 85% sand, 15% fines, angular to subangular, poorly to moderately sorted; reacts strongly to HCl; stream-flow deposit.

Test Pit HSTP5



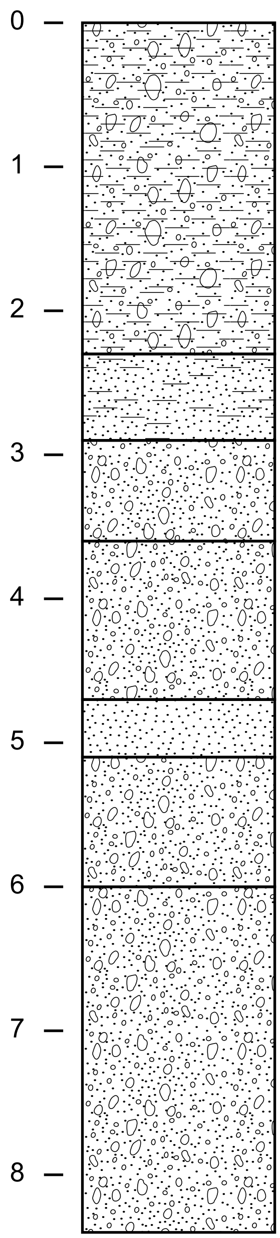
Depth (feet)	Description
0 - 2.6	Gravel with sand (GW/SW); light brown; loose, nonplastic, dry; 50% gravel, 50% sand, maximum clast size 0.7 feet, angular to subangular, poorly sorted, clast supported; reacts strongly to HCl, graded surface; basal cobble lag; stream-flow deposits with discrete gravel lenses up to 0.1 foot thick.
2.6 - 3.8	Sand (SW); light brown; loose, nonplastic, dry; 95% sand, 5% fines, angular to subangular, poorly to moderately sorted; reacts strongly to HCl; stream-flow deposit.
3.8 - 4.4	Gravel with sand (GW/SW); light brown; loose, nonplastic, dry; 50% gravel, 50% sand, maximum clast size 0.3 feet, angular to subangular, poorly sorted, clast supported; reacts strongly to HCl, graded surface; basal gravel bed; stream-flow deposit; hyperconcentrated-flow deposit.
4.4 - 5.6	Silty sand (SM); light brown; low density, nonplastic, dry; 85% sand, 15% fines, angular to subangular, poorly to moderately sorted, pinhole texture; reacts strongly to HCl; hyperconcentrated-flow deposit.
5.6 - 6.3	Silty sand (SM); light brown; low density, nonplastic, dry; 85% sand, 15% fines, angular to subangular, poorly to moderately sorted, prominent pinhole texture 5.1 to 6.1 foot depth; reacts strongly to HCl; hyperconcentrated-flow deposit.
6.3 - 7.3	Sand (SW); light brown; loose, nonplastic, dry; gravel 5%, 90% sand, 5% fines, angular to subangular, poorly to moderately sorted; reacts strongly to HCl; stream-flow deposit.
7.3 - 8.6	Silty sand (SM); light brown; loose, nonplastic, dry; 85% sand, 15% fines, angular to subangular, poorly to moderately sorted; reacts strongly to HCl; stream-flow deposit.

Test Pit CTP1



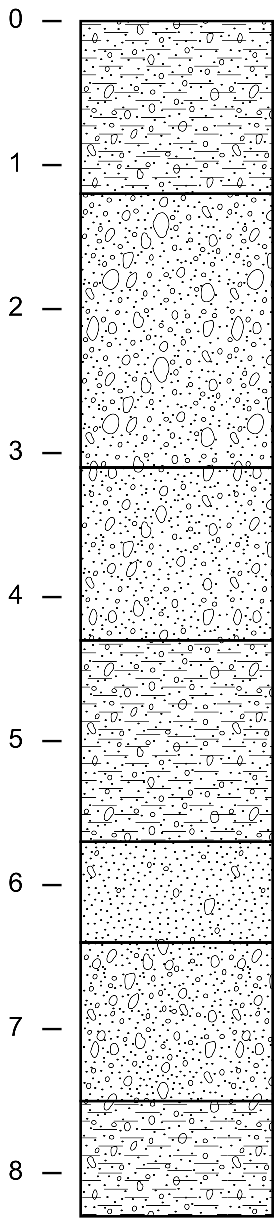
Depth (feet)	Description
0 - 2.2	Gravel with sand, silt and cobbles (GW-GM); brown; low density, slightly plastic, dry; 30% cobbles, 30% gravel, 20% sand, 20% fines, maximum clast size 1.0 feet, angular to subangular, poorly sorted, matrix supported, pinhole texture; reacts strongly to HCl; undisturbed alluvial fan surface; thin calcium carbonate rinds on the base of cobbles and gravel; debris-flow deposit.
2.2 - 3.0	Gravel with sand and cobbles (GW); brown; low density, nonplastic, dry; 20% cobbles, 50% gravel, 30% sand, maximum clast size 0.7 feet, angular to subangular, poorly sorted, clast supported; reacts strongly to HCl; thin calcium carbonate rinds on the base of cobbles and gravel; hyperconcentrated-flow deposit.
3.0 - 3.6	Gravel with sand and cobbles (GW); brown; low density, nonplastic, dry; 30% cobbles, 50% gravel, 20% sand, maximum clast size 0.5 feet, angular to subrounded, poorly sorted, clast supported; reacts strongly to HCl; thin calcium carbonate rinds on the base of cobbles and gravel; hyperconcentrated-flow deposit.
3.6 - 4.1	Sand with silt (SW-SM); brown; loose, nonplastic, dry; 90% sand, 10% fines, angular to subangular, poorly to moderately sorted; reacts strongly to HCl; laterally discontinuous; stream-flow deposit.
4.1 - 5.6	Silty gravel with sand (GM); brown; low density, nonplastic, dry; 60% gravel, 25% sand, 15 % fines, maximum clast size 0.3 feet, angular to subangular, poorly sorted, both clast and matrix supported; reacts strongly to HCl; debris-flow deposit.
5.6 - 6.4	Silty sand (SM); brown; low density, nonplastic, dry; 10% gravel, 70% sand, 20% fines, angular to subangular, poorly sorted, pinhole texture, both clast and matrix supported; reacts strongly to HCl; hyperconcentrated-flow deposit.
6.4 - 8.5	Gravel with sand (GW); brown; low density, nonplastic, dry; 65% gravel, 35% sand, maximum clast size 0.3 feet, angular to subrounded, poorly sorted, both clast and matrix supported; reacts strongly to HCl; debris-flow deposit.

Test Pit CTP2



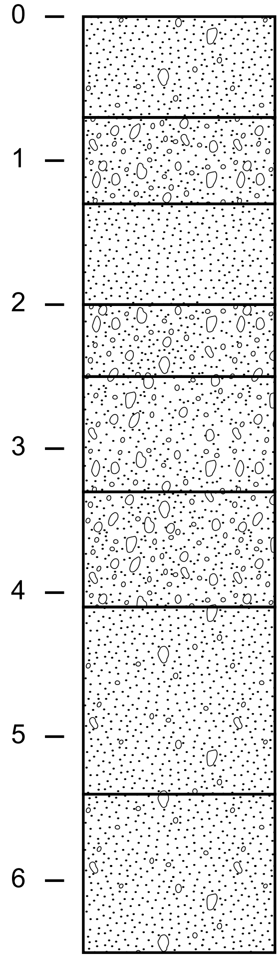
Depth (feet)	Description
0 - 2.3	Gravel with sand, silt, and cobbles (GW-GM); brown; low density, slightly plastic, dry; 10% cobbles, 40% gravel, 30% sand, 20% fines, maximum clast size 0.7 feet, angular to subrounded, poorly sorted, matrix supported, pinhole texture; reacts strongly to HCl; undisturbed alluvial-fan surface; thin calcium carbonate rinds on the base of cobbles and gravel; debris-flow deposit.
2.3 - 2.9	Silty sand (SM); brown; low density, nonplastic, dry; 5% gravel, 65% sand, 30% fines, angular to subangular, poorly to moderately sorted, pinhole texture; reacts strongly to HCl; stream-flow deposit.
2.9 - 3.6	Gravel with sand (GW); brown; low density, nonplastic, dry; 70% gravel, 30% sand, maximum clast size 0.1 feet, angular to subrounded, poorly sorted, clast supported, pinhole texture; reacts strongly to HCl; stream-flow deposit.
3.6 - 4.7	Gravel with sand (GW); brown; low density, nonplastic, dry; 70% gravel, 30% sand, maximum clast size 0.1 feet, angular to subrounded, poorly sorted, clast supported, pinhole texture; reacts strongly to HCl; stream-flow deposit.
4.7 - 5.1	Sand (SW); brown; loose, low density, nonplastic, dry; 10% gravel, 90% sand, angular to subangular, poorly sorted; reacts strongly to HCl; stream-flow deposit.
5.1 - 6.0	Gravel with sand (GW); brown; low density, nonplastic, dry; 60% gravel, 40% sand, maximum clast size 0.1 feet, angular to subrounded, poorly sorted, both matrix and clast supported; reacts strongly to HCl; debris-flow deposit.
6.0 - 8.4	Gravel with sand (GW); brown; low density, nonplastic, dry; 70% gravel, 30% sand, maximum clast size 0.1 feet, angular to subrounded, poorly sorted, both matrix and clast supported; reacts strongly to HCl; debris-flow deposit.

Test Pit CTP3



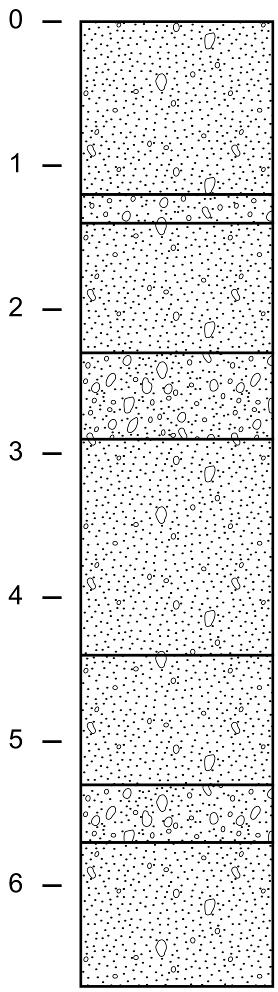
Depth (feet)	Description
0 - 1.2	Gravel with sand and silt (GW-GM); brown; low density, slightly plastic, dry; 50% gravel, 30% sand, 20% fines, maximum clast size 0.6 feet, angular to subrounded, poorly sorted, matrix supported, pinhole texture; reacts strongly to HCl; undisturbed alluvial fan surface; debris-flow deposit.
1.2 - 3.1	Gravel with sand and cobbles (GW); brown; low density, dry; 30% cobbles, 40% gravel, 30% sand, maximum clast size 0.7 feet, angular to subrounded, poorly sorted, clast supported, pinhole texture; reacts strongly to HCl; hyperconcentrated-flow deposit.
3.1 - 4.3	Gravel with sand (GW/SW); brown; loose, nonplastic, dry; 50% gravel, 50% sand, maximum clast size 0.2 feet, angular to subangular, poorly sorted, well stratified; reacts strongly to HCl; stream-flow deposit.
4.3 - 5.7	Gravel with sand and silt (GW-GC); brown; low density, dry; 60% gravel, 30% sand, 10% fines, maximum clast size 0.6 feet, angular to subrounded, poorly sorted, matrix supported; reacts strongly to HCl; debris-flow deposit.
5.7 - 6.4	Sand with gravel (SW); brown; loose, nonplastic, dry; 40% gravel, 60% sand, maximum clast size 0.1 feet, angular to subangular, poorly sorted; reacts strongly to HCl; stream-flow deposit.
6.4 - 7.5	Gravel with sand (GW); brown; loose, nonplastic, dry; 75% gravel, 25% sand, maximum clast size 0.2 feet, angular to subangular, poorly sorted, clast supported; reacts strongly to HCl; stream-flow deposit.
7.5 - 8.3	Gravel with sand and silt (GW-GM); brown; low density, nonplastic, dry; 65% gravel, 25% sand, 10% fines, maximum clast size 0.2 feet, angular to subangular, poorly sorted, matrix supported; reacts strongly to HCl; debris-flow deposit.

Test Pit PTP1



Depth (feet)	Description
0 - 0.7	Sand with gravel (SW); reddish brown; loose, nonplastic, dry; 15% gravel, 85% sand, maximum clast size 0.2 feet, angular to subrounded, poorly sorted; reacts strongly to HCl; roots; plowed surface, former cultivated field; stream-flow deposit.
0.7 - 1.3	Gravel with sand (GW); reddish brown; loose, nonplastic, dry; 60% gravel, 40% sand, maximum clast size 0.1 feet, angular to subangular, poorly sorted, matrix supported; reacts strongly to HCl; debris-flow deposit.
1.3 - 2.0	Sand (SW); reddish brown; loose, nonplastic, dry; 10% gravel, 90% sand, angular to subrounded, poorly sorted; reacts strongly to HCl; stream-flow deposit.
2.0 - 2.5	Gravel with sand (GW); reddish brown; loose, nonplastic, dry; 70% gravel, 30% sand, maximum clast size 0.4 feet, angular to subangular, poorly sorted; reacts strongly to HCl; hyperconcentrated-flow deposit.
2.5 - 3.3	Gravel with sand (GW/SW); reddish brown; loose, nonplastic, dry; 50% gravel, 50% sand, maximum clast size 0.1 feet, angular to subangular, poorly sorted; reacts strongly to HCl; debris-flow deposit.
3.3 - 4.1	Gravel with sand (GW); reddish brown; loose, nonplastic, dry; 60% gravel, 40% sand, maximum clast size 0.1 feet, angular to subangular, poorly sorted; reacts strongly to HCl; hyperconcentrated-flow deposit.
4.1 - 5.4	Sand with gravel (SW); reddish brown; loose, nonplastic, dry; 30% gravel, 70% sand, angular to subrounded, poorly sorted; reacts strongly to HCl; hyperconcentrated-flow deposit.
5.4 - 6.5	Sand with gravel (SW); reddish brown; loose, nonplastic, dry; 20% gravel, 80% sand, angular to subrounded, poorly sorted; reacts strongly to HCl; stream-flow deposit.

Test Pit PTP2



Depth (feet)	Description
0 - 1.2	Sand with gravel (SW); reddish brown; loose, nonplastic, dry; 15% gravel, 85% sand, maximum clast size 0.2 feet, angular to subrounded, poorly sorted; reacts strongly to HCl; roots; plowed surface, former cultivated field; stream-flow deposit.
1.2 - 1.4	Gravel with sand (GW/SW); reddish brown; loose, nonplastic, dry; 50% gravel, 50% sand, maximum clast size 0.2 feet, angular to subangular, poorly sorted, clast supported; reacts strongly to HCl; debris-flow deposit.
1.4 - 2.3	Sand with gravel (SW); reddish brown; loose, nonplastic, dry; 30% gravel, 70% sand, angular to subrounded, poorly sorted, massive; reacts strongly to HCl; stream-flow deposit.
2.3 - 2.9	Gravel with sand (GW); reddish brown; loose, nonplastic, dry; 60% gravel, 40% sand, maximum clast size 0.2 feet, angular to subangular, poorly sorted, clast supported; reacts strongly to HCl; hyperconcentrated-flow deposit.
2.9 - 4.4	Sand with gravel (SW); reddish brown; loose, nonplastic, dry; 40% gravel, 60% sand, maximum clast size 0.3 feet, angular to subangular, poorly sorted, matrix supported; reacts strongly to HCl; debris-flow deposit.
4.4 - 5.3	Sand with gravel (SW); reddish brown; loose, nonplastic, dry; 20% gravel, 80% sand, maximum clast size 0.1 feet, angular to subangular, poorly sorted, matrix supported; reacts strongly to HCl; hyperconcentrated-flow deposit.
5.3 - 5.7	Gravel with sand (GW); reddish brown; loose, nonplastic, dry; 60% gravel, 40% sand, maximum clast size 0.2 feet, angular to subangular, poorly sorted, clast supported; reacts strongly to HCl; hyperconcentrated-flow deposit.
5.7 - 6.7	Sand with gravel (SW); reddish brown; loose, nonplastic, dry; 30% gravel, 70% sand, maximum clast size 0.4 feet (platy), angular to subangular, poorly sorted, matrix supported; reacts strongly to HCl; stream-flow deposit.

APPENDIX C

AGENCIES PROVIDING INFORMATION ON GEOLOGIC HAZARDS AND RELATED ISSUES

LOCAL

Monroe City
10 North Main Street
Monroe, Utah 84754
(435) 527-4621

Information on planning, zoning, and community development issues.

Sevier County Building Inspector
250 North Main Street
Richfield, Utah 84701
(435) 893-0420
sevierutah.net

Information on current county development and building regulations.

STATE

Utah Department of Health
Central Utah Public Health Department
70 Westview Drive
Richfield, Utah 84701
(435) 637-3671
centralutahhealth.com

Information on current Health Department regulations concerning wastewater disposal and systems.

Utah Division of Emergency Services and Homeland Security
Rm. 1110, State Office Bldg.
Salt Lake City, Utah 84114
(801) 538-3400
des.utah.gov

Information concerning emergency response, preparedness, and mitigation. Source of information on FEMA National Flood Insurance Program.

Utah Division of Radiation Control
168 North 1950 West
Building #2, Room 212
P.O. Box 144850
Salt Lake City, Utah 84114-4850
(801) 536-4250
deq.state.ut.us/EQRAD/drc_hmpg.htm

Information on indoor-radon testing and mitigation.

Utah Division of Water Rights
1594 W. North Temple Suite 220
P.O. Box 146300
Salt Lake City, Utah 84114-6300
(801) 538-7240
waterrights.utah.gov

Regulations concerning appropriation and distribution of water in the state of Utah. Technical publications concerning local and regional water resources. Publications contain information on water source, amount, and quality in Utah.

Utah Geological Survey
1594 W. North Temple, Suite 3110
P.O. Box 146100
Salt Lake City, Utah 84114-6100
(801) 537-3300
geology.utah.gov

Geologic information concerning geologic hazards, ground water, geologic mapping, fossils, and economic geology. Geologic Hazards Program conducts local and regional geologic-hazards studies. Topographic and geologic maps, and publications on geologic hazards and other geology topics available through the Natural Resources Map and Bookstore; (801) 537-3320, 1-888-UTAH MAP, mapstore.utah.gov.

FEDERAL

U.S. Bureau of Land Management
150 East 900 North
Richfield, Utah 84701
(435) 896-1500
ut.blm.gov/richfield/index.html

Ownership and management of federal lands; knowledge of geology, water resources, and vegetation on lands under their jurisdiction.

U.S. Forest Service
Fishlake National Forest
115 East 900 North
Richfield, Utah 84701
(435) 896-9233
fs.fed.us/r4/fishlake/

Ownership and management of federal lands; knowledge of geology, water resources, and vegetation on lands under their jurisdiction.

U.S. Geological Survey
Salt Lake Information Office
2329 W. Orton Circle
West Valley City, Utah 84119
(801) 908-5000
usgs.gov
ut.water.usgs.gov

General geologic information, data on surface and ground water, and USGS publications available.

U.S. Natural Resources Conservation Service (formerly Soil Conservation Service)
Richfield Service Center
340 North 600 East
Richfield, Utah 84701
(435) 896-6441
nrcs.usda.gov

Regional and local soil surveys. Surveys contain information on soil type, description, engineering properties, and agricultural uses.

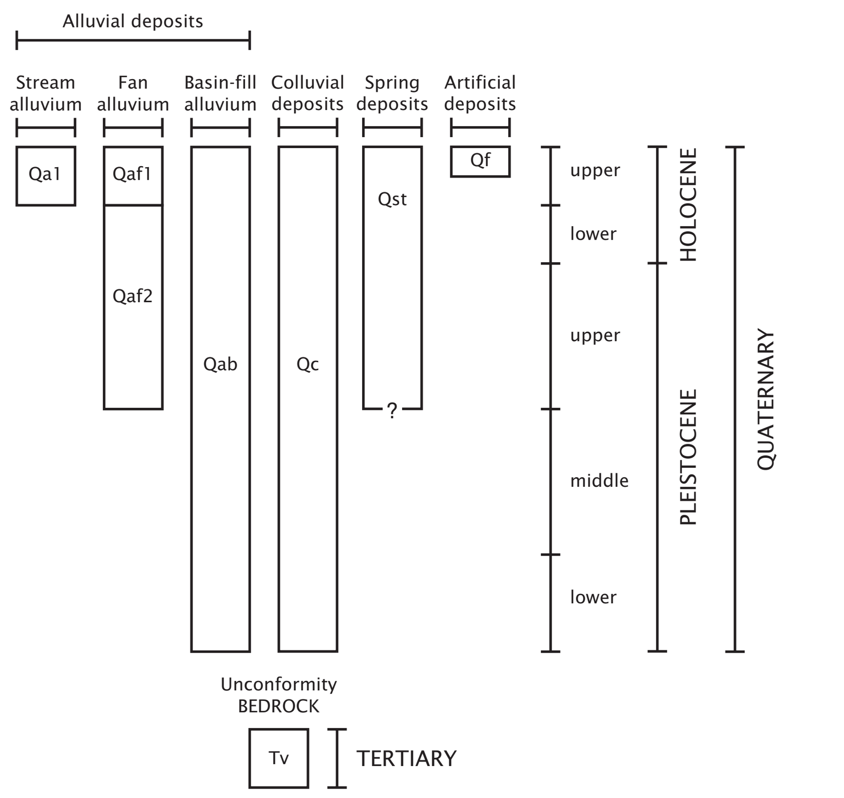
PLATE 1. SURFICIAL GEOLOGIC MAP OF THE MONROE AREA

By

Richard E. Giraud

2004

CORRELATION OF MAP UNITS



DESCRIPTION OF MAP UNITS

(Report text contains detailed descriptions)

ALLUVIAL DEPOSITS

STREAM ALLUVIUM

Qal — Stream alluvium (Upper Holocene)

FAN ALLUVIUM

Qaf_1 — Fan alluvium, unit 1 (Upper Holocene)

Qaf_2 — Fan alluvium, unit 2 (Lower Holocene to upper Pleistocene)

BASIN-FILL ALLUVIUM

Qab — Basin-fill alluvium (Holocene and Pleistocene)

COLLUVIAL DEPOSITS

Qc — Hillslope colluvium (Holocene and Pleistocene)

SPRING DEPOSITS

Qst — Spring travertine (Holocene to upper(?) Pleistocene)

ARTIFICIAL-FILL DEPOSITS

Qf — Artificial fill (historical)

BEDROCK

Tv — Tertiary volcanic rocks (Miocene and Oligocene)

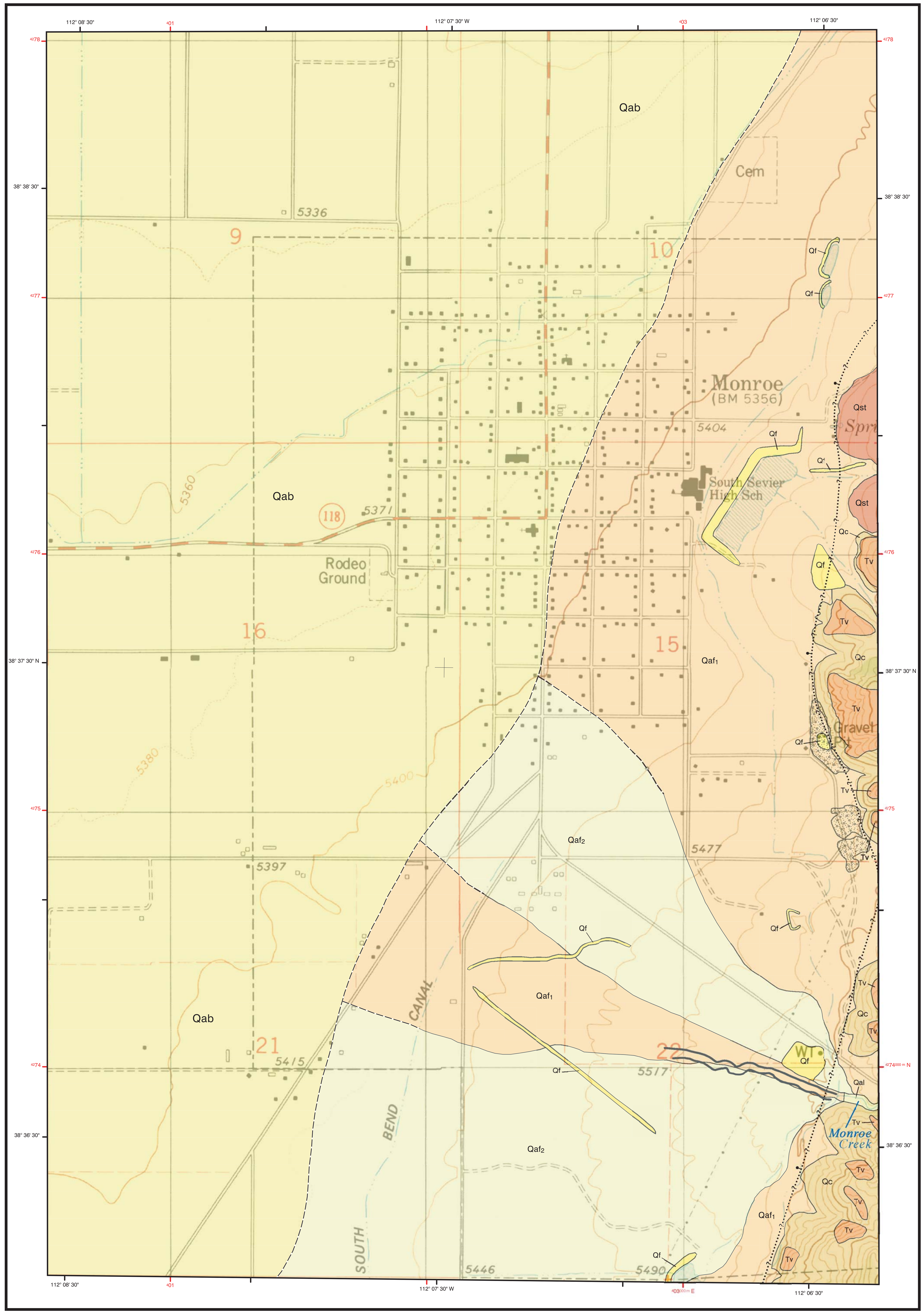
MAP SYMBOLS

Contact - dashed where approximately located

Normal fault - buried; location uncertain, bar and ball on downthrown side

Flood-control dike

Gravel pit outline (1995)



SCALE 1:10,000

0 — 1/4 — 1/2 — 1 MILE

0 500 1000 1500 2000 2500 3000 3500 4000 4500 5000 FEET

0 100 200 300 400 500 600 700 800 900 1000 METERS

CONTOUR INTERVAL 40 FEET

DOTTED SUPPLEMENTARY CONTOUR INTERVAL 20 FEET

Base map from U.S. Geological Survey 1:24,000 scale Annabella, Monroe Peak, Antelope Range, and Elsinore quadrangles Maps edited 1980

Projection and 1000-meter grid ticks: Universal Transverse Mercator, zone 12 North American Datum 1927

UTAH

MAP LOCATION

0°42' 14½°

1980 MAGNETIC DECLINATION [AT CENTER OF SHEET]

UTAH GEOLOGICAL SURVEY

UTAH GEOLOGICAL SURVEY
a division of
Department of Natural Resources

SPECIAL STUDY 110

PLATE 2. ALLUVIAL-FAN FLOODING AND DEBRIS-FLOW HAZARDS IN THE MONROE AREA

By

Richard E. Giraud

2004

FEDERAL EMERGENCY MANAGEMENT AGENCY (FEMA) FLOOD INSURANCE RATE MAP ZONES

Zone A - Flood insurance required under FEMA National Flood Insurance Program (boundaries approximate)

Zone C - Flood insurance available, but optional

MAP SYMBOLS

Flood-control dike

Debris basin embankment

Gravel pit outline (1995)

EXPLANATION

Map Category	Geologic Unit	Description	Alluvial-Fan-Flooding Type	Flood Insurance	Recommended Site-Specific Studies for New Development
MCFP	Qal	Monroe Creek stream channel and flood plain	Stream flow	Required in Zone A	Stream-flow-flooding study
MCAF$_1$	Qaf$_1$	Active part of the Monroe Creek alluvial fan	Stream flow	Required in Zone A; Optional inZone C	Stream-flow-flooding study (assess adequacy of flood-control dikes and ditch)
MCAF$_2$	Qaf$_2$	Potential flooding outside the active part of the Monroe Creek alluvial fan	Stream flow	Required in Zone A; Optional in Zone C	Stream-flow-flooding study (assess adequacy of flood-control dikes)
AF	Qaf$_1$	Active alluvial fans	Stream flow and debris flow	Required in Zone A; Optional in Zone C	Stream-flow-flooding and debris-flow studies
AFSH	Qaf$_1$	Active fan area protected by Sand H debris basin and associated dikes	Stream-flow and debris-flow risk reduced by Sand H debris basin	Optional in Zone C	None
AB	Qab	Alluvial basin fill	Stream flow	Required in Zone A; Optional in Zone C	None (assess adequacy of flood-control ditch on Monroe Creek)
HS	Qc Tv	Moderate to steep slopes in upland areas	Stream flow	Required in Zone A; Optional in Zone C	None (except for construction in drainage bottoms)

DISCUSSION

Alluvial-fan flooding consists of a continuum of flow types, from stream flows to debris flows, based on the proportion of sediment to water. Stream flows and debris flows are often related and can result from the same precipitation event. Alluvial-fan-flooding and debris-flow hazards are the most frequent and destructive geologic hazards affecting Monroe, and are caused by rapid snowmelt, prolonged rainfall, and intense thunderstorm rainfall (flash flooding). Damaging effects from flooding include ground saturation, erosion, deposition of sediment, and the force of the water itself, which can damage property and take lives. Alluvial-fan flooding generally begins at the highest point on the alluvial fan where flow is last confined and then spreads out as a sheet flood or debris slurry of varying sediment concentration in multiple channels along uncertain flow paths. Debris flows pose an additional hazard due to their high sediment concentration and destructive power. Debris flows can exert large impact pressures due to their density, flow thickness, and velocity. In addition to physical impact, debris flows can cause damage to buildings and infrastructure by sediment burial, erosion, and associated water flooding. Debris flows are capable of destroying buildings, roads, and bridges lying in their path and depositing thick layers of mud and rock on the alluvial fan. Alluvial-fan floods and debris flows are life-threatening because they occur with little warning and move rapidly, leaving little time for evacuation and emergency actions to protect property. Alluvial-fan floods and debris flows have great flow-path uncertainty on the active alluvial fan.

USING THIS MAP

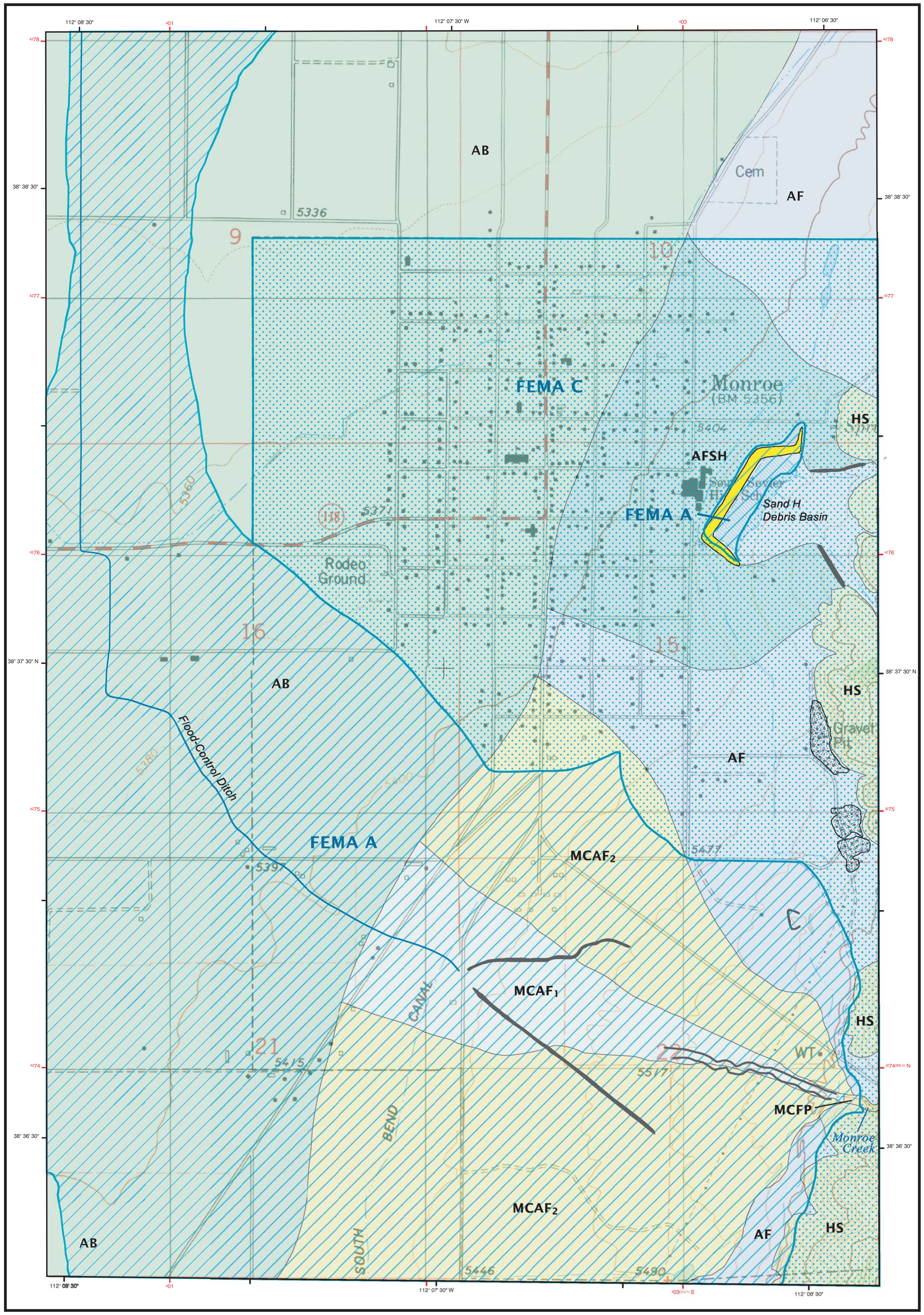
This map shows areas where site-specific studies concerning alluvial-fan flooding and debris flows are recommended prior to development. In these areas, site-specific studies are needed to evaluate hazards and, if necessary, recommend hazard-reduction measures. The studies must be prepared by qualified professionals (engineering geologists, geotechnical engineers, hydrologists) and signed by a licensed Professional Geologist or Engineer, as appropriate.

The Federal Emergency Management Agency Flood Insurance Rate Maps show Monroe Creek, the Monroe Creek alluvial fan, basin-fill areas downslope of the alluvial fan, and the area behind the Sand H debris basin as zone A, an area of 100-year flooding where flood insurance is required. Within zone A, both Appendix G of the *International Building Code* and Chapter 3, "Flood Damage Prevention," in the Monroe City Ordinance outline subdivision, flood-resistant construction, and permit information requirements.

UTAH GEOLOGICAL SURVEY

UTAH GEOLOGICAL SURVEY
a division of
Department of Natural Resources

SPECIAL STUDY 110



SCALE 1:10,000

0 1/4 1/2 1 MILE

0 500 1000 1500 2000 2500 3000 3500 4000 4500 5000 FEET

0 100 200 300 400 500 600 700 800 900 1000 METERS

CONTOUR INTERVAL 40 FEET
DOTTED SUPPLEMENTARY CONTOUR INTERVAL 20 FEET

Base map from U.S. Geological Survey 1:24,000 scale Annabella, Monroe Peak, Antelope Range, and Elsinore quadrangles Maps edited 1980

Projection and 1000-meter grid ticks: Universal Transverse Mercator, zone 12 North American Datum 1927

UTAH

MAP LOCATION

0°42'
14½°

1980 MAGNETIC DECLINATION
[AT CENTER OF SHEET]

PLATE 3. PROBLEM SOIL AND ROCK HAZARDS IN THE MONROE AREA

By

Richard E. Giraud

2004

MAP SYMBOLS

- (yellow dot) M-5-CTP1 — Test pit excavated by UGS for this study
- (green dot) M-3-TP1 — Test pit excavated in earlier study

All test-pit soil descriptions and other field and laboratory data are compiled in appendix A (included as Microsoft Excel spreadsheet on diskette). Logs of UGS test pits excavated for this study are included in appendix B.

EXPLANATION

Map Category	Geologic Unit(s)	Description	Hazard Type	Recommended Additional Site-Specific Studies for New Development
C_{AF}	Qaf_1	Young alluvial fans	Collapsible soil	Laboratory soil consolidation tests*
C_{MCAF}	Qal, Qaf_1, Qaf_2	Monroe Creek alluvial fan	Collapsible soil	Laboratory soil consolidation tests*
C_{AB}	Qab	Alluvial basin fill	Collapsible soil	None*
C_C/R_B	Qc	Hillslope colluvium	Collapsible soil, shallow bedrock	Laboratory soil consolidation tests*
R_B	Tv	Outcrops of volcanic bedrock on steep slopes	Shallow bedrock	None*
R_S	Qab	Travertine terrace of Monroe Hot Springs	Shallow bedrock, soluble rock	Soluble rock investigations*

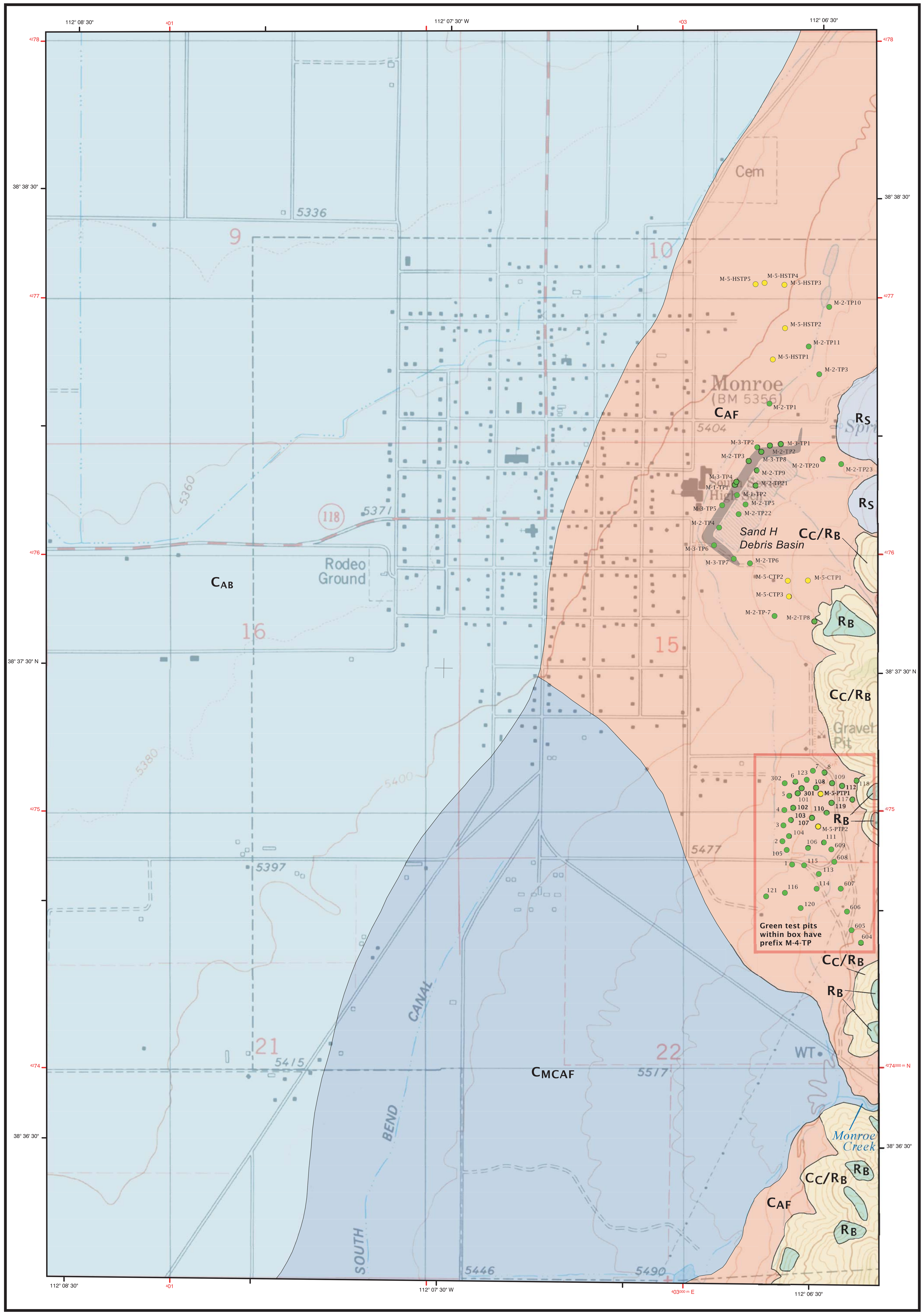
* A standard geotechnical soil and/or rock-investigation is recommended for all new development.

DISCUSSION

Soil and rock units having characteristics that make them susceptible to volumetric change, collapse, subsidence, or other engineering-geologic problems are classified as problem soil and rock. Collapsible soil is the principal soil problem in the Monroe area. Collapsible soil is soil that consolidates and settles in response to the addition of water, causing damage to structures. The soil collapse is usually triggered by human activity such as improper drainage, irrigation, urbanization, or disposal of wastewater. Shallow bedrock and soluble rock (spring-deposited travertine) are the rock-related problems identified in the map area. Shallow bedrock can impede excavation and the proper functioning of soil-absorption wastewater disposal systems. The flow of water through subsurface fractures can dissolve soluble rock, resulting in settlement or collapse. Activities that can cause problems in soluble rock include building structures that induce differential compaction of soils above an irregular soluble rock surface, building structures directly on unrecognized soluble-rock settlement or collapse features, and impounding water above or directing water into an unrecognized dissolution feature that may lead to further dissolution and collapse.

USING THIS MAP

The Utah Geological Survey recommends that standard geotechnical soil-foundation studies be performed for new development in all areas. The intent of this map is to show where additional special studies are recommended to address specific problem soil and rock hazards. Performing special studies for these hazards prior to development provides an understanding of the potential impacts and which risk-reduction measures are most feasible and cost effective. The boundaries between map categories are approximate and gradational. Small, localized areas of problem soil and rock hazard different than shown on the map are likely to exist, but their identification is precluded primarily because of the limitations of the map scale. Also, soil textural variations within young fan alluvium are known to influence the collapse potential of soils, and site-specific studies are needed to define these variations. Irrigation in some of the collapsible-soil areas may have induced collapse and possibly reduced or eliminated the hazard. Where development is proposed in areas identified as having problem soil and rock hazards, a geotechnical firm having practical experience with collapsible soil, shallow bedrock, and soluble rock should be retained early in the project design phase to conduct a site-specific investigation of the proposed site. If a hazard is present, the geotechnical consultant should provide design or site-preparation recommendations as necessary to reduce the hazard.



SCALE 1:10,000

0 1/4 1/2 1 MILE

0 500 1000 1500 2000 2500 3000 3500 4000 4500 5000 FEET

0 100 200 300 400 500 600 700 800 900 1000 METERS

CONTOUR INTERVAL 40 FEET
DOTTED SUPPLEMENTARY CONTOUR INTERVAL 20 FEET

Base map from U.S. Geological Survey 1:24,000 scale Annabella, Monroe Peak, Antelope Range, and Elsinore quadrangles Maps edited 1980

Projection and 1000-meter grid ticks: Universal Transverse Mercator, zone 12 North American Datum 1927

UTAH
MAP LOCATION

0°42' 14½'
1980 MAGNETIC DECLINATION
[AT CENTER OF SHEET]

UTAH GEOLOGICAL SURVEY

UTAH GEOLOGICAL SURVEY
a division of
Department of Natural Resources
SPECIAL STUDY 110

PLATE 4. SURFACE-FAULT-RUPTURE, ROCK-FALL, AND INDOOR-RADON HAZARDS IN THE MONROE AREA

By

Richard E. Giraud

2004

SURFACE-FAULT-RUPTURE AND ROCK-FALL HAZARDS

EXPLANATION

Surface-fault-rupture special-study area. Site-specific studies are recommended for critical facilities.

Rock-fall hazard special-study area. Site specific studies are recommended for new development.

MAP SYMBOLS

MC-2 • Location of geothermal drill-hole MC-2 that encountered bedrock at 610-foot depth. The drill hole is used to infer Sevier fault location.

..╿...?..... Inferred location of the Sevier fault, a normal fault, bar and ball on downthrown side.

DISCUSSION

Among the potential effects of large earthquakes (magnitude > 6.5) is surface fault rupture, which occurs when movement at depth on the fault causing the earthquake propagates to the surface. Buildings, bridges, dams, tunnels, canals, and pipelines have all been severely damaged by surface faulting. Because designing a structure to withstand surface faulting is generally considered impractical from an economic, engineering, and architectural standpoint for most structures, avoiding active fault traces is the recommended approach for reducing surface-faulting hazards. Rock falls are a potential hazard, particularly in earthquakes. Rock falls are the most common type of slope failure caused by earthquake ground shaking, and a large boulder traveling at high speed can cause significant impact damage. Slope modification such as cuts for roads and building pads for development can increase or create a local rock-fall hazard.

USING THIS MAP

This map shows where special studies are needed to address surface-fault-rupture and rock-fall hazards. The surface-fault-rupture special-study area is shown as an area extending 1,000 feet on either side of the inferred trace of the Sevier fault. When critical facilities are planned within this area, site-specific surface-fault-rupture studies are necessary. Within the rock-fall hazard area, a site-specific investigation of rock outcrops is required to determine if rock falls could occur, particularly in earthquakes. The boundaries between map categories are approximate and gradational. Small, localized areas of surface-fault-rupture and rock-fall hazard different than that shown on the map are likely to exist, but their identification is precluded primarily because of the limitations of the map scale. Where development is proposed in these areas, a geotechnical firm having practical experience with surface fault rupture and rock fall should be retained early in the project design phase to conduct a site-specific investigation of

INDOOR-RADON HAZARDS (INSET MAP)

DISCUSSION

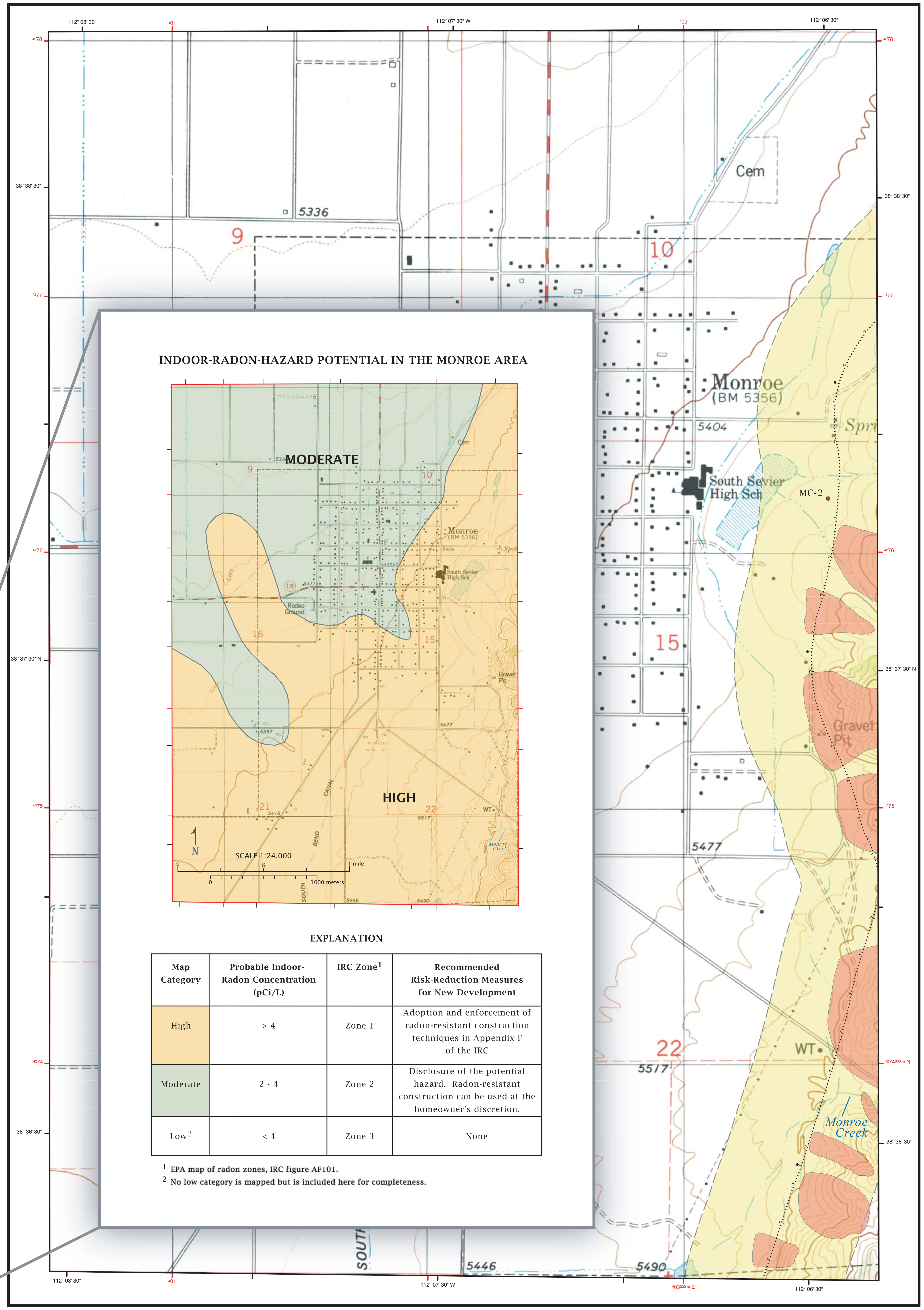
Radon is an odorless, tasteless, and colorless radioactive gas. The most common type of radon is a naturally occurring product of the radioactive decay of uranium found in small concentrations in nearly all soil and rock. The Monroe area is underlain by uranium-bearing Quaternary alluvial-fan deposits derived from Tertiary volcanic rocks to the east. Because radon is a gas, it is highly mobile and can enter buildings through small foundation cracks and other penetrations such as utility pipes. Indoor-radon concentrations may reach hazardous levels because of poor air circulation in buildings. Breathing any level of radon over time increases a person's risk of lung cancer, but long-term exposure to low radon levels is generally considered a small health risk. Smoking increases the health risk due to radon. The U.S. Environmental Protection Agency (EPA) recommends that action be taken to reduce indoor-radon levels when they exceed 4 picocuries per liter of air (pCi/L). Geologic factors influence radon levels in soil gas, but a number of non-geologic factors also influence radon levels in a building. Although the influence of geologic factors can be estimated, the influence of non-geologic factors such as occupant lifestyle and home construction methods is more variable. As a result, indoor-radon levels fluctuate and must be measured in each building to determine if a problem exists. Testing is easy, inexpensive, and may often be conducted by the building occupant.

USING THIS MAP

The indoor-radon-hazard-potential categories on this map are relative. This map should not be used to indicate absolute indoor-radon levels in specific buildings because a quantitative relationship between geologic factors and indoor-radon levels does not exist. Factors not considered can strongly affect indoor-radon levels. The mapped boundaries between radon-hazard categories are approximate and gradational. Small, localized areas of higher or lower radon potential are likely to exist within any given map area, but their identification is precluded because of the effects of unconsidered factors, the limitations of the map scale, and the relatively sparse data.

Although the radon-hazard map can be used to prioritize indoor testing by indicating where and the urgency with which it should be undertaken, ultimately all existing buildings should be tested. The radon-hazard map can be used to determine where radon-resitant construction techniques should be considered for new construction.

For new construction, appendix F in the *International Residential Code* (IRC, 2000) provides construction techniques that are intended to reduce radon entry and prepare the building for post-construction radon reduction, if necessary. Adoption and enforcement of IRC appendix F is left to local jurisdictions. The Utah Geological Survey recommends adoption and enforcement of construction techniques in IRC appendix F in the high areas and appropriate disclosure of the potential hazard in moderate areas, where radon-resistant construction can be used at the homeowner's discretion, but does not consider radon-resistant construction techniques necessary in low areas.



INDOOR-RADON-HAZARD POTENTIAL IN THE MONROE AREA

EXPLANATION

Map Category	Probable Indoor-Radon Concentration (pCi/L)	IRC Zone[1]	Recommended Risk-Reduction Measures for New Development
High	> 4	Zone 1	Adoption and enforcement of radon-resistant construction techniques in Appendix F of the IRC
Moderate	2 - 4	Zone 2	Disclosure of the potential hazard. Radon-resistant construction can be used at the homeowner's discretion.
Low[2]	< 4	Zone 3	None

[1] EPA map of radon zones, IRC figure AF101.

[2] No low category is mapped but is included here for completeness.

SCALE 1:10,000

0 1/4 1/2 1 MILE

0 500 1000 1500 2000 2500 3000 3500 4000 4500 5000 FEET

0 100 200 300 400 500 600 700 800 900 1000 METERS

CONTOUR INTERVAL 40 FEET
DOTTED SUPPLEMENTARY CONTOUR INTERVAL 20 FEET

Base map from U.S. Geological Survey 1:24,000 scale Annabella, Monroe Peak, Antelope Range, and Elsinore quadrangles Maps edited 1980

Projection and 1000-meter grid ticks: Universal Transverse Mercator, zone 12 North American Datum 1927

UTAH
MAP LOCATION

0°42' 14½'
1980 MAGNETIC DECLINATION
[AT CENTER OF SHEET]

UTAH GEOLOGICAL SURVEY

UTAH GEOLOGICAL SURVEY
a division of
Department of Natural Resources

SPECIAL STUDY 110