BRIGHAM YOUNG UNIVERSITY

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PART 2 TWO

EDITED BY PAUL KARL LINK AND BART J. KOWALLIS

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MESOZOIC TO RECENT GEOLOGY OF UTAH

Edited by
Paul Karl Link and Bart J. Kowallis

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Cover photos taken by Paul Karl Link.

Top: Upheaval Dome, southeastern Utah.
Middle: Lake Bonneville shorelines west of Brigham City, Utah.
Bottom: Bryce Canyon National Park, Utah.

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Preface

Guidebooks have been part of the exploration of the American West since Oregon Trail days. Geologic guidebooks with maps and photographs are an especially graphic tool for school teachers, University classes, and visiting geologists to become familiar with the territory, the geologic issues and the available references.

It was in this spirit that we set out to compile this two-volume set of field trip descriptions for the Annual Meeting of the Geological Society of America in Salt Lake City in October 1997. We were seeking to produce a quality product, with fully peer-reviewed papers, and user-friendly field trip logs. We found we were bucking a tide in our profession which de-emphasizes guidebooks and paper products. If this tide continues we wish to be on record as producing "The Last Best Geologic Guidebook."

We thank all the authors who met our strict deadlines and contributed this outstanding set of papers. We hope this work will stand for years to come as a lasting introduction to the complex geology of the Colorado Plateau, Basin and Range, Wasatch Front, and Snake River Plain in the vicinity of Salt Lake City. Index maps to the field trips contained in each volume are on the back covers.

Part 1 "Proterozoic to Recent Stratigraphy, Tectonics and Volcanology: Utah, Nevada, Southern Idaho and Central Mexico" contains a number of papers of exceptional interest for their geologic synthesis. Part 2 "Mesozoic to Recent Geology of Utah" concentrates on the Colorado Plateau and the Wasatch Front.

Paul Link read all the papers and coordinated the review process. Bart Kowallis copy edited the manuscripts and coordinated the publication via Brigham Young University Geology Studies. We would like to thank all the reviewers, who were generally prompt and helpful in meeting our tight schedule. These included: Lee Allison, Genevieve Atwood, Gary Axen, Jim Beget, Myron Best, David Bice, Phyllis Camilleri, Marjorie Chan, Nick Christie-Blick, Gary Christenson, Dan Chure, Mary Droser, Ernie Duebendorfer, Tony Ekdale, Todd Ehlers, Ben Everitt, Geoff Freethey, Hugh Hurlow, Jim Garrison, Denny Geist, Jeff Geslin, Ron Greeley, Gus Gustason, Bill Hackett, Kimm Harty, Grant Heiken, Lehi Hintze, Peter Huntoon, Peter Isaacson, Jeff Keaton, Keith Ketner, Guy King, Mel Kuntz, Tim Lawton, Spencer Lucas, Lon McCarley, Meghan Miller, Gautam Mitra, Kathy Nichols, Robert Q. Oaks, Susan Olig, Jack Oviatt, Bill Perry, Andy Pulham, Dick Robison, Rube Ross, Rich Schweickert, Peter Sheehan, Norm Silberling, Dick Smith, Barry Solomon, K.O. Stanley, Kevin Stewart, Wanda Taylor, Glenn Thackray and Adolph Yonkee. In addition, we wish to thank all the dedicated workers at Brigham Young University Print Services and in the Department of Geology who contributed many long hours of work to these volumes.

Paul Karl Link and Bart J. Kowallis, Editors

Geologic Hazards of the Wasatch Front, Utah

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ABSTRACT

The results of recent and ongoing research into six significant geologic hazards of the Wasatch Front region will be summarized on this field trip, including: (1) surface fault rupture on the Salt Lake City segment of the Wasatch fault zone; (2) seismic site response in the Salt Lake Valley, including ground shaking and liquefaction; (3) liquefaction-induced landsliding at the Farmington Siding landslide complex; (4) lake flooding along the shores of Great Salt Lake; (5) debris-flow deposition on alluvial fans at the base of the Wasatch Range; and (6) landsliding in the Ogden area. The trip will provide an opportunity to discuss the scientific, engineering, and administrative aspects involved in geologic-hazard evaluation in this rapidly growing region.

INTRODUCTION

Situated at the eastern margin of the Basin and Range physiographic province, the Wasatch Front is subject to a variety of geologic hazards due to a unique combination of geologic, topographic, and climatic conditions. The Wasatch Front occupies a series of north-trending valleys at the foot of the western slope of the Wasatch Range (fig. 1). The mountains rise steeply as much as 7,100 feet (2,165 m) above the valley floor, reaching elevations near 12,000 feet (3,660 m) above sea level. This impressive relief is the result of ongoing uplift along the Wasatch fault zone, a major intraplate tectonic boundary which is the longest active normal-slip fault zone in the United States and one of several fault zones in the region considered capable of producing large earthquakes that could generate strong ground shaking, surface fault rupture, and seismically induced liquefaction and landslides.

In the winter, frontal storms traveling east from the Pacific Ocean encounter the Wasatch Range and produce heavy snowfall in the mountains. Snow avalanches are common and present a significant, widespread hazard. Freeze-thaw cycles in steep exposures of fractured rock produce rock falls. Rapid melting of a lingering snowpack periodically results in slope failures, debris flows, and stream and alluvial-fan flooding. Convective storms in the spring and late summer also contribute to these hazards.

Great Salt Lake, the remnant of Pleistocene Lake Bonneville, forms the western boundary of the northern Wasatch Front. Because the lake occupies a closed basin within the internally draining Great Basin, it is subject to climate-induced fluctuations that may cause flooding in areas along and near its gently sloping shores. A seiche hazard also exists because of the regional earthquake hazard. Furthermore, thick deposits of soft, fine-grained lacustrine sediment from repeated cycles of deep-water lakes that inundated the valleys could amplify earthquake ground motions, and loose, saturated sands are potentially liquefiable.

This field trip provides an opportunity to observe and discuss six of the most significant types of geologic hazards of the Wasatch Front. These include (1) surface fault rupture on the Salt Lake City segment of the Wasatch fault zone; (2) seismic site response in the Salt Lake Valley, including ground shaking and liquefaction; (3) liquefaction-induced landsliding at the Farmington Siding landslide complex; (4) lake flooding along the shores of Great Salt Lake; (5) debris-flow deposition on alluvial fans at the base of the Wasatch Range; and (6) landsliding in the Ogden area. These topics are discussed in the following six sections, which in turn are followed by a road log that describes the field-trip route. The route and stop locations are shown on figures 25 through 27.

FIELD TRIP STOP NO. 1

Bill D. Black, Leader
Mouth of Little Cottonwood Canyon,
Wasatch Boulevard and 9800 South; see Figure 25.

PALEOSEISMIC STUDIES ON THE SALT LAKE CITY SEGMENT OF THE WASATCH FAULT ZONE

The Wasatch fault zone is one of the longest and most active normal-slip faults in the world. Situated near the

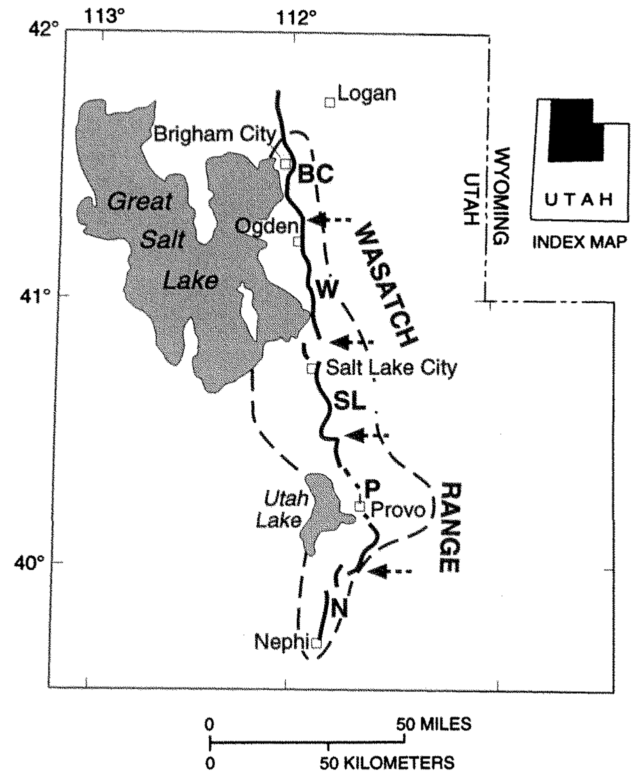

Figure 1. Generalized area of the Wasatch Front (dashed line). Central five segments of the Wasatch fault zone shown by heavy line with arrows indicating segment boundaries (modified from Machette et al., 1992): BC = Brigham City, W = Weber, SLC = Salt Lake City, P = Provo, N = Nephi.

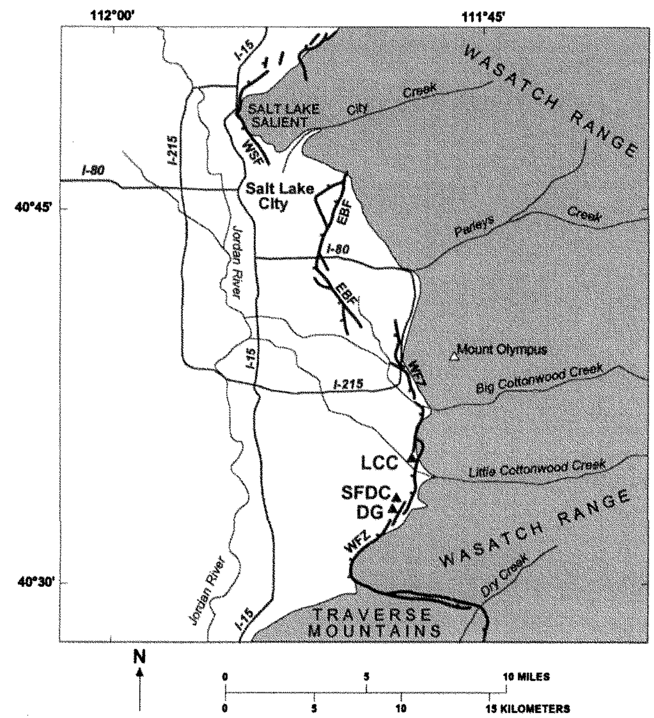

Figure 2. Salt Lake City segment of the Wasatch fault zone (WFZ) and locations of the Little Cottonwood Canyon (LCC), South Fork Dry Creek (SFDC), and Dry Gulch (DG) trench sites. WSF = Warm Springs fault, EBF = East Bench fault.

center of the Intermountain seismic belt (Smith and Sbar, 1974; Smith and Arabasz, 1991), a north-trending zone of historical seismicity that extends from northern Arizona to central Montana, the fault zone extends 213 miles (343 km) along the western base of the Wasatch Range from southeastern Idaho to north-central Utah (Machette et al., 1992) and comprises 10 independent, seismogenic segments (Schwartz and Coppersmith, 1984; Machette et al., 1992). Results of numerous trenching studies indicate that the central five segments (Brigham City, Weber, Salt Lake City, Provo, Nephi) (fig. 1) each have generated three or more surface-faulting earthquakes in the past 6,000 years.

The Salt Lake City segment of the Wasatch fault zone trends through the densely populated Salt Lake Valley, extending 29 miles (46 km) from the Traverse Mountains on the south to the Salt Lake salient on the north (fig. 2). The fault segment displays abundant evidence for multiple surface-faulting earthquakes during Holocene time (Schwartz and Coppersmith, 1984), and thus it poses a significant seismic risk to people living in the Salt Lake City metropolitan area. The Holocene chronology of surface-faulting earthquakes has been determined through fault-trenching studies at Little Cottonwood Canyon in 1979, South Fork Dry Creek in 1985 and 1994, and Dry Gulch in 1991.

Little Cottonwood Canyon (1979)

The first paleoseismic investigation of the Salt Lake City segment was at Little Cottonwood Canyon in 1979 (fig. 2) by Woodward-Clyde Consultants, under contract to the U.S. Geological Survey (USGS) (Swan et al., 1981). The fault zone at this site is defined by a prominent west-facing main scarp that splays northward into three sub-parallel scarps and an east-facing antithetic scarp. South of the site, the fault zone forms a wide, deep graben as it traverses moraines near the mouth of the canyon (fig. 3).

Four trenches were excavated across the scarps at Little Cottonwood Canyon, exposing evidence for two surface-faulting earthquakes. Radiocarbon dating of detrital charcoal showed the older earthquake occurred shortly before 8,000 to 9,000 years ago. However, no material suitable for radiocarbon dating was found to constrain the timing of the younger event. Based on scarp profiling and stratigraphic evidence in the trenches, Swan et al., (1981) calculated a recurrence interval of 2,200 years and an average net slip per event of 6 feet (2 m).

Figure 3. Wasatch fault zone at the mouth of Little Cottonwood Canyon. A. Aerial view, looking east, of fault scarps (arrows) cutting upper Pleistocene moraine and alluvial deposits. B. South view of fault scarps (in shadow) cutting Bells Canyon moraine (large arrow on Fig. 3A). Residential development in foreground occupies a graben along the fault zone.

South Fork Dry Creek (1985)

The Utah Geological Survey (UGS), in cooperation with the USGS, conducted a paleoseismic investigation at South Fork Dry Creek (fig. 2) in 1985 (Lund and Schwartz, 1987; Schwartz and Lund, 1988). The fault zone at South Fork Dry Creek consists of six sub-parallel, west-dipping main fault scarps and a single east-dipping antithetic scarp (Personius and Scott, 1992). Four trenches were excavated across three of the main scarps, but access restrictions precluded trenching all of the scarps.

Two trenches each exposed evidence for two surface-faulting earthquakes. The other two trenches each exposed evidence for one surface-faulting earthquake, but no material suitable for radiocarbon dating was found in these trenches. Radiocarbon age estimates indicated that the earthquakes occurred (1) shortly after 1,100 to 1,800 years ago, and (2) shortly after 5,500 to 6,000 years ago. Based on this information, Schwartz and Lund (1988) estimated a recurrence interval of 3,000 to 5,000 years. However, they acknowledged uncertainty regarding the paleoseismic history of the Salt Lake City segment, and cautioned that a true paleoseismic history could be developed only if information is obtained for every scarp at a site.

Dry Gulch (1991–92)

The incomplete nature of the Salt Lake City segment's earthquake history was demonstrated in 1991, when a nonresearch trench was excavated by a local consultant across the fault zone at Dry Gulch (fig. 2). Detailed geologic mapping by Personius and Scott (1992) shows the scarp at Dry Gulch extends northward to South Fork Dry Creek. However, this scarp was not trenched in 1985. The UGS inspected the Dry Gulch trench and found evidence for two surface-faulting earthquakes (Lund, 1992; Black et al., 1996). Radiocarbon dating indicated the earthquakes occurred: (1) roughly 1,600 years ago, which coincided with timing for the most recent event at South Fork Dry Creek; and (2) shortly after 2,400 years ago, which did not correspond to any previously known event. This newly discovered event showed that at least three (rather than two) surface-faulting earthquakes have occurred in the past 6,000 years, and at least four events (rather than three) in the past 8,000–9,000 years. Based on timing for the additional event, Lund (1992) calculated a surface-faulting recurrence interval of 2,150 ± 400 years for the past 6,000 years.

South Fork Dry Creek (1994)

In 1994, the UGS excavated five new trenches across fault scarps at South Fork Dry Creek to complete the investigation started there in 1985 (Black et al., 1996). With these additional trenches, all fault scarps at South Fork Dry Creek have now been trenched. The new trenches exposed evidence for one to four surface-faulting earthquakes, and documented a previously unrecognized earthquake (event X) which increased to four the total number of events on the Salt Lake City segment in the past 6,000 years. Radiocarbon age estimates show these earthquakes occurred: (1) shortly after 1,100–1,550 years ago (event Z), (2) shortly after 2,100–2,800 years ago (event Y), (3) shortly after 3,500–4,500 years ago (event X), and (4) shortly after 4,950–5,750 years ago (event W). Net slip per event could not be calculated, but earthquake timing combined with the age and cumulative offset of a debris-flow levee along South Fork Dry Creek suggests it is likely in the range of 5 to 8 feet (1.5–2.5 m), which is similar to that determined by Swan et al., (1981) at Little Cottonwood Canyon. Events W through Z show a varying pattern of surface rupture (fig. 4), indicating that in a wide fault zone containing many fault traces, subsequent earthquakes do not always rupture every trace.

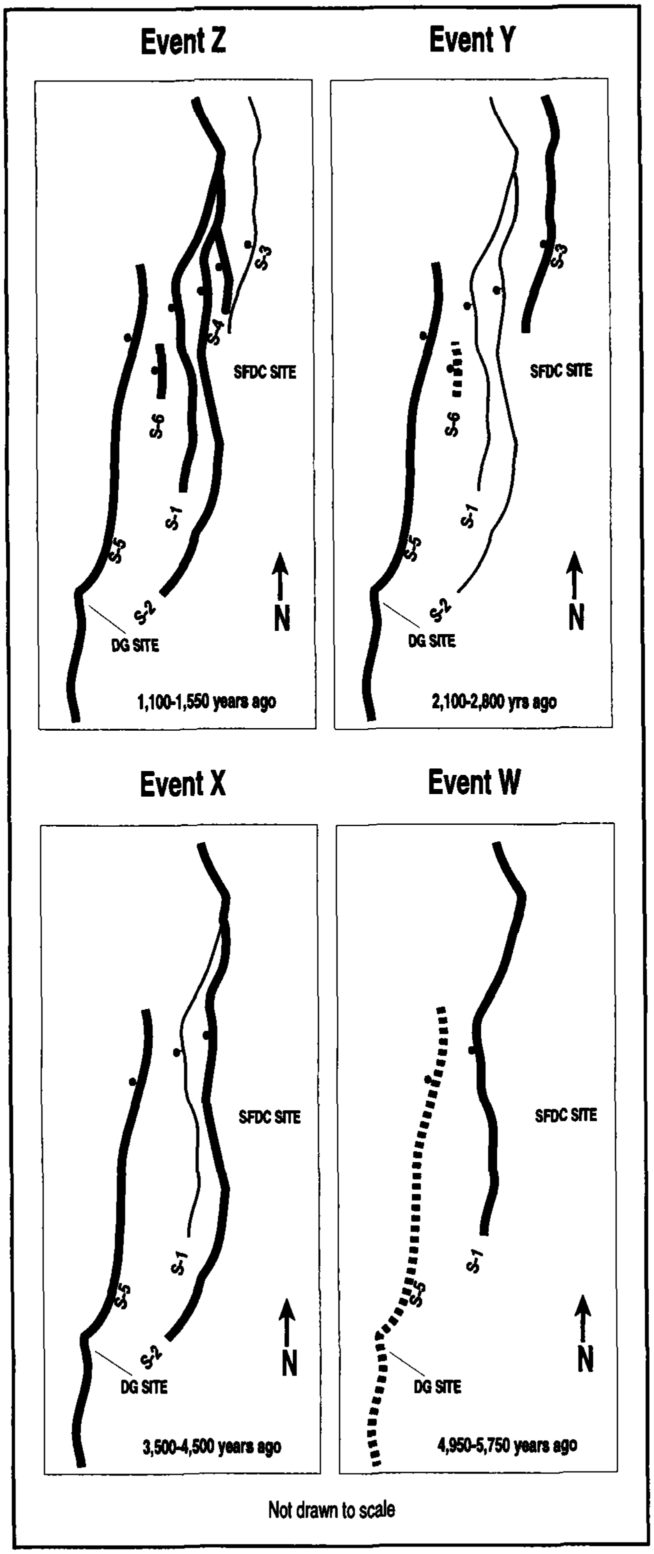

Figure 4. Pattern of surface rupture at the South Fork Dry Creek (SFDC) and Dry Gulch (DG) sites. Main scarps (S-1 through S-6) known to have been active during surface-faulting earthquakes on the Salt Lake City segment in the past 6,000 years are shown by heavy solid lines; scarps possibly active are shown by heavy dashed lines.

Based on mean elapsed times between events W through Z, Black et al., (1996) calculated a new recurrence interval for surface faulting in the past 6,000 years of 1,350 ± 200 years (fig. 5). Elapsed time since event Z (about 1,300 years) is close to the new shorter recurrence interval and within the assigned range of uncertainty, suggesting risk for a future surface-faulting earthquake is higher than previously thought. However, more work is needed to characterize the surface-faulting history of the Salt Lake City segment in early Holocene time and refine the recurrence interval.

FIELD TRIP STOP NO. 2

Michael D. Hylland, Leader

Salt Lake Valley overlook from Wasatch Boulevard at Pete's Rock; see Figure 25.

SEISMIC SITE RESPONSE IN THE SALT LAKE VALLEY

The Salt Lake Valley is a deep, sediment-filled structural basin formed by basin-and-range extensional block faulting. The combined thickness of unconsolidated Quaternary and semi-consolidated Tertiary basin-fill deposits locally exceeds 3,300 feet (1,000 m) (Zoback, 1983; Mabey, 1992). Quaternary deposits are dominated by lacustrine sediments deposited by repeated cycles of deep-water lakes during the Pleistocene. Coarse-grained Lake Bonneville shore facies consisting of sand and gravel are present along the margins of the Salt Lake Valley up to an elevation of about 5,180 feet (1,580 m), whereas deep-water facies consisting of clay, silt, and fine sand predominate toward the center of the valley (fig. 6). Post-Lake Bonneville materials include alluvial, flood-plain, and flood-plain/delta deposits.

The lateral and vertical variability of Quaternary deposits in the Salt Lake Valley results in a wide range of potential earthquake-induced ground motions. Furthermore, the presence of loose, sandy soils and shallow ground water makes many areas susceptible to liquefaction.

Earthquake Ground Shaking

Historical Seismicity and Building Damage

The Salt Lake Valley occasionally experiences ground shaking from earthquakes within and beyond the Wasatch

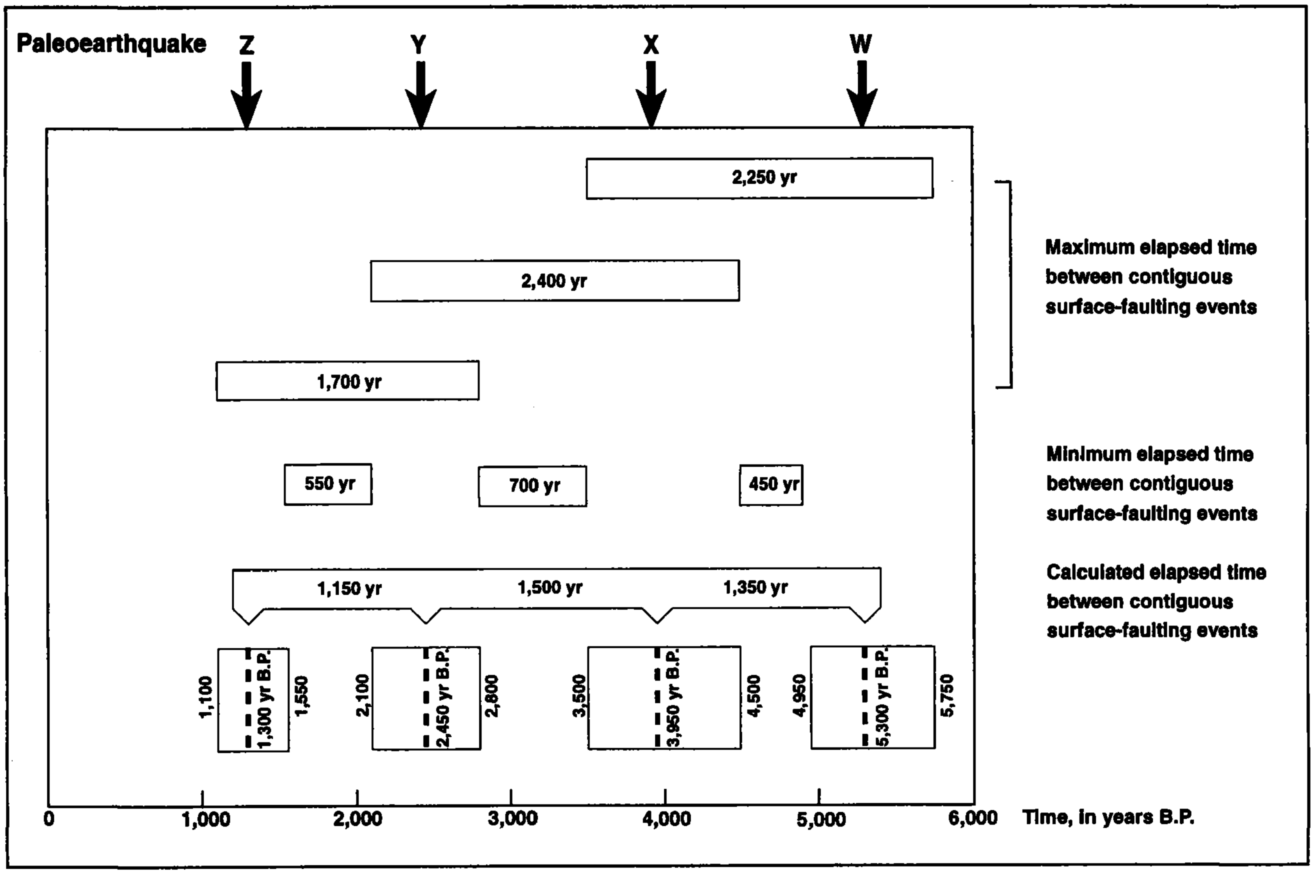

Figure 5. Timing of surface-faulting earthquakes on the Salt Lake City segment in the past 6,000 years.

Front region. Oaks (1987) summarized the effects of six moderate to large earthquakes (M_L 5.0 to 6.6) that produced ground shaking in the Salt Lake City area. These earthquakes occurred between 1909 and 1962 and resulted in damage consisting of toppled chimneys, cracked walls and windows, broken gas and water mains, and seiches on Great Salt Lake. The 1934 Hansel Valley earthquake, which produced surface rupture on the Hansel Valley fault at the north end of Great Salt Lake, generated the strongest ground shaking in the Salt Lake Valley in historical times. This earthquake had a maximum Modified Mercalli intensity of VIII in the Salt Lake City area and produced several long-period effects. Newspaper accounts described statues that shifted on the towers of the Salt Lake City and County Building and the LDS Salt Lake Temple, as well as adjacent six- and ten-story downtown buildings that swayed and battered against each other.

The Salt Lake Valley is in Uniform Building Code (UBC) seismic zone 3. Much of the development in the valley was originally constructed prior to implementation of the UBC seismic provisions. Many existing structures are being upgraded or retrofit, however, and some new structures are being built to seismic zone 4 standards. A well-known project is the seismic retrofit of the Salt Lake City and County Building. Several earthquakes have caused damage, primarily masonry cracking, to this historic landmark, which was originally constructed between 1892 and 1894. During the 1934 Hansel Valley earthquake, 2.5 tons of mechanical clock equipment fell from the 12-story clock tower and "crashed down through the building" (Kaliser, 1971), and ground shaking from the 1983 Borah Peak, Idaho earthquake (M_S 7.3) caused extensive masonry cracking. Concerns over the possibility of severe structural damage associated with near-field strong ground shaking prompted Salt Lake City to commission a study to determine the need for seismic strengthening of city buildings. The resulting upgrade of the City and County Building included structural reinforcement and base isolation designed for a ground acceleration of 0.2 g (Prudon, 1990). The retrofit was completed in 1989 at a cost of $30 million, and was the world's first application of seismic base isolation in the restoration of an historic structure (Bailey and Allen, 1988).

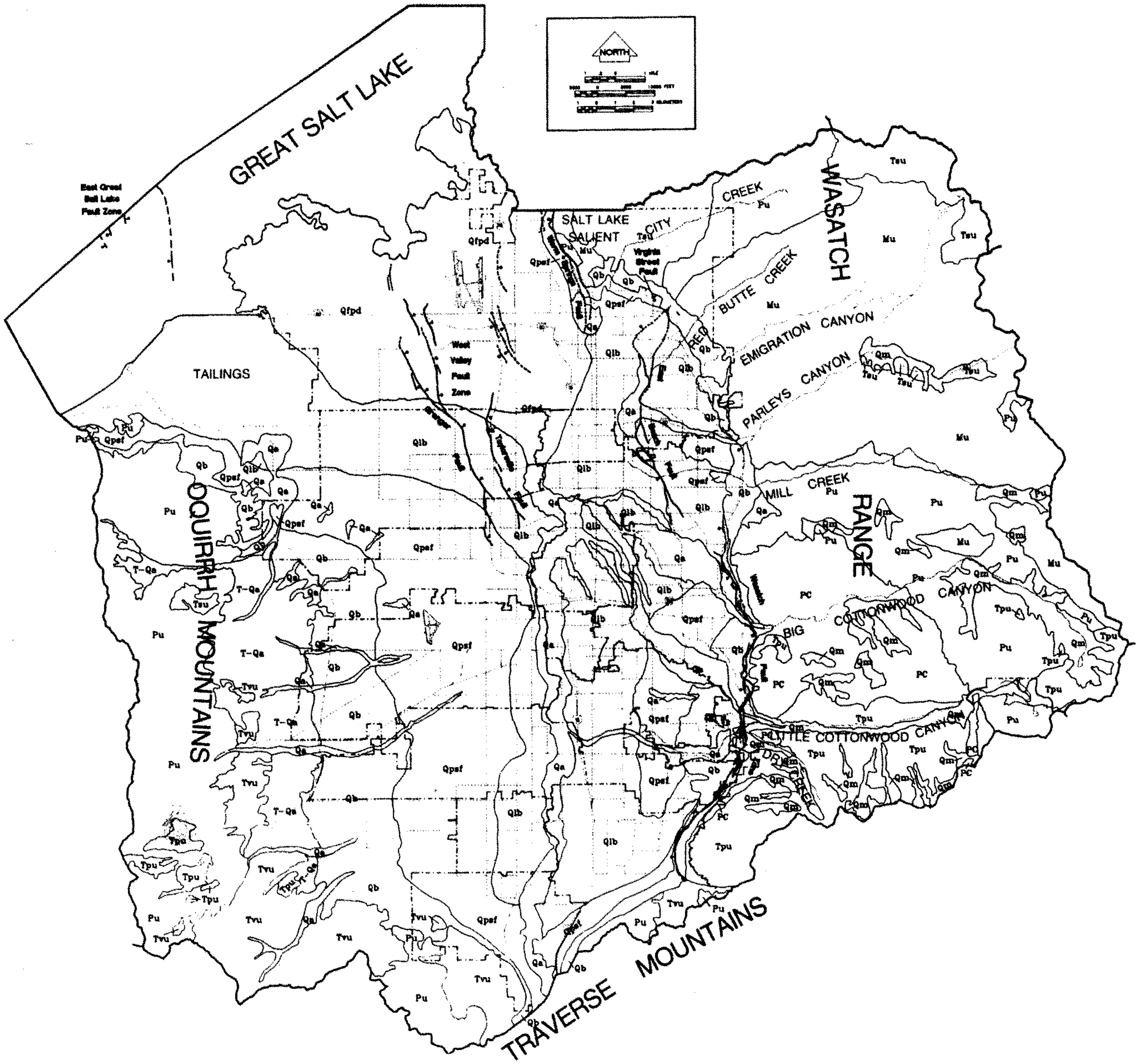

Figure 6. Generalized geologic map of the Salt Lake Valley (from Lund, 1990).

Ground-Motion Levels

Utah has few strong-motion accelerographs and meaningful earthquake records, so quantitative estimates of ground shaking are made using data from other areas, particularly California. However, federal, state, and private entities presently operate 20 three-component strong-motion accelerographs in the Salt Lake Valley, including eight instruments deployed in the last two years. Although statewide coverage still is relatively sparse, the new instruments increase the likelihood of measuring actual ground motions during future earthquakes, especially in the Wasatch Front area.

National probabilistic seismic-risk maps indicate that, for a 50-year exposure time, peak ground accelerations (PGA) at rock sites around the Salt Lake Valley have a 10 percent probability of exceeding 0.20 to 0.30 g (Algermissen et al., 1990; Building Seismic Safety Council, 1994). However, unconsolidated surficial deposits and basin effects could amplify earthquake ground motions, producing even higher accelerations at soil sites. Youngs et al., (1987) indi-

EXPLANATION

DESCRIPTION OF MAP UNITS

Quaternary and Recent Deposits:

Qa — Alluvial Deposits — *Stream alluvium, existing and abandoned flood plains, alluvial fans, and local mudflows.*

Qfpd — Flood-plain and Delta Complex — *Chiefly fine-grained and poorly drained sediments; includes deposits from the Jordan River and Great Salt Lake.*

Qm — Glacial Moraines and Talus — *Moraines, till, and outwash deposits consisting of unsorted mixtures of clay, silt, sand, gravel, and boulders; talus accumulations at the base of steep slopes or cliffs.*

Qlb — Provo-level and Younger Lake Bottom Sediments — *Clays, silts, sands, and locally offshore sand bars.*

Qpsf — Provo-level and Younger Shore Facies — *Chiefly sand and gravel in beach deposits, bars, spits, and deltas.*

Qb — Bonneville-level Shore Facies — *Chiefly sand and gravel in beach deposits, bars, spits, and deltas.*

T-Qa — Harkers Alluvium — *Unconsolidated and poorly sorted boulders, gravel, sand, silt, and clay deposited in pre-Lake Bonneville alluvial fans.*

Tsu — Tertiary Sedimentary Rock Units, *undifferentiated.*

Tvu — Tertiary Volcanic Rock Units, *undifferentiated.*

Tpu — Tertiary Plutonic Rock Units, *undifferentiated.*

Mu — Mesozoic Rock Units, *undifferentiated.*

Pu — Paleozoic Rock Units, *undifferentiated.*

P€ — Precambrian Rock Units, *undifferentiated.*

MAP SYMBOLS

Contact Between Units.

Suspected or Known Quaternary Faults — Dashed where approximately located, dotted where concealed, queried where suspected; Bar and Ball on downthrown side.

cate the PGA with a 10 percent probability of being exceeded in 50 years could be as high as 0.35 g at soil sites in the northern part of the Salt Lake Valley (fig. 7).

Ground-motion monitoring of Nevada Test Site nuclear tests confirmed amplifications of weak motions in the frequency range of engineering significance (0.2- to 0.7-second periods) in the Salt Lake Valley (Hays and King, 1984; Tinsley et al., 1991). The largest amplifications (in some cases greater than 10x) were in central valley areas and were attributed to deep, soft soil conditions. Recent studies along Interstate 15 identified areas underlain by significant thicknesses of soft clay having shear-wave velocities lower than average soft-soil shear-wave velocities in the San Francisco Bay area (Rollins and Gerber, 1995). Theoretical studies of stronger motions have also indicated the potential for significant amplifications, particularly of short-period motions, in areas around the edge of the valley having characteristics similar to where amplification was observed in the 1994 Northridge earthquake in California (Rollins and Adan, 1994). These amplifications are associated with shallow, stiff soil conditions (Adan and Rollins, 1993; Wong and Silva, 1993). Three-dimensional elastic-wave-propagation modeling indicates basin effects could produce significant amplification of low-frequency ground motions at sites over the deepest parts of the basin (Olsen et al., 1995).

Site-specific studies are helping to refine ground-shaking estimates in various parts of the Salt Lake Valley relative to estimates based on the existing regional maps. These studies include probabilistic ground-motion modeling for Kennecott Utah Copper Corp.'s Magna tailings impoundment (Wong et al., 1995) and the Interstate 15 reconstruction project (Dames & Moore, 1996). Also, a cooperative study by the UGS and Brigham Young University beginning in 1997 will result in a site-response map of the Salt Lake Valley that can be used in future probabilistic ground-shaking estimates.

The issue of appropriate ground-motion design levels for structures in the Wasatch Front region is complicated by long recurrence intervals (10^2 to 10^3 yr) for large earthquakes (see Machette et al., 1991). In other seismically active areas such as California, the probabilistic PGA does not continue to increase appreciably at long exposure times because crustal strain is dissipated by relatively frequent large earthquakes (fig. 8). In contrast, the infrequency of large earthquakes in the Wasatch Front region allows crustal strain to continue building over long periods of time, resulting in probabilistic PGAs associated with long exposure times being significantly greater than those associated with shorter exposure times.

Liquefaction

Much of the Salt Lake Valley is underlain at shallow depths by unconsolidated lacustrine and alluvial sand, silt, and clay, and has shallow ground water. The combination of soil gradation and density and shallow ground water results in extensive areas that are susceptible to liquefaction-induced ground failure (Anderson et al., 1986).

Anderson et al., (1986) mapped much of the Salt Lake Valley as having a moderate to high liquefaction potential (fig. 9) based on soil liquefaction susceptibility as determined from geotechnical parameters, calculated critical accelerations, and earthquake magnitude exceedance probability. Although prehistoric liquefaction-induced ground

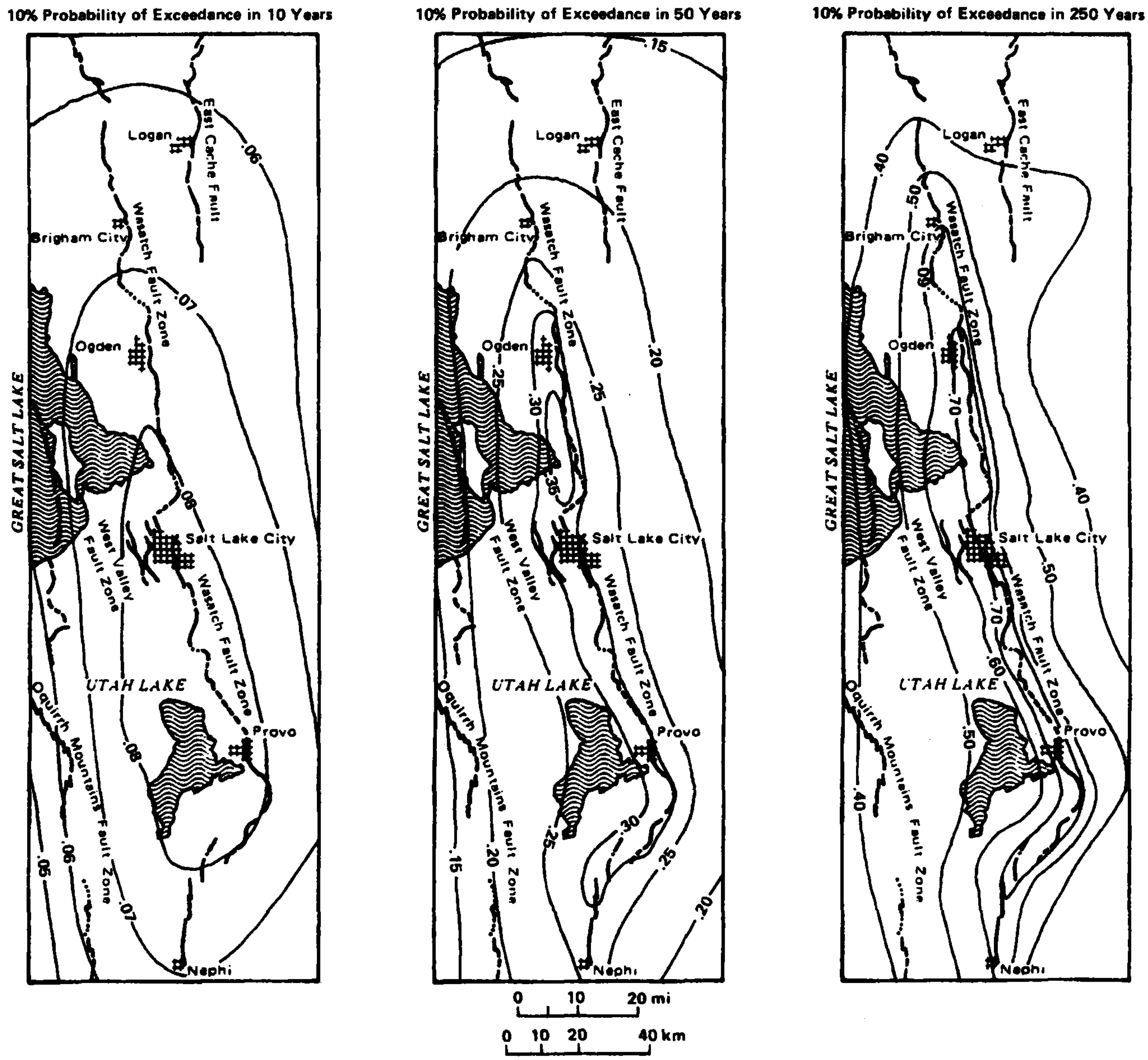

Figure 7. Contours of peak ground acceleration on soil sites with 10 percent probability of being exceeded in 10 years, 50 years, and 250 years (after Youngs et al., 1987).

failure has been verified in numerous excavations throughout the valley (Gill, 1987), many studies in areas mapped as having a high liquefaction potential have demonstrated moderate to very low liquefaction susceptibility based on an absence of sandy sediments, the presence of dense deposits, or the presence of undeformed Lake Bonneville sediments older than 10,000 years (Keaton and Anderson, 1995). More site-specific engineering-geologic information is needed to refine and update the existing liquefaction-potential maps.

FIELD TRIP STOP NO. 3

Michael D. Hylland, Leader
Corner of 1525 West and 675 North, west of Farmington; see Figure 26.

THE LIQUEFACTION-INDUCED FARMINGTON SIDING LANDSLIDE COMPLEX

The prehistoric Farmington Siding landslide complex, about 15 miles (25 km) north of Salt Lake City, comprises

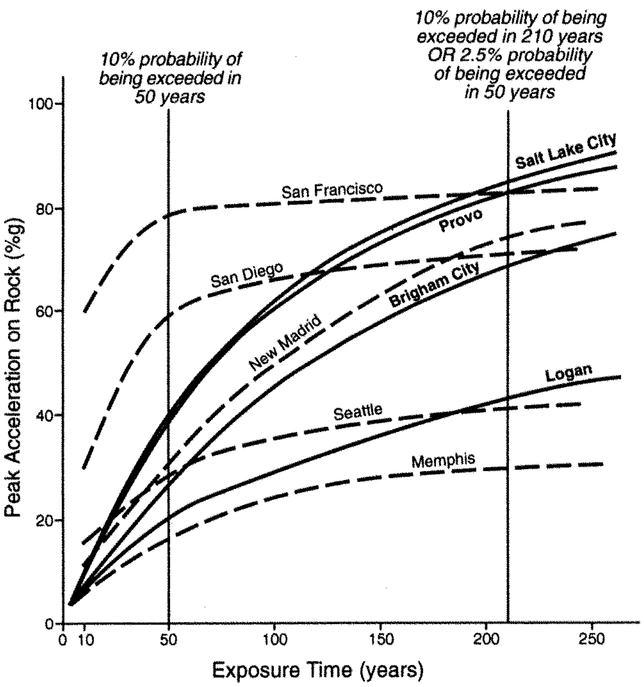

Figure 8. Plot of accelerations on rock with a 10 percent probability of being exceeded during various time periods (from Olig, 1991). Dashed curves are from Algermissen (1988) and solid curves were calculated from results of Youngs et al., (1987).

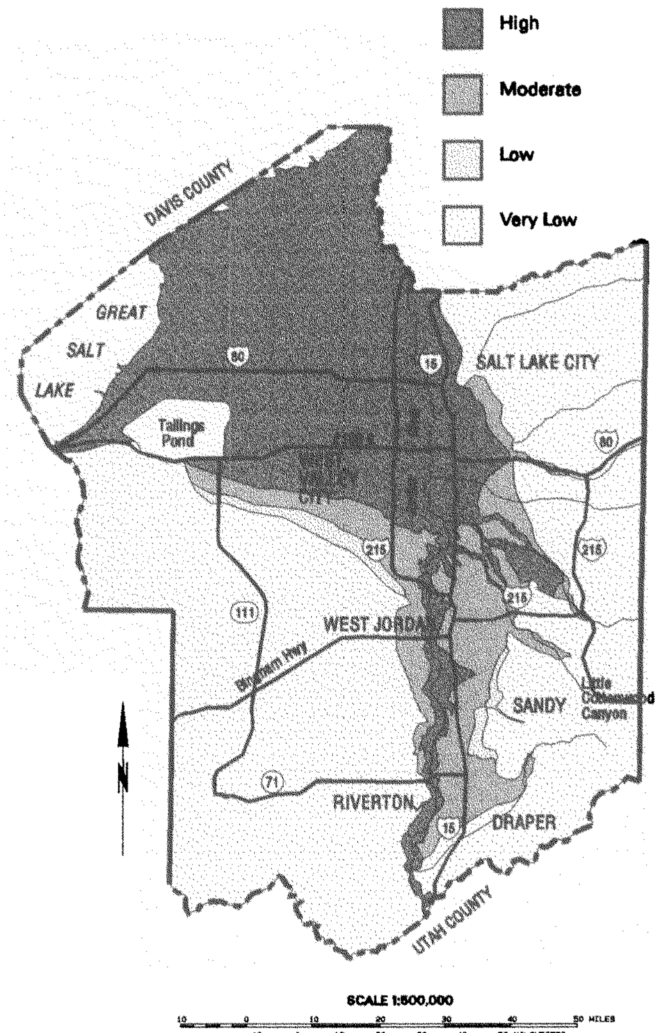

Figure 9. Liquefaction-potential map of the Salt Lake Valley (after Anderson et al., 1986).

some of the largest landslides triggered by earthquakes in the United States. The landslide complex covers an area of approximately 7.5 square miles (19.5 km^2) and is one of thirteen late Pleistocene/Holocene features along the Wasatch Front mapped by previous investigators as possible liquefaction-induced lateral spreads (Van Horn, 1975; Miller, 1980; Anderson et al., 1982; Nelson and Personius, 1993). Detailed discussions and results of recent investigations of the landslide complex are presented in Harty et al., (1993), Hylland and Lowe (1995), Lowe et al., (1995), Hylland (1996), and Hylland and Lowe (in press).

Geology and Geomorphology

The Farmington Siding landslide complex is in a gently sloping area underlain at shallow depths primarily by fine-grained, stratified, late Pleistocene to Holocene lacustrine deposits of Lake Bonneville and Great Salt Lake (fig. 10). Ground slopes within the landslide complex range from about 0.4 to 0.8 percent. Unfailed slopes adjacent to the complex range from about 1 to 2 percent along the flanks and 6 to 11 percent in the crown area. The deposits involved in landsliding consist of interbedded, laterally discontinuous layers of clayey to sandy silt, well-sorted fine sand to silty sand, and minor clay and gravel. The crown is underlain by Lake Bonneville sand and silt deposits and is at an elevation of about 4,400 feet (1,342 m) in the vicinity of the city of Farmington. The toe may have been encountered beneath Great Salt Lake during a drilling project in Farmington Bay to test foundation conditions for a proposed water-storage reservoir (Everitt, 1991).

The landslide deposits can be grouped in two age categories relative to the age of the Gilbert shoreline complex, which formed between 10,900 and 10,300 years ago (Currey, 1990). The northern part of the landslide complex truncates the Gilbert shoreline (Van Horn, 1975), indicating major post-Gilbert movement. However, the Gilbert shoreline can be traced across the southern part of the landslide complex (Anderson et al., 1982; Harty et al., 1993), indicating pre-Gilbert movement in this part of the complex.

Geomorphic features include scarps, hummocks, closed depressions, and transverse lineaments. Well-preserved

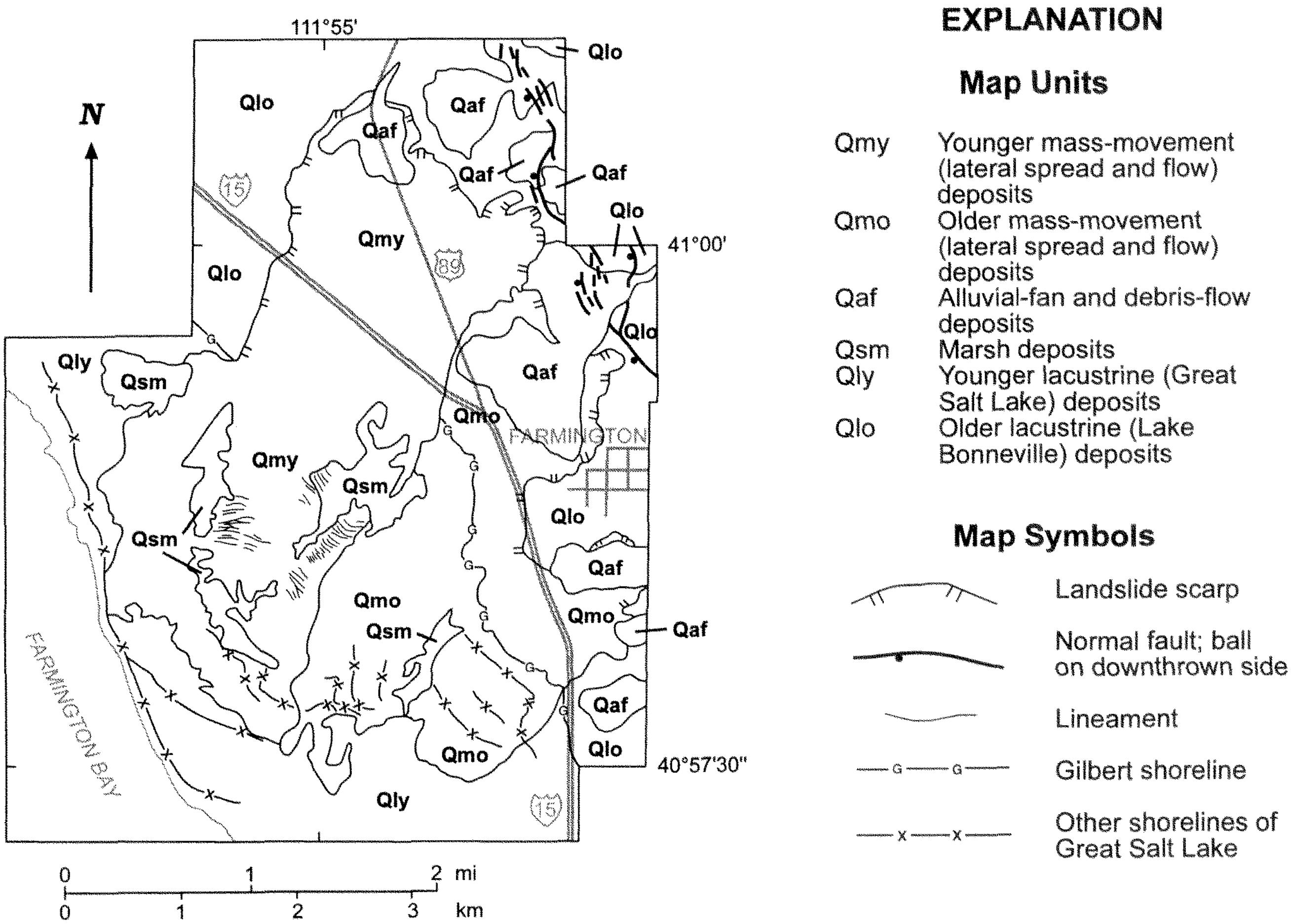

Figure 10. Simplified geologic map of the Farmington Siding landslide complex (modified from Harty et al., 1993).

lateral and main scarps in the northern part of the complex range in height from about 10 to 40 feet (3 to 12 m). Hummocks and closed depressions are present over most of the complex, but are more common in the northern part (fig. 11). Hummocks on the northern part are morphologically distinct, having as much as about 20 feet (6 m) of relief and lateral dimensions locally exceeding 1,000 feet. Hummocks on the southern part are morphologically subtle, generally having less than about 6 feet (2 m) of relief. Subtle transverse lineaments are present in the central part of the complex. Subsurface deformation of lacustrine deposits includes inclined strata, gentle to strong folding, and both low- and high-angle faulting. Small sand dikes are present locally, some of which were injected along fault planes (fig. 12).

Geotechnical Properties and Slope-Failure Mechanism

Soil grain-size distribution, standard-penetration resistance, and ground-water depth noted on logs of geotechnical boreholes (Anderson et al., 1982) indicate liquefiable deposits in the shallow subsurface beneath the landslide complex. Miller et al., (1981) drilled three boreholes in an attempt to correlate beds beneath and adjacent to the landslide complex. Using these and Anderson et al.'s data, Hylland and Lowe (1995) interpret a possible landslide failure zone that occurs within a depth range of 14 to 40 feet (4–12 m). This zone locally corresponds to the contact between a relatively dense transgressive lacustrine sequence consisting of nearshore sand and gravel deposited during the early part of the Bonneville paleolake cycle, or possibly pre-Bonneville alluvium, and overlying loose/soft, offshore, fine-grained sediment subsequently deposited in deeper water.

Landsliding probably occurred as a combination of lateral spread and flow (Hylland and Lowe, 1995). The transverse lineaments near the middle of the complex may represent regressive lake shorelines (Lowe et al., 1995), but Hylland and Lowe (1995) believe the pattern and relative age of the lineaments indicate they represent infilled ground cracks associated with lateral spread. By excavating trenches

Figure 11. Aerial view of hummocky landslide terrain on the northern part of the Farmington Siding landslide complex. Hummocks appear as light-colored patches.

across hummock flanks and adjacent ground in the northern part of the complex, Harty et al., (1993) determined the hummocks are relatively intact "islands" of lacustrine strata surrounded by liquefied sand which resulted from flow failure. Other evidence for flow failure includes the existence of a landslide main scarp up to 40 feet (12 m) high; the overall negative relief in the head region of the complex, indicating evacuation of a large volume of material; and the overall positive relief in the distal region of the complex, indicating deposition of landslide material.

Landslide Timing and Seismic Considerations

Relative timing information and limiting radiocarbon soil ages indicate at least three, and possibly four, landslide events (fig. 13). Hylland and Lowe (1995) considered the timing of these landslide events within the context of paleoclimatic and lacustral fluctuations, and observed that landsliding was associated with climate-induced highstands of Great Salt Lake. The apparent correspondence between landslide events and lacustral highstands suggests that landsliding may have occurred under conditions of relatively high soil pore-water pressures, and possibly increased artesian pressures, associated with rising lake and groundwater levels.

Many features (for example, evidence of lateral spread, flow failure of gentle slopes, sand dikes, deposits susceptible to liquefaction, and proximity to faults with recurrent Holocene activity) indicate landsliding was likely triggered by strong earthquake ground shaking. Numerous fault studies (Machette et al., 1987; Schwartz et al., 1988; Personius, 1990; Forman et al., 1991; Lund et al., 1991; McCalpin and Forman, 1994; Black et al., 1996) constrain the timing of prehistoric surface-faulting earthquakes on the active segments of the Wasatch fault zone; comparison of the results of these

Figure 12. Liquefied sand (arrow) injected along fault plane in trench exposure of thin-bedded lacustrine deposits. Trowel for scale.

studies with the timing of landslide events indicates a close correspondence between landsliding and certain earthquakes (fig. 14). Within uncertainty limits, surface-faulting earthquakes on the Brigham City segment coincide with all four possible landslide events. Surface-faulting earthquakes on the Weber, Salt Lake City, and Provo segments also coincide with the more recent landslide events. Earthquake chronologies for these segments generally do not extend beyond 7,000 years ago, so unrecognized and/or undated earthquakes on these segments may also correspond to the earlier landslide events.

Hylland and Lowe (in press) used a variety of deterministic analyses to evaluate the relative likelihood of large-scale liquefaction-induced landsliding being triggered by earthquakes on various source zones, including: (1) empirical earthquake magnitude-distance relations, (2) comparison of expected peak horizontal ground accelerations with calculated critical accelerations, (3) liquefaction severity index, and (4) estimated Newmark landslide displacements. All of these analyses indicate that widespread liquefaction-induced ground failure involving significant lateral displacements is most likely associated with large earthquakes on the nearby Weber segment of the Wasatch fault zone.

At least two large earthquakes have occurred on the Weber segment that apparently do not coincide with land-

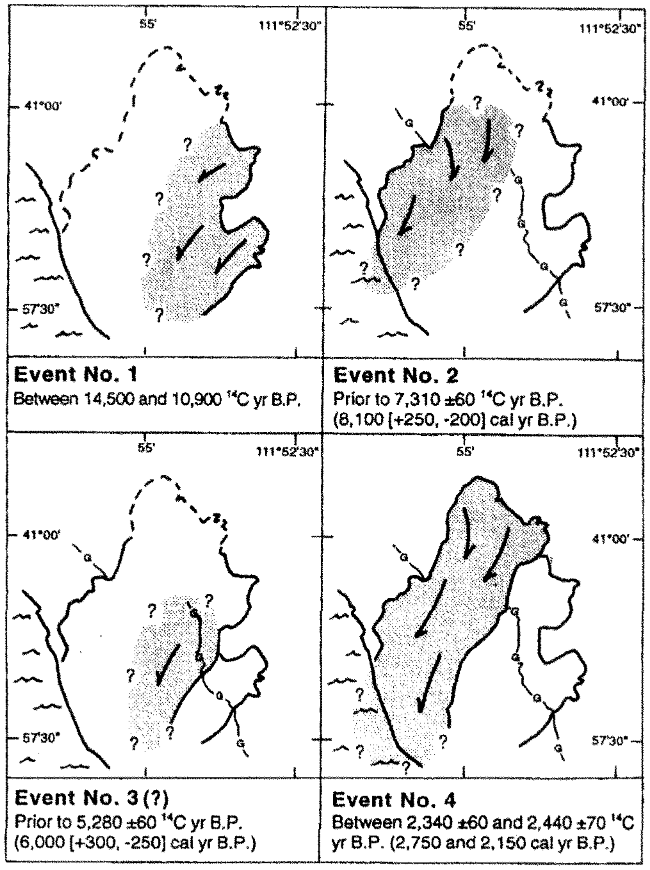

Figure 13. Timing and generalized areas (shaded) of landsliding within the Farmington Siding landslide complex. Arrows show speculated direction of movement; "G" indicates Gilbert shoreline.

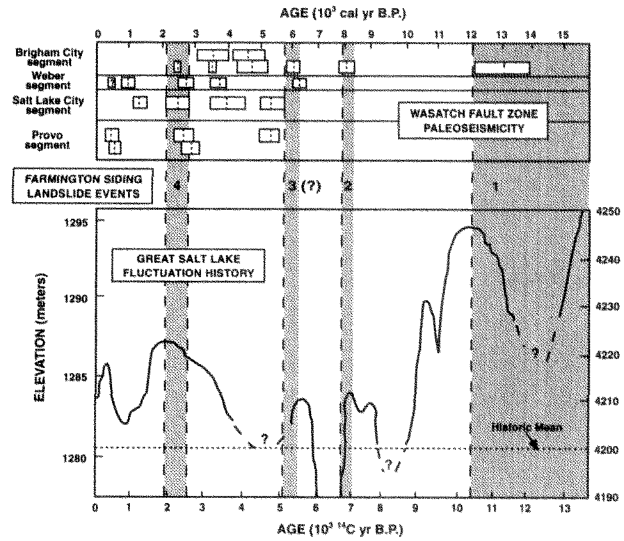

Figure 14. Comparison of the timing of landslide events within the Farmington Siding landslide complex (shaded areas) with Wasatch fault zone paleoseismicity (top) and Great Salt Lake fluctuations (bottom) (modified from Hylland and Lowe, 1995). Dashed lines represent limiting ages. Paleoseismic data summarized from Machette et al., (1987), Schwartz et al., (1988), Personius (1990), Forman et al., (1991), Lund et al., (1991), McCalpin and Forman (1994), Black et al., (1996), and McCalpin and Nishenko (1996). Great Salt Lake hydrograph after Murchison (1989).

slide events. Either geologic and hydrologic conditions at the time of these earthquakes were such that little or no slope movement occurred, or evidence for landsliding has not yet been observed. Because present lake and groundwater levels are relatively low, the likelihood of liquefaction-induced landsliding may be somewhat less than at other times during the Holocene. However, a higher potential for landsliding would exist if the area experienced strong ground shaking during a time of increased soil pore-water pressures associated with abnormally high groundwater levels.

FIELD TRIP STOP NO. 4

Bill D. Black, Leader

Buffalo Point on Antelope Island; see Figure 26.

FLOOD HAZARD FROM GREAT SALT LAKE

Great Salt Lake is located in the Great Salt Lake basin of northwestern Utah (fig. 15), and presents unique geologic hazards and engineering-geology problems to development. Flooding from lake rises and seiches are the greatest hazards, and flooding historically has caused millions of dollars in damage. Rising lake levels between 1983–1985 from above-normal precipitation caused $240 million damage.

Fluctuating water levels are a particular problem along lakes which, like Great Salt Lake, have no natural outlet. Lake-level fluctuations occur daily, seasonally, and on a long-term basis. Natural factors causing fluctuations include precipitation, evaporation, runoff, ground water, aquatic growth, and wind; human factors include dredging, diversions, consumptive use, and regulation by engineered works (Federal Emergency Management Agency, 1985).

Daily fluctuations are commonly caused by strong winds, which produce oscillations in the main body of the lake (seiches). Seiches may also be caused by earthquakes. However, unlike long-term and seasonal fluctuations, daily fluctuations do not result from changes in the amount of water in the lake. Seasonal fluctuations reflect the annual hydrologic cycle. Great Salt Lake levels gradually rise in the spring in response to snow-melt runoff, increased precipitation, and warmer temperatures, until the lake level peaks in early summer (Atwood and Mabey, 1985; Federal Emergency Management Agency, 1985). As the amount of water flowing into the lake becomes less than the amount of water

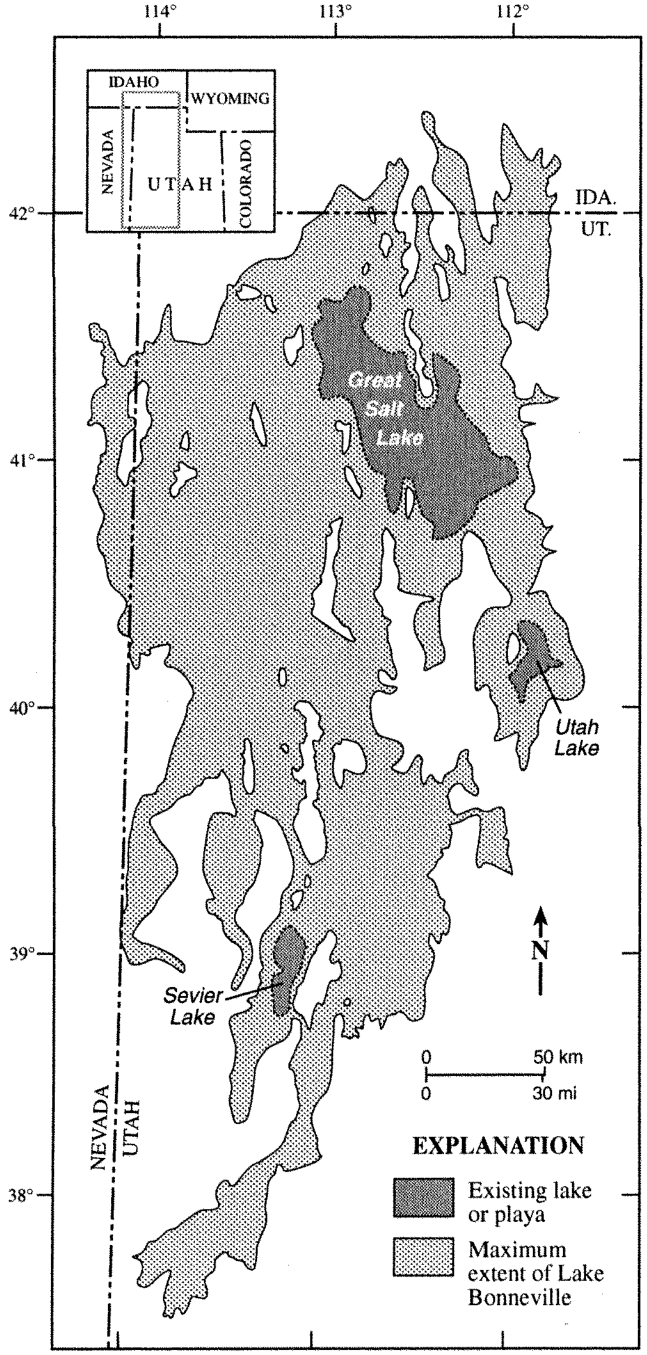

Figure 15. Location of Great Salt Lake and maximum extent of Pleistocene Lake Bonneville (modified from Currey et al., 1984).

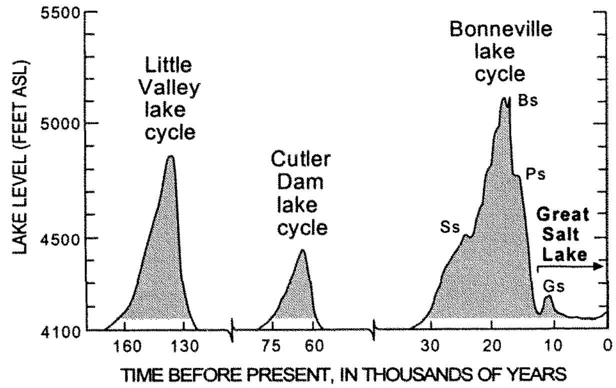

Figure 16. Hydrograph of probable lake levels in the Great Salt Lake basin for the past 150,000 years (modified from Currey and Oviatt, 1985; Machette et al., 1987). Ss = Stansbury shoreline, Bs = Bonneville shoreline, Ps = Provo shoreline, Gs = Gilbert shoreline.

removed by evaporation, lake levels drop to winter minima. Great Salt Lake levels fluctuate on average 2 feet (0.6 m) between winter low and summer high. Long-term fluctuations result from persistent low or high water-supply conditions, and lake levels are highly sensitive to minor precipitation, inflow, and evaporation variations. Long-term climatic trends play a major role in determining lake levels, as do diversion and consumptive use of water sources by man. Fluctuations in Great Salt Lake have a profound effect on the surface area of the lake because of the flatness of the lake basin. Extreme low or high lake levels are likely to persist even after the factors which caused them have changed.

Lake History and Flood Hazard

Lakes have occupied the Bonneville basin several times over the past several million years. Water levels in lakes such as Lake Bonneville and Great Salt Lake have oscillated with great elevation differences between highstands and lowstands (fig. 16). Lake Bonneville reached a maximum elevation (Bonneville shoreline) of 5,092 feet (1,552 m) around 15,000 years ago, and receded to a post-Bonneville lowstand after about 13,000 years ago (Currey and Oviatt, 1985). In the Salt Lake Valley, the elevation of the Bonneville shoreline varies from 5,161 to 5,216 feet (1,573 to 1,590 m) (Van Horn, 1972; Currey, 1982), due to a combination of isostatic rebound as the lake lowered and post-lake faulting (Miller, 1980). Isostatic rebound was generally greater near the center of the Bonneville basin than at the edges of the basin where water depths were shallower. Great Salt Lake reached a Holocene highstand of approximately 4,221 feet (1,287 m) between about 2,500 and 1,400 years ago (Currey et al., 1988; Murchison, 1989). A late prehistoric highstand of Great Salt Lake was at 4,215 feet (1,286 m) sometime during the 1600s (Murchison, 1989; Currey, 1990).

Although no significant diurnal tides occur on Great Salt Lake, wind seiches are common. Such seiches develop on the main body of the lake in response to strong winds from

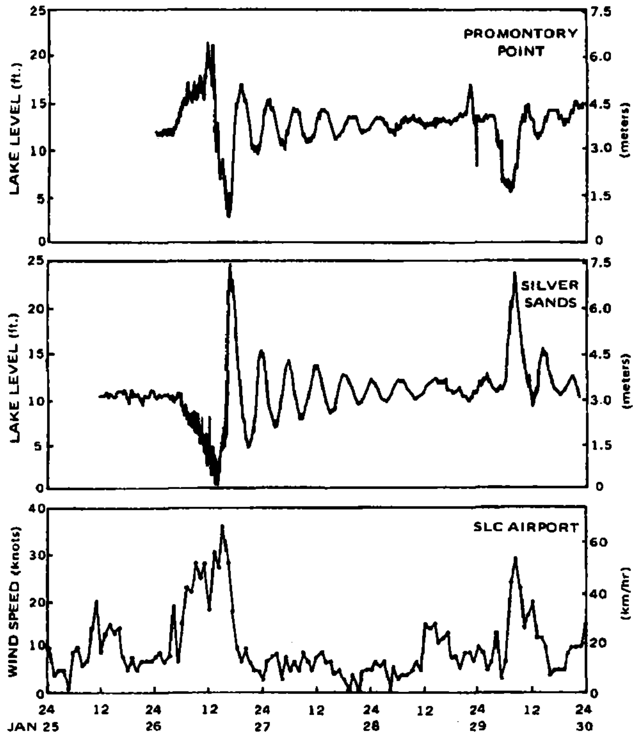

Figure 17. Great Salt Lake seiche hydrographs for Promontory Point (north) and Silver Sands (south), and wind speed at the Salt Lake City International Airport, showing wind seiches over a five-day period (from Lin and Wang, 1978).

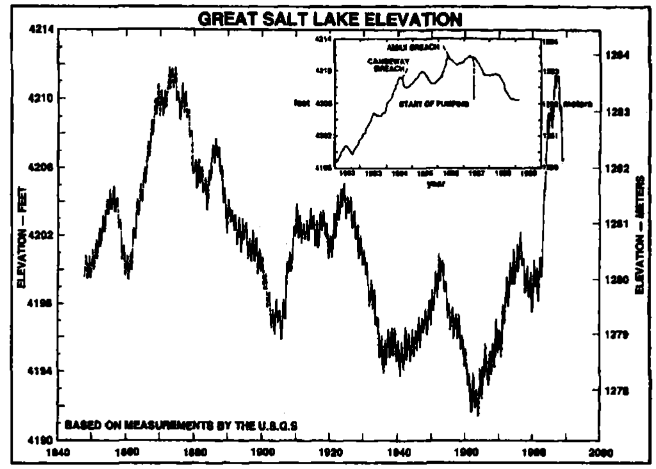

Figure 18. Hydrograph of Great Salt Lake. Elevations before 1875 are estimated from traditional accounts (from Atwood et al., 1990).

the south or west. A major wind seiche commonly needs wind velocities in excess of 10 knots (18.5 km/hr) (Lin and Wang, 1978). Sustained, strong south winds cause the water level to decline in the south and increase in the north (wind setup). When the wind velocity drops, water levels try to reach equilibrium. These wind-induced oscillations have a fundamental period of about 6 hours and seiching lasts about 2 days (fig. 17; Atwood et al., 1990). During this time, up to 2 feet (0.6 m) of flooding may occur along the south shore.

Great Salt Lake levels go through a seasonal cycle, waxing in spring or early summer in response to spring runoff, and waning in the fall at the end of the period of high evaporation (fig. 18). The maximum seasonal lake rise (measured in 1983) is 5 feet (1.5 m), and the maximum seasonal lake decline (measured in 1988) is 3 feet (0.9 m) (Atwood et al., 1990; Atwood and Mabey, 1995). Seasonal fluctuations are largely controlled by weather and are difficult to predict, but generally do not present a direct threat to life due to their slow rate of rise (maximum of about 1 inch per day [2.5 cm/day]).

Historical water levels in Great Salt Lake have also fluctuated over the long term (fig. 18). Until mid-1986, the historical high of Great Salt Lake was 4,211.5 feet (1,283.6 m) (Arnow and Stephens, 1990), which was reached in the early 1870s (Gilbert, 1890). The lake dropped slowly from its high in the 1870s, reaching an historical low of 4,191.35 feet (1,277.46 m) in 1963. Above-average precipitation in the 1980s caused Great Salt Lake to attain a new historical high of 4,211.85 feet (1,283.71 m) in June 1986 (Arnow and Stephens, 1990) and April 1987 (USGS records). This lake-level rise caused damage to structures and other property along the shoreline and within the lake. The cost to Salt Lake County for flooding at lake elevations greater than 4,212 feet (1,284 m) is believed to be in the millions of dollars (Atwood et al., 1990). If the lake rises to 4,217 feet (1,285 m), potential additional costs could exceed $3 billion (Steffen, 1986).

Flood Mitigation

The rapid rise of Great Salt Lake between 1982 and 1986 doubled the lake volume and increased its surface area by nearly 500,000 acres (Atwood et al., 1990). Flooding associated with the lake rise caused more than $240 million damage to facilities within and adjacent to the lake (Austin, 1988). The Southern Pacific Railroad causeway divided the lake into two unequal areas of different elevations: the north arm and the main Great Salt Lake. Most of the inflow was to the main Great Salt Lake. The causeway was breached in 1984, reducing the elevation of the main Great Salt Lake by about 8 inches (20 cm) and increasing the elevation of the north arm by about 16 inches (40 cm). However, the lake continued to rise and peaked (at its historical high) two years later.

In response to flooding, the Utah State Legislature authorized a study of potential lake-level control measures

(Utah Division of Water Resources, 1984). Pumping excess water into the shallow desert basin west of Great Salt Lake was the only measure that could be implemented quickly enough to provide flood-damage relief. Thus, construction began in 1986 on the West Desert Pumping Project (Atwood et al., 1990). By the end of 1988 2.05 million acre-feet (2.52 billion m^3) of water had been pumped from Great Salt Lake (James Palmer, written communication, 1989). The lake dropped 5.4 feet (1.6 m) by the end of 1988 due to a combination of pumping, evaporation, and decreased inflow from two drier than average years. The pumps are kept in reserve for future lake rises.

FIELD TRIP STOP NO. 5

Mike Lowe, Leader
Turn-out along North Ogden Canyon Road east of North Ogden; see Figure 27.

CAMERON COVE DEBRIS FLOW, NORTH OGDEN

A debris flow from an unnamed canyon deposited material on an alluvial fan in North Ogden (fig. 19) on September 7, 1991, damaging seven houses in the Cameron Cove subdivision (Mulvey and Lowe, 1991, 1994; Lowe et al., 1992). Over the 24-hour period prior to the debris-flow event, rainfall in the North Ogden area ranged from 2.5 to 8.4 inches (6.4 to 21.3 cm) (Brenda Graham, National Weather Service, verbal communication, 1991). This rainstorm set a new state record for a 24-hour period, and was estimated to be equivalent to a 1,000-year storm. Runoff from the storm was concentrated in channels on Tintic Quartzite cliffs at the head of the canyon and formed waterfalls which cascaded several hundred feet to talus slopes at the base of the cliffs. The runoff mobilized talus and other debris in and near tributary channels at the base of the cliffs, initiating debris flows. As the tributary flows moved downstream and combined with the main channel, additional channel material was incorporated into the debris flow. The flow exited the canyon mouth and traveled down an alluvial fan for a distance of about 1,300 feet (400 m), damaging the houses (Mulvey and Lowe, 1991).

An examination of the main and tributary channels indicated that channel material, from the base of the cliffs to the mouth of the canyon, had been incorporated into the debris flow (Mulvey and Lowe, 1991). Depth of scour in the main channel averaged 5 to 6 feet (1.5 to 1.8 m), and was as much as 17 feet (5 m) locally. Soils on drainage-basin slopes did not appear to have contributed much material to the flow except from an area of limited extent near the base of the cliffs where grasses were absent, cobbles were left standing on soil pedestals, and small rills were present. This was the only place damaged by a wildfire in 1990 that noticeably contributed sediment to the debris flow. Mulvey and Lowe (1991) concluded that sediment contribution from the burned area was low because of rapid revegetation of oakbrush, woody plants, and grasses.

Figure 19. Aerial view, looking northeast, of the September 7, 1991 Cameron Cove debris flow in North Ogden (photo taken in August 1996).

Mulvey and Lowe (1991, 1994) observed that much debris remained in and along the main and tributary channels after the debris-flow event. Considerable debris was trapped behind several natural dams composed of large boulders. In many places along the channel, side slopes had been destabilized by scour and undercutting of channel banks. Mulvey and Lowe (1991) were not able to accurately estimate the volume of debris still in the channel, but they believed that enough debris remained in the channel that another large debris-flow event from the drainage basin was possible.

The volume of the debris-flow deposit was about 25,728 cubic yards (19,553 m^3) (Mulvey and Lowe, 1991). Using the Pacific Southwest Inter-Agency Committee (PSIAC) (1968) Sediment Yield Rating Model, Lowe et al., (1990) estimated an average annual post-fire sediment yield of approximately 387 cubic yards (294 m^3) per year from

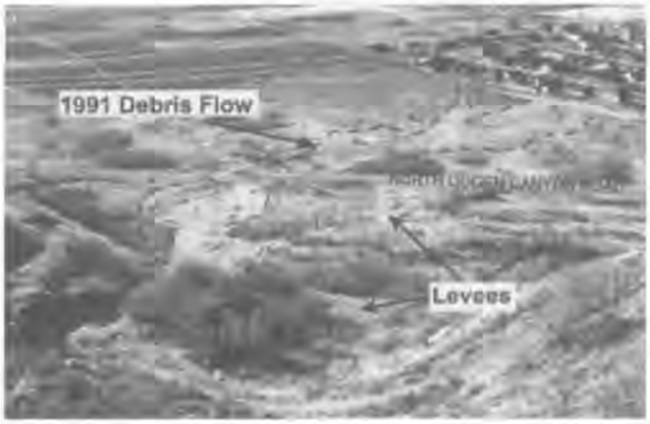

Figure 20. View, looking southwest, from near the apex of the alluvial fan above the Cameron Cove subdivision showing levees from past debris flows (modified from Mulvey and Lowe, 1994).

slopes within the drainage basin. The large difference between the PSIAC estimate and the actual volume of the debris flow supports Mulvey and Lowe's (1991) field observation that a small percentage of the total volume of debris was derived from the slopes and that the 1990 fire was not a significant cause of the debris flow. The majority of debris-flow material in the 1991 event was derived from scour of stream channels and talus on slopes immediately below the cliffs.

Relative Hazard

Future debris flows from the unnamed canyon are inevitable. Levees from prehistoric debris flows are present on the steep, active alluvial fan at the mouth of the canyon (fig. 20), indicating the 1991 debris flow was not a geologically unusual event for this canyon, but instead is part of the alluvial-fan-building process (Mulvey and Lowe, 1991). Ridd and Kaliser (1978) recognized that the alluvial fan is active, and mapped relative flood-hazard zones on the fan. Lowe (Weber County Planning Commission, 1988; Lowe, 1990) mapped debris-flow hazards as part of a comprehensive evaluation of geologic hazards in Weber County and placed the alluvial fan in a debris-flow-hazard special-study zone. The Cameron Cove subdivision was approved prior to completion of these geologic-hazard studies. The Ridd and Kaliser (1978) study led to enactment of a hazard ordinance regulating development on alluvial fans in the City of North Ogden where the Cameron Cove subdivision is located.

In spite of the existence of these geologic-hazard studies and ordinance, homeowners and North Ogden City officials were apparently unaware that flooding and debris-flow hazards existed in the Cameron Cove subdivision (Mulvey and Lowe, 1994). North Ogden City was named in a lawsuit brought by the owner of the home most severely damaged by the 1991 debris flow (Dennis Shupe, North Ogden City Manager, verbal communication, 1992). The lawsuit alleged that North Ogden City was negligent for not mitigating the debris-flow hazard on the alluvial fan after the hazard was identified by geologic studies (Mulvey and Lowe, 1994). The case judge ruled that the city could not be sued due to governmental immunity. The homeowner has subsequently erected a debris wall that can be seen along the eastern edge of the subdivision. Because no major sediment deposition has occurred on the alluvial fan since 1991, stream channels in the canyon above still contain debris that could be mobilized and incorporated into another large debris flow. Debris flows will likely be deposited again on the alluvial fan, and houses within the Cameron Cove subdivision remain at risk until a long-term, permanent solution to the problem is implemented.

FIELD TRIP STOP NO. 6

Mike Lowe, Leader

Rainbow Gardens parking lot, Ogden; see Figure 27.

RAINBOW IMPORTS LANDSLIDE, OGDEN

The Rainbow Imports landslide, near the mouth of Ogden Canyon in Weber County, is part of the Ogden River landslide complex of Pashley and Wiggins (1972). Vandre and Lowe (1995) delineated four domains within this landslide complex (fig. 21), each characterized by unique combinations of topography, ground-water conditions, soil properties, and movement mechanisms. They named the easternmost domain the frontage trough. After Pashley and Wiggins (1972), Vandre and Lowe (1995) referred to two other landslide domains, which include topographic reentrants, as the eastern amphitheater and western amphitheater. The fourth domain, the Rainbow Imports landslide, is along the eastern margin of the eastern amphitheater (figs. 21 and 22) and is the most active of the landslide domains. The landslide was named after the Rainbow Imports (now Rainbow Gardens) commercial development north of the landslide.

Geology

The Wasatch Range east of the Ogden River landslide complex is characterized by a lower section of near-vertical cliffs, consisting predominantly of Precambrian Farmington Canyon Complex granitic gneiss and Cambrian Tintic quartzite, and an upper section of more gently sloping mountainous terrain consisting predominantly of Paleozoic sedimentary rocks (Crittenden and Sorensen, 1985; Yonkee and Lowe, in preparation). Below 5,200 feet (1,585 m) in elevation, bedrock is generally covered by Lake Bonneville lacustrine sediments, or by post-Lake Bonneville alluvial-fan deposits. The bench area south of the landslide complex

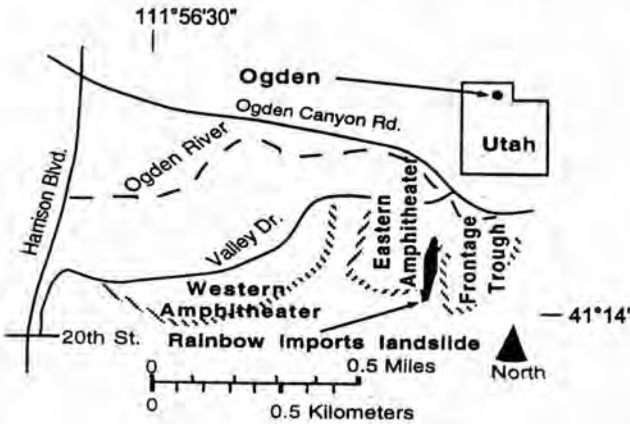

Figure 21. Landslide domains within the Ogden River landslide complex, and location of the Rainbow Imports landslide (from Vandre and Lowe, 1995).

Figure 22. Aerial view, looking south, of the eastern amphitheater of the Ogden River landslide complex. Rainbow Imports landslide indicated by arrow. Photo taken August 1996.

is the Provo-level delta of the Ogden and Weber Rivers and consists of gravel, sand, and silt deposited as Lake Bonneville occupied and then regressed from the Provo shoreline after about 14,000 years ago (Oviatt et al., 1992). The deltaic deposits overlie fine-grained, cyclically bedded sand, silt, and clay deposited during the earlier transgressional phase of Lake Bonneville.

Several ephemeral streams flow westward from the Wasatch Range and have deposited various ages of alluvial fans onto the delta. The four drainages between the Ogden River and Taylor Canyon, about 1.5 miles (2.4 km) south of the landslide complex, are ephemeral with catchment areas of less than 0.5 square mile (1.3 km^2). Taylor Canyon Creek has a much larger catchment area of about 2 square miles (5.2 km^2) and may be a significant source of recharge to ground water in the Lake Bonneville deposits at the landslide (Vandre and Lowe, 1995).

The Weber segment of the Wasatch fault zone offsets Lake Bonneville and alluvial-fan deposits along the eastern margin of the deltaic bench. Paleoseismic trenching studies of the Weber segment on the deltaic bench just north of the Ogden River show evidence of three to four surface-faulting events during the past 6,000 to 7,000 years (Nelson and Personius, 1993). Most of the fault scarps in the vicinity of the Ogden River landslide complex are west-facing, valley-side-down scarps. An antithetic, east-facing, mountain-side-down scarp is also present on the delta south of the Ogden River landslide complex, and this fault terminates along the eastern margin of the Rainbow Imports landslide (Yonkee and Lowe, in preparation). Two large conical depressions, probably sinkholes, along the base of the westernmost west-facing fault scarp (fig. 23) may be evidence of northward ground-water flow along the Wasatch fault zone.

The Ogden River incised and eroded laterally into the deltaic and lacustrine deposits at the mouth of Ogden Canyon as Lake Bonneville regressed from the Provo shoreline, leaving steep bluffs (Lowe et al., 1992) and depositing fluvial sand and gravel between the bluffs. The Ogden River landslide complex is along the erosional bluffs south of the Ogden River. All landslides in the complex are below about 4,710 feet (1,435 m) in elevation (Vandre and Lowe, 1995).

Movement History

The Rainbow Imports landslide initiated on March 9, 1987, damaging a steel transmission tower (fig. 24) causing a loss of power to much of Ogden's east bench area (Kaliser, 1987). Additional movement occurred on either the night of March 9 or early in the morning of March 10. Kaliser (1987) attributed the movement to soil saturation from melting snow and ice. Landsliding occurred again during April 1988 and February 1992. These landslide events involved mostly earth flows, and landslide activity generally stopped within a week or two.

The landslide moved again in early March 1994 (fig. 24) (Delta Geotechnical Consultants, 1994). Movement again involved mostly earth flows; however, the main scarp continuously retreated after the earth flows ceased. The main scarp of the landslide retreated an additional 50 feet (15 m) southward between April and August 1994, and two homes south of the landslide were removed in October 1994 due to concerns caused by the retreating main scarp (Vandre and Lowe, 1995). The main scarp had retreated southward an additional 15 to 20 feet (4 to 6 m) by April 1995. The overall slope of the main scarp during April 1995 was approximately 80 percent, with the top 15 to 20 feet (4 to 6 m) nearly vertical (Vandre and Lowe, 1995).

Figure 23. Sinkholes along a normal fault crossing the frontage trough, Ogden River landslide complex.

Figure 24. Rainbow Imports landslide in 1987 (A) and 1994 (B).

Vandre and Lowe (1995) estimated the width of historical landsliding to be approximately 50 yards (45 m). From 1987 to 1990, most of the movement involved sandy landslide debris. From 1990 to 1994, movement involved mostly deltaic and lacustrine deposits that had not previously been disturbed by landsliding (Vandre and Lowe, 1995). The volume of landslide material was about 25,000 cubic yards (19,000 m^3) between 1987 and 1990 and about 50,000 cubic yards (38,000 m^3) between 1990 and 1994.

Vandre and Lowe (1995) noted two springs discharging in the landslide area near the contact between the regressive deltaic and transgressive lacustrine deposits. They projected the top of the 1990 main scarp to be slightly below the elevation of the springs. A fault trace was noted in the 1994 main-scarp area; water moving northward along the Wasatch fault zone may have contributed to the spring flow.

Movement Mechanisms

SHB AGRA (1994) noted different soil movement mechanisms in different areas of the Rainbow Imports landslide. Vandre and Lowe (1995) refer to these areas as the undercut, erosion, and deposition zones.

The approximately 90-foot- (27 m) high main scarp is the undercut zone. The overall slope of this area was very steep with the finer grained soil layers generating near-vertical faces and the granular soils raveling to their angle of repose (Vandre and Lowe, 1995). The main soil movement mechanism in this area is collapse due to undercutting of fine-grained layers in response to wind and water erosion, and raveling of granular soils.

The erosion zone is the area immediately downslope from the undercut zone. The erosion zone's vertical extent was approximately 50 feet (15 m) with side scarps on the order of 20 to 30 feet (6–9 m) high (Vandre and Lowe, 1995). Soil movement in this zone was primarily erosion caused by runoff from springs discharging at the top of the zone, and earth flows.

The deposition zone is below the erosion zone. The ground slope at the top of this zone is 25 to 30 percent, but lower in the zone is 20 percent or less (Vandre and Lowe, 1995). Soil deposition is caused by decreases in slope and spreading out of flowing water due to lack of confinement.

Potential for Additional Movement

Conditions contributing to slope failure at the Rainbow Imports landslide include the presence of: (1) slopes steeper than 60 to 70 percent which are subject to undercutting and raveling, (2) soils prone to erosion by wind and water, (3) ground water in close proximity to the contact between the deltaic and lacustrine deposits, and (4) saturated sandy soils which have the potential to undergo liquefaction. Due to these conditions, a high potential for future movement exists (Vandre and Lowe, 1995). The most significant landslide hazard is to homes south of the present main scarp.

The Rainbow Imports landslide will continue to retreat southward into the delta as the main scarp is undermined by erosion, flow slides, and/or raveling of the sand and gravel in the scarp. The rate of main-scarp retreat cannot be predicted. The time needed to reach stability may be 10, 50, or 100 years or more, and Vandre and Lowe (1995) expect the rate of main-scarp retreat to decrease as its slope decreases. Major earthquakes will likely accelerate the raveling of the main scarp, possibly causing liquefaction of the saturated sands deposited in the erosion zone, thereby causing liquefaction-induced slope failures and more erosion and undercutting. Runoff over the main scarp may accelerate the rate of retreat (Vandre and Lowe, 1995).

ROAD LOG

The following road log describes the route of the field trip and indicates selected geologic features and other points of interest. Space limitations preclude reference to many sites and features along the route, however, and the reader is encouraged to consult guidebooks for previous geologic field trips along the Wasatch Front (for example, Utah Geological Association, 1971; Gurgel, 1983; Machette, 1988; Lowe et al., 1992; Horns et al., 1995) for additional information.

Mileage		
0.0		The field trip departs from the Salt Palace Convention Center at 100 South West Temple in Salt Lake City (fig. 25); proceed SOUTH on WEST TEMPLE.
0.4	(0.4)	Turn LEFT (EAST) on 400 SOUTH.
0.7	(0.3)	Turn RIGHT (SOUTH) on STATE STREET.
3.5	(2.8)	Turn LEFT (EAST) onto I-80 eastbound; follow signs for I-215, SOUTH BELT ROUTE, at the mouth of Parleys Canyon. Rocks exposed in the vicinity of Parleys Canyon consist of folded Mesozoic strata.
10.0	(6.5)	On the left (east) side of the freeway, residences along the upper margins of Olympus Cove are periodically affected by rock falls. The prominent peak rising above the southern part of Olympus Cove is Mt. Olympus, the north face of which is a dip slope of Cambrian Tintic Quartzite (Crittenden, 1965a).
13.0	(3.0)	Take EXIT 6 (6200 SOUTH), turn LEFT (SOUTHEAST) under freeway, proceed up hill and continue SOUTH on WASATCH BOULEVARD.
14.0	(1.0)	Active sand and gravel mining operations on the left (east) side of the road in outwash-fan/delta-complex sediments (Scott, 1981; Personius and Scott, 1992).
14.9	(0.9)	Mouth of Big Cottonwood Canyon. Rocks exposed at the mouth of the canyon con-

Figure 25. Route of field trip showing stops 1 and 2. Base from USGS Salt Lake City 30 X 60 minute quadrangle.

sist of quartzite, shale, and siltstone of the Precambrian Big Cottonwood Formation locally intruded by quartz monzonite of the Tertiary Little Cottonwood stock (Crittenden, 1965b).

17.0 (2.1) Turn RIGHT (SOUTH) and continue on WASATCH BOULEVARD; the road is in a graben bounded by scarps of the main trace of the Wasatch fault zone on the left (east) and an antithetic fault on the right (west) (Scott and Shroba, 1985; Personius and Scott, 1992).

18.1 (1.1) Turn RIGHT (WEST) on 9800 SOUTH, then RIGHT (SOUTH) into large vacant lot near the mouth of Little Cottonwood Canyon for **STOP 1** (fig. 25) and discussion of **PALEOSEISMIC STUDIES ON THE SALT LAKE CITY SEGMENT OF THE WASATCH FAULT ZONE**. From here, Wasatch fault zone scarps can be seen to the southeast cutting the Pinedale-aged Bells Canyon moraine.

Retrace route to NORTH on WASATCH BOULEVARD.

22.6 (4.5) Turn RIGHT (EAST) at traffic light and continue NORTH on WASATCH BOULEVARD.

23.3 (0.7) New golf course on the left (west) side of the road is in a reclaimed sand and gravel pit in Lake Bonneville regressive-phase deltaic deposits (Personius and Scott, 1992).

24.1 (0.8) Park at Pete's Rock, an outcrop of Precambrian Mutual Formation quartzite (Crittenden, 1965a) and local climbing area, for **STOP 2** (fig. 25) and discussion of **SEISMIC SITE RESPONSE IN THE SALT LAKE VALLEY**. This stop provides an overlook of the Salt Lake Valley with views from left (south) to right (north) of the Traverse Mountains, Oquirrh Mountains and Bingham open-pit mine, Great Salt Lake and Antelope Island, downtown Salt Lake City, and the Salt Lake salient.

Continue NORTH on WASATCH BOULEVARD.

27.5 (3.4) At 3300 SOUTH, continue NORTH on I-215 and follow signs for FOOTHILL DRIVE.

32.0 (4.5) University of Utah campus. FOOTHILL DRIVE turns to the LEFT (WEST) and becomes 500 SOUTH.

32.7 (0.7) Robert L. Rice Stadium on the right (south) will be the locale for the opening and closing ceremonies of the 2002 Winter Olympics. Foundation excavations for the stadium, as well as the George S. Eccles Tennis Center on the south side of 500 South, revealed evidence of faulting in pre-Bonneville alluvial-fan deposits.

33.2 (0.5) 500 SOUTH turns to the RIGHT (NORTH) to descend a hill formed by the scarp of the East Bench fault. At the base of the scarp, the road turns to the LEFT (WEST) and becomes 400 SOUTH.

34.5 (1.3) At the intersection of 400 SOUTH and 200 EAST, the Salt Lake City and County Building is on the left. The seismic retrofit of this historic building is summarized above in the discussion for field-trip stop 2.

35.2 (0.7) Turn RIGHT (NORTH) on 300 WEST.

37.0 (1.8) 300 WEST becomes BECK STREET. Several hot springs occur in this area along the Warm Springs fault at the base of the slope to the right (east).

38.5 (1.5) Active quarry operations on the right (east) side of the road in Paleozoic carbonates. Crushed stone is produced here for use in aggregate and other engineering applications. A faulted Holocene alluvial fan observed here by G.K. Gilbert (1890) has been removed by quarrying; striated bedrock in the footwall of the fault is now exposed at the base of the slope.

39.4 (0.9) Continue NORTH on I-15. The Bonneville and Provo shorelines of Lake Bonneville are well exposed near the base of the Wasatch Range on the right (east). The Bonneville shoreline marks the highest level reached by Lake Bonneville around 15,000 years ago (Currey and Oviatt, 1985); the Provo shoreline is a regressive shoreline about 350 feet (107 m) below the Bonneville shoreline. Several of the canyons on the west slope of the Wasatch Range between Bountiful and Farmington have produced damaging and, in some cases, fatal debris flows and floods. Notable debris flows occurred in the 1920s, 1930s, and 1983. Debris flows during the 1920s and 1930s were primarily generated by overland erosion during summer cloudburst storms (Woolley, 1946; Butler and Marsell, 1972; Keaton, 1988), whereas debris flows during the spring of 1983 were mobilized from landslides caused by rapid melting of an unusually thick snowpack (Wieczorek et al., 1983, 1989).

49.7 (10.3) Take EXIT 325 (LAGOON DRIVE–FARMINGTON) and bear RIGHT to continue NORTH on 200 WEST.

50.6 (0.9) Turn LEFT (WEST) on STATE STREET (U.S. 227). Cross over freeway, pass new Davis County Criminal Justice Complex on the left (south), which is near the center of the prehistoric Farmington Siding landslide complex.

52.1 (1.5) Turn RIGHT (NORTH) on 1525 WEST. Note hummocky landslide terrain in this area.

52.7 (0.6) Park near the intersection of 1525 WEST and 675 NORTH in hummocky landslide terrain for **STOP 3** (fig. 26) and discussion of **THE LIQUEFACTION-INDUCED FARMINGTON SIDING LANDSLIDE COMPLEX**.

Continue WEST on 675 NORTH.

53.7 (1.0) Turn RIGHT (EAST) on SHEPARD LANE and cross over freeway. The golf course was constructed on naturally hummocky landslide terrain; the clubhouse and parking lot (on the left [north]) are at the top of the landslide main scarp.

54.9 (1.2) Turn RIGHT (SOUTH) on U.S. 89.

55.2 (0.3) Turn RIGHT (WEST) onto I-15 NORTHBOUND.

63.5 (8.3) Take EXIT 335 (SYRACUSE).

63.8 (0.3) Turn LEFT (WEST) on ANTELOPE DRIVE (UTAH 108). Proceed WEST, following signs for Syracuse and Antelope Island.

70.6 (6.8) Antelope Island State Park fee station. The causeway that provides vehicle access to Antelope Island was completely submerged by high lake levels in 1985. The

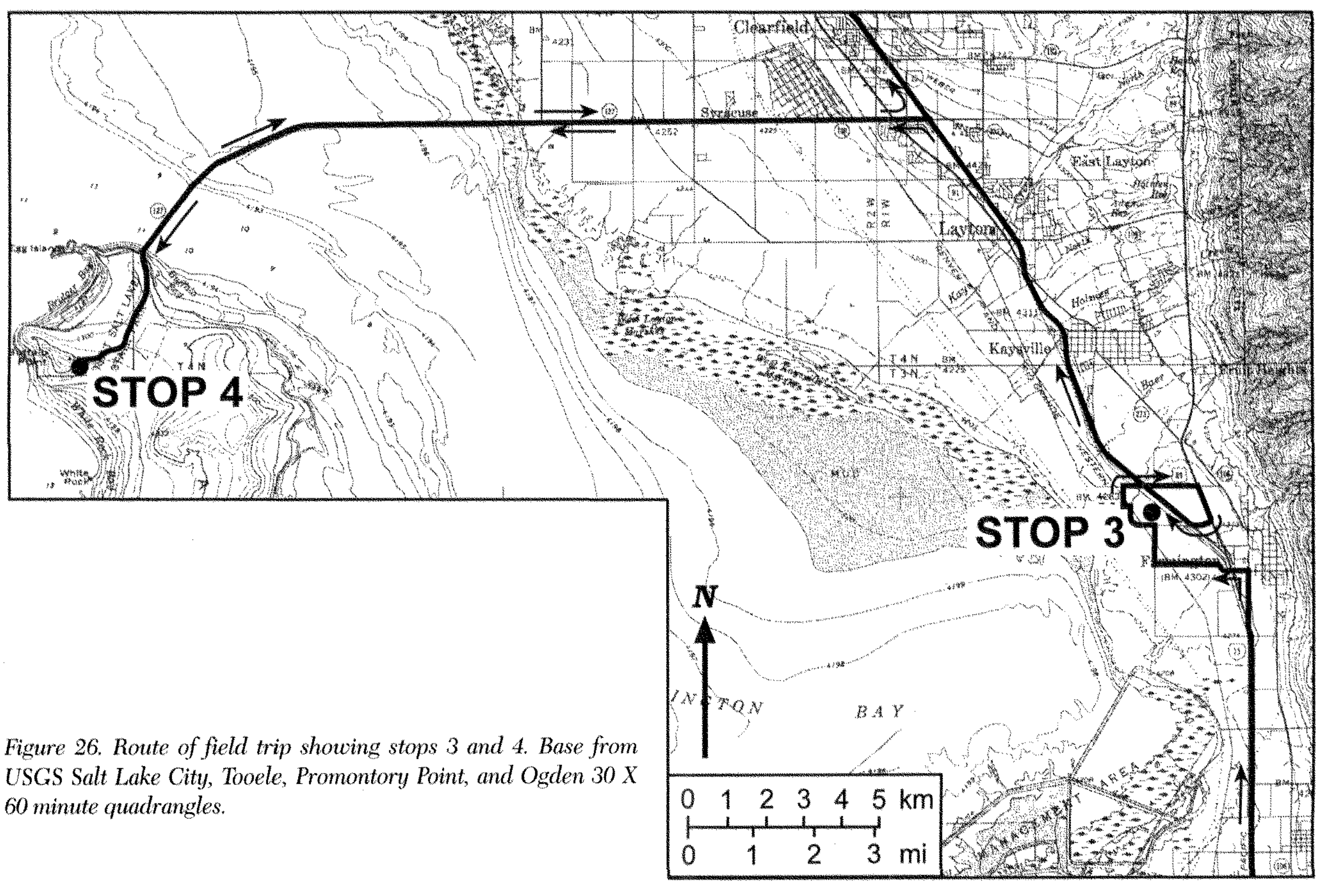

Figure 26. Route of field trip showing stops 3 and 4. Base from USGS Salt Lake City, Tooele, Promontory Point, and Ogden 30 X 60 minute quadrangles.

island was inaccessible to the public until Davis County rebuilt the causeway in 1993.

77.4 (6.8) Bear LEFT (SOUTHWEST) and follow paved road to Buffalo Point.

79.8 (2.4) Stop at Buffalo Point for **STOP 4** (fig. 26), discussion of **FLOOD HAZARD FROM GREAT SALT LAKE**, and lunch. Antelope Island has excellent exposures of Lake Bonneville and Great Salt Lake shorelines. Because of isostatic rebound, the elevation of the Bonneville shoreline is as much as 150 feet (45 m) higher on Antelope Island than at the margins of the Bonneville basin (Doelling et al., 1988).

Retrace route to I-15.

95.6 (15.8) Turn LEFT (NORTH) onto I-15 NORTHBOUND.

111.6 (16.0) Take EXIT 352 (PLAIN CITY–NORTH OGDEN) and turn RIGHT (EAST) on 2700 NORTH. View to the left (north) of Ben Lomond Peak. Rocks exposed on the south flank of the mountain consist of quartz monzonite gneiss of the Lower Proterozoic Farmington Canyon Complex overlain by a thrust-fault-repeated sequence of Cambrian marine strata (Crittenden and Sorensen, 1985). The prominent escarpment on the alluvial fan at the base of the mountain marks the Bonneville shoreline.

112.8 (1.2) Turn RIGHT (SOUTH) on U.S. 89.

112.9 (0.1) Turn LEFT (EAST) on UTAH 235 (2550 NORTH). The road between the freeway exit and Washington Boulevard crosses landslide deposits of the prehistoric liquefaction-induced North Ogden landslide complex (Miller, 1980; Personius, 1990; Harty et al., 1993).

114.7 (1.8) Turn LEFT (NORTH) on WASHINGTON BOULEVARD.

114.8 (0.1) Turn RIGHT (EAST) on 2600 NORTH.

115.8 (1.0) Turn LEFT (NORTH) on 1050 EAST.

116.5 (0.7) Turn RIGHT (EAST) on 3100 NORTH (NORTH OGDEN CANYON ROAD).

117.1 (0.6) Debris flow in 1991 exited canyon mouth on the left (north), crossed the road, and deposited material in the residential subdivision at the base of the alluvial fan.

117.3 (0.2) Park in turn-out on the right side of the road for **STOP 5** (fig. 27) and discussion of the **CAMERON COVE DEBRIS FLOW**. View to the west of the 1991 debris-flow deposit on the alluvial fan.

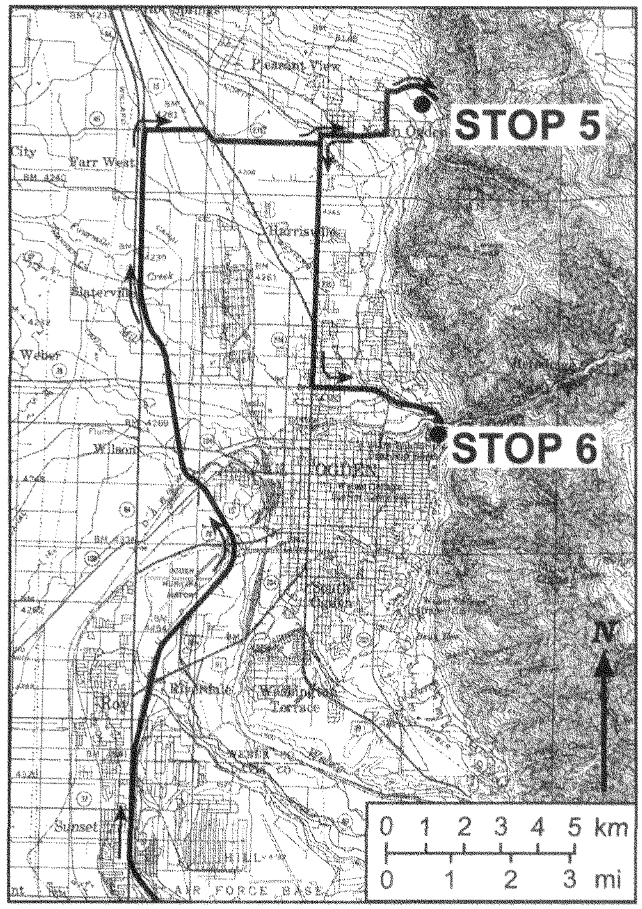

Figure 27. Route of field trip showing stops 5 and 6. Base from USGS Promontory Point and Ogden 30 X 60 minute quadrangles.

Retrace route to WASHINGTON BOULEVARD.

119.9 (2.6) Turn LEFT (SOUTH) on WASHINGTON BOULEVARD.

124.0 (4.1) Turn LEFT (EAST) on 12TH STREET.

125.2 (1.2) Continue straight at the traffic light where 12TH STREET becomes UTAH 39.

126.2 (1.0) Turn RIGHT (WEST) on VALLEY DRIVE and then LEFT (SOUTH) into the Rainbow Gardens parking lot, located in the eastern amphitheater of the Ogden River landslide complex, for **STOP 6** (fig. 27) and discussion of the **RAINBOW IMPORTS LANDSLIDE**. The landslide is on the bluff south of the parking lot.

Continue WEST on VALLEY DRIVE. Landslides within the Ogden River landslide complex are on the left (south). At the golf course, the road crosses landslide toe deposits.

127.3 (1.1) Cross HARRISON BOULEVARD and continue WEST on 20TH STREET. Follow signs for I-15.

130.7 (3.4) Turn LEFT (SOUTH) onto I-15 SOUTHBOUND and return to Salt Palace Convention Center.

REFERENCES CITED

Adan, S.M., and Rollins, K.M., 1993, Damage potential index mapping for Salt Lake Valley, Utah: Utah Geological Survey Miscellaneous Publication 93-4, 64 p.

Algermissen, S.T., 1988, Earthquake hazard and risk assessment—Some applications to problems of earthquake insurance, *in* Hays, W.W., ed., Workshop on "Earthquake Risk—Needs of the Insurance Industry": U.S. Geological Survey Open-File Report 88-669, p. 9–39.

Algermissen, S.T., Perkins, D.M., Thenhaus, P.C., Hanson, S.L., and Bender, B.L., 1990, Probabilistic earthquake acceleration and velocity maps for the United States and Puerto Rico: U.S. Geological Survey Miscellaneous Field Studies Map MF-2120, scale 1:7,500,000.

Anderson, L.R., Keaton, J.R., Aubrey, K., and Ellis, S.J., 1982, Liquefaction potential map for Davis County, Utah: Logan, Utah State University Department of Civil and Environmental Engineering and Dames & Moore Consulting Engineers, final technical report for the U.S. Geological Survey, 50 p. (published as Utah Geological Survey Contract Report 94-7).

Anderson, L.R., Keaton, J.R., Spitzley, J.E., and Allen, A.C., 1986, Liquefaction potential map for Salt Lake County, Utah. Logan, Utah State University Department of Civil and Environmental Engineering and Dames & Moore Consulting Engineers, final technical report for the U.S. Geological Survey, 48 p. (published as Utah Geological Survey Contract Report 94-9).

Arnow, T., and Stephens, D., 1990, Hydrological characteristics of the Great Salt Lake, Utah—1847–1986. U.S. Geological Survey Water-Supply Paper 2332, 32 p.

Atwood, G., and Mabey, D.R., 1995, Flooding hazards associated with Great Salt Lake, *in* Lund, W.R., ed., Environmental and engineering geology of the Wasatch Front region. Utah Geological Association Publication 24, p. 483–493.

Atwood, G., Mabey, D.R., and Lund, W.R., 1990, The Great Salt Lake—A hazardous neighbor, *in* Lund, W.R., ed., Engineering geology of the Salt Lake City metropolitan area, Utah: Utah Geological and Mineral Survey Bulletin 126, p. 54–58.

Austin, L.H., 1988, Problems and management alternatives related to the rising level of Great Salt Lake, *in* Proceedings 6th International Water Resources Association World Congress on Water Resources: Ottawa, Canada, International Water Resources Association.

Bailey, J.S., and Allen, E.W., 1988, Massive resistance: Civil Engineering, v. 58, no. 9, p. 52–55.

Black, B.D., Lund, W.R., Schwartz, D.P., Gill, H.E., and Mayes, B.H., 1996, Paleoseismic investigation on the Salt Lake City segment of the Wasatch fault zone at the South Fork Dry Creek and Dry Gulch sites, Salt Lake County, Utah, *in* Lund, W.R., ed., Paleoseismology of Utah, Volume 7: Utah Geological Survey Special Study 92, 22 p.

Building Seismic Safety Council, 1994, NEHRP recommended provisions for seismic regulations for new buildings: Washington, D.C., Federal Emergency Management Agency Publications 222A (Part 1—Provisions, 290 p.) and 223A (Part 2—Commentary, 335 p.).

Butler, E., and Marsell, R.E., 1972, Cloudburst floods in Utah, 1939–69: Utah Department of Natural Resources, Division of Water Resources, Cooperative Investigations Report No. 11, 103 p.

Crittenden, Jr., M.D., 1965a, Geology of the Sugar House quadrangle, Salt Lake County, Utah: U.S. Geological Survey Geologic Quadrangle Map GQ-380, scale 1:24,000.

Crittenden, Jr., M.D., 1965b, Geology of the Draper quadrangle, Utah: U S. Geological Survey Geologic Quadrangle Map GQ-377, scale 1:24,000.

Crittenden, Jr., M.D., and Sorensen, M.L., 1985, Geologic map of the North Ogden quadrangle and part of the Ogden and Plain City quadrangles, Box Elder and Weber Counties, Utah: U.S. Geological Survey Miscellaneous Investigations Series Map I-1606, scale 1:24,000.

Currey, D.R., 1982, Lake Bonneville—Selected features of relevance to neotectonic analysis. U.S. Geological Survey Open-File Report 82-1070, 30 p.

Currey, D.R., 1990, Quaternary paleolakes in the evolution of semidesert basins, with special emphasis on Lake Bonneville and the Great Basin, U.S.A.: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 76, p. 189–214.

Currey, D.R., Atwood, G., and Mabey, D.R., 1984, Major levels of Great Salt Lake and Lake Bonneville: Utah Geological and Mineral Survey Map 73, scale 1:750,000.

Currey, D.R., Berry, M.S., Douglass, G.E., Merola, J.A., Murchison, S.B., and Ridd, M.K., 1988, The highest Holocene stage of Great Salt Lake, Utah [abs.]: Geological Society of America Abstracts with Programs, v. 20, no. 6, p. 411.

Currey, D.R., and Oviatt, C.G., 1985, Durations, average rates, and probable causes of Lake Bonneville expansions, still-stands, and contractions during the last deep-lake cycle, 32,000 to 10,000 years ago, *in* Kay, P.A., and Diaz, H.F., eds., Problems of and prospects for predicting Great Salt Lake levels—Proceedings of a NOAA Conference, March 26–28, 1985: Salt Lake City, University of Utah, Center for Public Affairs and Administration, p. 9–24.

Dames & Moore, 1996, Final report, seismic hazard analysis of the I-15 corridor, 10600 South to 500 North, Salt Lake County, Utah: Seattle and Salt Lake City, unpublished consultant's report, variously paginated.

Delta Geotechnical Consultants, 1994, Preliminary assessment, Ogden Canyon landslide, Ogden, Utah: Salt Lake City, unpublished consultant's report, 3 p.

Doelling, H.H., Willis, G.C., Jensen, M.E., Hecker, S., Case, W.F., and Hand, J.S., 1988, Geology of Antelope Island, Davis County, Utah: Utah Geological and Mineral Survey Open-File Release 144, 82 p.

Everitt, B., 1991, Stratigraphy of eastern Farmington Bay: Utah Geological and Mineral Survey, Survey Notes, v. 24, no. 3, p. 27–29.

Federal Emergency Management Agency, 1985, Reducing losses in high risk flood hazard areas—A guidebook for local officials: Federal Emergency Management Agency Publication No. 116, 225 p.

Forman, S.L., Nelson, A.R., and McCalpin, J.P., 1991, Thermoluminescence dating of fault-scarp-derived colluvium—deciphering the timing of paleoearthquakes on the Weber segment of the Wasatch fault zone, north central Utah: Journal of Geophysical Research, v. 96, no. B1, p. 595–605.

Gilbert, G.K., 1890, Lake Bonneville: U.S. Geological Survey Monograph 1, 438 p.

Gill, H.E., 1987, Utah Geological and Mineral Survey excavation inspection program—A tool for earthquake hazard recognition in Utah, *in* Gori, P.L., and Hays, W.W., eds., Assessment of regional earthquake hazards and risk along the Wasatch Front, Utah, Volume II: U.S. Geological Survey Open-File Report 87-585, p. U1–U19.

Gurgel, K D., ed., 1983, Geologic excursions in neotectonics and engineering geology in Utah, Geological Society of America Guidebook—Part IV. *Utah Geological and Mineral Survey Special Studies 62, 109 p*

Harty, K M , Lowe, Mike, and Christenson, G E., 1993, Hazard potential and paleoseismic implications of liquefaction-induced landslides along the Wasatch Front, Utah Utah Geological Survey, unpublished Final Technical Report for the U.S Geological Survey, 57 p.

Hays, W.W., and King, K.W., 1984, The ground-shaking hazard along the Wasatch fault zone, Utah, *in* Hays, W.W., and Gori, P.L., eds., A workshop on "Evaluation of regional and urban earthquake hazards and risk in Utah". U.S. Geological Survey Open-File Report 84-763, p. 133–147.

Horns, D., Evenstad, N., Amodt, L., Atwood, G , Black, B.D., Hylland, M., Keaton, J.R., Lund, W.R , Rollins, K., and Vandre, B., 1995, Environmental and engineering geology of the Wasatch Front region, 1995 Utah Geological Association Field Conference, September 23, 1995, road log, *in* Lund, W.R., ed., Environmental and engineering geology of the Wasatch Front region: Utah Geological Association Publication 24, p. 533–541

Hylland, M.D., 1996, Paleoseismic analysis of the liquefaction-induced Farmington Siding landslide complex, Wasatch Front, Utah [abs.]. Geological Society of America Abstracts with Programs, v. 28, no. 7, p A–157.

Hylland, M.D, and Lowe, M., 1995, Hazard potential, failure type, and timing of liquefaction-induced landsliding in the Farmington Siding landslide complex, Wasatch Front, Utah· Utah Geological Survey Open-File Report 332, 47 p.

Hylland, M.D, and Lowe, M., in press, Characteristics, timing, and hazard potential of liquefaction-induced landsliding in the Farmington Siding landslide complex, Wasatch Front, Utah. Utah Geological Survey Special Study.

Kaliser, B.N , 1971, Engineering geology of the City and County Building, Salt Lake City, Utah. Utah Geological and Mineralogical Survey Special Studies 38, 10 p.

Kaliser, B N., 1987, Rainbow Gardens landslide of March 9, 1987, Weber County: Utah Geological Survey, unpublished memorandum, 2 p.

Keaton, J R , 1988, A probabilistic model for hazards related to sedimentation processes on alluvial fans in Davis County, Utah: College Station, Texas A&M University, 441 p

Keaton, J.R., and Anderson, L.R., 1995, Mapping liquefaction hazards in the Wasatch Front region—Opportunities and limitations, *in* Lund, W.R , ed., Environmental and engineering geology of the Wasatch Front region. Utah Geological Association Publication 24, p 453–468.

Lin, A., and Wang, P., 1978, Wind tides of the Great Salt Lake Utah Geological and Mineral Survey, Utah Geology, v. 5, no 1, p 17–25.

Lowe, M., 1990, Geologic hazards and land-use planning—Background, explanation, and guidelines for development in Weber County in designated special study areas. Utah Geological and Mineral Survey Open-File Report 197, 70 p.

Lowe, M., Black, B D., Harty, K M , Keaton, J.R., Mulvey, W.E., Pashley, Jr., E.F., and Williams, S.R., 1992, Geologic hazards of the Ogden area, Utah, *in* Wilson, J.R., ed., Field guide to geologic excursions in Utah and adjacent areas of Nevada, Idaho, and Wyoming: Utah Geological Survey Miscellaneous Publication 92-3, p 231–285.

Lowe, M., Harty, K M , and Hylland, M.D., 1995, Geomorphology and failure history of the earthquake-induced Farmington Siding landslide complex, Davis County, Utah, *in* Lund, W.R., ed., Environmental and engineering geology of the Wasatch Front region. Utah Geological Association Publication 24, p. 205–219.

Lowe, M., Harty, K.M., and Rasely, R.C., 1990, Reconnaissance of area burned by wild fire northeast of North Ogden and evaluation of potential sediment yield. Utah Geological and Mineral Survey, unpublished memorandum to Dennis R. Shupe, North Ogden City Administrator, 5 p.

Lund, W.R., ed., 1990, *Engineering geology of the Salt Lake City metropolitan area, Utah* Utah Geological and Mineral Survey (in conjunction with the Association of Engineering Geologists) Bulletin 126, 66 p

Lund, W R , 1992, New information on the timing of earthquakes on the Salt Lake City segment of the Wasatch fault zone—Implications for increased earthquake hazard along the central Wasatch Front: Utah Geological Survey, Wasatch Front Forum, v 8, no 3, p 12–13.

Lund, W.R., and Schwartz, D.P., 1987, Fault behavior and earthquake recurrence at the Dry Creek site, Salt Lake City segment, Wasatch fault zone, Utah [abs.]: Geological Society of America Abstracts with Programs, v. 19, no. 5, p 317.

Lund, W.R., Schwartz, D P, Mulvey, W E , Budding, K.E., and Black, B.D , 1991, Fault behavior and earthquake recurrence on the Provo segment of the Wasatch fault zone at Mapleton, Utah County, Utah Utah Geological and Mineral Survey Special Studies 75, 41 p.

Mabey, D R , 1992, Subsurface geology along the Wasatch Front, *in* Gori, P.L., and Hays, W.W., eds., Assessment of regional earthquake hazards *and risk along the Wasatch Front, Utah U.S. Geological Survey* Professional Paper 1500-A-J, p. C1–C16.

Machette, M.N., ed., 1988, In the footsteps of G.K. Gilbert—Lake Bonneville and neotectonics of the eastern Basin and Range Province, Geological Society of America Guidebook for Field Trip Twelve. Utah Geological and Mineral Survey Miscellaneous Publication 88-1, 120 p.

Machette, M.N., Personius, S.F, and Nelson, A.R., 1987, Quaternary geology along the Wasatch fault zone—Segmentation, recent investigations, and preliminary conclusions, *in* Gori, P.L , and Hays, W.W., eds , Assessment of regional earthquake hazards and risk along the Wasatch Front, Utah. U.S. Geological Survey Open-File Report 87-585, p A1–A72.

Machette, M.N., Personius, S.F., and Nelson, A R , 1992, Paleoseismology of the Wasatch fault zone—A summary of recent investigations, interpretations, and conclusions, *in* Gori, P.L , and Hays, W.W, eds., Assessment of regional earthquake hazards and risk along the Wasatch Front, Utah: U.S Geological Survey Professional Paper 1500, p A1–A71.

Machette, M.N., Personius, S.F., Nelson, A R., Schwartz, D P., and Lund, W.R., 1991, The Wasatch fault zone, Utah—Segmentation and history of Holocene earthquakes Journal of Structural Geology, v 13, no 2, p 137–149.

McCalpin, J , and Forman, S.L., 1994, Assessing the paleoseismic activity of the Brigham City segment, Wasatch fault zone, Utah—Site of the next major earthquake on the Wasatch Front? Utah State University and Byrd Polar Research Institute, unpublished Final Technical Report for the U S Geological Survey, 19 p

McCalpin, J P., and Nishenko, S.P., 1996, Holocene paleoseismicity, temporal clustering, and probabilities of future large ($M>7$) earthquakes on the Wasatch fault zone, Utah Journal of Geophysical Research, v. 101, no B3, p. 6233–6253.

Miller, R D , 1980, Surficial geologic map along part of the Wasatch Front, Salt Lake Valley, Utah. U.S. Geological Survey Miscellaneous Field Studies Map MF-1198, scale 1:100,000, 13 p. pamphlet.

Miller, R.D., Olsen, H.W, Erickson, G S , Miller, C.H., and Odum, J.K., 1981, Basic data report of selected samples collected from six test holes at five sites in the Great Salt Lake and Utah Lake valleys, Utah. U.S. Geological Survey Open-File Report 81-179, 49 p

Mulvey, W.E., and Lowe, M , 1991, Cameron Cove subdivision debris flow, North Ogden, Utah, *in* Mayes, B.H , compiler, Technical reports for 1990–1991, Applied Geology Program Utah Geological Survey Report of Investigation 222, p. 186–191

Mulvey, W.E., and Lowe, M , 1994, 1991 Cameron Cove subdivision debris flow, North Ogden, Utah, U.S.A.. Proceedings of the 1992 Arid West Flood Plain Managers Conference, p. 117–123

Murchison, S.B., 1989, Fluctuation history of Great Salt Lake, Utah, during the last 13,000 years. Salt Lake City, University of Utah, Ph.D. thesis, 137 p.

Nelson, A.R., and Personius, S.F., 1993, Surficial geologic map of the Weber segment, Wasatch fault zone, Weber and Davis Counties, Utah. U.S. Geological Survey Miscellaneous Investigations Series Map I-2199, 22 p. pamphlet, scale 1:50,000.

Oaks, S.D., 1987, Effects of six damaging earthquakes in Salt Lake City, Utah, *in* Gori, P.L., and Hays, W.W., eds., Assessment of regional earthquake hazards and risk along the Wasatch Front, Utah, Volume II. U.S. Geological Survey Open-File Report 87-585, p. P1–P95.

Olig, S.S., 1991, Earthquake ground shaking in Utah. Utah Geological and Mineral Survey, Survey Notes, v. 24, no. 3, p. 20–25

Olsen, K.B., Pechmann, J.C., and Schuster, G.T., 1995, Simulation of 3D elastic wave propagation in the Salt Lake basin: Bulletin of the Seismological Society of America, v. 85, no. 6, p. 1688–1710.

Oviatt, C.G., Currey, D.R., and Sack, D., 1992, Radiocarbon chronology of Lake Bonneville, eastern Great Basin, U.S.A.: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 99, p. 225–241.

Pacific Southwest Inter-Agency Committee, 1968, Report on factors affecting sediment yield in the Pacific Southwest area and selection and evaluation of measures for reduction of erosion and sediment yield: Report of the Water Management Subcommittee, 10 p.

Pashley, E.F., Jr., and Wiggins, R.A., 1972, Landslides of the northern Wasatch Front, *in* Environmental geology of the Wasatch Front, 1971: Utah Geological Association Publication 1, p. K1–K16.

Personius, S.F., 1990, Surficial geologic map of the Brigham City segment and adjacent parts of the Weber and Collinston segments, Wasatch fault zone, Box Elder and Weber Counties, Utah. U.S. Geological Survey Miscellaneous Investigations Map I-1979, scale 1:50,000.

Personius, S.F., and Scott, W.E., 1992, Surficial geologic map of the Salt Lake City segment and parts of adjacent segments of the Wasatch fault zone, Davis, Salt Lake, and Utah Counties, Utah. U.S. Geological Survey Miscellaneous Investigation Series Map I-2106, scale 1:50,000.

Prudon, T.H.M., 1990, The seismic retrofit of the City & County Building in Salt Lake City—A case study of the application of base isolation to a historic building, *in* The City and County Building, Salt Lake City, Utah—Earthquake risks and the architectural landmark. Salt Lake City Corporation, Proceedings from the International Seismic Isolation/Historic Preservation Symposium, May 11–14, 1988, variously paginated.

Ridd, M.K., and Kaliser, B.N., 1978, North Ogden sensitive area study. Salt Lake City, unpublished report to North Ogden Planning Commission, 124 p.

Rollins, K.M., and Adan, S.M., 1994, Soil response in the Salt Lake Basin Salt Lake City, EERI Wasatch Front Seismic Risk Regional Seminar, Seminar 2—Earthquake Research and Mitigation, p. 3-1 to 3-22.

Rollins, K.M., and Gerber, T.M., 1995, Seismic ground response at two bridge sites on soft-deep soils along Interstate 15 in the Salt Lake Valley, Utah. Provo, Brigham Young University, unpublished Interim Report for the Utah Department of Transportation, 116 p.

Schwartz, D.P., and Coppersmith, K.J., 1984, Fault behavior and characteristic earthquakes—Examples from the Wasatch and San Andreas fault zones: Journal of Geophysical Research, v. 89, no. B7, p. 5681–5698.

Schwartz, D.P., and Lund, W.R., 1988, Paleoseismicity and earthquake recurrence at Little Cottonwood Canyon, Wasatch fault zone, Utah, *in* Machette, M.N., ed., In the footsteps of G.K. Gilbert—Lake Bonneville and neotectonics of the eastern Basin and Range Province. Utah Geological and Mineral Survey Miscellaneous Publication 88-1, p. 82–85.

Schwartz, D.P., Lund, W.R., Mulvey, W.E., and Budding, K.E., 1988, New paleoseismicity data and implications for space-time clustering of large earthquakes on the Wasatch fault zone, Utah [abs.]. Seismological Research Letters, v. 59, no. 1, p. 15.

Scott, W.E., 1981, Field-trip guide to the Quaternary stratigraphy and faulting in the area north of the mouth of Big Cottonwood Canyon, Salt Lake County, Utah. U.S. Geological Survey Open-File Report 81-773, 12 p.

Scott, W.E., and Shroba, R.R., 1985, Surficial geologic map of an area along the Wasatch fault zone in the Salt Lake Valley, Utah. U.S. Geological Survey Open-File Report 85-448, scale 1:24,000.

SHB AGRA, 1994, Report, geotechnical evaluation, effect of proposed demolition of residences at 1846 and 1850 East and 1950 South Street on stability of active landslide in the Ogden River landslide complex, Ogden, Utah: Salt Lake City, unpublished consultant's report, 8 p

Smith, R.B., and Arabasz, W.J., 1991, Seismicity of the Intermountain seismic belt, *in* Slemmons, D.B., Engdahl, I.R., Zoback, M.L., and Blackwell, D.D., eds., Neotectonics of North America: Geological Society of America Decade Map Volume 1, p. 185–228.

Smith, R.B., and Sbar, M.L., 1974, Contemporary tectonics and seismicity of the western United States with emphasis on the Intermountain seismic belt. Bulletin of the Geological Society of America, v. 85, p. 1205–1218.

Steffen, C.C., 1986, Economic impact of flooding on the Great Salt Lake. Speech presented to the Natural Resources Law Forum, J. Reuben Clark Law School, Brigham Young University, Provo, Utah, October 3, 1986, 14 p.

Swan, F.H., III, Hanson, K.L., Schwartz, D.P., and Black, J.H., 1981, Study of earthquake recurrence intervals on the Wasatch fault at the Little Cottonwood Canyon site, Utah. U.S. Geological Survey Open-File Report 81-450, 30 p.

Tinsley, J.C., King, K.W., Trumm, D.A., Carver, D.L., and Williams, Robert, 1991, Geologic aspects of shear-wave velocity and relative ground response in Salt Lake Valley, Utah, *in* McCalpin, J.P., ed., Proceedings of the 27th Symposium on Engineering Geology and Geotechnical Engineering. Logan, Utah State University, p. 25-1 to 25-9.

Utah Division of Water Resources, 1984, Great Salt Lake—Summary of technical investigations for water level control alterations. Utah Department of Natural Resources unpublished report, variously paginated.

Utah Geological Association, 1971, Environmental Geology of the Wasatch Front, 1971. Utah Geological Association Publication 1, variously paginated.

Van Horn, Richard, 1972, Surficial geologic map of the Sugar House quadrangle, Salt Lake County, Utah. U.S. Geological Survey Miscellaneous Geologic Investigations Map I-766-A, scale 1:24,000

Van Horn, R., 1975, Largest known landslide of its type in the United States—A failure by lateral spreading in Davis County, Utah. Utah Geology, v. 2, no. 1, p. 83–87.

Vandre, B.C., and Lowe, M., 1995, The Rainbow Imports landslide—A window for looking at landslide mechanisms within the Ogden River landslide complex, Weber County, Utah, *in* Lund, W.R., ed., Environmental and engineering geology of the Wasatch Front region: Utah Geological Association Publication 24, p. 137–156

Weber County Planning Commission, 1988, Geologic hazards and land-use planning—Background, explanation, and guidelines for development in designated geologic hazards special study areas as required in Weber County ordinances. Ogden, unpublished Weber County Planning Commission report and maps, 69 p., scale 1:24,000

Wieczorek, G.F., Ellen, S., Lips, E.W., Cannon, S.H., and Short, D.N., 1983, Potential for debris flow and debris flood along the Wasatch Front between Salt Lake City and Willard, Utah, and measures for their mitigation: U.S. Geological Survey Open-File Report 83-635, 45 p.

Wieczorek, G.F., Lips, E.W., and Ellen, S.D., 1989, Debris flows and hyperconcentrated floods along the Wasatch Front, Utah, 1983 and 1984: Bulletin of the Association of Engineering Geologists, v. 26, no. 2, p. 191–208.

Wong, I., Olig, S., Green, R., Moriwaki, Y., Abrahamson, N., Baures, D., Silva, W., Somerville, P., Davidson, D., Pilz, J., and Dunne, B., 1995, Seismic hazard evaluation of the Magna tailings impoundment, *in* Lund, W.R., ed., Environmental and engineering geology of the Wasatch Front region: Utah Geological Association Publication 24, p. 95–110

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

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

Yonkee, W.A., and Lowe, M., in preparation, Geologic map of the Ogden quadrangle, Utah. Utah Geological Survey Map, scale 1:24,000.

Youngs, R.R., Swan, F.H., Power, M.S., Schwartz, D.P., and Green, R.K., 1987, Probabilistic analysis of earthquake ground shaking hazard along the Wasatch Front, Utah, *in* Gori, P.L., and Hays, W.W., eds., Assessment of regional earthquake hazards and risk along the Wasatch Front, Utah, Volume II. U.S. Geological Survey Open-File Report 87-585, p. M1–M110.

Zoback, M.L., 1983, Structure and Cenozoic tectonism along the Wasatch fault zone, Utah, *in* Miller, D.M., Todd, V.R., and Howard, K.A., eds., Tectonic and stratigraphic studies in the eastern Great Basin: Geological Society of America Memoir 157, p. 3–28