DATABASE COMPILATION, COORDINATION OF EARTHQUAKE-HAZARDS MAPPING, AND STUDY OF THE WASATCH FAULT AND EARTHQUAKE-INDUCED LANDSLIDES, WASATCH FRONT, UTAH

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April 2004

Final Technical Report
National Earthquake Hazards Reduction Program
Effective date: January 1, 2003
Expiration date: December 31, 2003
Award number 03HQAG0008

PREFACE

The Utah Geological Survey (UGS) and U.S. Geological Survey (USGS) entered into an agreement in 2003 for cooperative earthquake-hazards studies in Utah. One goal of the cooperative studies is to produce the next generation of earthquake-hazards maps for Utah. Under this cooperative agreement, the UGS established working groups and convened a series of working group meetings to define a multi-year plan for developing earthquake ground shaking, liquefaction, and earthquake-induced landslide hazard maps. In support of the planning effort, the UGS compiled interactive shallow shear-wave-velocity, deep-basin-structure, and geotechnical landslide shear-strength databases to identify data available for earthquake-hazards mapping. In addition, the UGS mapped the surficial geology of the Levan segment of the Wasatch fault zone (WFZ) and initiated studies to identify likely earthquake-induced landslides in the Salt Lake County area for later detailed geotechnical characterization and paleoseismic investigations to better understand their behavior in earthquakes.

We present the results of these studies in the following series of self-contained reports for each part of the project. Part I includes both a technical and non-technical summary of the entire project. Part II discusses the working group process and results, and databases. Part III presents results of surficial geologic mapping of the Levan segment of the WFZ, and Part IV summarizes the results of the earthquake-induced landslide studies.

DISCLAIMER

Research supported by the U.S. Geological Survey (USGS), Department of the Interior, under USGS award number 03HQAG0008. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

DATABASE COMPILATION, COORDINATION OF EARTHQUAKE-HAZARDS MAPPING, AND STUDY OF THE WASATCH FAULT AND EARTHQUAKE-INDUCED LANDSLIDES, WASATCH FRONT, UTAH

PART I: TECHNICAL AND NONTECHNICAL SUMMARIES

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Effective date: January 1, 2003
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INTRODUCTION

The Utah Geological Survey (UGS), in cooperation with the U.S. Geological Survey (USGS) and Utah Seismic Safety Commission, convened a series of working group meetings to define a multi-year plan for developing the next generation of earthquake ground shaking, liquefaction, and earthquake-induced landslide hazard maps for Utah. Three working groups were established and meetings were held to develop long-term plans, partnerships for investigations, and topics for future proposals. In support of the planning effort, the UGS compiled interactive shallow shear-wave-velocity, deep-basin-structure, and geotechnical landslide shear-strength databases to identify data available for earthquake-hazards mapping along the Wasatch Front.

In addition, the UGS mapped the surficial geology of the Levan segment of the Wasatch fault zone (WFZ) as a continuation of USGS and UGS surficial geologic mapping of segments of the WFZ. This mapping is used in paleoseismic characterization of the fault for both the UGS and USGS Quaternary fault databases used in the National Seismic Hazard Maps. We also initiated studies to identify likely earthquake-induced landslides in the Salt Lake County area for later detailed geotechnical characterization and paleoseismic investigations (trenching to date events, back-calculating accelerations needed to induce movement) to better understand their behavior in earthquakes.

We present the results of these studies in a series of reports for each part of the project. Part I (this report) includes both a technical and non-technical summary of the entire project. Part II discusses the working group process and results, and databases. Part III presents results of surficial geologic mapping of the Levan segment of the WFZ, and Part IV summarizes the results of the earthquake-induced landslide studies.

EARTHQUAKE-HAZARDS-MAPPING WORKING GROUPS

An initial one-day meeting of the Ground Shaking and Liquefaction Working Groups was held in Salt Lake City on March 18, 2003, and of the Earthquake-Induced Landslide Working Group on July 21, 2003. Working groups held follow-up meetings and e-mail correspondence to finalize long-term plans and identify partnerships and projects for future proposals. Working group members include geologists, engineers, seismologists, and geophysicists from Utah State University, Brigham Young University, University of Utah, UGS, USGS, and various consulting companies and other state agencies. Each working group developed a consensus among the technical experts regarding the types of hazards maps that could be produced, new data required, preferred data-collection and mapping techniques, and possible funding sources. Working group results helped define the State’s plan for new earthquake-hazards maps so that investigators can use the plan to demonstrate the relevance of their proposed work. Final working group plans for future earthquake-hazards maps are available on the UGS Web site at geology.utah.gov.

The Ground-Shaking Working Group plan identifies steps to develop detailed spectral-acceleration maps for ground motions at various periods that consider both shallow shear-wave velocities (Vs30) and deep-basin structure. The first maps will be completed for Salt Lake Valley. The Liquefaction and Earthquake-Induced Landslide plans outline steps to compile databases and pilot projects to evaluate various hazard mapping methods, with final-product formats to be determined pending these studies. Working group plans were used to help identify investigations and potential partnerships for future proposals.

DATABASES

To help working groups develop earthquake-hazards-mapping plans, the UGS compiled three databases to show: 1) shallow shear-wave velocities (Vs30), 2) deep-basin-structure data, and 3) geotechnical landslide shear strengths. All databases are in an interactive, searchable GIS format (HTML Image Mapper®, version 3.0).

The shallow shear-wave-velocity database was originally compiled for the UGS site-response map of Salt Lake Valley for another National Earthquake Hazards Reduction Program (NEHRP) project. That database included shear-wave-velocity data to depths of 100 feet (30 m) or greater in Salt Lake Valley only. We have updated that database, changed the format, and extended coverage to statewide under this grant. The database includes direct shear-wave-velocity measurements, including downhole, cone penetrometer (CPT), and geophysical (spectral analysis of surface waves [SASW], Rayleigh-wave inversion) data.

The deep-basin-structure database includes deep water wells and geotechnical boreholes, particularly those that encountered bedrock. Deep geophysical data, mostly oil-company seismic-reflection lines in and around Great Salt Lake, are also included. Existing maps of the depth of Quaternary deposits and gravity interpretations of the thickness of unconsolidated and semiconsolidated alluvial/lacustrine basin fill are included.

The geotechnical landslide shear-strength database includes soil-test data from various sources, principally from geotechnical consultants and the Utah Department of Transportation. For each data point, the soil type, geologic unit, type of test, and shear strength (friction angle, cohesion) are given.

SURFICIAL GEOLOGIC MAPPING OF THE LEVAN SEGMENT OF THE WASATCH FAULT ZONE

We have mapped the geology of the Levan segment of the Wasatch fault zone in central Utah, with an emphasis on relations between surficial Quaternary deposits and faults. The Levan segment extends about 33 km from just south of the town of Nephi to

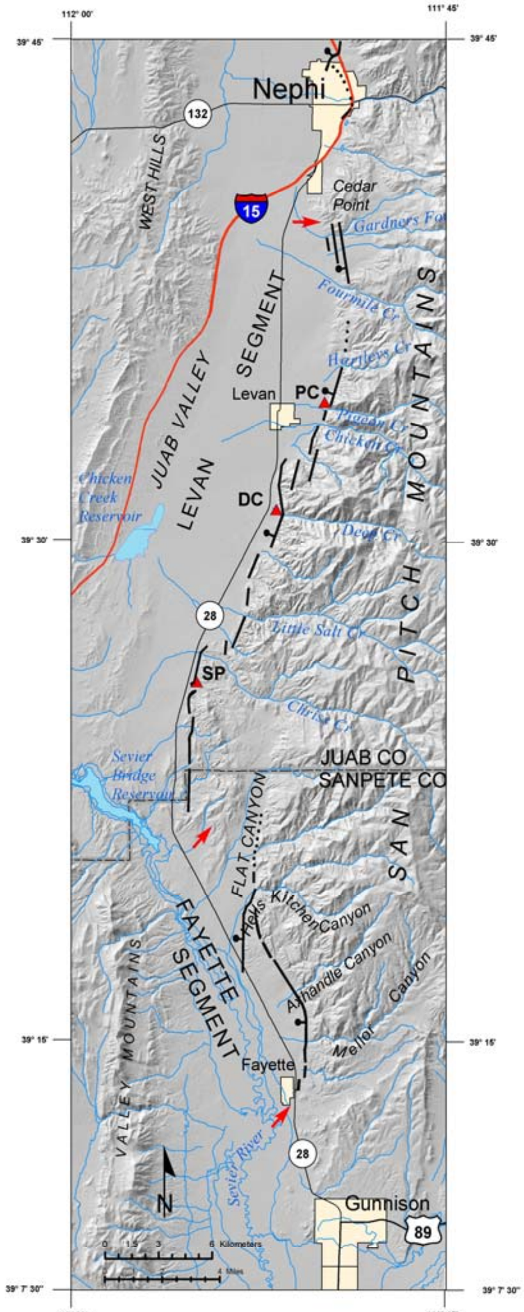

Figure 1. Levan and Fayette segments of Wasatch fault zone. Faults shown by heavy lines, dotted where uncertain, bar and ball on downthrown side; arrows show segment boundaries. PC, Pigeon Creek (site of radiocarbon age of faulted fan alluvium); DC, Deep Creek stream-cut exposure of fault; SP, Skinner Peaks trench.

just south of the Juab-Sanpete County line (figure 1). Quaternary deposits along Levan segment are dominated by coalesced alluvial fans ranging in age from middle Pleistocene to late Holocene, but also include stream alluvium, landslide and debris-flow deposits, and undifferentiated basin fill.

Prior to this study, the northern segment boundary was identified at Hartleys Canyon, which is at the northern limit of Holocene fault scarps on the segment, and the southern segment boundary was identified at the pronounced left step in Quaternary faulting between the southern end of Juab Valley and Flat Canyon to the east. We propose that the northern segment boundary be moved about 8 km north to Cedar Point, to include a zone of Pleistocene fault scarps within the Levan segment. We define this revised segment boundary on the basis of range-front geometry and a 5-km gap in Quaternary faulting between the Levan and Nephi segments.

The Levan segment has had one, or possibly two, surface-faulting events during the Holocene based on estimated ages of faulted geomorphic surfaces, geomorphic expression of scarps, numeric age control on faulted deposits, empirical scarp-height – slope-angle relationships, and preliminary results of scarp diffusion age modeling. Because the segment has likely had at most two surface-faulting events in the Holocene, fault scarps provide a relatively straightforward view of the pattern of faulting along the segment. The age of the most recent event (MRE) is well established at about 1000 years ago at Deep Creek. Trenching by others near Skinner Peaks has provided evidence for two faulting events, and composite scarp profiles between the trench site and Chriss Canyon are consistent with two events. Scarps along the southernmost part of the segment have a simple morphology that could have resulted from either a single event (the penultimate event [PE] recorded at the trench site, which occurred sometime before 3100-3900 yr B.P.) or possibly two events. We conclude that the MRE ruptured the segment from Hartleys Canyon southward to at least the Skinner Peaks area (20-km surface rupture length), and possibly all the way to the southern end of the segment (26-km surface rupture length). The PE may have ruptured at least the southern 15 km of the segment, but the northern limit of this rupture is uncertain; we see no clear evidence of the PE preserved in Holocene deposits from Deep Creek northward. Scarps at the very northern end of the segment lack evidence for Holocene faulting. Taken together, the scarps along the Levan segment provide evidence suggesting at least one partial-segment rupture during the late Pleistocene and Holocene.

Slip rates on the Levan segment are uncertain because the age of the PE is unknown. Using data from the Deep Creek and Skinner Peaks sites, we calculate maximum Holocene vertical slip rates ranging from 0.25 to about 1 mm/yr; the true slip rate is undoubtedly closer to the low end of this range. Long-term average vertical slip rates since the middle Pleistocene are about 0.05-0.15 mm/yr based on the height of the scarp on late to middle Pleistocene fan alluvium near the middle of the segment.

EARTHQUAKE-INDUCED LANDSLIDE STUDIES

Earthquake-induced landslides, with the exception of liquefaction-induced lateral spreads, have not been recognized in the Salt Lake City metropolitan area. This study assesses the feasibility of identifying such earthquake-induced landslides given the documented latest Pleistocene to present surface-faulting chronology for the Wasatch fault zone; mapped hillslope areas with moderate to high potential for shallow, disrupted slides; and large inventory of pre-existing landslides, many with inferred low factors of safety and vulnerability to earthquake-induced reactivation. We examined three types of potential earthquake-induced landslides: (1) a catastrophic rockslide, (2) a large, recurrently moving, prehistoric landslide, and (3) shallow, disrupted soil slides. Each represents a type of landslide triggered by moderate to large earthquakes elsewhere in the western United States.

Based on the inferences of previous researchers that some prehistoric, catastrophic rockslides in the Wasatch Front may have been triggered by earthquakes, we evaluated the feasibility of dating the Grandview Peak rockslide in upper City Creek Canyon northeast of Salt Lake City (figure 2) and correlating it with a documented surface-faulting earthquake. Recognition of the seismic origin of the landslide would provide a model for characterizing the earthquake-induced catastrophic rockslide hazard elsewhere in the Wasatch Range and provide guidance for future earthquake-induced landslide studies. Our reconnaissance revealed similarities to the Madison Slide triggered by the 1959 Hebgen Lake earthquake, suggesting the rockslide may be a candidate for an earthquake-induced landslide. Radiocarbon dating of buried trees and paleosols, or organic-rich sediments at the base of ponds that formed upstream of the rockslide deposit where it blocked City Creek and three tributary drainages, may constrain the age of the landslide, but is considered impractical given the probable depths of the ponds and the setting of the landslide. Cosmogenic dating of quartzite and limestone boulders on the surface of rockslide deposit or of exposed Paleozoic rock in the main scarp or on the slide surface appear the most practical approach to obtaining an age of the landslide.

Using geomorphic analysis and radiocarbon ages from a consultant's landslide investigation, we developed a partial movement history for the Little Valley landslide at the south end of Salt Lake Valley (figure 2) and an approach for recognizing earthquake-induced reactivation in pre-existing slides in the Wasatch Front. The landslide is a large, prehistoric, dormant debris slide, parts of which are proposed for residential development. The presence of rotated blocks with deformed and faulted latest Pleistocene-Holocene sag pond sediments and local troughs with latest Pleistocene-Holocene alluvium allowed dating of movement episodes and periods of dormancy. The age of graben-fill sediments in the head of the landslide (>29,120 ^{14}C yr B.P.) indicates that the slide had formed prior to the onset of Late Pleistocene Lake Bonneville. A latest Pleistocene movement episode (estimated at about 17,000 cal yr B.P.) is suggested based on the preservation (lack of erosion) of the foot of the landslide that extends about 110 meters downslope of the Bonneville shoreline. The youngest dated movement episode (4,700 cal yr B.P.) is based on the age of the base of a colluvial wedge associated with an antithetic, sag-pond-bounding fault that offsets organic silt (loess or sag-pond sediments) in the head of the landslide. This movement overlaps in time with surface-faulting event W on the Salt Lake City segment of the Wasatch fault zone. The movement occurred during a dry period of the Holocene, supporting a seismic origin for the episode.

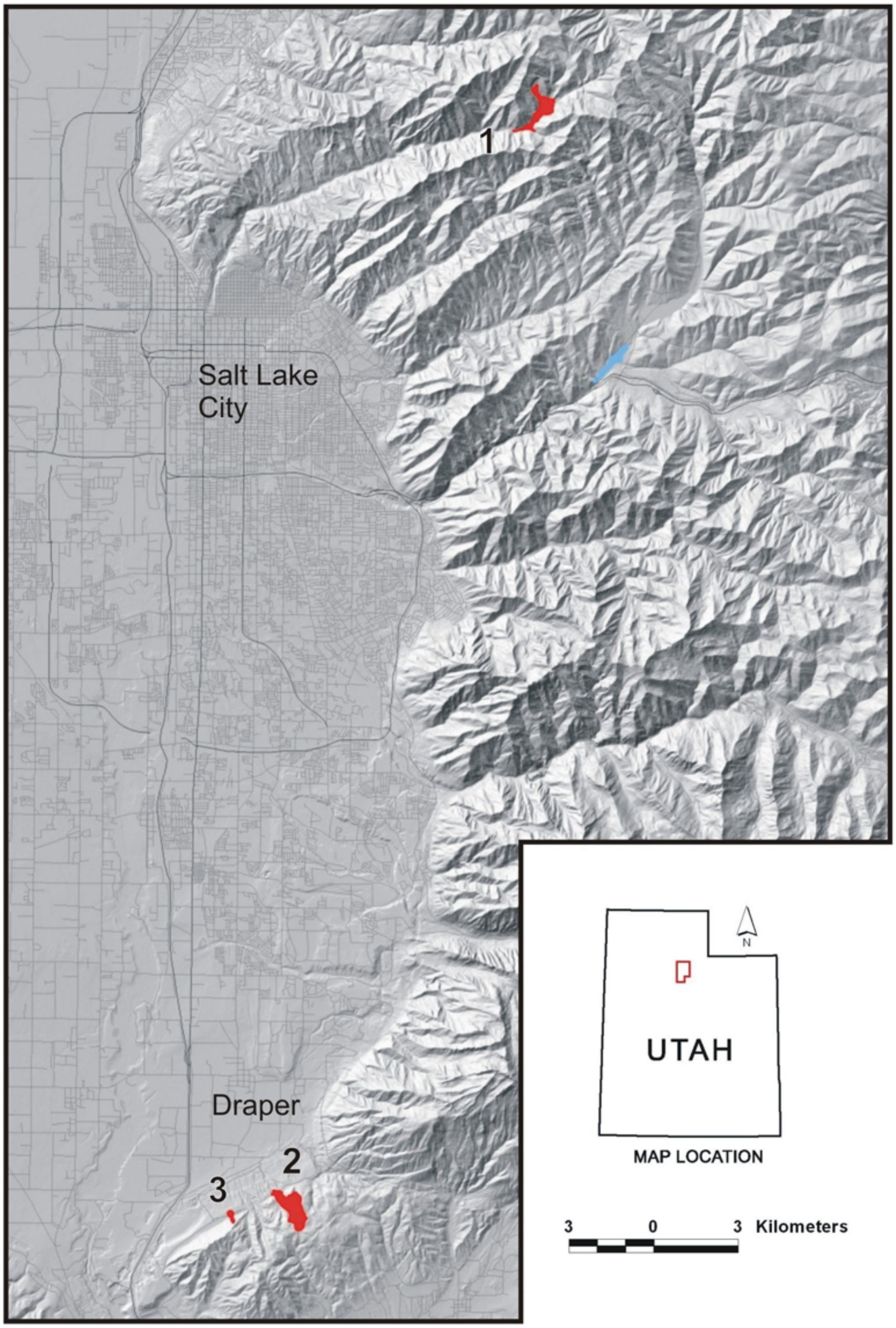

Figure 2. *Map showing earthquake-induced landslide study areas. Landslide study areas include (1) the Grandview Peak rockslide in upper City Creek Canyon, (2) the Little Valley landslide, Draper, and (3) the Draper Heights landslide and nearby possible shallow, disrupted landslides (not shown) near Steep Mountain, Draper.*

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Previous researchers mapped a high earthquake-induced shallow landslide hazard on the north slope of Steep Mountain, but did not identify any earthquake-triggered slides. We interpret the Draper Heights landslide (figure 2) as a possible earthquake-induced shallow, disrupted soil slide, one of the most common landslide types triggered by the 1994 Northridge earthquake. Other nearby flat-bottomed scars upslope of cone-shaped deposits are also possible earthquake-induced shallow, disrupted soil slides. Limited opportunities exist for radiocarbon and cosmogenic dating of the slides. The Draper Heights landslide postdates the Bonneville shoreline (younger than 16,800 cal yr B.P.) and likely overlaps with the documented surface-faulting chronology of the Wasatch fault zone. Slope-stability analysis, however, suggests that this and other possible landslides on the north slope of Steep Mountain may be triggered by earthquakes of smaller magnitude than surface-faulting events.

ACKNOWLEDGEMENTS

This work was partially funded under USGS National Earthquake Hazards Reduction Program grant 03HQAG0008. We thank Mark Petersen, USGS, for his support and in helping to coordinate earthquake studies in Utah. Specific acknowledgments for individual parts of the project are included in the Part II, III, and IV reports.

NON-TECHNICAL SUMMARY

The UGS, in cooperation with the USGS and university/private sector personnel, established working groups to build consensus and develop plans for the next generation of earthquake-hazards maps in Utah. Working groups defined data needs and established partnerships to produce new ground shaking, liquefaction, and earthquake-induced landslide hazard maps. In support of this effort, the UGS compiled databases needed to produce the maps. We extended the surficial geologic mapping of the Wasatch fault to the south to include the Levan segment in central Utah. We performed geologic studies of several important landslides in the Salt Lake County area to help determine whether movement was likely earthquake induced.

DATABASE COMPILATION, COORDINATION OF EARTHQUAKE-HAZARDS MAPPING, AND STUDY OF THE WASATCH FAULT AND EARTHQUAKE-INDUCED LANDSLIDES, WASATCH FRONT, UTAH

PART II: EARTHQUAKE-HAZARDS-MAPPING WORKING GROUPS AND DATABASES

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April 2004

Effective date: January 1, 2003
Expiration date: December 31, 2003
Award number 03HQAG0008

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DATABASES (on CD in pocket)

ABSTRACT

The Utah Geological Survey (UGS), in cooperation with the U.S. Geological Survey (USGS) and Utah Seismic Safety Commission, convened a series of working group meetings in 2003 to define a multi-year plan to develop the next generation of ground-shaking, liquefaction, and earthquake-induced-landslide hazard maps for Utah. Three working groups were established and meetings were held to develop long-term plans for producing maps, partnerships for investigations, and topics for future proposals.

To support development of earthquake-hazards-mapping plans, the UGS compiled three databases to accurately reflect the status of existing data on 1) shallow-shear-wave velocities (Vs30), 2) deep-basin structure, and 3) geotechnical landslide shear strengths. The shallow-shear-wave-velocity (Vs30) database is statewide and includes shear-wave-velocity data to depths of 30 m or more using downhole, cone penetrometer, and geophysical (spectral analysis of surface waves, Rayleigh-wave inversion) methods. The deep-basin-structure database covers the Wasatch Front from Weber to Utah Counties, and includes selected deep water wells and oil and gas/geothermal exploration boreholes, particularly those that encountered bedrock, and deep geophysical data, mostly oil-company seismic-reflection lines in and around Great Salt Lake. The geotechnical landslide shear-strength database is statewide and includes laboratory soil-test data from various sources, principally geotechnical consultants and the Utah Department of Transportation.

INTRODUCTION

The Utah Geological Survey (UGS) and U.S. Geological Survey (USGS) entered into an agreement in 2003 for cooperative earthquake-hazards studies in Utah. One goal of the cooperative studies ultimately is to produce the next generation of earthquake-hazards maps, including 1) large-scale ground-shaking maps incorporating the latest fault source parameters and shallow shear-wave-velocity (Vs30), deep-basin-structure, and other effects; and 2) new liquefaction and earthquake-induced landslide maps depicting ground displacements or other parameters as appropriate. To initiate the process, the UGS established three technical working groups (Ground Shaking, Liquefaction, and Earthquake-Induced Landslide) and held meetings to develop plans for producing the maps. The initial meeting was co-sponsored by the UGS, USGS, and Utah Seismic Safety Commission.

Each working group developed a consensus among the technical experts regarding the types of maps needed, new data required, preferred data-collection and mapping techniques, and possible funding sources. Working groups developed partnerships and identified projects to pursue funding. Plans were kept brief so that investigators could include them in proposals to demonstrate the relevance of their proposed work to Utah State priorities. One goal of our first-year efforts was to define potential projects and partnerships for proposals in time to respond to the 2004 USGS National Earthquake Hazards Reduction Program (NEHRP) Request for Proposals (RFP). In the future, results of this program will help define research objectives, data requirements, and hazards mapping needs that may be used by the USGS to help develop priorities in Utah for the USGS NEHRP RFP for Intermountain West studies.

To aid in assessing data needs, the UGS compiled databases to identify existing shear-wave-velocity, basin-structure, and geotechnical landslide shear-strength data. All databases are in an interactive GIS format (HTML Image Mapper®, version 3.0), and are included on the CD in the pocket and are also available on the UGS Web site. Information needed to use and understand each database is included below and in the introductory material on the CD and Web site. Each database includes a description of the information contained, criteria used in compiling data, and comprehensiveness of the database.

RESULTS OF EARTHQUAKE-HAZARDS-MAPPING WORKING GROUPS

An initial one-day meeting of the Ground Shaking and Liquefaction Working Groups was held in Salt Lake City on March 18, 2003, and of the Earthquake-Induced Landslide Working Group on July 21, 2003. Both the Ground Shaking and Liquefaction Working Groups held follow-up meetings to finalize the plans and identify partnerships and projects for future proposals. The Earthquake-Induced Landslide Working Group developed its final plan via email correspondence. Working group members (appendix A) include geologists, engineers, seismologists, and geophysicists from Utah State University, Brigham Young University, University of Utah, UGS, USGS, and various consulting companies and other state agencies. Personnel representing the American Society of Civil Engineers, Association of Engineering Geologists, Utah Seismic Safety Commission, Salt Lake County, and other state agencies were invited to observe the proceedings and participate as desired (appendix A). Final working group plans outlining research needs for future earthquake-hazards mapping were formally adopted by the Utah Seismic Safety Commission and UGS.

Working group plans are shown in appendices B, C, and D. The Ground Shaking Working Group concentrated on identifying data needed to develop a community velocity model to incorporate both shallow shear-wave velocity (Vs30) and deep-basin-structure effects on ground motions. The model will ultimately be used by the USGS, UGS, and their partners to develop larger scale spectral acceleration maps for the Wasatch Front for use in design that incorporate site and basin-shape effects. The Liquefaction Working Group determined that the long-term goal is to produce maps showing annual probabilities of liquefaction and liquefaction-induced ground displacement, and keyed in on proposing a pilot project in the northern Salt Lake Valley to develop hazard-mapping methods. Ground-motion inputs for the analyses will be from the National Seismic Hazard Maps adjusted for soil effects. Compilation of a comprehensive geotechnical database will also be included. The Earthquake-Induced Landslide Working Group saw a lack of data as a significant problem, and so identified several pilot projects to investigate methods for producing maps that may be appropriate given the lack of data. For details of each plan, see appendices B, C, and D.

Initial planning for the 2004 earthquake conference and working group meetings on February 26 and 27, 2004, was also completed under this grant. The conference was held on February 26 preceding the working group meetings. The purpose of the conference was to summarize the 2003 working group plans and inform working group members of the results of 2003 research for consideration in the 2004 meetings. The conference was open to all local earth scientists and engineers as well to inform them of working group activities and research results. Total conference attendance was about 150. The conference program is included in appendix E.

In a parallel process under another NEHRP grant, the UGS established a Utah Quaternary Fault Parameter Working Group to develop a consensus among paleoseismologists working in Utah regarding earthquake timing, slip rates, and recurrence intervals for Utah faults. The working group includes fault experts from the UGS, USGS, U.S. Bureau of Reclamation, and various universities and consulting companies (appendix A). The final meeting was held with other working group meetings on February 27, 2004. The final report will be submitted separately in mid-2004.

DATABASES

Working groups hope to facilitate production of 1) large-scale ground-shaking maps, based on a community velocity model incorporating shallow shear-wave-velocity (Vs30), deep-basin-structure, and other effects; and 2) new liquefaction and earthquake-induced landslide maps. To aid in assessing data needs, the UGS compiled databases to identify existing data on 1) shallow-shear-wave velocities (Vs30), 2) deep-basin structure, and 3) geotechnical landslide shear strengths.

The databases are in an interactive GIS-format (HTML Image Mapper®, version 3.0) that includes "point and click" maps, summary tables, and downloadable scans of original data and logs. A description of the data contained, criteria used in compiling data, and comprehensiveness of each database is given below. Sources of data are included in database entries and in the References section.

Shallow-Shear-Wave Velocities (Vs30)

The shallow- (upper 30 m) shear-wave-velocity (Vs) database was originally compiled for the site-response map of Salt Lake Valley (Ashland and Rollins, 1999) and updated for the later revised shear-wave-velocity/site-class map (Ashland and McDonald, 2003). We expanded the Vs30 database beyond Salt Lake County to include data statewide.

The database includes only shear-wave-velocity measurements to depths of 30 m or greater measured directly using downhole, cone penetrometer (CPT), and Rayleigh-wave inversion/spectral analysis of surface waves (SASW) methods. No data shallower than 30 m, and no standard-penetration test or undrained shear-strength conversions are included. A database summary table is available that includes Vs30 (mean Vs for the upper 30 m) values calculated using equation 16-44 in the 2003 International Building Code (International Code Council, 2003).

Most of the Vs data in the database were obtained for the Ashland and Rollins (1999) study which was limited to Salt Lake Valley. They contacted local geotechnical consultants and government agencies to obtain Vs data for private developments and public projects, including Utah Department of Transportation (UDOT) data. We have subsequently obtained the remaining UDOT and other data outside of Salt Lake Valley. We also contacted local contractors that perform downhole and CPT Vs testing. Additional data may be available from one contractor, Conetec Inc., which will be added later. In addition, recent work done by Utah State University, UGS, and the University of Utah Seismograph Stations under a 2003 USGS NEHRP grant will add an additional 44 SASW-method Vs sites to the database.

The summary table of the database is downloadable as an MS Excel® spreadsheet that contains general location and source information as well as Vs30, engineering-geologic unit, and IBC site-class information. The data are indexed using a numbering system originated by Ashland and Rollins (1999). In many cases, location coordinates are not precise and may represent a general site locality rather than individual test locations. Shear-wave-velocity data for individual tests are available as downloadable scans (PDF format) of graphic and/or tabulated logs and supplemental information, including lithologic logs and geotechnical lab data where available.

Deep-Basin Structure

The deep-basin-structure database includes selected logs of deep water wells and oil and gas/geothermal-exploration boreholes, and deep seismic reflection and refraction sections. We included only logs of boreholes and wells that encountered bedrock or are near wells that encountered bedrock in Wasatch Front valleys from Weber to Utah Counties. Two good-quality lithologic logs west of Brigham City are included although no other logs for that area have been compiled yet. Deep geophysical data consist mostly of publicly available oil-exploration seismic sections and are limited to Salt Lake Valley, Great Salt Lake, and the eastern shore area of Great Salt Lake.

The deep-basin data are summarized in two MS Excel® spreadsheets (Deep Well and Seismic) that contain general location, source, and depth information. Individual logs are available as PDF-format scans of delimited text files or graphic logs. The data were plotted from coordinates or figures in referenced reports, and in many cases locations are not precise and limited by original map scales. Most of the water-well locations were supplied by the Utah Division of Water Rights (UDWR) as a GIS shape file. The locations are not precise and have not been verified. In many cases, location coordinates may represent a general site locality rather than individual test locations.

For Salt Lake Valley, borehole and well logs are from a variety of sources, including data compiled by Radkins (1990) for Salt Lake County; logs from Case (1985);

logs from various deeper geothermal, oil, and gas exploration wells (Murphy and Gwynn, 1979a, 1979b; Glenn and others, 1980; Davis and Cook, 1983; Meiiji Resource Consultants, 1983); and data from USGS and Utah Department of Natural Resources basic-data reports (Feth and others, 1966). Most logs from these sources are ultimately from the UDWR well driller's report database. Outside of Salt Lake Valley, the wells shown are selected mainly from the UDWR database and include only those that encountered bedrock or are near those that encountered bedrock, and deep wells in areas where few data exist.

Seismic reflection/refraction data from published references are few and limited to surveys performed in Salt Lake Valley and Great Salt Lake. The data consist of several deep seismic-reflection lines in Great Salt Lake and the east shore area (McNeil and Smith, 1992), two good-quality seismic-reflection lines in northern Salt Lake Valley (Radkins and others, 1989), two unreversed seismic-refraction profiles in western and southern Salt Lake Valley (Bashore, 1982), and a short seismic-refraction survey near the mouth of Little Cottonwood Canyon (Schuster, 2003). Seismic data are downloadable as PDF-format scans of seismic sections found in the referenced material.

Geotechnical Landslide Shear Strengths

The geotechnical landslide shear-strength database includes laboratory soil-test data performed for landslide studies. The database is statewide although most data are concentrated along the Wasatch Front. Because shear-strength testing methods and parameters are highly variable, the test results are separated into many categories. In many cases, the types of detailed information regarding testing conditions and methods needed to properly use the data were not provided in the reports, so considerable judgment is required when using the data.

The data will ultimately be summarized in an MSAccess database providing for easy searching, sorting, and statistical analysis of the data. The database includes shear-strength test type, test results, soil type using the Unified Soil Classification System (USCS), and geologic unit (if given; otherwise interpreted by UGS). The data were plotted from coordinates or location maps from the original reports and may represent a general site locality rather than individual sample locations.

Sources of data are principally geotechnical consultant's reports and UDOT. Specific sources are identified according to their HAZBIB number in the UGS Hazards Bibliography (Harty and others, 1992; updated edition available in UGS library). Most data were collected in the late 1980s as UGS personnel contacted local geotechnical consultants and copied test results when compiling HAZBIB. Subsequent data (1990s through present) are less comprehensive and are compiled from consultant's reports done for public agencies (local governments, UDOT) or submitted to public agencies and reviewed by the UGS.

ACKNOWLEDGMENTS

This work was partially funded under USGS NEHRP grant 03HQAG0008. We thank Mark Petersen, USGS, for his support and in facilitating involvement by USGS personnel. We appreciate the willingness and dedication of all working group members for donating their time and expertise to this process. We particularly thank Ivan Wong, Steven Bartlett, and Francis Ashland for facilitating the Ground Shaking, Liquefaction, and Earthquake-Induced Landslide Working Group discussions, respectively, and Barry Solomon for work as the UGS liaison to the Liquefaction Working Group. We also thank Leslie Heppler and others at UDOT for their help and access to UDOT files, and local consultants, particularly LaMont Sorensen of LGS, Inc., for assisting us in obtaining data for the databases.

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APPENDIX A

WORKING GROUP MEMBERS/INVITEES

Earthquake-Hazards-Mapping Working Groups

Listed below are invited members of the Utah Ground Shaking, Liquefaction, and Earthquake-Induced Landslide Working Groups. Those listed as Invited Observers have an interest in the process and were invited to participate as desired. Some invited Observers joined a Working Group, and active Working Group members that participated in developing each plan are listed in the plans.

Ground Shaking Working Group
Ivan Wong, URS, Facilitator
Gary Christenson, UGS
Walter Arabasz, UUSS
Jim Pechmann, UUSS
Kris Pankow, UUSS
Bob Smith, UUSS
Gerard Schuster, UUGG
Kim Olsen, UCSB
Mark Petersen, USGS
Jim Bay, USUCEE
Marv Halling, USUCEE
Francis Ashland, UGS
Steve Bartlett, UUCE
Matt Mabey, BYUG
Kyle Rollins, BYUCE

Invited Observers (all Working Groups)
Bob Carey, DES
Barry Welliver, USSC Chair
Joergen Pilz, USSC Geoscience Committee Chair
Darlene Batatian, Salt Lake County Geologist
David Marble, Utah Dam Safety
Greg Schlenker, Chair, Utah Section, AEG
Kent Hartley, Chair, Utah Geotechnical Group, ASCE

Liquefaction Working Group
Steve Bartlett, UUCE, Facilitator
Barry Solomon, UGS
Matt Mabey, BYUG
Les Youd, BYUCE
Kyle Rollins, BYUCE
Loren Anderson, USUCEE
David Simon, SBI
Bill Turner, Kleinfelder

Earthquake-Induced Landslide Working Group
Francis Ashland, UGS, Facilitator
Randy Jibson, USGS
Tim McCrink, CGS
Robert Pack, USUCEE
Barry Solomon, UGS
Leslie Heppler, UDOT
Loren Anderson, USUCEE
Fulvio Tonon, UUGG
Jim Nordquist, AGEC
Jim Higbee, UDOT
Danny Horns, UVSC

Quaternary Fault Parameters Working Group

William R. Lund, UGS
Suzanne Hecker, USGS
Michael Hylland, UGS
Michael Machette, USGS

James McCalpin, GEO-HAZ Consulting
Alan Nelson, USGS
Craig Nelson, Western Geologic
Susan Olig, URS Corporation
Dean Ostenaa, U.S. Bureau of Reclamation
Stephen Personius, USGS
David Schwartz, USGS
Mark Petersen, USGS
Kathleen Haller, USGS
Philip Pearthree, Arizona Geological Survey
James Pechmann, UUSS
Craig dePolo, Nevada Bureau of Mines and Geology
Robert Smith, UUSS
Ivan Wong, URS Corporation

APPENDIX B

UTAH PLAN FOR DEVELOPING THE NEXT GENERATION OF GROUND-SHAKING HAZARD MAPS

Developed by the Utah Ground-Shaking Working Group*
Adopted by the Utah Seismic Safety Commission and Utah Geological Survey
March-April, 2003

OBJECTIVE: The objective of this plan is to define future earth science research (exclusive of fault source characterization) that will provide vital information needed for developing earthquake ground-shaking microzonation hazard maps for the Wasatch Front, Utah. These maps will be useful for raising public and government awareness, emergency preparedness and response, urban planning, risk analyses, and as a comparison to building code-based and site-specific seismic design. Eventually, if acceptance is reached with the Utah IBC Commission, and the engineering community, these maps could replace the Maximum Considered Earthquake Ground Motion maps and site coefficients contained in the IBC. Study-area priorities will be Salt Lake Valley, Utah Valley, Weber-Davis Counties, and Cache Valley.

<u>Research Needs</u>

1. Develop a "community velocity model" for both site-response analysis (shallow site effects) and basin modeling of Wasatch Front basins to characterize Vs30 and Vs structure down to R1 (boundary between unconsolidated and semi-consolidated sediments) and R2 (boundary between semi-consolidated and consolidated sediments), principally using SASW/seismic-reflection surveys but any other velocity data as they become available. Timing: 2003-2006.

2. Evaluate seismic source and propagation path characteristics of Utah earthquakes (e.g., Q, kappa, stress drops, crustal effects, hanging-wall effects, directivity), and site amplification and geotechnical characteristics of Utah soils and rock (e.g., non-linear dynamic material properties) to improve ground-motion estimates. Timing: 2003-2007.

3. Perform 3D modeling using the "community velocity model" to evaluate the importance of basin structure (e.g., depth to R2, basin edge effects, steep basin boundary effects, focusing) on strong ground motions. Timing: 2004-2007.

4. Calculate the hazard and prepare large-scale probabilistic and scenario ground-shaking maps (scale of 1:50,000 to 1:100,000) incorporating site response, basin effects, and results of other investigations described above. These maps will undergo extensive peer review by the earthquake research community, the engineering community, and potential users. Timing: 2007+.

***Ground-Shaking Working Group Members**

Ivan Wong, URS/U of U	Gary Christenson, UGS	Walter Arabasz, U of U
Jim Pechmann, U of U	Kris Pankow, U of U	Robert Smith, U of U
Gerard Schuster, U of U	Kim Olsen, UCSD	Mark Petersen, USGS
James Bay, USU	Marv Halling, USU	Francis Ashland, UGS
Kyle Rollins, BYU	Barry Welliver, USSC	

APPENDIX C

UTAH PLAN FOR DEVELOPING THE NEXT GENERATION OF LIQUEFACTION HAZARD MAPS

Developed by the Utah Liquefaction Working Group*
Adopted by the Utah Seismic Safety Commission and Utah Geological Survey
March-April, 2003

1. Create a liquefaction database of relevant geotechnical factors and develop Geographic Information System (GIS) methods for probabilistic liquefaction hazard assessment using the database, strong motion estimates from the USGS National Seismic Hazard Map Program, and International Building Code 2000 site amplification coefficients to modify the strong motion estimates for soil effects. The proposed methods will first be tested with a pilot liquefaction-mapping project in the Salt Lake Valley during 2003 to 2005.

2. Correlate the GIS liquefaction database and surficial geological mapping to infer geotechnical and subsurface properties for similar geological units. These correlations will be used to better understand the liquefaction susceptibility of a given geological unit or facies and improve the quality of the liquefaction assessment for units that are either undersampled or have no subsurface sampling. These correlations will be developed throughout the project with the main emphasis during 2003 to 2005.

3. Compile the GIS database for other areas along the Wasatch Front area using the pilot-project methods and complete mapping for these areas. The preliminary priority of data compilation and mapping is: Salt Lake, Utah, Weber-Davis, Cache Counties. Also, methods will be developed to perform uncertainty analyses and/or quantify the uncertainties associated with the liquefaction susceptibility mapping during 2004-2007.

4. Develop probabilistic methods to map the amount of liquefaction-induced ground deformation (i.e., lateral spread displacement and liquefaction-induced settlement). These methods will use existing correlations that relate thickness of liquefiable layers and other soil factors to the potential for lateral spread displacement and settlement. This mapping will be done for the same areas as the liquefaction susceptibility maps and will be completed during 2007 to 2008.

*** Liquefaction Working Group Members**

Loren Anderson, Utah State University
Steve Bartlett, University of Utah
Matt Mabey, Brigham Young University
Dave Simon, Simon-Bymaster, Inc.
Barry Solomon, Utah Geological Survey
Bill Turner, Kleinfelder, Inc.
Les Youd, Brigham Young University
Dave Marble, Utah Div. Water Rights

APPENDIX D

UTAH PLAN FOR DEVELOPING THE NEXT GENERATION OF EARTHQUAKE-INDUCED LANDSLIDE-HAZARD MAPS

Utah Earthquake-Induced Landslide Working Group*
July-September 2003

Future moderate and large earthquakes in Utah may cause damaging landslides including 1) the reactivation of pre-existing landslides and triggering of new deep-seated landslides in susceptible areas, 2) shallow landslides on moderate to steep slopes, and 3) rock falls from steep mountain slopes.

OBJECTIVE: Develop maps that illustrate the potential for earthquake-induced landsliding, including on slopes where otherwise a landslide hazard may not exist. These maps will be used for raising public awareness, emergency preparedness and response, urban planning, and risk analyses by land-use planners (special-study maps), emergency managers, and lifeline managers including the Utah Department of Transportation.

Research Options

1. Investigate and select an approach, possibly that of McCrink (2001), for generating earthquake-induced landslide-hazard maps as a pilot project. The pilot project would evaluate several options to map geologic units with similar shear strengths based on: 1) the existing shear-strength database, supplemented by a renewed search of data available from consulting firms and state agencies, 2) additional laboratory testing to obtain shear-strength data (if funding becomes available), and 3) the use of “best estimates” from an expert panel. Criteria for selecting a pilot project study area include the availability of 1:24,000-scale geologic mapping, shear-strength data, an adequate landslide inventory, and 10-meter digital elevation models (DEMs). Sensitivity analyses should evaluate the relative importance of these criteria in the final map outcome. The pilot project should address the relation between static and earthquake-induced landslide-hazard maps, and methods to produce dual-purpose maps. The feasibility of incorporating SINMAP (Stability Index Mapping) software into the project will be evaluated.

2. Create earthquake-induced rock-fall susceptibility maps using the methods of Harp and Noble (1993) in study areas along the Wasatch Front urban corridor (Ogden-Provo) and/or important transportation/lifeline corridors in mountain areas. Evaluate the practicality of the technique for covering large areas and define methods for determining runout distances and potential for larger rock avalanches.

3. Inventory existing landslides in an area of similar geology (such as the bluffs in the Weber River delta complex), collect data (such as slope, dominant grain size, and ground-water conditions) that provides an understanding of stability/susceptibility to reactivation or local failure (including failure of slopes adjacent to landslides) during an earthquake, and assess the likely effects of earthquakes to improve our understanding of the actual hazard from earthquake-induced landslides.

4. Identify possible earthquake-induced landslides in the Wasatch Front and assess whether subsurface investigations could reveal ages of deposits or movement events allowing correlation with documented Wasatch Front surface-faulting earthquakes. Perform "paleoseismic" investigations of selected landslides and characterize site conditions that contribute to earthquake-induced landsliding.

***Earthquake-Induced Landslide Working Group**

Randy Jibson, USGS	Fulvio Tonon, U of U	Bob Pack, USU
Tim McCrink, CGS	Loren Anderson, USU	Barry Solomon, UGS
Jim Nordquist, AGEC	Leslie Heppler, UDOT	Francis Ashland, UGS
Danny Horns, UVSC	Jim Higbee, UDOT	Gary Christenson, UGS

APPENDIX E

EARTHQUAKE HAZARDS IN UTAH: IMPROVING OUR UNDERSTANDING

Thursday, February 26, 2004
Utah Department of Natural Resources Building, Room 1050
1594 W. North Temple, Salt Lake City

<u>Moderator: Gary E. Christenson</u>

8:30 a.m.	Welcome; Utah Earthquake Working Groups Gary Christenson, Utah Geological Survey
8:45	USGS NEHRP 2005 Priorities Mark Petersen, U.S. Geological Survey
9:00	Ground-Shaking Working Group Results Ivan Wong, URS Corporation
9:15	Liquefaction Working Group Results Steve Bartlett, University of Utah, Civil Engineering
9:30	Earthquake-Induced Landslide Working Group Results Francis Ashland, Utah Geological Survey
9:45	Quaternary Fault Parameter Working Group Results William R. Lund, Utah Geological Survey
10:00-10:20	Break

<u>Moderator: William R. Lund</u>

10:20	Extending the Paleoseismic Record of the Provo Segment of the Wasatch Fault: Preliminary Results from the Mapleton "Megatrench" Susan Olig, URS Corporation
10:40	Active Tectonics of the Nephi Segment, Revisited Chris DuRoss, University of Utah, Geology and Geophysics
11:00	Levan Segment WFZ Surficial Geologic Map Michael D. Hylland, Utah Geological Survey, and Michael N. Machette, U.S. Geological Survey
11:20	Segmentation and Holocene Displacement History of the East Great Salt Lake Fault David Dinter and James C. Pechmann, University of Utah, Geology and Geophysics

11:40 Guidelines for Evaluating Surface-Fault-Rupture Hazards
Gary Christenson, Utah Geological Survey, Darlene Batatian, Salt Lake County, and Craig Nelson, Western GeoLogic

12:00 noon -1:20 p.m. Lunch (not provided)

Moderator: Ivan Wong

1:20 p.m. USGS 2003 and Planned 2004 Seismic Imaging Studies
Bill Stephenson, U.S. Geological Survey

1:40 2003 SASW Shallow Shear-Wave-Velocity Results
James Bay and Jeff Gilbert, Utah State University, and Francis X. Ashland and Greg McDonald, Utah Geological Survey

2:00 Profiling in the 100-300 m Depth Range with Surface Waves
Kenneth Stokoe, University of Texas

2:20 Plans for Determining Sediment Thickness and Site Amplification Factors in Salt Lake Valley, Utah, using ANSS Data
James C. Pechmann, and Kris Pankow, University of Utah Seismograph Stations

2:35 GPS Studies of the Wasatch Fault Zone, Utah, with Implications for Fault Behavior and Earthquake Hazard
WuLung Chang and Robert B. Smith, University of Utah, Geology and Geophysics

2:55-3:15 Break

Moderator: Barry J. Solomon

3:15 Demonstration of UGS Shear-Wave-Velocity, Deep Basin, and Soil Shear-
Strength Databases
Greg McDonald and Bill Case, Utah Geological Survey

3:30 Plans for Construction and Verification of a Wasatch Front Community Velocity Model
Kim Olsen and Harold Magistrale, San Diego State University

3:50 Developing Response Spectra for Site Class E Soils
Steven Bartlett, University of Utah, Civil Engineering

4:10 UGS Earthquake-Induced Landslide Studies
Francis Ashland, Utah Geological Survey

4:30 EARTHSCOPE in Utah
Robert. B. Smith, University of Utah, Geology and Geophysics

4:50 Adjourn

DATABASE COMPILATION, COORDINATION OF EARTHQUAKE-HAZARDS MAPPING, AND STUDY OF THE WASATCH FAULT AND EARTHQUAKE-INDUCED LANDSLIDES, WASATCH FRONT, UTAH

PART III: INTERIM SURFICIAL GEOLOGIC MAP OF THE LEVAN SEGMENT OF THE WASATCH FAULT ZONE, JUAB AND SANPETE COUNTIES, UTAH

by

Michael D. Hylland, Utah Geological Survey
and
Michael N. Machette, U.S. Geological Survey

Utah Geological Survey
P.O. Box 146100
Salt Lake City, Utah 84114

April 2004

Effective date: January 1, 2003
Expiration date: December 31, 2003
Award number 03HQAG0008

CONTENTS

FIGURES

TABLES

PLATE

ABSTRACT

The Levan segment of the Wasatch fault zone extends about 33 km from just south of the town of Nephi to just south of the Juab-Sanpete County line. Quaternary deposits along the Levan segment are dominated by coalesced alluvial fans ranging in age from middle Pleistocene to late Holocene, but also include stream alluvium, landslide and debris-flow deposits, and undifferentiated basin fill.

Prior to this study, the northern segment boundary was identified at Hartleys Canyon, which is at the northern limit of Holocene fault scarps on the segment, and the southern segment boundary was identified at the pronounced left step in Quaternary faulting between the southern end of Juab Valley and Flat Canyon to the east. We propose that the northern segment boundary be moved about 8 km north to Cedar Point, to include a zone of Pleistocene fault scarps within the Levan segment. We define this revised segment boundary on the basis of range-front geometry and a 5-km gap in Quaternary faulting between the Levan and Nephi segments.

The Levan segment has had one, or possibly two, surface-faulting events during the Holocene based on estimated ages of faulted geomorphic surfaces, geomorphic expression of scarps, numeric age control on faulted deposits, empirical scarp-height – slope-angle relationships, and preliminary results of scarp diffusion age modeling. Because the segment has likely had at most two surface-faulting events in the Holocene, fault scarps provide a relatively straightforward view of the pattern of faulting along the segment. The age of the most recent event (MRE) is well established at about 1000 years ago at Deep Creek. Trenching by others near Skinner Peaks has provided evidence for two faulting events, and composite scarp profiles between the trench site and Chriss Canyon are consistent with two events. Scarps along the southernmost part of the segment have a simple morphology that could have resulted from either a single event (the penultimate event [PE] recorded at the trench site, which occurred sometime before 3100-3900 yr B.P.) or possibly two events. We conclude that the MRE ruptured the segment from Hartleys Canyon southward to at least the Skinner Peaks area (20 km), and possibly all the way to the southern end of the segment (26 km). The PE may have ruptured at least the southern 15 km of the segment, but the northern limit of this rupture is uncertain; we see no clear evidence of the PE preserved in Holocene deposits from Deep Creek northward. Scarps at the very northern end of the segment lack evidence for Holocene faulting. Taken together, the scarps along the Levan segment provide evidence suggesting at least one partial-segment rupture during the late Pleistocene and Holocene.

Slip rates on the Levan segment are uncertain because the age of the PE is unknown. Using data from the Deep Creek and Skinner Peaks sites, we calculate maximum Holocene vertical slip rates ranging from 0.25 to about 1 mm/yr; the true slip rate is undoubtedly closer to the low end of this range. Long-term average vertical slip rates since the middle Pleistocene are about 0.05-0.15 mm/yr based on the height of the scarp on late to middle Pleistocene fan alluvium near the middle of the segment.

INTRODUCTION

This map (plate 1) shows the geology along the Levan segment of the Wasatch fault zone in central Utah, with an emphasis on the relations between surficial Quaternary deposits and faults. The Levan segment is near the southern end of the Wasatch fault zone, the longest active normal-slip fault zone in the western United States and the most active fault zone in Utah. This map extends 1:50,000-scale surficial-geologic mapping of the fault zone south of the five central segments that trend through the populous Wasatch Front area of north-central Utah (figure 1). The Levan segment trends through a rural area of low population density and therefore presents less of a seismic risk than segments to the north. Still, the Levan segment shows evidence for Holocene surface faulting, and detailed mapping provides the basis for accurately characterizing the relative contribution of the segment to the overall seismic hazard of north-central Utah.

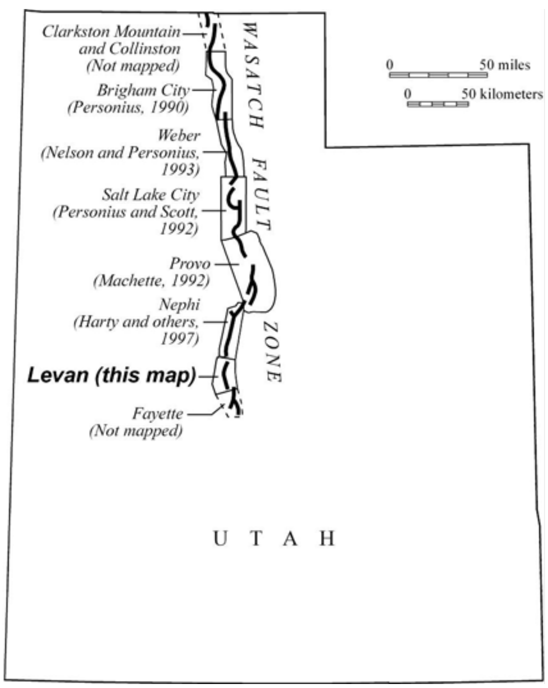

Figure 1. *Index map of Wasatch fault zone in Utah, showing segments and published 1:50,000-scale strip maps (modified from Harty and others, 1997).*

The Levan segment is along the eastern margin of southern Juab Valley, at the base of the western slope of the San Pitch Mountains (Gunnison Plateau) (figure 2). The segment extends about 33 km from just south of Nephi to just south of the Juab-Sanpete County line. Utah Highway 28 passes through the town of Levan near the northern end of the segment, and closely parallels the fault zone between Levan and the county line. Sevier Bridge Dam (spillway elevation 1529 m [5014 ft on base map]) is about 9 km west of the southern end of the Levan segment; impounded water of the Sevier River forms Sevier Bridge Reservoir, which extends southward on the west side of Highway 28 to the town of Fayette (figure 2).

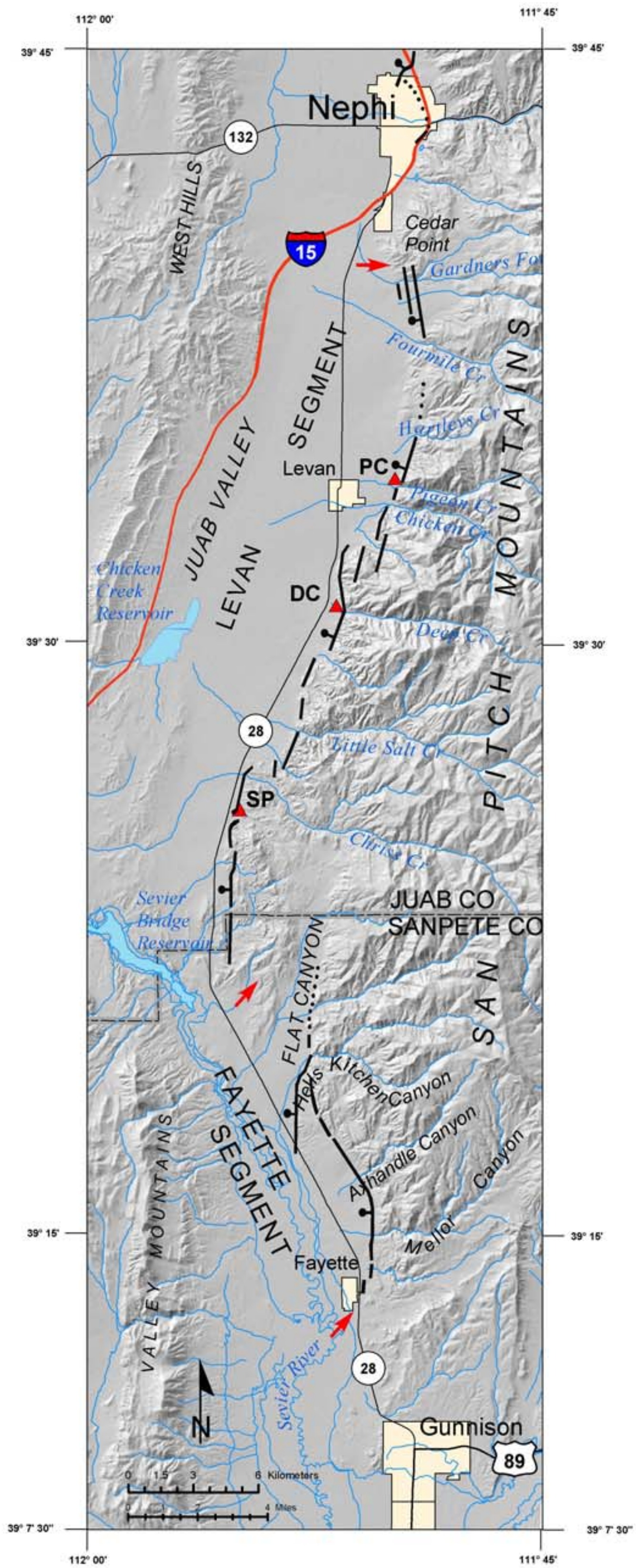

Figure 2. Levan and Fayette segments of Wasatch fault zone; faults shown by heavy lines, dotted where uncertain, bar and ball on downthrown side. PC, Pigeon Creek (site of radiocarbon age of faulted fan alluvium reported by Schwartz and Coppersmith, 1984); DC, Deep Creek stream-cut exposure of fault; SP, Skinner Peaks trench of Jackson (1991).

The discussion that follows includes a summary of existing paleoseismic information on the Levan segment, descriptions of Quaternary geologic deposits and fault scarps along the fault zone, and descriptions of the segment boundaries. Readers should note that the northern segment boundary as identified on this map is different from that identified by Machette and others (1992a), as discussed below under Segment Boundaries.

Geologic Setting

The Wasatch fault zone extends approximately 343 km from Malad City, Idaho, to Fayette, Utah, and comprises 10 segments that have been active in the late Quaternary (Machette and others, 1991, 1992a, 1992b). The Levan segment is near the southern end of the fault zone, between the Nephi segment to the north and the Fayette segment to the south (figures 1 and 2). The San Pitch Mountains are in the footwall of the fault and Juab Valley is in the hanging wall.

Along the Levan segment, bedrock exposed in the footwall consists of mudstone, siltstone, sandstone, limestone, and evaporites of the Jurassic Arapien Shale; limestone and shale of the Tertiary Green River Formation; volcaniclastic rocks of the Tertiary Goldens Ranch and Moroni Formations; and Tertiary intrusive rocks of intermediate composition. Quaternary-Tertiary alluvial-fan deposits locally overlie bedrock at the northern and southern ends of the segment. The hanging wall is dominated by coalesced alluvial-fan deposits of Holocene to middle Pleistocene age; drillers' logs indicate that the maximum thickness of these deposits exceeds about 180 m (Utah Division of Water Rights, 2003). Holocene alluvium and alluvial-fan deposits are present along the fault zone, and in many places the fault cuts these deposits.

A shallow arm of Late Pleistocene Lake Bonneville occupied the southern part of Juab Valley during the Bonneville highstand. Crittenden (1963) and Currey (1982) reported erosional Bonneville shoreline features in this area at altitudes of 1552 m (reported as 5090 ft) and 1556 m, respectively. Unfortunately, these altitudes are below the Levan segment, so Lake Bonneville deposits cannot be used as an aid in documenting the presence or absence of post-Bonneville (latest Pleistocene to Holocene) surface faulting as they are along the Wasatch fault zone farther to the north.

The overall structure in the footwall rocks along much of the Levan segment is that of a broad, north- to northeast-trending anticlinal fold and parallel subsidiary folds ("Levan anticline" of John [1972] and Auby [1991]; "Levan culmination" of Weiss and others [2003]). These folds formed probably as the combined result of compressional tectonism during the Late Cretaceous – early Tertiary Sevier orogeny (Standlee, 1982; Auby, 1991) and at least local diapirism associated with salt in the Arapien Shale (Witkind, 1983; 1994; 1999). Some pre-existing Sevier-aged structures may in part control the location of the Wasatch fault zone in this area (Smith and Bruhn, 1984). Standlee (1982) interprets the Levan segment as flattening into the Pavant thrust in the subsurface beneath the West Hills on the west side of Juab Valley.

Geophysical data indicate southern Juab Valley occupies an asymmetric, east-dipping structural basin (Smith and Bruhn, 1984; Zoback, 1992). Based on a seismic-reflection profile at Levan, Smith and Bruhn (1984) interpret the Wasatch fault to be relatively planar to a depth of about 5 km, dipping west beneath the valley at about 34º. Poor data quality precluded confident interpretation below 5 km. Another seismic-reflection profile near the southern end of the valley indicates a listric geometry for the Wasatch fault, with near-surface dips similar to those at Levan flattening to near horizontal at a depth of about 5 km (Standlee, 1982). In the vicinity of Nephi, Zoback (1992) interpreted a maximum thickness for the late Tertiary to Quaternary basin fill of about 1.6 km based on seismic-reflection and gravity data, and the gravity data indicate a similar thickness at Levan.

In the San Pitch Mountains, summit elevations are lower and the range front is less abrupt than in the Wasatch Range to the north. Wheeler and Krystinik (1988) noted that topographic relief is in a broad sense almost 2 km greater in the central part of the Wasatch Range than in the northern part of the range and in the San Pitch Mountains. Although at least some of this difference in relief may be due to geologic factors such as structural thickening and differential erosion, the overall pattern of topographic variation is mimicked by variation in late Quaternary slip rates, which are higher along the central part of the Wasatch fault zone and lower on the ends (Machette and others, 1992a; Black and others, 2003).

Methods

This map compiles previous geologic quadrangle mapping by Witkind and others (1987), Auby (1991), Biek (1991), Felger (1991), Witkind and Weiss (1991), and Weiss and others (2003) (figure 3). Because documentation of late Quaternary faulting was not the primary purpose of these maps, Hylland remapped the Quaternary deposits along the Levan segment using 1:20,000-scale black-and-white aerial photographs (1965, U.S. Department of Agriculture). U.S. Soil Conservation Service maps (Swenson and others, 1981; Trickler and Hall, 1984) were used as an aid in differentiating gradational alluvial-fan contacts in Juab Valley. Our fault-scarp mapping included use of lineament maps generated from low-sun-angle aerial photography (Cluff and others, 1973), reconnaissance field mapping by Machette in 1984, and detailed aerial-photograph and field mapping by Hylland in 2003.

We differentiated Quaternary geologic units using standard relative-age criteria such as geomorphic expression, landform preservation, stratigraphic position, and soil development. For pedogenic carbonate morphology, we use the stage classification summarized in Machette (1985) and Birkeland and others (1991). A few numeric ages obtained from bulk soil and charcoal, including one radiocarbon age obtained for this study (see Quaternary Faulting below), helped constrain the age of Holocene alluvial-fan deposits. The map-unit symbols used here follow the convention used on the previously published strip maps of the other Wasatch fault zone segments (figure 1). Detailed descriptions of the map units are given in the appendix.

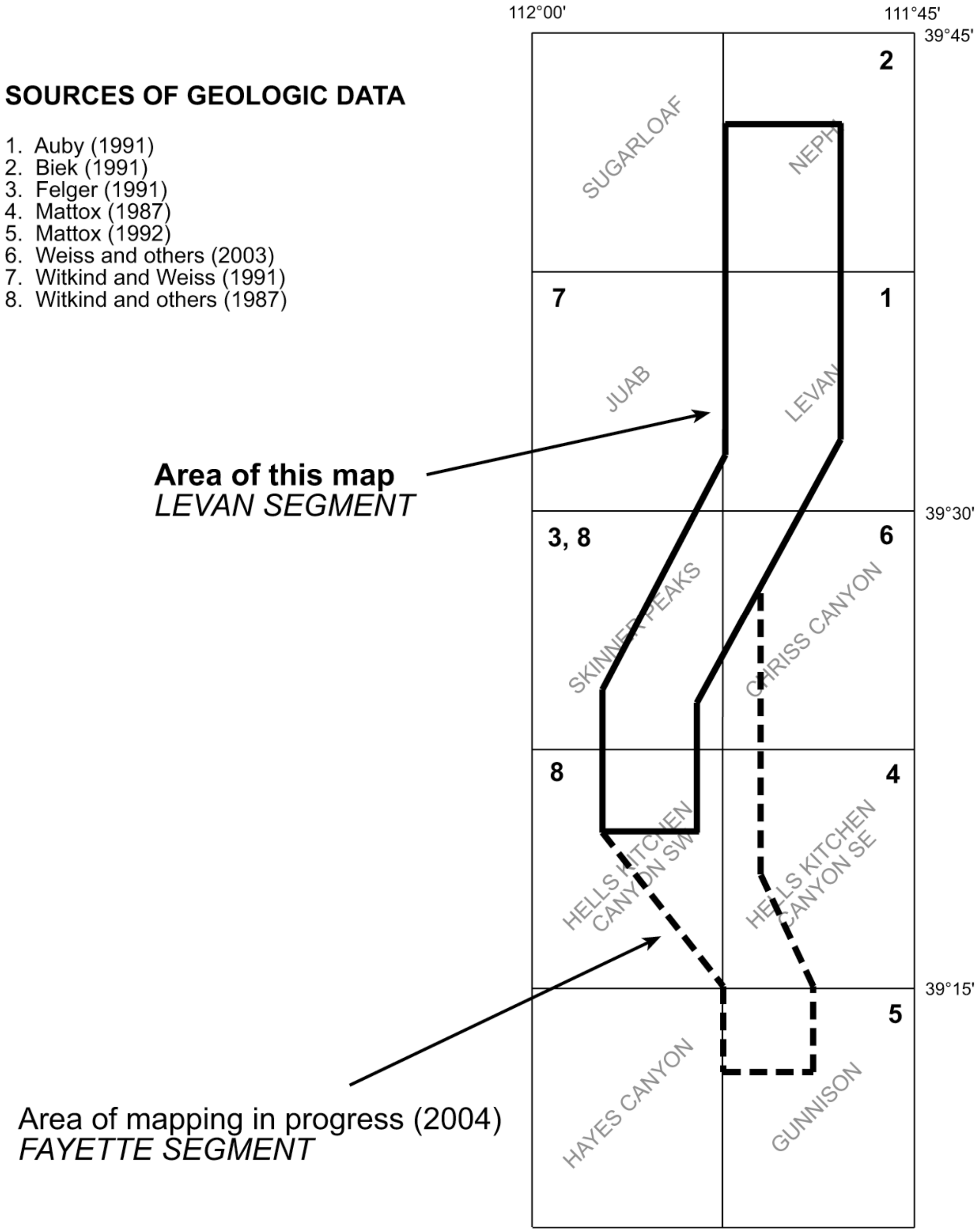

Figure 3. *Index of map coverage relative to USGS 7.5-minute quadrangles, and sources of geologic mapping used in compilation of this map.*

During his reconnaissance mapping in 1984, Machette measured 25 fault-scarp profiles along the Levan segment using a stadia rod and Abney level. Scarp heights and slope angles were determined from computer plots of the scarp profiles, and we used these data to estimate single-event fault-scarp ages. Our analyses, using the empirical method of Bucknam and Anderson (1979) and the diffusion model of Andrews and Bucknam (1987), are described below under Fault Scarp Age.

Results of Previous Paleoseismic Studies

The limited paleoseismic data for the Levan segment come from a faulted alluvial fan at Pigeon Creek, a natural stream-channel exposure at Deep Creek, and a trench excavated near Skinner Peaks (figure 2). At Pigeon Creek, 2 km east of Levan, geologists from Woodward-Clyde Consultants obtained radiocarbon ages of 1750 ± 350 and 2100 ± 300 ^{14}C yr B.P. on charcoal from faulted alluvial-fan deposits (Crone, 1983b; Schwartz and Coppersmith, 1984), providing a maximum limiting age for the most recent surface-faulting event (MRE). At Deep Creek, about 5 km south of Levan and 0.8 km east of Highway 28, a graben is exposed in the north bank of the stream channel (figure 4). The graben, approximately 30 m wide, is formed by a west-facing main scarp about 3.2 m high and an antithetic scarp about 0.5 m high. Schwartz and Coppersmith (1984), Machette (unpublished mapping, 1984-86), and Jackson (1991) concluded that the main scarp resulted from a single faulting event. During reconnaissance mapping between Levan and Gunnison, Schwartz and Coppersmith (1984) obtained a radiocarbon age of 7300 ± 1000 ^{14}C yr B.P. on charcoal from an unspecified position low in the footwall exposure at Deep Creek (Jackson, 1991, p. 9), providing a broad maximum limiting age for the surface-faulting event. Jackson (1991) logged the Deep Creek exposure and obtained a thermoluminescence (TL) age estimate of 1000 ± 100 yr B.P. for a buried A horizon that formed on the ground surface prior to faulting; Jackson considers this age estimate to closely approximate the time of faulting. Jackson (1991) also suggested the Schwartz and Coppersmith (1984) radiocarbon age provides a broad minimum limiting age for any unexposed penultimate event (PE), presumably based on the apparent lack of stratigraphic evidence for offset associated with a PE. However, given the limited depth of exposed hanging-wall deposits and the uncertainty of the charcoal-sample location, the exact significance of the radiocarbon age relative to PE age is unclear. Jackson (1991) calculated 1.8 m of net vertical tectonic displacement (NVTD) at Deep Creek, similar to the 1.75 m of displacement measured by Machette (Machette and others, 1992a).

The Skinner Peaks trench site is about 15 km south of Levan and 200 m east of Highway 28 (figure 2). The trench was cut across a 3.3-m-high scarp on a Holocene alluvial fan (Jackson, 1991). Jackson interpreted the stratigraphic relations exposed in the trench as providing evidence for two surface-faulting events. A combination of TL and calendar-calibrated radiocarbon age estimates on samples from a burn horizon in the footwall block provide maximum limiting ages for the MRE, which Jackson interpreted as having occurred between 1500 and 1000 yr B.P. Jackson (1991) interpreted similarly derived age estimates on samples (including disseminated charcoal) from a buried incipient A horizon in the hanging-wall block as indicating the PE occurred sometime before 3100 to 3900 yr B.P. The relatively small vertical distance (about 1 m) of this

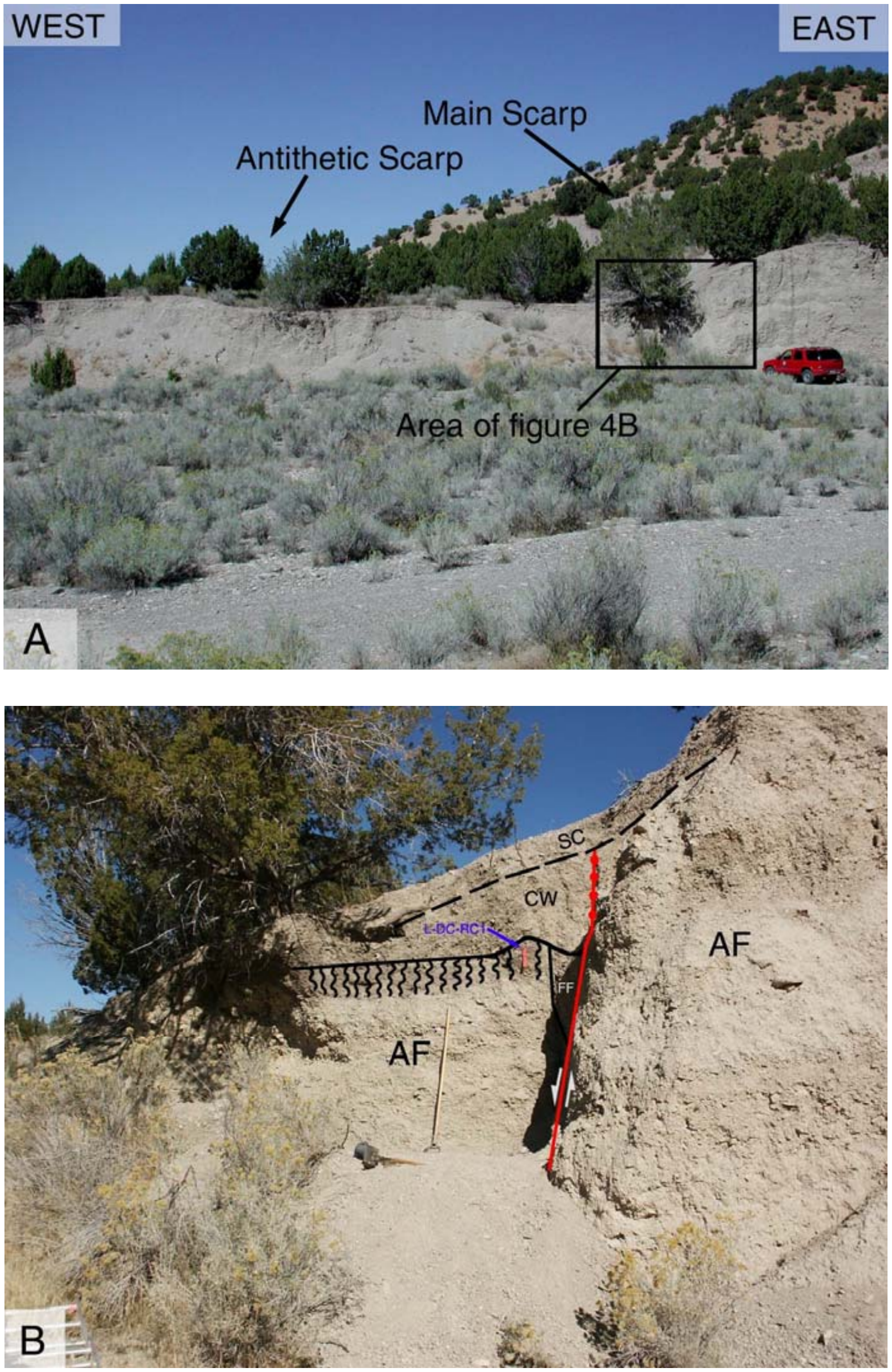

Figure 4. *Natural exposure of Wasatch fault zone in north bank of Deep Creek channel. A. Main scarp is about 3.2 m high, antithetic scarp is about 0.5 m high, and graben is about 30 m wide. B. Exposure reveals a single fault trace cutting alluvial-fan deposits (AF), an accumulation of fissure-fill deposits (FF), a single scarp-derived colluvial wedge (CW) that buries an organic soil A horizon, and surficial slope colluvium (SC). Bulk-soil sample L-RC-DC1 yielded an AMRT age of 1200 ± 80 ^{14}C yr B.P. (see "Fault Scarp Age" in text). Handle of scraping tool is 1.4 m long.*

buried soil below the bottom of the MRE colluvial wedge seems to support Jackson's minimum-limiting-age interpretation; however, the exact significance of the soil ages is somewhat ambiguous. Machette and others (1992a) speculated that the PE could have occurred in latest Pleistocene or early Holocene time. Jackson (1991) estimated NVTD of 2.0 m for the MRE and a minimum of 0.8 m for the PE.

QUATERNARY DEPOSITS AND DEPOSITIONAL HISTORY

Relative uplift of the San Pitch Mountains since latest Tertiary time has been accompanied by alluvial-fan deposition in Juab Valley, and fan alluvium dominates Quaternary-age deposits along the Levan segment. We differentiate Quaternary fan alluvium along the Levan segment into four map units: older fan alluvium (unit afo), intermediate-age fan alluvium (unit afi), younger fan alluvium (unit afy), and coalesced fan alluvium (unit afc).

Older fan alluvium is preserved as relatively small, isolated surfaces that are about 5-15 m above adjacent younger alluvial fans and modern stream channels. Continuous, thin to relatively thick coatings of secondary $CaCO_3$ are present on the undersides of clasts, and sometimes completely encase clasts (stage II to possibly stage III carbonate morphology). Comparison with soil carbonate morphology studied by Machette (1985) in the Beaver basin, about 150 km southwest of Levan and in a similar climatic zone, indicates the older fan alluvium is probably late to middle Pleistocene in age. Intermediate-age fan alluvium forms isolated surfaces that are up to about 5 m above adjacent younger alluvial fans and modern stream channels. Thin, discontinuous to continuous $CaCO_3$ coatings are present on the undersides of clasts (stage I+), and these deposits are probably early Holocene in age. Younger fan alluvium forms small, discrete alluvial fans where depositional processes are still active. Surface gradients of these fans range from about 3º to 10º, and the deposits grade downslope into coalesced fan alluvium. Active alluvial deposition also occurs on the low-gradient coalesced alluvial fans that fill Juab Valley, although mostly on the proximal parts of the fans near the mountain front; surface gradients of these fans range from about 1.5º to 3º. Exposures of coalesced fan alluvium are rare, but a stream cut along Fourmile Creek in the NE1/4NW1/4 section 5, T. 14 S., R. 1 E. exposes a 3-m-thick sequence of sandy alluvial deposits and interbedded eolian silt. The deposits at this locality are likely early to late Holocene in age, but coalesced fan alluvium may be as old as late Pleistocene in places.

Alluvial-fan deposits of Pleistocene to possibly Miocene age (unit QTaf) are preserved in the foothills at the northern and southern ends of the Levan segment. These deposits, some of which are now up to 300 m above the floor of Juab Valley (Auby, 1991), consist of material shed westward off the Gunnison Plateau (San Pitch Mountains) and may contain strata that record the initial uplift of the Gunnison Plateau (Biek, 1991; Felger, 1991). Similar deposits at the southern end of Juab Valley, all west of the fault zone, have been mapped as pediment alluvium (unit QTpm) by Witkind and others (1987) and Felger (1991).

Stream alluvium is present as channel deposits, as a broad alluvial apron in the area of Old Pinery Canyon and Gardners Fork at the northern end of the Levan segment, and as basin fill at the southern end of Juab Valley. Older stream alluvium (unit alo) forms surfaces typically up to about 20 m, but locally up to 40 m, above modern streams, and displays stage I-II carbonate morphology; we interpret these deposits to be early Holocene to middle Pleistocene in age. The deposits in the Old Pinery Canyon – Gardners Fork area form a thick alluvial apron that extends into Juab Valley, forming a drainage divide known as Levan Ridge. Machette (in Machette and others, 1992a) observed that the streams supplying sediment to Levan Ridge are grossly underfit, and speculated most of the Levan Ridge alluvium was deposited by a paleochannel of Salt Creek, which was diverted to its present location east of the town of Nephi by stream capture as recently as the late Pleistocene. Younger stream alluvium (unit aly) represents late Holocene deposition in the relatively larger modern stream channels and flood plains. Minor, shallow drainages and basins contain stream alluvium mixed with a significant component of hillslope colluvium (unit ac). In the southern part of Juab Valley, low hills of Tertiary volcanic rocks intervene between the valley and the main range front of the San Pitch Mountains, and alluvial fans are poorly developed or absent. We map the valley-floor deposits here as basin-fill alluvium (unit ab).

Colluvial deposits along the Levan segment include older landslide deposits (unit clso), younger landslide deposits (unit clsy), debris-flow deposits (unit cd), rock-fall and talus deposits (unit crf), and deposits of mixed colluvium and alluvium (unit ca). The relative ages of landslide deposits are poorly constrained and are based primarily on geomorphic expression. Older (Pleistocene) landslide deposits include the Fourmile Creek landslide complex (Auby, 1991), which consists of a large (6.5 km^2), stratigraphically disrupted, lithologically heterogeneous area along the range front just south of Fourmile Creek. This landslide complex lacks a well-defined source area, probably formed as the result of local instability rather than significant translational movement of a large landslide mass, and includes areas of active landsliding too small to map separately. Auby (1991) recognized strata of the Salt Creek Fanglomerate, Goldens Ranch Formation, and Arapien Shale within the landslide complex. Younger (Holocene) landslide deposits are scattered throughout the map area. We mapped individual late Holocene debris-flow deposits on range-front alluvial fans where the deposits are large enough to show at the map scale. Many of these deposits are immediately downslope of a fault scarp, and document relative uplift and incision of the upper part of the alluvial fan as a result of faulting. Talus deposits of Holocene to possibly late Pleistocene age are present mostly on the relatively steep slopes of Pigeon and Chicken Creeks east of Levan, where beds of fractured Arapien limestone are rock-fall source areas. Colluvium of Holocene to possibly late Pleistocene age is widespread throughout the map area, but we mapped only relatively significant accumulations that also include an alluvial component.

QUATERNARY FAULTING

Relatively fresh-looking (Holocene) scarps are present along most, but not all, of the Levan segment. The scarps are mostly in unconsolidated fan and stream alluvium, but locally are in bedrock. Lithologic characteristics of the fan and stream alluvium exposed in the scarps vary somewhat along the fault, but generally can be characterized as follows: (1) at the north end of the segment – sandy pebble and cobble gravel, dominated by well-rounded quartzite clasts; (2) between Hartleys Canyon and Chriss Canyon – pebble gravel in a matrix of sand, silt, and clay, dominated by tabular clasts of shaly limestone; and (3) south of Chriss Canyon – sandy pebble and cobble gravel with silt and clay, dominated by subangular, felsic volcanic clasts. The scarps have relatively low maximum scarp angles (≤32º), and are generally in the wash-controlled stage of development of Wallace (1977), although debris-slope processes may still be active on some of the steeper scarps. We suspect that lithologic characteristics contribute to relatively high rates of scarp degradation along the Levan segment.

In the discussion that follows, we give a general description of faulting along the Levan segment, present data and modeling results relative to the age of faulting, and address the issue of late Quaternary slip rates. Terminology used to describe fault-scarp morphology (figure 5) follows that established by Bucknam and Anderson (1979) for single-event scarps and Machette (1982) for multiple-event scarps. Our characterization of fault-scarp age is based on (1) estimated ages of faulted geomorphic surfaces, (2) geomorphic expression of scarps, (3) numeric age control on faulted deposits, (4) comparison of scarp-height – slope-angle relationships with the empirical regression lines of Bucknam and Anderson (1979), and (5) calculation of scarp age using the diffusion model of Andrews and Bucknam (1987). Figure 6 shows the general locations of our measured scarp profiles, and table 1 summarizes the scarp-profile data and preliminary diffusion-modeling results.

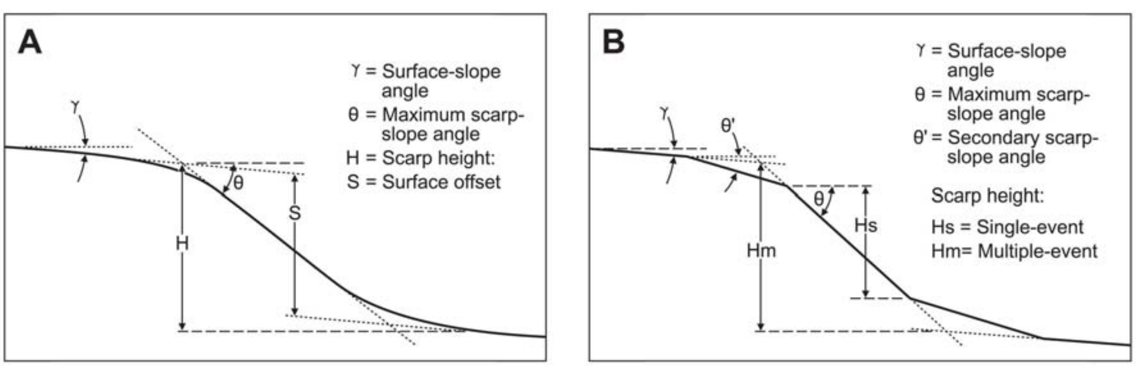

***Figure 5.** Schematic diagrams illustrating fault-scarp nomenclature used in this report. A. Single-event scarp (modified from Bucknam and Anderson, 1979). B. Multiple-event scarp (modified from Machette, 1982).*

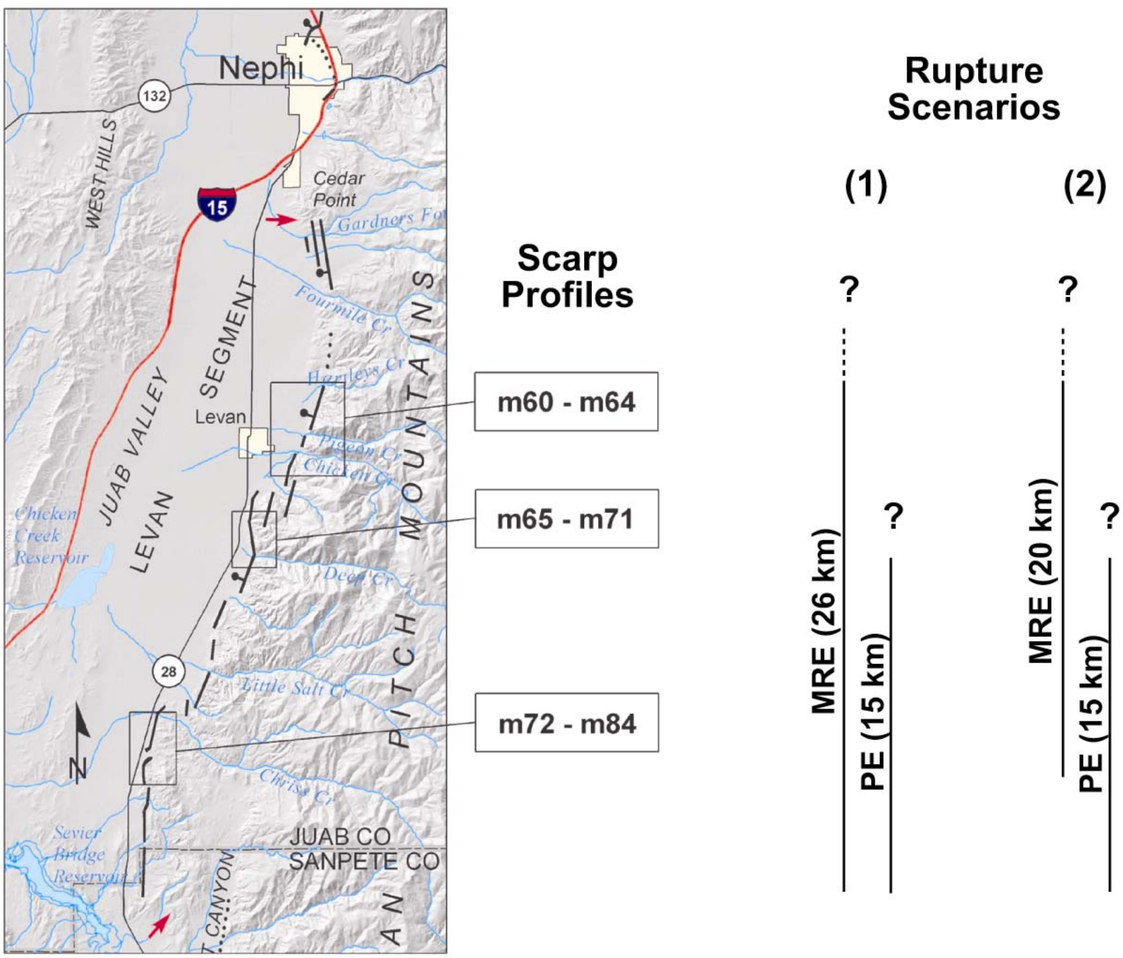

Figure 6. *General locations of measured scarp profiles, and proposed rupture scenarios for the last two surface-faulting events on the Levan segment. Vertical lines indicate extent of scarps formed during the most recent faulting event (MRE) and penultimate event (PE); see "Fault Scarp Age" in text for discussion of rupture scenarios. Scarp-profile data are summarized in table 1.*

Table 1. *Levan-segment fault-scarp profile data. General locations of profiles shown on figure 6. Preliminary diffusion ages calculated using the model of Andrews and Bucknam (1987); diffusion constant (K_0) = 0.35 ± 0.13 m^2/kyr (back-calculated from Deep Creek scarp data, profile m71).*

Scarp Profile	Scarp Height (m)	Surface Offset[1] (m)	NVTD[2] (m)	Scarp Angle (θ)[3] (º)	Ambient Slope Angle (γ) (º)	Uncertainty (º)	Dimensionless Scarp Age (t')[4]	Uncertainty	Diffusion Age (t)[5] (yr B.P.)	Comments
m60	3.1	2.2	1.5	30	8	1	0.0265	0.0265	366±137	-
m61	-	-	-	-	-	-	-	-	-	Unable to determine footwall γ
m62	2.5	1.7	1.4	27	8	1	0.097	0.035	801±149	-
m63	2.5	2.0	1.2	24	5	1	**0.148**	0.047	1691±295	-
m64	12.2	8.1	4.8	-	-	-	-	-	-	Composite scarp on unit afo
m65	3.2	2.5	1.8	28	7	1	0.0655	0.0245	1170±218	-
m66	3.0	2.2	1.9	28	7	1	0.0655	0.0245	906±170	-
m67	4.3	2.7	2.0	32	12	2	-	-	-	γ exceeds max. value to determine t'
m68	-	-	-	-	-	-	-	-	-	Unable to determine footwall γ
m69	0.9	0.5	0.5	17	8	1	1.462	0.708	1044±267	θ – γ < 10
m70	2.7	2.0	2.0	22	5	1	**0.233**	0.076	2663±470	-
m71	3.2	2.3	2.0	27	4	1	0.0655	0.0215	990±174	Scarp at Deep Creek natural exposure
m72	2.7	2.0	2.0	-	-	-	-	-	-	Composite scarp morphology
m73	1.7	1.2	1.2	-	-	-	-	-	-	Composite scarp morphology
m74	1.2	0.7	0.7	12	5	1	4.04	2.32	5656±1467	θ – γ < 10
m75	2.1	1.7	1.7	-	-	-	-	-	-	Composite scarp morphology
m76	2.6	1.9	1.9	19	4	1	**0.407**	0.138	4198±755	-
m77	3.9	3.1	3.1	-	-	-	-	-	-	Composite scarp morphology
m78	3.6	2.7	2.7	25	6	1	0.13	0.043	2708±477	Just north of Skinner Peaks trench site
m79	3.6	3.1	3.1	25	4	2	0.111	0.044	3048±584	Just south of Skinner Peaks trench site
m80	1.6	1.3	1.3	16	3	2	**0.795**	0.395	3839±859	Multiple-event scarp?
m81	2.2	1.8	1.8	17	3	2	**0.614**	0.289	5684±1213	Multiple-event scarp?
m82	3.1	2.7	2.7	20	3	1	**0.286**	0.0905	5957±1029	Multiple-event scarp?
m83	3.9	3.0	3.0	22	5	1	**0.233**	0.076	5991±1046	Multiple-event scarp?
m84	3.8	2.6	2.6	22	7	2	**0.324**	0.149	6258±1306	Multiple-event scarp?

1 Uncertainty ± 0.2 m.
2 Net vertical tectonic displacement (= surface offset except where graben-forming antithetic fault is present).
3 Uncertainty ± 1º.
4 Bold values indicate t' derived from independently dated scarps (calibrated part of table 2 in Andrews and Bucknam, 1987).
5 $t = t' (SO)^2/K_0$; t, age of scarp (ka); t', dimensionless scarp age; SO, vertical surface offset across scarp (m); K_0, diffusion constant (mass diffusivity) at 0º fan slope (m^2/kyr).

General Description of Fault Scarps

Hartleys Canyon, 4.3 km northeast of Levan, marks the boundary between fault scarps that are clearly Holocene in age and fault scarps to the north that are no younger than late Pleistocene. North of Hartleys Canyon, fault scarps are present on middle Pleistocene stream and fan alluvium, but we found no evidence of Holocene faulting. Subparallel fault scarps form a zone approximately 1 km wide on the alluvial apron in the area of Old Pinery Canyon and Gardners Fork; scarp heights range from about 3 to 5 m, scarp-slope angles are low (12º-14º), and the scarps have smooth, rounded crests. South of this zone, the Fourmile Creek landslide complex occupies the area between Fourmile Creek and Hartleys Canyon. The presence or absence of Quaternary fault scarps within the landslide complex is difficult to document because fault scarps may resemble landslide scarps, and reactivated landslide movement may obliterate pre-existing fault scarps.

South of Hartleys Canyon, discontinuous Holocene fault scarps extend southward to the Juab-Sanpete County line, 22 km south of Levan. Where these scarps are formed on Holocene deposits, scarp heights are typically about 2.5-4 m and scarp-slope angles generally range from 17º to 30º (table 1). In a few places, channels associated with intermittent streams that have breached the scarps have sharp knickpoints that have retreated less than 10 m from the scarps. Small antithetic scarps are present to the west of the main scarps in many places, forming small grabens (less than 10 m wide) and causing stream channels to make an abrupt bend and follow the fault trace for a short distance. Net vertical tectonic displacement across the zone of deformation is typically about 50% of the scarp height where a graben is present, and about 75% of the scarp height where a graben is not present (table 1). Between Hartleys Canyon and Chriss Canyon, fault scarps on Holocene deposits appear to be the result of a single faulting event. South of Chriss Canyon, at least some of the scarps on Holocene deposits are the result of two faulting events, based primarily on stratigraphic data from the Skinner Peaks trench (Jackson, 1991); these scarps are discussed further below. Where the scarps cross upper to middle Pleistocene alluvial-fan deposits, the scarps are as high as about 12 m and are clearly the result of multiple late Quaternary faulting events.

The Holocene fault scarps comprise several discrete geometric sections along the length of the Levan segment, defined by scarp terminations in bedrock and (or) lateral step-overs to adjacent sections. From Hartleys Canyon, scarps on Holocene alluvial fans extend south-southwest about 6 km along the base of the roughly linear range front. About 2.5 km south of Levan, where the range front makes a bend to the south, the southernmost of these scarps trend into and terminate in bedrock. The fault zone steps right, and scarps on Holocene alluvial fans continue south along the base of the range front for another 6 km to just north of Little Salt Creek. Here, the range front makes a shallow reentrant, and the fault zone steps left. Within the reentrant, Holocene fault scarps extend to the prominent unnamed drainage 1.5 km south of Little Salt Creek, where they trend into bedrock and terminate north of Chriss Canyon. At Chriss Canyon, the fault zone again steps right, and scarps on Holocene alluvial fans extend about 3 km along the range front to a point west of Skinner Peaks. From here, the range front to the south is less well defined, and Holocene scarps step left and continue about 4 km south in shallow basins that parallel the eastern margin of Juab Valley. At the southern end of the shallow basins, the fault scarps trend into bedrock and terminate in the Quaternary-Tertiary alluvial-fan deposits between the southern end of Juab Valley and Flat Canyon to the east.

Fault Scarp Age

Data from the natural exposure of the fault at Deep Creek provide a good estimate of scarp age for the northern part of the Levan segment that has undergone Holocene movement. Stratigraphic relations exposed in the stream cut show that the scarp formed during a single faulting event, and Jackson's (1991) thermoluminescence (TL) age of 1000 ± 100 yr B.P. for the A horizon soil buried by the scarp-derived colluvial wedge provides a close maximum age of the scarp-forming earthquake. As a check of this age, we resampled the uppermost 5 cm of the same buried A horizon to obtain an apparent mean residence time (AMRT) radiocarbon age. Our radiocarbon age for the bulk soil of 1200 ± 80 ^{14}C yr B.P. calendar calibrates to 950-1280 cal yr B.P. (2σ). Because of the thin sample interval, we apply a relatively small mean residence correction of 100 years (following the approach described by Machette and others, 1992a [appendix] and McCalpin and Nishenko, 1996) and subtract this from the calendar-calibrated age. The resulting median AMRT age of 1015 ± 165 cal yr B.P. agrees closely with the TL age, and provides additional support for a scarp age of about 1000 yr B.P.

Stratigraphic data from the Skinner Peaks trench indicate the scarp there formed as the result of two faulting events (Jackson, 1991). Although poorly constrained, Jackson's age estimate for the MRE (between 1000 and 1500 yr B.P.) is consistent with the age of scarp formation at Deep Creek. The age of the PE at Skinner Peaks is constrained only by Jackson's (1991) minimum limiting age of 3100-3900 yr B.P. For the most part, the multiple-event nature of fault scarps on the southern part of the Levan segment cannot be distinguished directly from scarp morphology. This problem has been noted by other workers on other faults; for example, Colman (1986) found that fault scarps in the Rio Grande rift in Colorado rarely show morphologic evidence of multiple events despite other documentation of recurrent movement. However, four of our measured scarp profiles on Holocene deposits between the Skinner Peaks trench site and Chriss Canyon show composite forms (maximum scarp-slope angle and secondary scarp-slope angle, both steeper than the ambient surface-slope angle) consistent with two faulting events. Also, the highest values of NVTD (surface offset) obtained from the scarp profiles on Holocene deposits are all associated with scarps south of Chriss Canyon, possibly indicating multiple faulting events.

We present two scenarios for the pattern of rupture associated with the last two surface-faulting events on the Levan segment (figure 6). (1) If the scarps south of Chriss Canyon are multiple-event scarps, the PE may have ruptured at least the southern 15 km of the segment, but the northern limit of this rupture is uncertain; we see no clear evidence of the PE preserved in Holocene deposits from Deep Creek northward. The MRE would have ruptured the segment from the southern segment boundary to at least as far north as Hartleys Canyon, a distance of about 26 km. (2) If the scarps south of the Skinner Peaks trench site are single-event scarps, as their morphology might indicate, then they may have formed during the PE, and the composite scarps between the trench site and Chriss Canyon may represent a zone of overlap between the PE to the south (15-km maximum rupture length) and the MRE to the north (20-km minimum rupture length, from just south of the Skinner Peaks trench site to at least as far north as Hartleys Canyon). Regardless of the scenario, the scarps along the Levan segment provide evidence suggesting at least one partial-segment rupture during the late Pleistocene and Holocene.

Figure 7 shows our scarp profile data (scarp height and maximum scarp-slope angle) plotted along with the best-fit empirical regression lines of Bucknam and Anderson (1979) for the Fish Springs and Drum Mountains fault scarps in western Utah. The Fish Springs scarps are about 2000 years old (Bucknam and others, 1989), and the early Holocene Drum Mountains scarps (Crone, 1983a) are estimated to be about 9000 years old (Pierce and Colman, 1986). All of the Levan data plot to the left of (younger than) the Drum Mountains regression line, and a few points plot to the left of the Fish Springs regression line. The Deep Creek scarp (data point m71) plots older than its 1000 yr B.P. age, so other Levan-segment data may plot too old as well, probably due to differences in lithology, microclimate, or other fault-degradation factors that may exist between the Levan and Fish Springs scarps. With the exception of one point, all of the data from north of Chriss Canyon plot younger than the data from south of Chriss Canyon. This either indicates a difference in scarp age if all the data represent single-event scarps, or is merely an artifact of a mix of data from both single- and multiple-event scarps (the multiple-event scarps having maximum scarp-slope angles that correspond only to the most recent faulting event).

Preliminary scarp-age calculations using the nonlinear diffusion model of Andrews and Bucknam (1987) (table 1) indicate a difference in mean age between fault scarps north of Chriss Canyon and south of the Skinner Peaks trench site. However, these results are valid only if the scarps are all single-event scarps, because the difficulty in accurately estimating the pre-faulting geometry of multiple-event scarps generally contributes to a very high degree of uncertainty (McCalpin, 1996, p. 135). We use a diffusion-constant (K_0) value of 0.35 m^2/kyr, which was back-calculated using data from the scarp at Deep Creek. Mean diffusion ages calculated from our results (table 1) are 1204 ± 235 yr B.P. for scarps north of Chriss Canyon and 5973 ± 1148 yr B.P. for scarps south of the Skinner Peaks trench site. Apparent diffusion ages (including the mean) for the fault scarps south of the trench site are consistent with Jackson's (1991) minimum limiting age of 3100-3900 yr B.P. for the PE. However, because of the uncertainty in the number of faulting events (one or two) that created these scarps, the apparent diffusion ages of the southern scarps may be invalid.

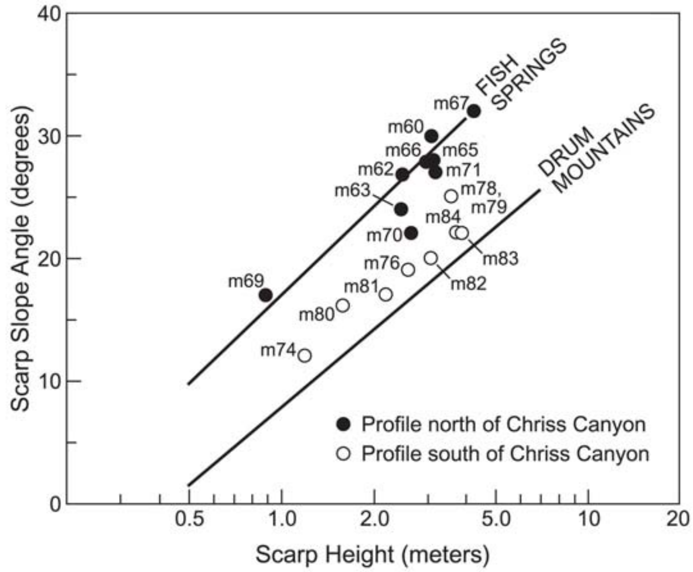

Figure 7. *Levan-segment scarp-profile point data and best-fit empirical regression lines of Bucknam and Anderson (1979) for the Fish Springs and Drum Mountains scarps. Data are omitted for scarps interpreted to likely be the result of multiple faulting events. Profiles m74 through m84 are on scarps that may or may not be the result of multiple faulting events. Scarp-profile data are summarized in table 1.*

Late-Quaternary Slip Rates

Accurate determination of late Quaternary slip rates for the Levan segment is presently not possible because the age of only one faulting event is known, and therefore the only seismic cycle for which we have data (between the MRE and PE) is an open cycle. However, we can use scarp height and estimated age of older (late to middle Pleistocene) fan alluvium to estimate a long-term average vertical slip rate, and data from the Deep Creek exposure and Skinner Peaks trench to estimate a maximum Holocene vertical slip rate. These results, which are summarized in table 2, indicate at the very least the order of magnitude of slip rates on the Levan segment.

We estimate age of the older fan alluvium (unit afo) using degree of secondary $CaCO_3$ development and comparison with data from the Beaver basin (Machette, 1985). The older fan alluvium is probably no younger than about 80 ka and no older than about 250 ka. Dividing a scarp height of 12 m by these ages gives a range in estimated long-term vertical average slip rate of about 0.05-0.15 mm/yr.

A maximum Holocene vertical slip rate for the Levan segment of about 0.3 mm/yr has been reported in the literature (Hecker, 1993; Black and others, 2003). This value is based on 1.8 to 2.0 m of NVTD for the MRE and the minimum elapsed time between the MRE and PE at Deep Creek, calculated by subtracting Jackson's (1991) MRE age of 1000 yr B.P. from Schwartz and Coppersmith's (1984) 7300 ^{14}C yr B.P. age obtained on material near the bottom of the footwall exposure, which probably(?) post-dates any unexposed earlier event. However, the age obtained by Schwartz and Coppersmith has a large uncertainty (±1000 yr) that was not considered in the slip-rate calculation, and is reported as a radiocarbon age, which would need to be calendar calibrated to be consistent with the thermoluminescence age for the MRE. Subtracting our radiocarbon age for the MRE from Schwartz and Coppersmith's radiocarbon age gives an approximate maximum vertical slip rate of 0.25-0.36 mm/yr (table 2), indicating 0.3 mm/yr is probably a reasonable maximum vertical rate for the Levan segment at Deep Creek.

A maximum Holocene vertical slip rate can also be calculated using data from the Skinner Peaks trench, where all of Jackson's (1991) reported ages are calendar calibrated. Using a vertical displacement of 2.0 m for the MRE, an age of 1000 yr B.P. for the MRE, and the upper and lower bounds (3100-3900 yr B.P.) of the minimum limiting age of the PE, Jackson's data indicate a maximum vertical slip rate of 0.69-0.95 mm/yr for the Levan segment at Skinner Peaks (table 2). Because the PE may be considerably older than the minimum limiting age, these slip-rate estimates may be considerably too high. Calculations using the mean diffusion age for the scarps south of the trench site result in a vertical slip rate of 0.33 to 0.53 mm/yr (table 2). Given that slip rates on the more active central segments of the Wasatch fault are in the 1-2 mm/yr range (Black and others, 2003), the high end of these maximum slip-rate estimates for the Levan segment are likely not realistic.

Table 2. *Estimated slip rates for the Levan segment of the Wasatch fault zone. Slip rates for the Deep Creek and Skinner Peaks sites are maximum rates. LT, long-term; MRE, most recent event; NVTD, net vertical tectonic displacement; PE, penultimate event; SH, scarp height.*

Site	SH or NVTD	Deposit Age	MRE Age yr B.P.	PE Min. Age yr B.P.	Elapsed Time yr	Slip Rate mm/yr
Spring Hollow	12 m (SH)	80-250 ka	—	—	—	0.05-0.15 (av. LT)
Deep Creek	1.8 m (NVTD)	—	1120-1280*	6300-8300*	5020-7180	0.25-0.36
Skinner Peaks	2.0 m (NVTD)	—	1000	3100-3900**	2100-2900	0.69-0.95
		—	1000	4825-7121***	3825-6121	0.33-0.53

* Ages are in ^{14}C yr B.P.
** Age data from Jackson (1991).
*** Age data from diffusion modeling in this study.

SEGMENT BOUNDARIES

Schwartz and Coppersmith (1984) originally defined the Levan segment as extending 40 km from east of Levan southward to near Gunnison (figure 2). Based on recency of faulting and fault geometry, Machette and others (1986, 1987) divided the segment into the Levan segment (restricted sense) and the Fayette segment to the south.

Machette and others (1991, 1992a) described a 15-km-long gap in Holocene faulting between the northern end of the Levan segment and the southern end of the Nephi segment, and Machette and others (1992a) identified Hartleys Canyon as the northern boundary of the Levan segment. However, gravity data show a broad, continuous gravity low beneath Juab Valley adjacent to this gap in recent faulting (Zoback, 1983, 1992), suggesting that the Wasatch fault is a continuous structural feature beneath this gap (Machette and others, 1992a). Although Hartleys Canyon marks the northernmost Holocene fault scarps on the segment, we suspect that Quaternary faulting, and possibly even Holocene faulting, extended northward but is unrecognized in the Fourmile Creek landslide complex. Also, fault scarps are present on middle Pleistocene alluvium in the area of Gardners Fork and Old Pinery Canyon (Biek, 1991; Machette and others, 1991, 1992a; this map). These late to middle Pleistocene fault scarps terminate to the north in Quaternary-Tertiary alluvial-fan deposits (Salt Creek Fanglomerate of Biek, 1991) on the southern slopes of Cedar Point in section 28, T. 13 S., R. 1 E. To the north, in the NW1/4 section 21, T. 13 S., R. 1 E., short escarpments are present on an isolated remnant of middle Pleistocene fan alluvium, but we are uncertain whether these were formed by faulting or erosion. Otherwise, no unambiguous evidence of Quaternary faulting exists between Cedar Point, which forms a minor salient in the range front, and Holocene fault scarps that mark the southern end of the Nephi segment just southeast of the town of Nephi (Machette and others, 1992a; Harty and others, 1997). Based on this 5-km-long gap in Quaternary faulting and range-front geometry, we propose that the northern boundary of the Levan segment be placed at Cedar Point.

The southern end of Holocene fault scarps on the Levan segment is about 0.5 km east of Utah Highway 28, just south of the southern jog in the Juab-Sanpete County line (section 4, T. 17 S, R. 1 W.). Here, Quaternary faulting steps 3.5 km to the east and 5 km to the south, to the east side of Flat Canyon, and continues southward in the Fayette segment, which shows no evidence of Holocene movement (Machette and others, 1991, 1992a).

RECOMMENDATIONS FOR ADDITIONAL STUDY

The main unresolved issues related to latest Quaternary faulting on the Levan segment are the number of faulting events represented by the southernmost scarps, and the age and amount of displacement of the PE. Resolving these issues is critical to understanding the pattern of surface faulting since the late Pleistocene and determining a meaningful Holocene slip rate. Several investigative techniques may be useful in addressing these issues. Additional scarp profiling on the southern end of the segment may provide insight into the number of faulting events that formed the scarps. Refined diffusion-age modeling, using different values of diffusivity relative to variations in dominant scarp lithology and incorporating the constant-slip-rate solution of Mattson and Bruhn (2001), could help constrain both scarp age and slip rate. Evaluating relations between surface rupture length and displacement, using the empirical regressions of Wells and Coppersmith (1994), would likely provide insight into the number of scarp-forming faulting events and the pattern of surface faulting. Finally, trenching across known and possible multiple-event scarps would likely provide stratigraphic evidence to constrain the number of faulting events and determine NVTD, and possibly datable materials that could be used to constrain event age. With the exception of trenching, we plan to undertake these additional studies as we continue our surficial geologic mapping of the Fayette segment to the south (study in progress 2004).

SUMMARY AND CONCLUSIONS

The Levan segment of the Wasatch fault zone extends about 33 km southward from Cedar Point, south of the town of Nephi, to just south of the Juab-Sanpete County line. We define the northern segment boundary on the basis of range-front geometry and a 5-km gap between late to middle Pleistocene fault scarps of the Levan segment and Holocene fault scarps of the Nephi segment. The southern segment boundary is marked by a pronounced left step and difference in age of Quaternary fault scarps (the Fayette segment shows no evidence of Holocene movement; Machette and others, 1992a).

The northernmost part of the Levan segment shows no evidence of Holocene movement. Holocene fault scarps are present from Hartleys Canyon to the southern end of the segment. Data from a natural exposure of the fault at Deep Creek indicate the scarp there formed as the result of a single faulting event about 1000 years ago. Trench data from the Skinner Peaks area indicate the scarp there formed as the result of two faulting events, one between 1000 and 1500 yr B.P. and the other sometime before 3100-3900 yr B.P. (Jackson, 1991). Several measured scarp profiles between the trench site and Chriss Canyon show composite forms consistent with two faulting events. Profiles of scarps south of the trench site do not show composite forms, and we are unsure whether these scarps formed as the result of one or two faulting events. Calculated mean diffusion age for these southern scarps is 5973 ± 1148 yr B.P., consistent with Jackson's (1991) minimum limiting ages for the earlier event at the trench site. However, the diffusion modeling results are valid only if these scarps are in fact single-event scarps.

The penultimate event (PE) on the Levan segment may have ruptured at least the southern 15 km of the segment, but the northern limit of this rupture is uncertain; we see no clear evidence of the PE preserved in Holocene deposits from Deep Creek northward. If the scarps south of Chriss Canyon are multiple-event scarps, that would indicate that the most recent event (MRE) ruptured the segment between Hartleys Canyon and the southern end of the segment (26 km). If the scarps south of the Skinner Peaks trench site are single-event scarps, then they may have formed during the PE, and the composite scarps between the trench site and Chriss Canyon may represent a zone of overlap between the PE to the south and the MRE to the north (MRE length 20 km). Regardless of the scenario, the scarps along the Levan segment provide evidence suggesting at least one partial-segment rupture during the late Pleistocene and Holocene.

Lack of a well-constrained age for the PE precludes accurate determination of a Holocene slip rate on the Levan segment. Using net vertical tectonic displacement and the minimum elapsed time between the MRE and PE at the Deep Creek and Skinner Peaks sites, we calculate maximum vertical slip rates ranging from 0.25 to about 1 mm/yr; the true slip rate is undoubtedly closer to the low end of this range. Based on scarp height and estimated age of late to middle Pleistocene fan alluvium near the middle of the segment, long-term average vertical slip rates since the middle Pleistocene are about 0.05-0.15 mm/yr.

ACKNOWLEDGMENTS

This map was funded through a cooperative agreement between the Utah Geological Survey (UGS) and U.S. Geological Survey (USGS) (contract no. 03HQAG0008). We thank Mark Peterson (USGS) for his support in funding this study. Gary Christenson and Bill Lund (UGS) provided valuable advice and visited several field sites, and Gary reviewed this report. Chris DuRoss (University of Utah) discussed his scarp diffusion-age modeling on the Nephi segment, and Doug Sprinkel (UGS) and Don Clark (Roux Associates, Inc.) shared their insights into the bedrock geology of the area. Jim Parker and Lucas Shaw (UGS) created many of the figures, and Lori Douglas (UGS) digitally compiled the map.

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APPENDIX

Description of Map Units

These map-unit descriptions are organized by genesis (mode of formation) and increasing age. Quaternary geologic units were differentiated using relative-age criteria such as stratigraphic position, geomorphic expression, and soil-profile development. Map-unit symbols follow the convention used on the previously published strip maps of the other Wasatch fault zone segments. Unit thicknesses are rounded to the nearest 5 m.

Stream Alluvium

aly **Younger stream alluvium (upper Holocene)** – Gravel, sand, and silt with minor clay and scattered cobbles and boulders; clasts well rounded to subangular; generally stratified. Deposited in modern stream channels and flood plains; locally forms terraces less than 10 m above stream level that grade downslope into upper Holocene alluvial-fan deposits (unit afy). May include small alluvial fans and minor amounts of locally derived colluvium along steep stream embankments. Exposed thickness <10 m.

alo **Older stream alluvium (lower Holocene to middle Pleistocene)** – Gravel, sand, and silt with cobbles and minor clay, locally bouldery; clasts well rounded to subangular; generally stratified. May include minor amounts of locally derived colluvium along steep stream embankments. Most deposits show stage I carbonate morphology and form terraces up to 20 m above modern streams. In the area of Old Pinery Canyon and Gardners Fork, deposits show stage II carbonate morphology, and are incised up to about 40 m. Exposed thickness about 10-40 m.

ab **Basin-fill alluvium (upper Holocene to middle? Pleistocene)** – Gravel, sand, and silt with minor clay and scattered cobbles and boulders; clasts well rounded to subangular; generally stratified. Deposited by intermittent streams in the southern part of Juab Valley where alluvial fans are poorly developed or absent. Thickness variable.

ac **Alluvium and colluvium, undivided (Holocene)** – Undifferentiated stream and fan alluvium and hillslope colluvium; may also locally include an eolian component. Deposited in shallow drainages associated with intermittent streams, and in small, shallow basins. Thickness variable.

Fan Alluvium

afy **Younger fan alluvium (upper Holocene)** – Pebble and cobble gravel, locally bouldery, in a matrix of sand, silt, and minor clay; clasts angular to subrounded. Deposited by intermittent streams, debris flows, and debris floods graded to modern stream level. Deposits form discrete fans, typically with bar and swale topography. Locally includes deposits of unit cd too small to map separately. Local weak stage I carbonate morphology. Exposed thickness <2 m.

afc **Coalesced fan alluvium (upper Holocene to upper? Pleistocene)** – Proximal facies: pebble and cobble gravel, locally bouldery, in a matrix of sand, silt, and minor clay; clasts subangular to well rounded. Distal facies: silt and fine sand with minor clay. Deposited by perennial and intermittent streams, debris flows, and debris floods graded to or slightly above modern stream level; includes a significant component of eolian silt. Deposits form large, low-gradient fans that cover most of the floor of Juab Valley. Includes local areas of active fan deposition (unit afy) and deposits of unit cd too small to map separately. Thickness variable; maximum thickness >180 m.

afi **Intermediate-age fan alluvium (lower Holocene)** – Pebble and cobble gravel, locally bouldery, in a matrix of sand, silt, and minor clay; clasts angular to well rounded. Preserved as intermediate-level remnants incised by modern streams and locally buried by younger fan alluvium (unit afy). Incised by, and grades downslope into, coalesced fan alluvium (unit afc). Stage I+ carbonate morphology. Exposed thickness <5 m.

afo **Older fan alluvium (upper to middle Pleistocene)** – Pebble and cobble gravel, locally bouldery, in a matrix of sand, silt, and minor clay; clasts subangular to well rounded. Preserved as relatively high, isolated remnants that lack fan morphology. Stage II to III carbonate morphology. Exposed thickness <15 m.

QTaf **Alluvial-fan deposits (Pleistocene to Miocene?)** – Unconsolidated to semiconsolidated, poorly sorted fan alluvium generally preserved as high, isolated remnants; clasts include quartzite, sandstone, limestone, and volcanics. Northern deposits mapped as Salt Creek Fanglomerate by Auby (1991) and Biek (1991); up to about 150 m thick; possibly as old as Pliocene. Southern deposits mapped as "rubble" by Witkind and others (1987) and as "older alluvial fans" by Felger (1991); up to about 90 m thick; possibly as old as Miocene.

Pediment Alluvium

QTpm **Pediment mantle deposits (Pleistocene to Miocene?)** – Unconsolidated to well-cemented deposits having similar texture and composition as unit QTaf, but with more abundant volcanic clasts and local pebbly sandstone and sandy limestone; as mapped by Witkind and others (1987) and Felger (1991). Characterized by even surfaces that slope gently away from uplands. Exposed thickness up to about 10 m.

Colluvial Deposits

cd **Debris-flow deposits (upper Holocene)** – Clast- and matrix-supported pebble and cobble gravel, locally bouldery; clasts angular; matrix consists of sand, silt, and clay. Commonly covered with coarse, angular rubble and have relatively fresh-appearing levees and channels. Deposited on surface of upper Holocene alluvial fans (unit afy); deposits too small to map separately are included in unit afy. Exposed thickness <5 m.

crf **Rock-fall and talus deposits (Holocene to upper Pleistocene)** – Clast-supported pebble, cobble, and boulder gravel; unsorted and unstratified; angular to subangular. Typically forms cones and sheets at or near the angle of repose (~35°). Exposed thickness <5 m.

clsy **Younger landslide deposits (Holocene)** – Unsorted, unstratified deposits, primarily derived from the Arapien Shale, that have moved downslope by rotational or translational gravity-induced slip. Scarps and hummocky topography are relatively fresh in appearance. Thickness highly variable.

clso **Older landslide deposits (Pleistocene)** – Unsorted, unstratified deposits that have moved downslope by rotational or translational gravity-induced slip. Scarps and landslide surfaces are dissected and landslide morphology is subdued. Includes the Fourmile Creek landslide complex of Auby (1991). May include Holocene landslides (unit clsy) too small to map separately. Thickness highly variable.

ca **Colluvium and alluvium, undivided (Holocene to upper Pleistocene)** – Undifferentiated hillslope colluvium, stream and fan alluvium, and small landslide deposits. Thickness variable.

Artificial Deposits

f **Artificial fill and associated disturbed ground (historical)** – Primarily locally derived surficial material placed or disturbed during construction or mining activities. Includes embankments, waste rock piles, and landfills. Present throughout the map area, but only the largest areas shown.

Bedrock

Pre-Quaternary deposits are not shown in detail on the map. For more information on the pre-Quaternary geology of the area, consult the geologic quadrangle maps listed in Sources of Geologic Data (figure 3 in the report). Bedrock areas may include unmapped deposits of hillslope colluvium.

Ti **Tertiary intrusive rocks (Miocene)** – Monzonite porphyry, leucomonzonite, and syenite of the Levan intrusive suite (Auby, 1991).

Tv **Tertiary volcaniclastic rocks (Oligocene to Eocene)** – Conglomerate, sandstone, and tuff of the Goldens Ranch and Moroni Formations.

Ts **Tertiary sedimentary rocks (Eocene)** – Limestone, shale, sandstone, and conglomerate of the fluviolacustrine Green River Formation. Locally includes a relatively thin sequence of alluvial and lacustrine strata of early Tertiary-Late Cretaceous age, possibly correlative with the Flagstaff Limestone and North Horn Formation, on the northeast side of Skinner Peaks (Felger, 1991).

Mz **Mesozoic sedimentary rocks (Jurassic)** – Shaly limestone, sandstone, siltstone, mudstone, and gypsum of the shallow-marine Arapien Shale. At least on a local scale, the Arapien Shale shows evidence of salt-related diapirism (Witkind, 1983; 1994; 1999).

INTERIM SURFICIAL GEOLOGIC MAP OF THE LEVAN SEGMENT OF THE WASATCH FAULT ZONE, JUAB AND SANPETE COUNTIES, UTAH

by

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and
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2004

Research supported by the U.S. Geological Survey (USGS), Department of the Interior, under USGS award number 03HQAG0008. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

DESCRIPTION OF MAP UNITS

(see text booklet appendix for detailed descriptions, and figure 3 for sources of compiled geologic mapping.)

STREAM ALLUVIUM

- aly — Younger stream alluvium (upper Holocene)
- alo — Older stream alluvium (lower Holocene to middle Pleistocene)
- ab — Basin-fill alluvium (upper Holocene to middle? Pleistocene)
- ac — Alluvium and colluvium, undivided (Holocene)

FAN AND PEDIMENT ALLUVIUM

- afy — Younger fan alluvium (upper Holocene)
- afc — Coalesced fan alluvium (upper Holocene to middle Pleistocene)
- afi — Intermediate-age fan alluvium (lower Holocene)
- afo — Older fan alluvium (upper to middle Pleistocene)
- QTaf — Alluvial-fan deposits (Pleistocene to Miocene?)
- QTpm — Pediment mantle deposits (Pleistocene to Miocene?)

COLLUVIAL DEPOSITS

- cd — Debris-flow deposits (upper Holocene)
- crf — Rock-fall and talus deposits (Holocene to upper Pleistocene)
- clsy — Younger landslide deposits (Holocene)
- clso — Older landslide deposits (Pleistocene)
- ca — Colluvium and alluvium, undivided (Holocene to upper Pleistocene)

ARTIFICIAL DEPOSITS

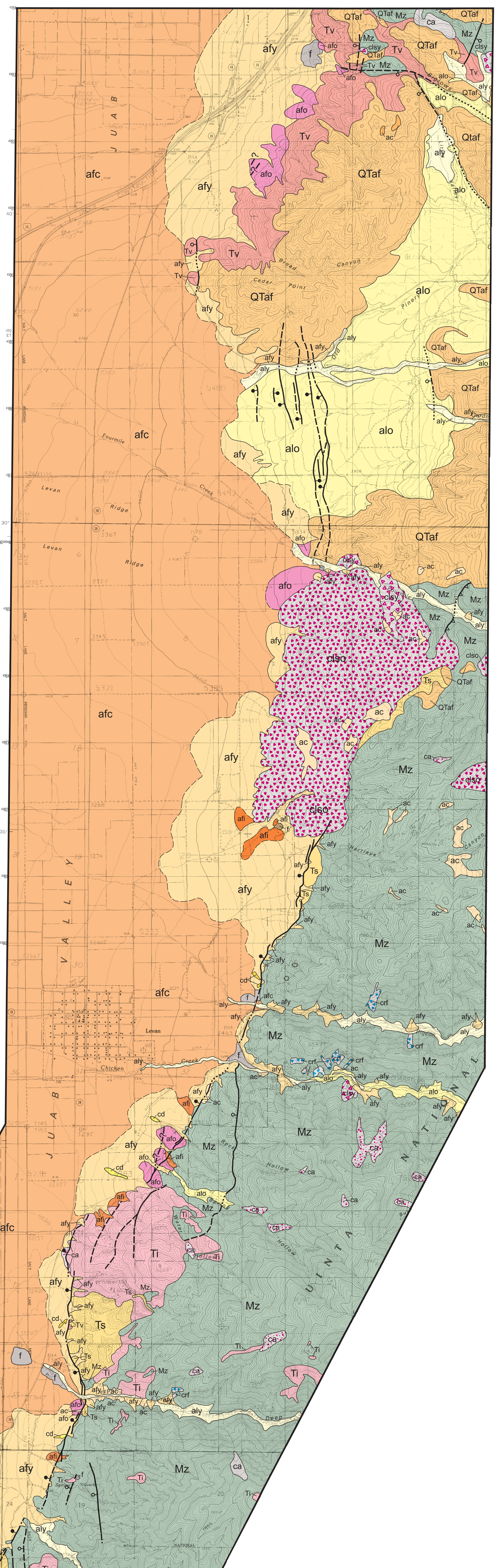
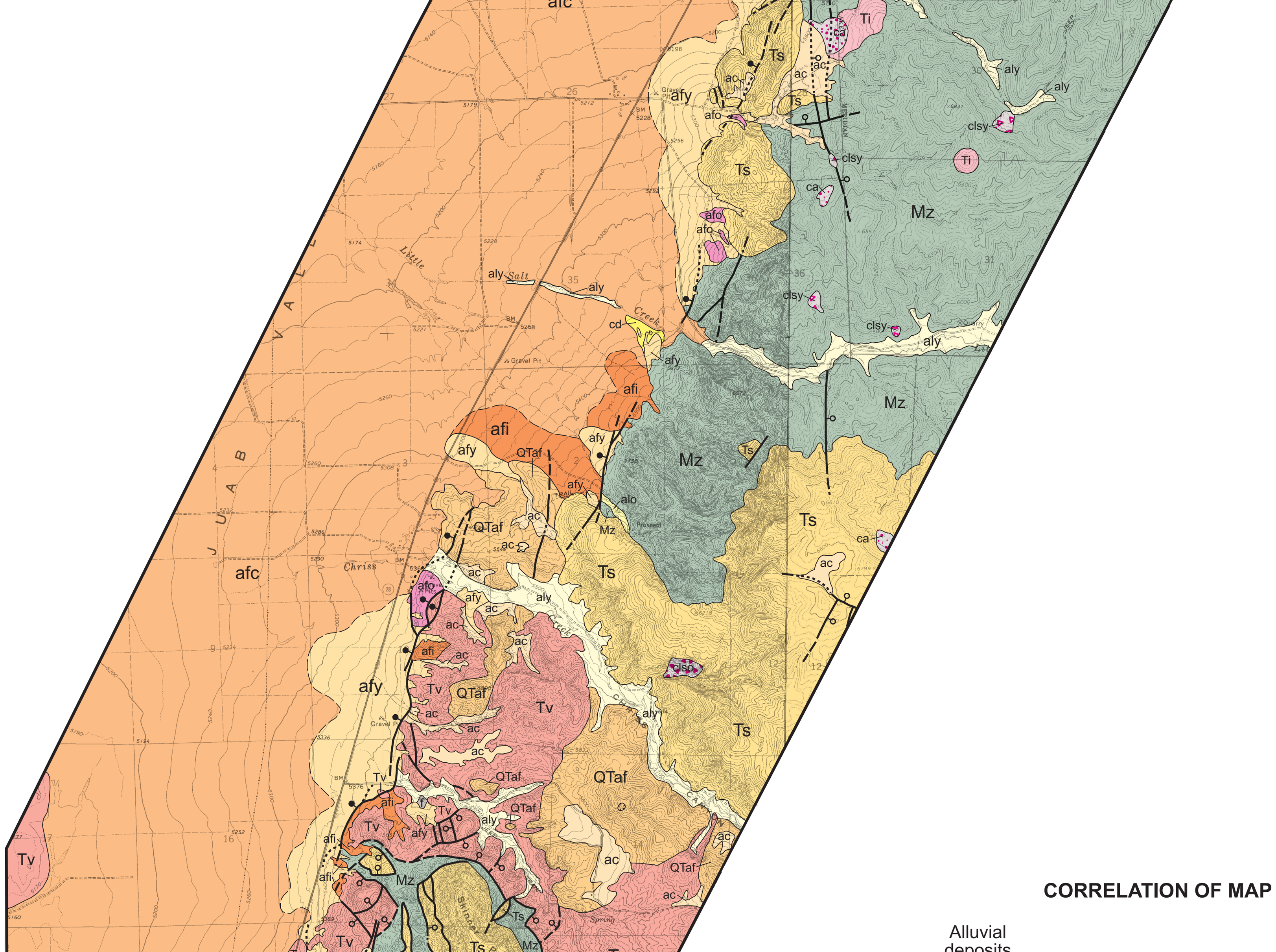
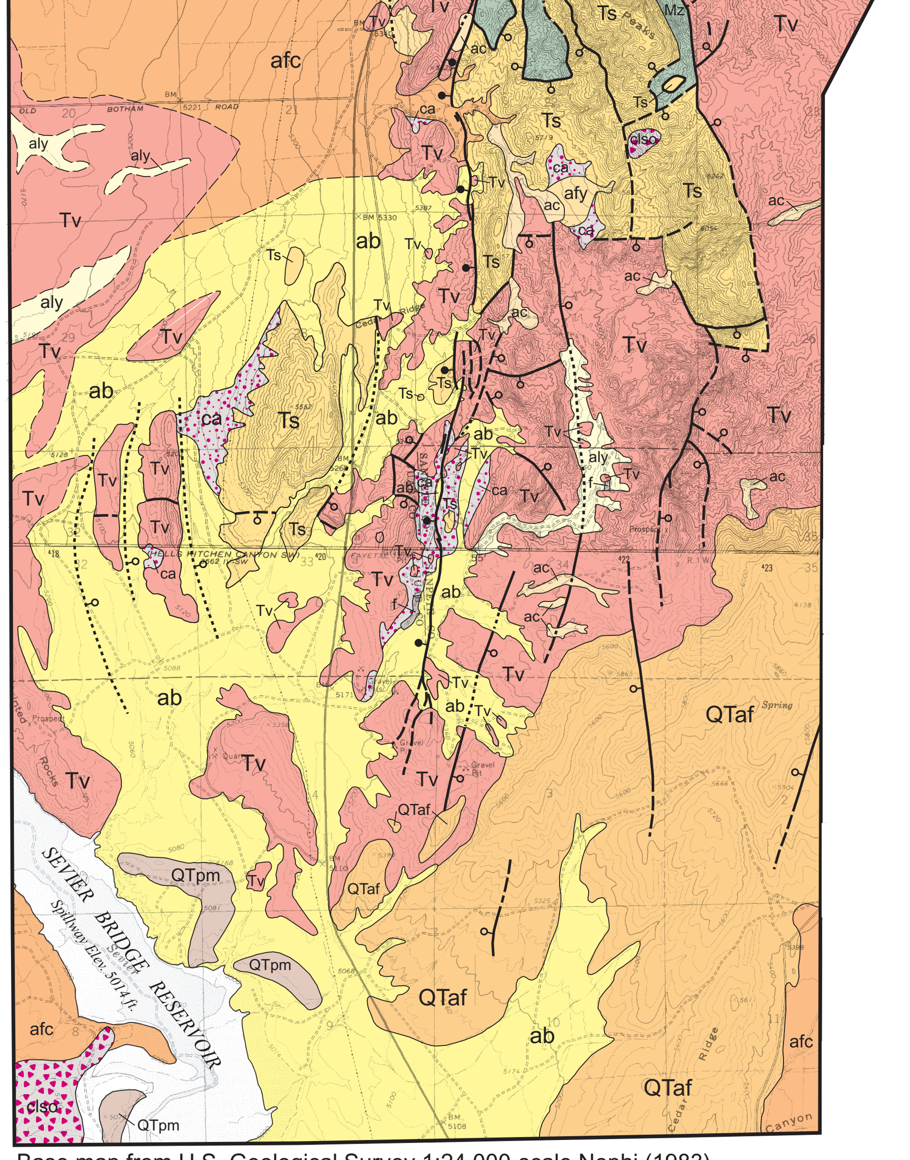
- f — Artificial fill and associated disturbed ground (historical)

BEDROCK

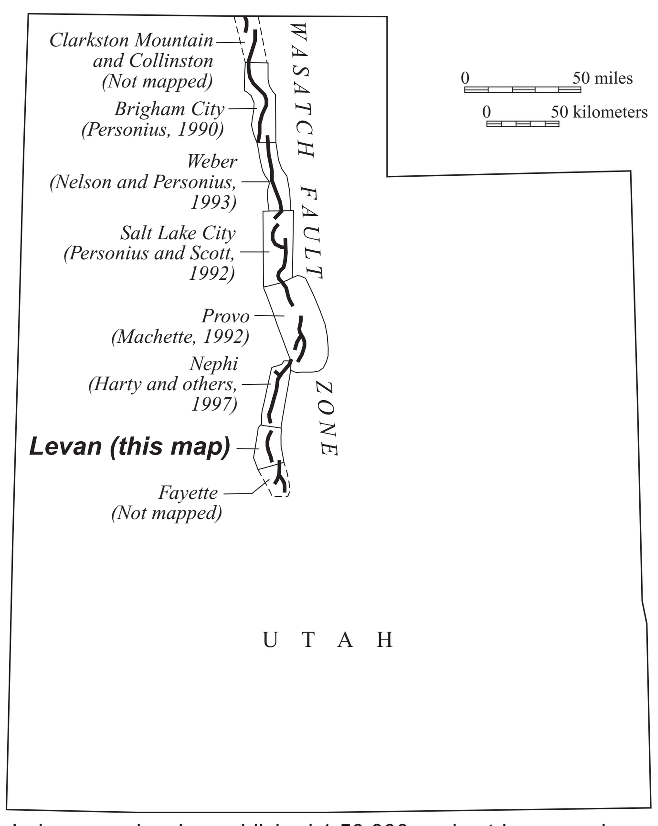
- Ti — Tertiary intrusive rocks (Miocene)
- Tv — Tertiary volcaniclastic rocks (Oligocene to Eocene)
- Ts — Tertiary sedimentary rocks (Eocene)
- Mz — Mesozoic sedimentary rocks (Jurassic)

MAP SYMBOLS

- Contact - Dashed where approximately located.
- Normal fault - Wasatch fault zone. Bar and ball on downdropped side. Dashed where approximately located; dotted where concealed; queried where tectonic origin of scarp is uncertain.
- Normal fault - Bar and ball on downdropped side (where sense of displacement is known). Dashed where approximately located, dotted where concealed.
- Reverse fault - Sawteeth on overriding plate or block in bedrock. Dotted where concealed.
- Sinkhole

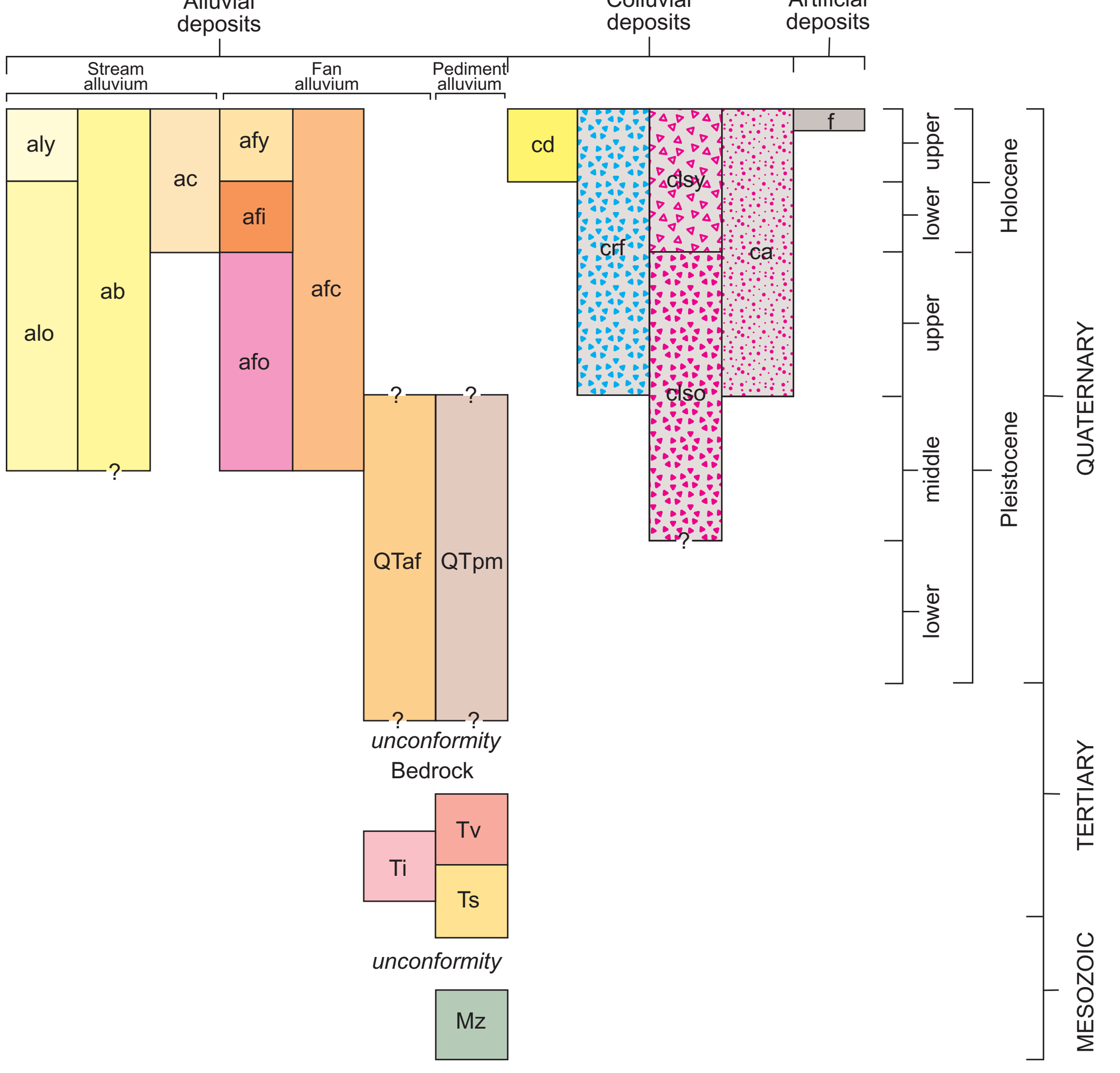




Base map from U.S. Geological Survey 1:24,000-scale Nephi (1983), Levan (1983), Juab (1983), Chriss Canyon (1965), Skinner Peaks (1965), and Hells Kitchen Canyon SW (1965) quadrangles.



Index map showing published 1:50,000-scale strip maps along the Wasatch fault zone.

CORRELATION OF MAP UNITS



1 0 1 2 MILES

5,000 0 5,000 10,000 FEET

1 0 1 2 KILOMETERS

SCALE 1:50,000

DATABASE COMPILATION, COORDINATION OF EARTHQUAKE-HAZARDS MAPPING, AND STUDY OF THE WASATCH FAULT AND EARTHQUAKE-INDUCED LANDSLIDES, WASATCH FRONT, UTAH

PART IV: EARTHQUAKE-INDUCED LANDSLIDE STUDIES, SALT LAKE COUNTY

by

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April 2004

Effective date: January 1, 2003
Expiration date: December 31, 2003
Award number 03HQAG0008

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ABSTRACT

Earthquake-induced landslides, with the exception of liquefaction-induced lateral spreads, have not been recognized in the Salt Lake City metropolitan area. This study assesses the feasibility of identifying such earthquake-induced landslides given the documented latest Pleistocene to present surface-faulting chronology for the Wasatch fault zone; mapped hillslope areas with moderate to high potential for shallow, disrupted slides; and large inventory of pre-existing landslides, many with inferred low factors of safety and vulnerability to earthquake-induced reactivation. We examined three types of potential earthquake-induced landslides: (1) a catastrophic rockslide, (2) a large, recurrently moving, prehistoric landslide, and (3) shallow, disrupted soil slides. Each represents a type of landslide triggered by moderate to large earthquakes elsewhere in the western United States.

Based on the inferences of previous researchers that some prehistoric, catastrophic rockslides in the Wasatch Front may have been triggered by earthquakes, we evaluated the feasibility of dating the Grandview Peak rockslide in upper City Creek Canyon northeast of Salt Lake City and correlating it with a documented surface-faulting earthquake. Recognition of the seismic origin of the landslide would provide a model for characterizing the earthquake-induced catastrophic rockslide hazard elsewhere in the Wasatch Range and provide guidance for future earthquake-induced landslide studies. Our reconnaissance revealed similarities to the Madison Slide triggered by the 1959 Hebgen Lake earthquake, suggesting the rockslide may be a candidate for an earthquake-induced landslide. Radiocarbon dating of buried trees and paleosols, or organic-rich sediments at the base of ponds that formed upstream of the rockslide deposit where it blocked City Creek and three tributary drainages, may constrain the age of the landslide, but is considered impractical given the probable depths of the ponds and the setting of the landslide. Cosmogenic dating of quartzite and limestone boulders on the surface of the rockslide deposit or of exposed Paleozoic rock in the main scarp or on the slide surface appear the most practical approach to obtaining an age of the landslide.

Using geomorphic analysis and radiocarbon ages from a consultant's landslide investigation, we developed a partial movement history for the Little Valley landslide at the south end of Salt Lake Valley and an approach for recognizing earthquake-induced reactivation in pre-existing slides in the Wasatch Front. The landslide is a large, prehistoric, dormant debris slide, parts of which are proposed for residential development. The presence of rotated blocks with deformed and faulted latest Pleistocene-Holocene sag pond sediments and local troughs with latest Pleistocene-Holocene alluvium allowed dating of movement episodes and periods of dormancy. The age of graben-fill sediments in the head of the landslide (>29,120 ^{14}C yr B.P.) indicates that the slide had formed prior to the onset of Late Pleistocene Lake Bonneville. A latest Pleistocene movement episode (estimated at about 17,000 cal yr B.P.) is suggested based on the preservation (lack of erosion) of the foot of the landslide that extends about 110 meters downslope of the Bonneville shoreline. The youngest dated movement episode (4,700 cal yr. B.P.) is based on the age of the base of a colluvial wedge associated with an antithetic, sag-pond-bounding fault that offsets organic silt (loess or sag-pond sediments)

in the head of the landslide. This movement overlaps in time with surface-faulting event W on the Salt Lake City segment of the Wasatch fault zone. The movement occurred during a dry period of the Holocene, supporting a seismic origin for the episode.

Previous researchers mapped a high earthquake-induced shallow landslide hazard on the north slope of Steep Mountain, but did not identify any earthquake-triggered slides. We interpret the Draper Heights landslide as a possible earthquake-induced shallow, disrupted soil slide, one of the most common landslide types triggered by the 1994 Northridge earthquake. Other nearby flat-bottomed scars upslope of cone-shaped deposits are also possible earthquake-induced shallow, disrupted soil slides. Limited opportunities exist for radiocarbon and cosmogenic dating of the slides. The Draper Heights landslide postdates the Bonneville shoreline (younger than 16,800 cal yr B.P.) and likely overlaps with the documented surface-faulting chronology of the Wasatch fault zone. Slope-stability analysis, however, suggests that this and other possible landslides on the north slope of Steep Mountain may be triggered by earthquakes of smaller magnitude than surface-faulting events.

INTRODUCTION

Previous researchers (Keaton and others, 1987; Solomon and others, 2002) have recognized the potential for earthquake-induced landslides in the Wasatch Front despite that few, if any, landslides have been identified as being directly triggered by earthquakes. Harp and Jibson (1995, 1996) reported that the most common types of landslides triggered by the 1994 M6.7 Northridge earthquake were highly disrupted, shallow falls and slides of rocks and debris. These included many very small landslides as little as 1 to 2 meters in width. The lack of readily apparent earthquake-induced landslides in the Wasatch Front may be, in part, due to the difficulty of recognizing these types of landslides, and particularly the very small ones, in the geologic record.

Harp and Jibson (1996) indicated that larger, deeper coherent landslides caused by the 1994 Northridge earthquake were relatively rare and consisted mostly of reactivated pre-existing slides. Utah's best-documented landslide of this type is the Springdale landslide in the southwestern part of the state (Jibson and Harp, 1996) that was triggered by the 1992 M 5.8 St. George earthquake. In the Wasatch Front, no mapped landslide, excluding liquefaction-induced lateral spreads (Harty and Lowe, 2003; Hylland and Lowe, 1998), has been documented as having been triggered or reactivated by a prehistoric major earthquake. We speculate that movement of most large landslides in northern Utah occurs in response to climatically controlled factors such as the rise in ground-water levels during wet periods, although earthquakes may be a significant additional factor. The number of recently reactivated pre-existing landslides due to wet periods in the last two decades suggests that many northern Utah landslides are dormant (inactive for at least a year but have the potential to reactivate) and have low factors of safety (Ashland, 2003).

This study focuses primarily on the recognition of possible earthquake-induced landslides in the Salt Lake City metropolitan area taking advantage of ongoing efforts by the Utah Geological Survey (UGS) to inventory landslides in Salt Lake County, landslide investigations being conducted by geologic consultants, and the documented chronology of the Salt Lake City segment of the Wasatch fault zone since the latest Pleistocene (McCalpin, 2002). We investigated three landslide areas and landslide types as part of this study (figure 1):

1. the Grandview Peak rockslide (a catastrophic rock avalanche) in upper City Creek Canyon, Salt Lake County,
2. the Little Valley landslide (a recurrent debris slide) in Draper, and
3. shallow, disrupted landslides in and near Steep Mountain in Draper.

Our study included:

1. geologic reconnaissance of the landslides (all slides),
2. preliminary geologic mapping (slides 2 and 3),
3. topographic profiling (slides 1 and 3),
4. slope-stability analysis (slide 3), and
5. assessment of the feasibility of dating the landslides and correlating each with documented major earthquakes (all slides).

The prehistoric Grandview Peak rockslide resulted from the failure of a bedrock spur underlain by fractured Paleozoic rocks and is possibly analogous to the Madison Slide triggered by the 1959 Hebgen Lake earthquake (Hadley, 1964). By determining if the rockslide could have been triggered by an earthquake, a better understanding of the potential earthquake-scenario catastrophic-landslide hazard in the canyons and mountain front areas of the Wasatch Range may be obtained. The Little Valley landslide is one of the largest prehistoric slides in the Salt Lake City metropolitan area. Residential development is currently proposed on the lower part of the landslide and the slide is characteristic of other Wasatch Front landslides that underlie existing residential development. The landslide is also a potential candidate for a slide that may have been reactivated, at least locally, by large earthquakes. Steep Mountain is an area previously recognized as having the potential for shallow, earthquake-induced landslides (Keaton and others, 1987), but to date, prehistoric shallow, disrupted landslides have not been identified in the area. The one mapped landslide in the north slope of the mountain is a shallow, disrupted soil slide and a candidate for an earthquake-triggered slide.

GRANDVIEW PEAK ROCKSLIDE

Introduction

Van Horn and Crittenden (1987) mapped a large rockslide deposit (figures 2 and 3) in the upper part of City Creek Canyon that was described previously by Van Horn and others (1972). The rockslide formed due to the failure of a southeast-trending spur of

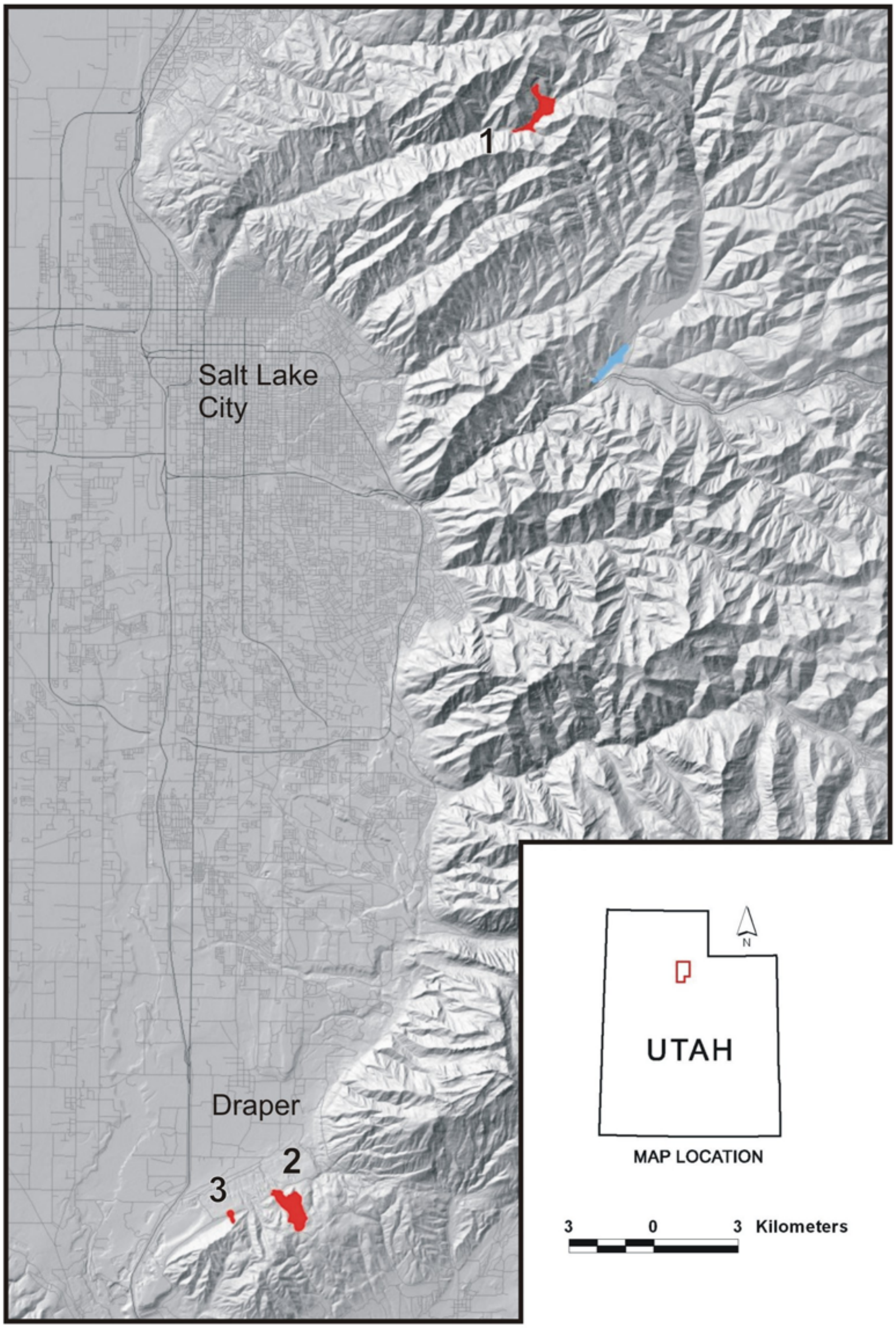


Figure 1. *Map showing earthquake-induced landslide study areas. Landslide study areas include (1) the Grandview Peak rockslide in upper City Creek Canyon, (2) the Little Valley landslide, Draper, and (3) the Draper Heights landslide and nearby possible shallow, disrupted landslides (not shown) near Steep Mountain, Draper.*

Figure 2. *View to the north of the upper part of the Grandview Peak rockslide. Southeast-facing main scarp visible in background exposes fractured Pennsylvanian-Permian Weber Quartzite. Talus buries the lower part of the main scarp. Rockslide debris occupies most of the right edge (right of saddle in front of talus slope) and lower foreground of the photograph. Note boulder-debris field along the north flank of the rockslide (lower central part of the photograph). Aspen-covered, southeast-facing slope left of the rockslide is a relatively shallow colluvial debris slide (DS). An aspen-Douglas fir forest occupies the rockslide deposit and adjacent slopes.*

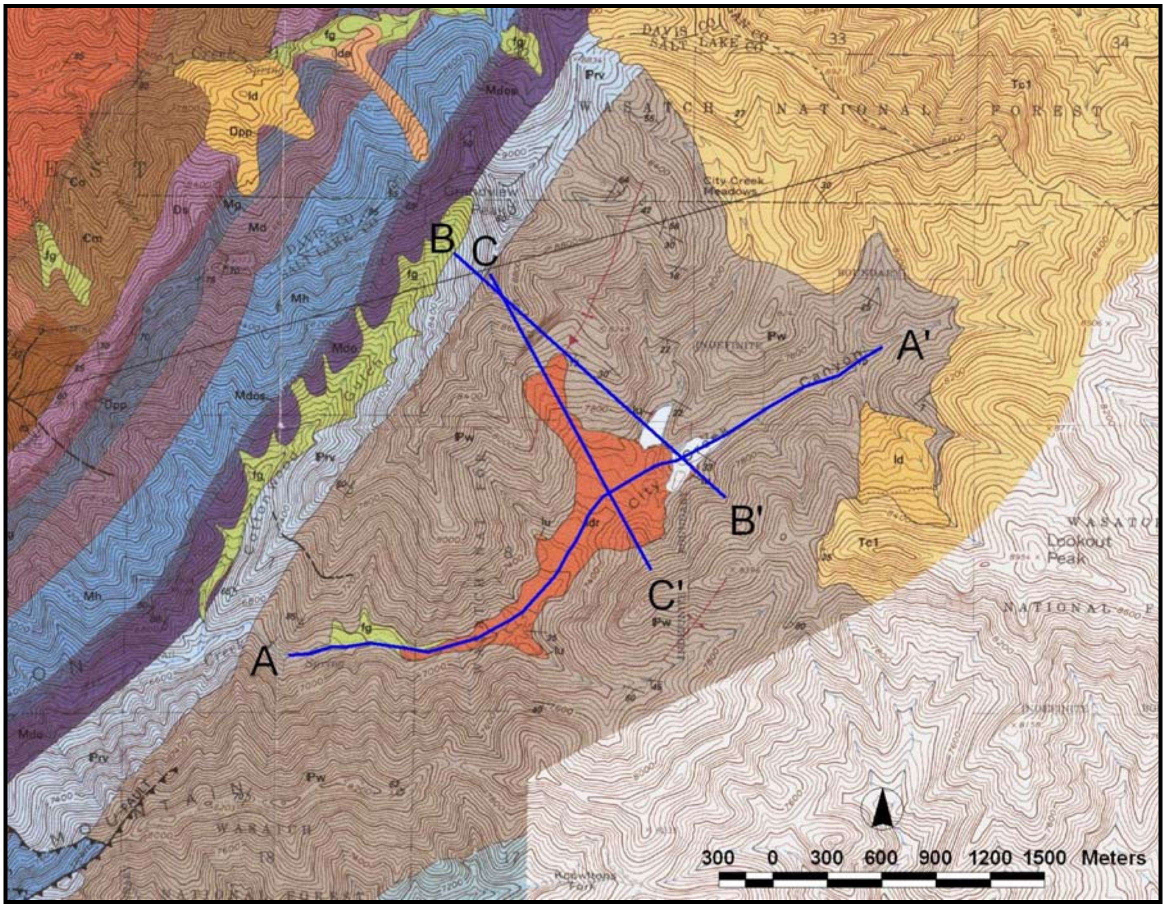
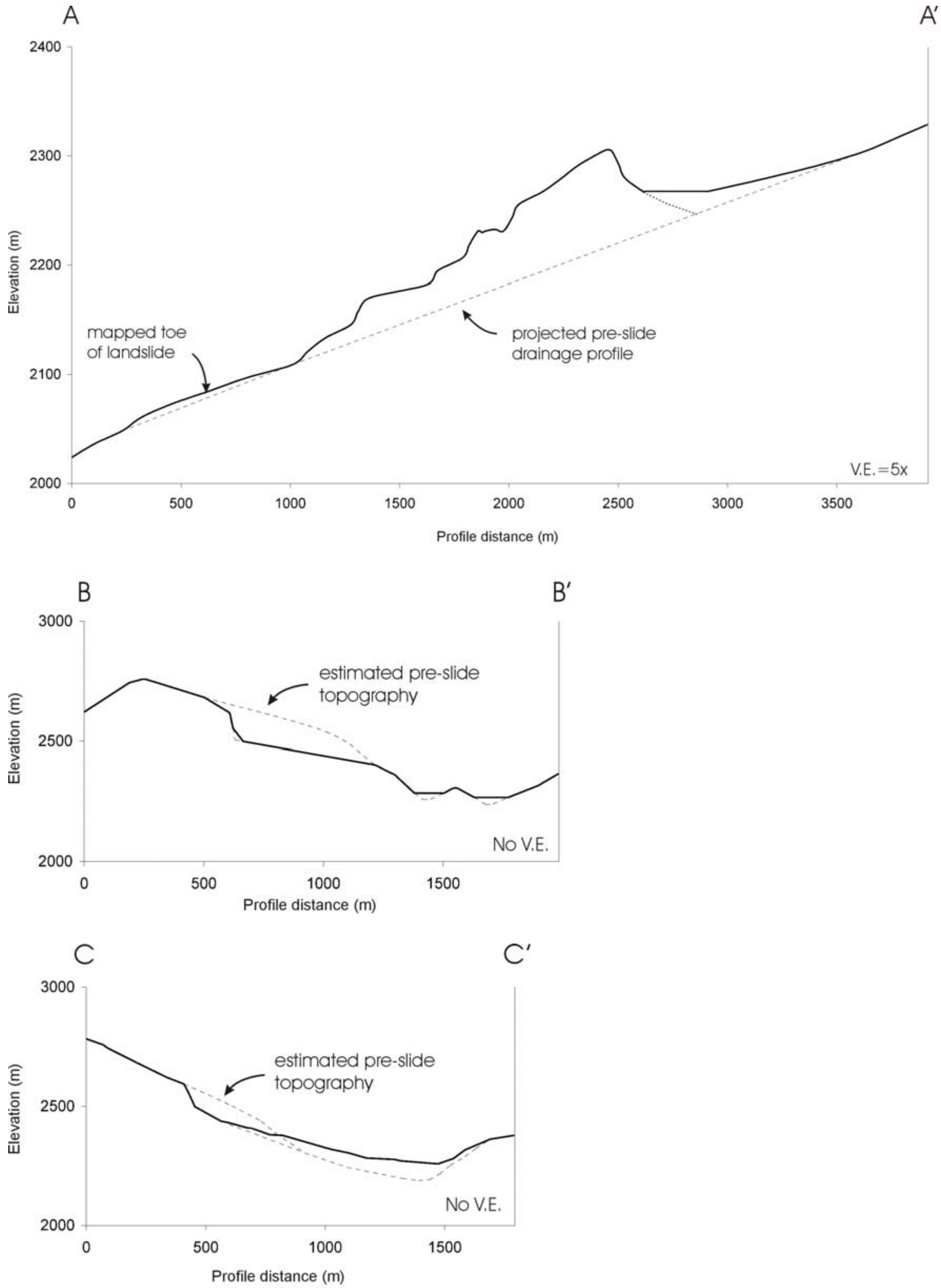


Figure 3. *Geologic map and profiles of the Grandview Peak rockslide. Geologic map from Van Horn and Crittenden (1987). Profile A-A' follows the City Creek drainage and shows the upstream and downstream stream profiles, the approximate height of the deposit, and depth of upstream pond sediments in the main City Creek drainage. Profile B-B' is perpendicular to the main scarp and shows the estimated pre-slide topography and the elevation differences between the two upstream pond areas. Profile C-C' follows the axis of the northwest arm of the rockslide deposit.*

***Figure 3** (continued)*



Grandview Peak, and, thus, is referred to in this report as the Grandview Peak rockslide. The Grandview Peak rockslide is a candidate for a catastrophic earthquake-induced landslide, and with detailed study could provide an understanding of the hazard from catastrophic failure elsewhere in the Wasatch Range.

Landslide Description and Geology

Van Horn and Crittenden (1987) mapped the Grandview Peak rockslide as a large, irregularly shaped deposit that measures about 1.9 kilometers along the main City Creek drainage and about 1.1 kilometers between the base of the main scarp and runup on the opposite canyon wall (figure 3). The main scarp of the rockslide faces southeast and is about 430 meters wide and about 120 meters high. A portion of the main scarp is buried by talus.

Van Horn and others (1972) described the Grandview Peak rockslide as a possible rock-fall avalanche. However, based on an interpretation by Van Horn and others (1972) that the landslide failed initially along a moderately dipping bedding plane, the slide is more accurately described as an extremely rapid rockslide using the terminology of Cruden and Varnes (1996). Slide debris traveled southeastward from the source area and blocked City Creek and an unnamed tributary drainage north of City Creek. Debris also traveled down City Creek Canyon about 1.6 kilometers from the main body of the slide, blocking two other tributaries.

Van Horn and Crittenden (1987) mapped the Grandview Peak rockslide as being solely in the Pennsylvanian-Permian Weber Quartzite. The formation consists of fine- to medium-grained, cross-bedded quartzite and medium-gray to pale-gray limestone (Van Horn and Crittenden, 1987). Our reconnaissance confirmed that rockslide debris consists of these two rock types. In upper City Creek Canyon, the Weber Quartzite is apparently thickened as a result of folding and fault repetition. Van Horn and Crittenden (1987) mapped a plunging syncline intersecting the source area of the rockslide; however, bedding attitudes on their map do not unequivocally support this structural interpretation. Based on our review of aerial photographs of the area and the structural information on Van Horn and Crittenden's (1987) map, bedding in the Weber Quartzite directly upslope of the main scarp appears to strike northeast and dip steeply. Thus, the main scarp may have broken along bedding and sliding occurred along another type of discontinuity such as a shallow-dipping fault or joint.

Similarities to the Historical, Earthquake-Induced Madison Slide

Our reconnaissance of the Grandview Peak rockslide revealed similarities to the Madison Slide triggered by the 1959 Hebgen Lake earthquake (Hadley, 1964), including topographic setting, local relief, landslide area, and rock-mass condition (table 1). In addition, both slides formed landslide dams. These similarities, although possibly coincidental, are noted as a basis of comparison of the Grandview Peak rockslide with a landslide known to be triggered by an earthquake. Both slides occurred in narrow and steep walled canyons, but occurred on opposite sides of the canyons. The pre-existing local relief of the Grandview Peak rockslide is estimated to be nearly identical to that of the Madison Slide, about 410 meters. Whereas the rock types differ in the two slides, the Madison Slide occurring in Precambrian dolomite, schist, and gneiss and the Grandview Peak rockslide occurring in Pennsylvanian-Permian quartzite and limestone, some similarities exist in the overall rock-mass condition such as the fractured nature of the rock. Hadley (1964) described the role of a shear zone in controlling the upper extent of the Madison Slide. In the Grandview Peak rockslide, the main scarp appears to have broken along a steeply dipping bedding discontinuity.

Table 1.
Comparison of the Grandview Peak rockslide and Madison Slide.

	Grandview Peak rockslide	**Madison Slide**
Local relief	412 m	407 m
Area	60 hectares	53 hectares
Head width	427 m	671 m
Maximum depth of deposit	89 m	67 m

Feasibility of Dating the Rockslide

We assessed the feasibility of dating the slide and correlating it with a documented large earthquake on the nearby Wasatch fault zone. Dating methods considered include cosmogenic and radiocarbon dating, and dendrochronology.

Cosmogenic Dating

Cosmogenic dating of slide debris and exposed rock in the main scarp and on the slide surface may be the most feasible method to date the failure (see Zreda, 2003). ^{3}He and ^{36}Cl methods are most applicable to the quartzite and limestone rock types in the slide. Numerous boulders locally cover the ground surface including areas that are unlikely to have been significantly eroded since the failure (figure 4). In addition, a steep main scarp exposes fractured limestone and quartzite (figure 4c). However, the talus slope at the base of the main scarp suggests possible main scarp retreat since the initial failure, indicating that dating of the scarp face or talus may yield a date younger than the event. A part of the slide surface exposed downslope of the talus is likely the best site for cosmogenic dating.

Radiocarbon Dating

Slide debris blocked City Creek and three other tributary forks resulting in temporary ponds (figure 5). Radiocarbon dating the lowermost pond sediments, buried soils (paleosols) beneath the pond sediments, or buried stumps of trees predating the landslide preserved in the pond sediments would likely provide the approximate age of the slide. However, profiling across the two ponds upstream of the landslide (profiles A-A' and B-B' in figure 3) suggests they may exceed tens of meters in depth requiring a drill rig to

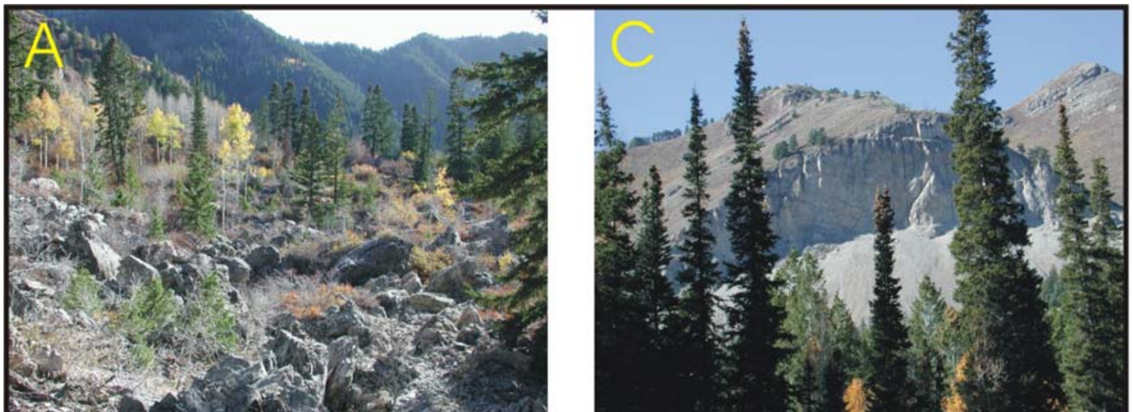


Figure 4. *Possible opportunities for cosmogenic dating of the Grandview Peak rockslide. (A) Large boulder field along north flank of deposit. (B) Cluster of cobbles and boulders on central part of deposit. (C) Main scarp of rockslide.*

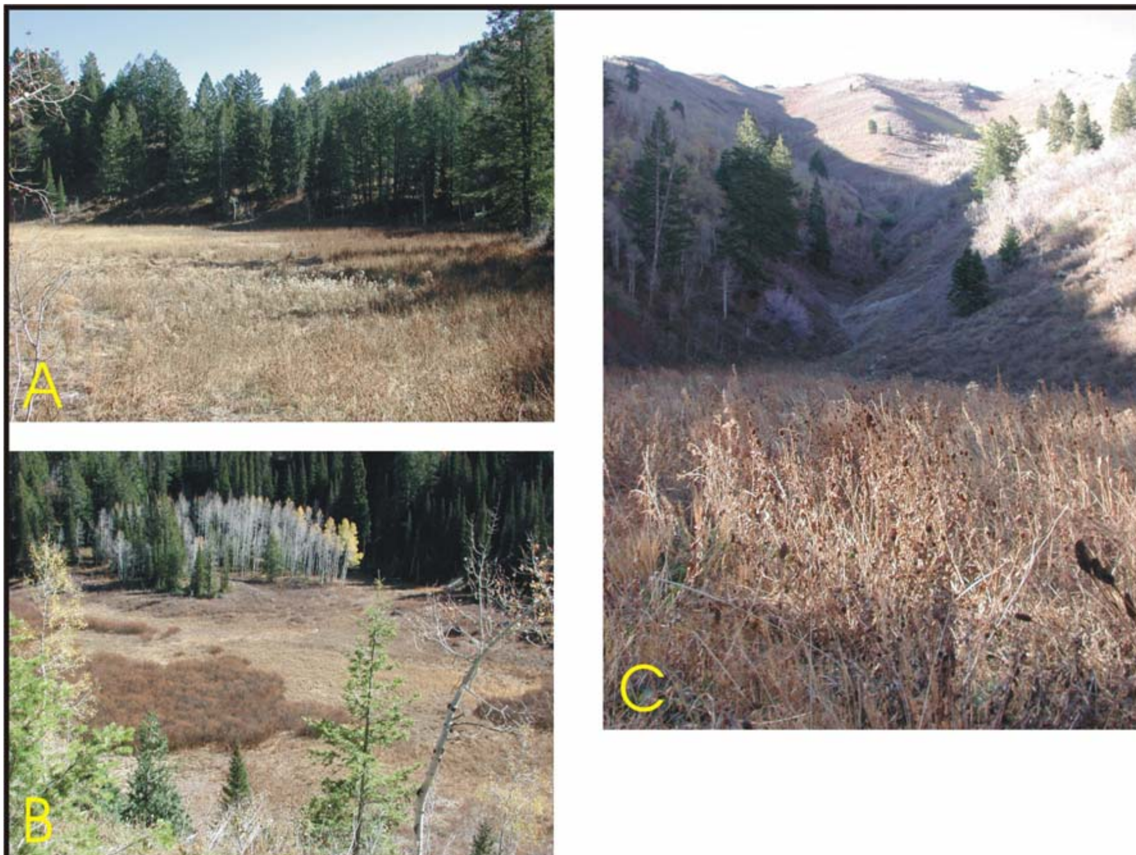


Figure 5. *Possible opportunities for radiocarbon dating of the Grandview Peak rockslide. (A) Pond sediments in northern fork upstream of deposit (edge of deposit visible along the right edge of the photograph). Low ridge in background separates pond from lower (southern) pond in main City Creek drainage (shown in B). (B) Pond sediments in main City Creek drainage upstream of deposit. View is from spillway notch in ridge dividing the northern and southern ponds. (C) Pond sediments and alluvium (?) in northern tributary drainage downstream of rockslide source area. Base of the pond sediments is likely shallower than in either of the upstream pond areas. Specific targets for radiocarbon dating in the pond areas include buried soil developed on the valley fill/slope sediments beneath the pond sediments, the lowermost organic-rich pond sediments (unit lu of Van Horn and Crittenden, 1987), and buried trees preserved in the pond sediments.*

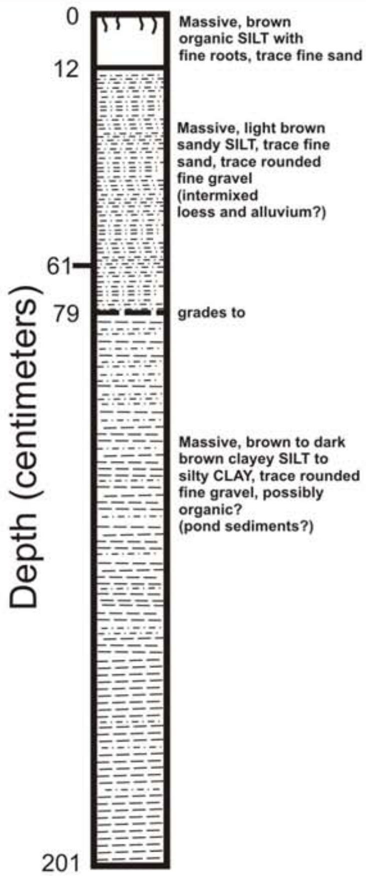
reach the base of the pond sediments. We evaluated the nature of the shallow sediments in the two upstream pond areas by a combination of hand-excavated test pits and hand auger holes. Figure 6 shows the logs of the two shallow explorations that reached depths of about 2 meters in the northern (tributary drainage) pond and 2.5 meters in the southern (main City Creek drainage) pond. In general, the shallow sediments appeared to contain adequate organic content to obtain a bulk radiocarbon age. However, dating of the uppermost pond sediments would poorly constrain the age of the Grandview Peak rockslide unless sedimentation in the pond areas was relatively rapid following the slide. In such a case, the difference in age of the uppermost sediments and the event could be small. However, we believe a more accurate age estimate of the rockslide would be obtained by dating either the lowermost pond sediments or underlying paleosols.

The backcountry setting of the rockslide, accessed only by a narrow hiking trail, and its location in a protected watershed, make drilling impractical. The base of pond sediments in the northern of two downstream tributaries blocked by debris is likely shallower than in the upstream ponds. Reaching the lowermost pond sediments or underlying paleosols in this area may be feasible using a hand auger or by excavating test pits by hand.

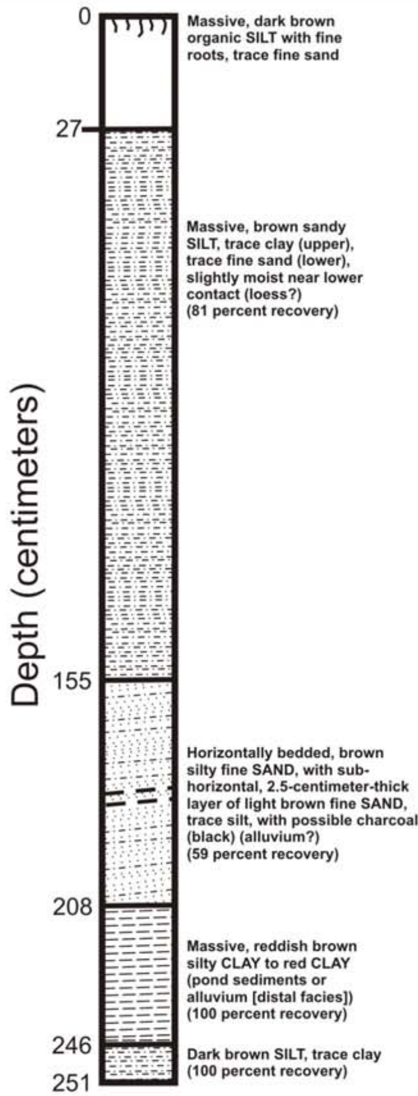
Dendrochronology

Our observations suggest limited opportunities for using either living or toppled (by the slide) trees to date the failure. The slide is currently covered by an aspen-Douglas fir forest. The largest observed trunks of living Douglas firs on the landslide reach a diameter of 69 centimeters. However, we observed no obvious difference between the trunk diameters of trees on or off the slide, suggesting the age of the forest is related to a natural event younger than the slide such as a forest fire (i.e., the existing live trees are not first-generation growth subsequent to the slide).

Nevertheless, tree-ring dating of the largest living trees on the rockslide using an increment borer could provide a minimum age for the event that could be of some use in correlating the slide with a documented earthquake on the Wasatch fault zone. The oldest known Douglas fir is about 1,300 years old (Rocky Mountain Tree-Ring Research, 2003) while one of the oldest known Douglas firs in the Rocky Mountains is an 820-year-old tree in Colorado. Since the observed Douglas firs on the rockslide are unlikely to be this old, a tree-ring age from one of the largest trees on the rockslide would probably not be useful in correlating the event to a surface-faulting earthquake unless the slide was triggered by one of the youngest events on the Wasatch fault zone, specifically Weber segment events dated at 200 to 800 cal yr B.P. and 550 to 1,450 cal yr. B.P. (William Lund, Utah Geological Survey, written communication, 2003). Use of a minimum tree-ring date to correlate the rockslide to the latter earthquake would not be possible unless the earthquake occurred in the younger part of the estimated event age. In addition, the sole use of a minimum date to correlate the Grandview Peak rockslide to one of the youngest Wasatch fault zone events is insufficient because an older age of the slide cannot be precluded.



AH-1
North Upstream Pond
Tributary Drainage



AH-2
South Upstream Pond
Main City Creek Drainage

Photograph of AH-1 location.

***Figure 6**. Logs of composite test pits and auger holes in upstream pond areas. Hand-excavated test pits extend to depths of 61 and 27 centimeters in AH-1 and AH-2, respectively. Exploration continued with hand auger below those depths.*

Photographs of the Madison Slide (Hadley, 1964) show toppled trees covering areas of the slide debris. However, rare dead Douglas fir trunk fragments on the ground surface of the Grandview Peak rockslide are likely associated with the modern forest and do not represent, in our opinion, trees toppled by the slide debris.

Summary

Our preliminary evaluation of the Grandview Peak rockslide reveals similarities to the earthquake-triggered Madison Slide. Whereas these similarities alone do not indicate the rockslide was triggered by an earthquake, they provide justification, in our opinion, for further evaluation of the possibility that the rockslide is an earthquake-induced catastrophic landslide that may characterize the hazard elsewhere in the Wasatch Range. Additionally, the recognition of an earthquake-induced rockslide in the Wasatch Range may provide the impetus for continuation of seismic rock-slope-stability studies such as that of Harp and Noble (1993) to define where future earthquake-induced rockslides and falls are most likely to occur. Our assessment of the feasibility of dating the rockslide suggests that cosmogenic dating of exposed slide plane and boulder debris may be the most cost-effective method of obtaining an age estimate. Radiocarbon dating of the lowermost pond sediments deposited adjacent to the deposit or underlying paleosols would provide the most accurate age of the slide, but obtaining these soils may be costly and impractical given their probable depths and the setting of the slide.

LITTLE VALLEY LANDSLIDE

Introduction

The Little Valley landslide in Draper is the largest landslide in southern Salt Lake County (figure 7). The landslide consists of several stacked lobes, possibly suggesting different episodes of movement, and rotational block slides in the head and along the right flank. The landslide's topographic and geologic setting, proximity to the Wasatch fault zone, and characteristics suggest a potential vulnerability to earthquake-induced movement. Wong and others (2002) predicted peak horizontal accelerations resulting from a Salt Lake City segment, Wasatch fault M 7.0 scenario earthquake to reach 0.7-0.8 g in the vicinity of the landslide. Whereas we do not know whether the landslide was initially triggered by an earthquake, we speculate that the landslide, or parts of it, may have been episodically reactivated by earthquakes. Geomorphic characteristics and ongoing landslide evaluations by consultants also made this landslide a reasonable candidate to test whether earthquake-induced movement could be recognized in large Wasatch Front landslides.

Landslide Description and Geology

Biek (2003b) mapped the Little Valley landslide as extending about 1,770 meters between the ridgeline and Bonneville-level bench on the north slope of the Traverse Mountains (also see the mapping of Van Horn, 1975) (figure 7). The landslide varies in

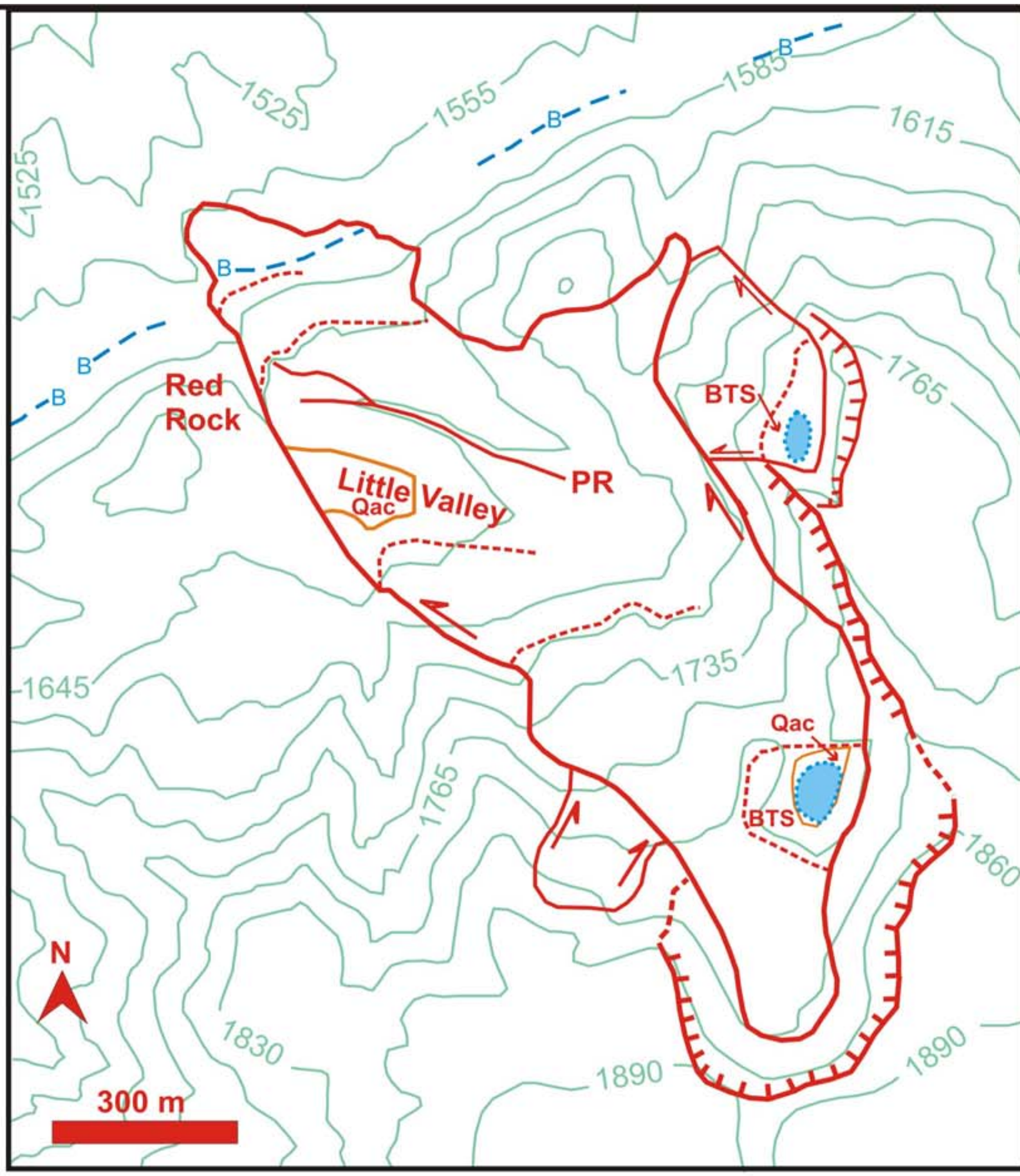


Figure 7. *Map of the Little Valley landslide (modified from Biek, 2003b). Little Valley occupies the lower central and western part of the landslide. A large northwest-trending pressure ridge (PR) bounds Little Valley on the northeast. Two rotational blocks with back-tilted surfaces (BTS) are present in the head and along the east flank. Sag ponds occupy the upslope sides of the back-tilted surfaces. Biek (2003b) mapped alluvium and colluvium (Qac) in lower Little Valley and the upper sag pond area in the head of the landslide. Dashed lines show crest lines of the back-tilted surfaces. Dashed lines in lower and central part of landslide show the base of steep slopes that are likely thrust systems of separate lobes that may have formed during separate episodes of movement or were contemporaneous overriding events. Biek (2003b) tentatively mapped the Bonneville shoreline (B) across the lowermost part of the landslide, which overrides Bonneville highstand shoreline deposits by at least 110 meters, suggesting a movement episode at about 16.8 cal yr B.P. The original formation and movement of the landslide predates 29,120 ^{14}C yr B.P. The most recent movement in the head of the landslide occurred about 4,700 cal yr B.P.*

width reaching a maximum of about 550 meters in the Little Valley area. The landslide consists of several stacked lobes that suggest multiple episodes of movement or overriding by upslope parts of the landslide mass atop downslope parts during the main episode of movement. Two rotational landslide blocks exist; one in the head and one along the east flank of the slide. Each is characterized by a back-tilted surface partly buried by pond deposits. Ephemeral sag ponds still occupy the upslope parts of the rotated blocks.

The Little Valley landslide overlies and is surrounded on the east and south by deeply weathered and altered Tertiary volcanic rocks (Biek, 2003b). Highly fractured, intensely brecciated, and locally pulverized orthoquartzite of the Pennsylvanian-Mississippian Oquirrh Group abut the landslide on the west and flank the lowermost part of the slide. Late Pleistocene lacustrine gravels deposited during the Bonneville lake cycle likely underlie the lowermost foot of the landslide. Landslide debris is a heterogeneous mix of coarse material that includes large blocks of volcanic rock. Thus, the landslide is a prehistoric, deep-seated, dormant debris slide.

Movement History

Geomorphic evidence and radiocarbon ages of both deformed and undeformed soils on the Little Valley landslide suggest episodic movement since the Late Pleistocene. Tilted and faulted graben-fill sediments in the head of the landslide are older than 29,120 ^{14}C yr B.P. (Intermountain GeoEnvironmental Services, 2003) indicating that the Little Valley landslide initially formed prior to Lake Bonneville (dated at about 28,000 to 12,000 radiocarbon years ago). We infer that the rotational block in the head of the landslide was triggered by the removal of lateral support as downslope movement of the landslide mass evacuated the upper part of the slide. If the landslide enlarged retrogressively (in an upslope direction) and laterally to its present size, then the rotational block in the head is likely younger than initial movement of the main body of the slide.

Exactly how the original landslide formed is unknown, but the present slide mass may have grown from gradual accumulation of landslide debris from local landsliding along the flanks of the original canyon that the slide now occupies in combination with retrogressive enlargement. At some point these processes would have broadened the canyon and resulted in a large enough accumulation of landslide debris at a steep enough slope to initiate global movement of the debris. Landsliding appears to have involved not only shallow slope materials, such as colluvium, but also the underlying weathered and fractured volcanic rock units.

The toe of the landslide overrides Lake Bonneville highstand shoreline deposits by at least 110 meters indicating that a major episode of movement postdates or is contemporaneous with the highest level of the lake that existed until approximately 14,300 radiocarbon years ago. Biek (2003b) tentatively mapped the Bonneville level shoreline across the lowermost part of the landslide suggesting that the movement episode is contemporaneous with the Lake Bonneville highstand rather than postdating it.

Given the inferred rate of erosion of the nearby Steep Mountain area during the Lake Bonneville highstand, the present foot of the landslide that extends downslope of the Bonneville-level shoreline is unlikely older than 17.3 ka. In addition, for the landslide foot to have been preserved, movement must have either occurred late during the Lake Bonneville highstand period, continued for a brief time after the lowering of the lake level at the time of the Bonneville flood, or kept pace with erosion. Radiocarbon ages of undeformed alluvium in Little Valley (figure 7) in the lower and western main body of the landslide (Intermountain GeoEnvironmental Services, 2003) suggest stability, at least in the lower part of the slide, by about 12.5 to 13.0 ka.

The geomorphic characteristics of the two rotational blocks, one in the head and one on the east flank (figures 7, 8, and 9), suggest more recent (Holocene), but perhaps local, movement. The blocks are defined by back-tilted surfaces (BTS on figures 7 and 8) that are partly covered on the upslope side by sag pond sediments. The rotational block in the head of the slide is also characterized by a beheaded drainage that is severed at the intersection of the crest of the back-tilted surface. The drainage exists only downslope of the crest, but is absent upslope and shows no relationship to the existing topography on or upslope of the back-tilted surface. Ephemeral sag ponds on the landslide are apparently the result of water that perches atop the shallowest soils and have not yet been captured by downstream drainages, suggesting a Holocene age.

Trenching across the back-tilted surface downslope of the upper sag pond in the rotational block in the head of the landslide (figures 8 and 10) conducted as part of a consultant's geologic study (Intermountain GeoEnvironmental Services, 2003) revealed an antithetic (landslide-related) fault. The antithetic fault likely accommodates stretching of the rotational block and bounds clay-rich graben-fill sediments between the structure and the main scarp. The graben-fill sediments are juxtaposed across a wide fault zone (figure 10) against rotated Tertiary volcanic rock indicating that the total offset on the antithetic fault exceeds the depth of the trench (about 4.1 meters). Based on a trench log in the Intermountain GeoEnvironmental Services (2003) report, the total offset along the fault is greater than 5.6 meters and the net vertical displacement is more than 4.4 meters. As stated above, the age of graben-fill sediments (radiocarbon age older than 29,120 ^{14}C yr B.P.) indicates the graben formed prior to Lake Bonneville. Tilting and faulting of these sediments may be associated with the movement episode that overrode latest Pleistocene Lake Bonneville highstand shoreline deposits, but is poorly constrained. No colluvial wedges are apparent between the graben-fill sediments and the fault zone in the lower two-thirds of the trench, but these may be obscured by fault zone deformation. Their absence possibly also suggests offset along the fault at an extremely slow and perhaps nearly continuous rate so that an upslope-facing (antithetic) scarp did not form during this period of movement (Ferreli and others, 2002). If offset along the antithetic fault occurred at an extremely slow rate, the maximum antithetic scarp height may have measured only millimeters in height at any one time, insufficient for a colluvial wedge to form. Deposition into the graben would have been solely from erosion of the main scarp.

The most recent movement on the antithetic fault offsets organic silt (loess and/or pond sediments) and formed an upslope-facing (antithetic) scarp (now buried). The base

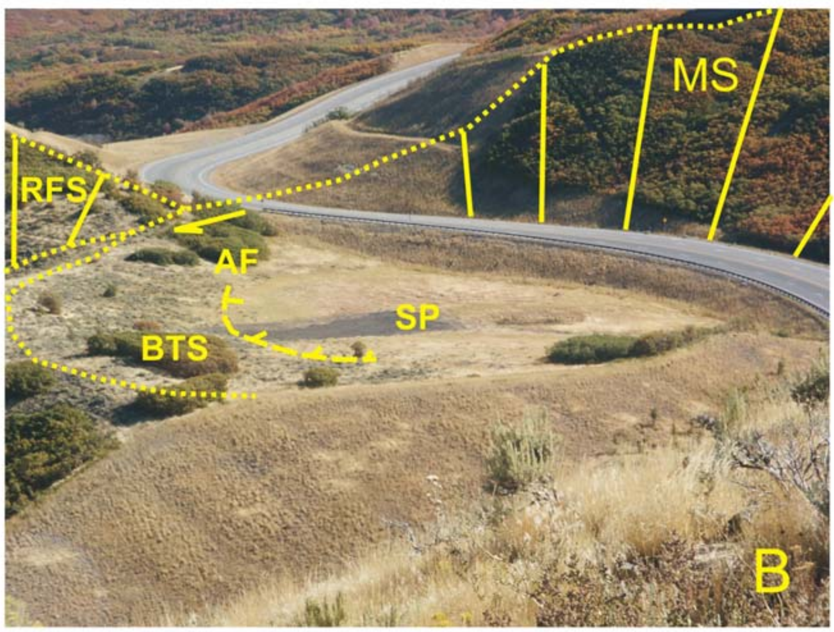


Figure 8 . *Photographs of upper sag pond area in the Little Valley landslide, Draper. Sag pond sits on a rotational block in the head of the landslide that has been deformed by stretching. (A) View to the east-northeast of upper part of landslide and sag pond area. (B) Detail showing trench location (area of bare gray soil) on northwest side of sag pond (SP). Also shown are main scarp (MS), right-flank scarp (RFS), back-tilted surface (BTS), and approximate location of antithetic fault (AF). Curvature on antithetic fault is assumed based on observed curvature of back-tilted surface.*

Figure 9. *Photographs of sag pond area along the east flank of the Little Valley landslide, Draper. (A) View to the south-southeast of the sag pond area, southern part of the main scarp, and back-tilted surface (foreground). (B) View to the northeast of east-flank rotational block (arrow).*

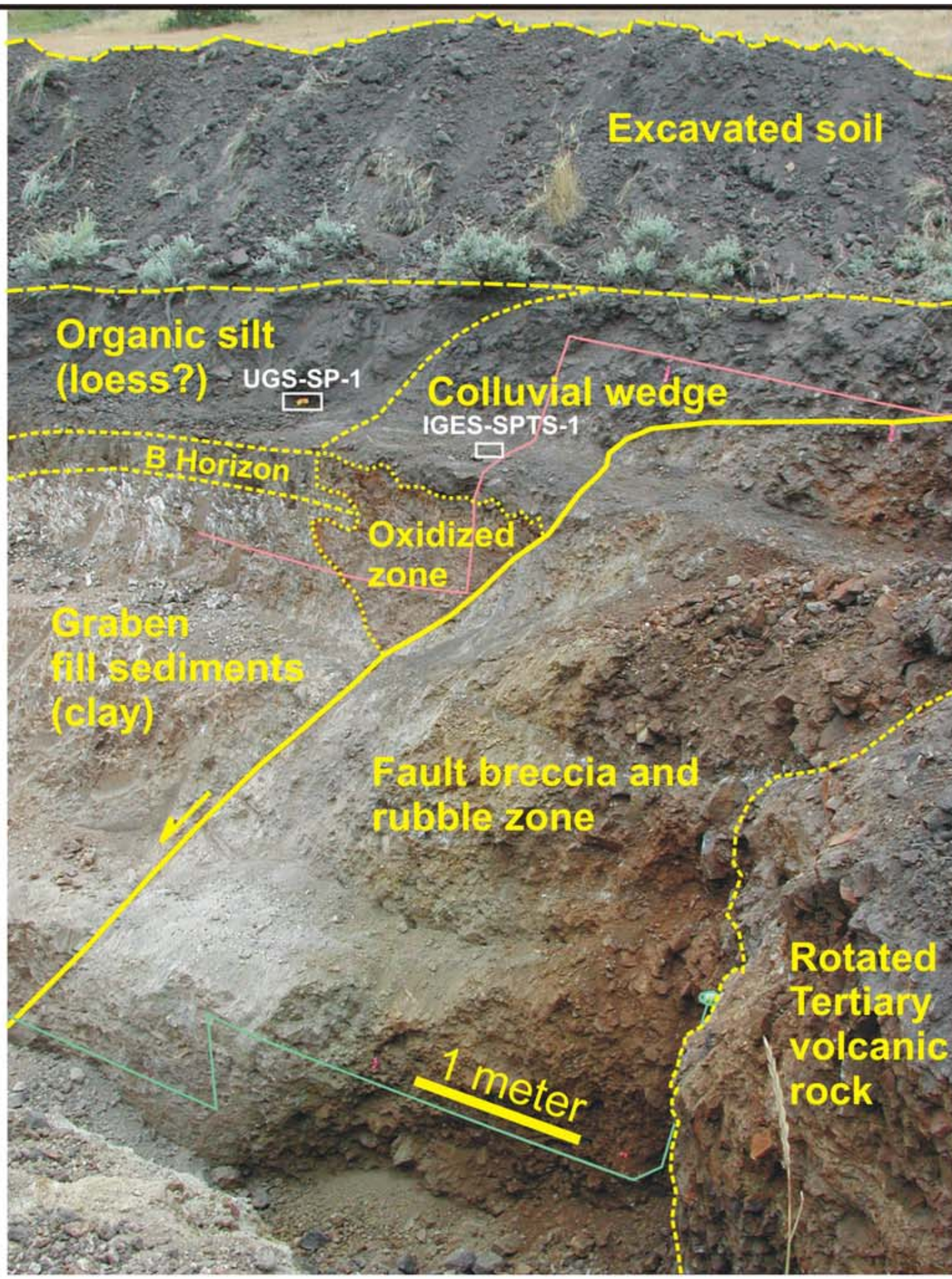


Figure 10. *Photolog of antithetic fault zone in a trench across the northwestern part of the upper sag pond in the Little Valley landslide, Draper. Trench was excavated by Intermountain GeoEnvironmental Sevices (IGES) as part of a landslide evaluation for a proposed subdivision downslope of the area (IGES, 2003). A single colluvial wedge exists at the top of the antithetic scarp fault zone. Soils at the base of the wedge (IGES SPTS-1) range in age from 4555 to 4860 cal yr B.P. constraining the timing of the most recent offset along the scarp as slightly older. This age range overlaps with the estimated timing of surface-faulting event W on the Salt Lake City segment of the Wasatch fault zone (4550 to 6050 cal yr B.P.) allowing the possibility that landslide movement was triggered by event W. Pink and green lines are level lines.*

of a colluvial wedge (figure 10) yielded an age of about 4,700 cal yr B.P. (4,555-4,860 cal yr B.P.) (Intermountain GeoEnvironmental Services, 2003). This age represents a maximum limiting age for the onset of colluvial-wedge deposition. Therefore, an episode of landslide scarp formation likely occurred at this location shortly before this time. This episode marks an apparently abrupt change from extremely slow and possibly continuous movement on the structure to movement more typical for Wasatch Front landslides in which measurable offset on the antithetic fault resulted in an upslope-facing (antithetic) scarp. The net vertical displacement caused by the most recent movement on the fault is about 1 meter. The age of this scarp-forming movement episode postdates by about 600 years the estimated mean age of a documented mid-Holocene large earthquake on the Salt Lake City segment of the Wasatch fault zone (event W) estimated to have occurred shortly after 5,300 cal B.P. (William Lund, Utah Geological Survey, written communication, 2003), but could be contemporaneous if the uncertainty in the age estimates is considered. Thus, the possibility exists that the most recent documented movement episode was triggered by a Wasatch fault zone surface-faulting earthquake.

Some corroborating data support a seismic origin for this movement episode. The age of the movement episodes falls within a dry period of the Holocene (figure 11) that occurred between about 5,900 and 3,400 radiocarbon years ago (Murchison, 1989). Ground-water levels sufficient to trigger landslide movement under static conditions seem unlikely during this extended regional dry period. In addition, the apparent increase in the movement rate of the antithetic fault appears compatible with earthquake triggering. This increase may have been caused by a reduction in shear strength resulting from earthquake-induced displacement of the landslide mass, possibly subsequent to a gradual reduction during periods of extremely slow movement (or creep) prior to that time.

The Feasibility of Recognizing Earthquake-Induced Movement of Large Wasatch Front Landslides

This study demonstrates the feasibility of documenting the movement history of large landslides by careful geomorphic analysis and the use of traditional paleoseismic methods such as trenching and radiocarbon dating. This study benefited from data obtained by a coincidental geologic study of the Little Valley landslide (Intermountain GeoEnvironmental Services, 2003).

The success in establishing a preliminary movement history of the landslide was due in part to the geomorphic characteristics of this particular landslide that provided opportunities to locate datable paleosols and colluvial wedges. Specifically, the presence of organic-rich graben fill and silt in the sag pond area in the head of the landslide and alluvium in Little Valley allowed radiocarbon dating of both movement episodes and periods of stability. In the absence of these geomorphic characteristics, establishing the age of landslide movement has proven challenging, including on other nearby landslides in the Draper area. A paucity of organic deposits exists in the debris of the Little Valley landslide as well as in other nearby slides that also overlie Tertiary volcanic rocks. In addition, where one of these landslides has overridden Lake Bonneville highstand

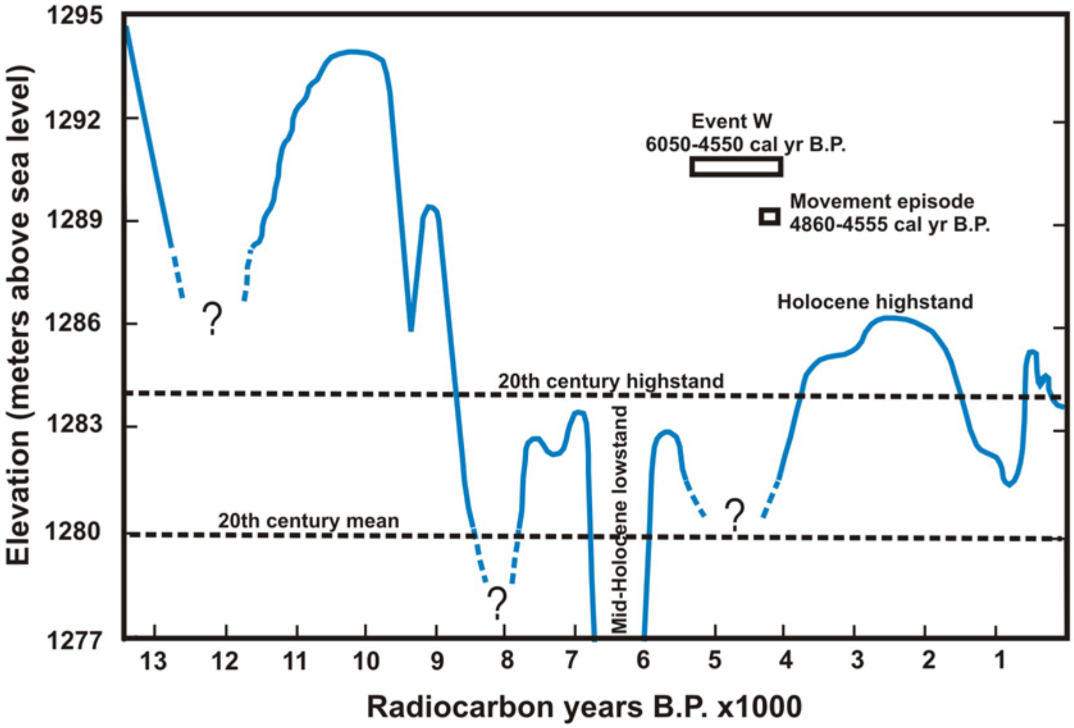


Figure 11. *Comparison of the timing of the most recent dated movement episode of the Little Valley landslide with the estimated age of event W on the Salt Lake City segment of the Wasatch fault zone and Great Salt Lake fluctuations. Plot shows that the most recent dated movement episode overlaps with the younger part of the age estimate for event W of the Salt Lake City segment of the Wasatch fault zone. Movement also occurred during a period inferred to be as dry as the 20th century and subsequent to the driest period of the Holocene, suggesting movement was unlikely climatically triggered. Great Salt Lake hydrograph from Murchison (1989). Age estimate for event W from William Lund (UGS, written communication, 2003).*

shoreline deposits, a datable paleosol was absent, perhaps due to erosion of the topsoil by persistent and strong winds that currently characterize the area and may have been present in the geologic past.

Access to the best available sites is a critical factor to successfully dating landslides. The trench across the sag pond area in the head of the landslide (figure 8) was limited in extent due to landowner concerns about disturbance to the pond. In addition, the existence of a road at the base of the main scarp prohibited trenching where the best colluvial wedges may be preserved documenting a more complete record of landslide movement in the upper part of the slide. A test-pit log (Delta Geotechnical Consultants, 1997) from the area currently beneath the road at the base of the main scarp indicates that three episodes of movement were evident and suggests that soil A horizons (paleosols) were offset by the main scarp. Thus, the one Holocene event documented by the Intermountain GeoEnvironmental Services (2003) trench (figure 10) may be only one of several Holocene movement episodes. Ashland (2002) recognized that in structurally complex landslides, individual landslide deformation features, such as the antithetic fault in figures 8 and 10, are not consistently active despite movement of the overall slide. Thus, the reactivation of the antithetic scarp may not have occurred with every movement episode of the landslide, but rather coincided with episodes that caused significant stretching of the head block.

Other opportunities exist for dating possible Holocene movement episodes of the Little Valley landslide and nearby slides that overlap with the documented chronology of the Wasatch fault zone. The best remaining site is the main scarp and sag pond area of the rotational block along the east flank of the landslide (figures 7 and 9). The area is currently undeveloped; however, access to the site is difficult, possibly requiring construction of a temporary access road. Despite the access challenges, the possible favorable geologic conditions include:

- organic-rich sag pond sediments,
- progressively tilted and/or faulted sediments in the rotational block,
- colluvial wedges and buried paleosols at the base of the main scarp, and
- possible antithetic faults and colluvial wedges.

One limitation of this area is the uncertainty of the relation between movement of the main landslide and the east-flank rotational block. Biek (2003b) interprets the east-flank rotational block as a separate landslide of uncertain age. We infer the landslide developed in part by evacuation of its toe due to movement of the main body of the Little Valley landslide and in part by subsequent downcutting of an unnamed drainage. Thus, we infer that movement of this block represents enlargement of the Little Valley landslide along its flank caused by removal of lateral support as the main slide evacuated the region downslope of the block.

DRAPER HEIGHTS LANDSLIDE AND SEISMIC STABILITY OF THE STEEP MOUNTAIN NORTH SLOPE

Introduction

Recent residential development at the base of Steep Mountain in Draper increases the vulnerability of this community to earthquake-induced landsliding. Geomorphic characteristics have been recognized during ongoing landslide research (in part this study) and mapping (Biek, 2003a, 2003b) by the UGS suggesting a susceptibility of the north slope of the mountain to earthquake-induced landsliding. In addition, one previously mapped landslide and other nearby scars in steep colluvial slopes may be evidence of prehistoric earthquake-induced landsliding in and near Steep Mountain in the past 16,800 years.

Keaton and others (1987) recognized a significant potential for earthquake-induced landsliding in the Steep Mountain area, but did not identify prehistoric landslides that may have been triggered by large earthquakes. Keefer (1984) listed disrupted soil and rock slides and falls as the most common types of landslides caused by earthquakes. Harp and Jibson (1995, 1996) noted that the majority of landslides caused by the 1994 M 6.7 Northridge earthquake in southern California were these types of slides and observed that disrupted slides were generally shallow. As part of this study, we:

- evaluated the possibility that the Draper Heights landslide on the north slope of Steep Mountain is an earthquake-induced slide,
- assessed the feasibility of dating the landslide,
- evaluated the potential for future earthquake-induced landslides on the Steep Mountain north slope using the ground motion estimates of Frankel and others (1996),
- mapped and evaluated other possible shallow, disrupted slides in the vicinity of Steep Mountain.

Physiography and Geology of Steep Mountain

Steep Mountain is an east-northeast trending ridge that reaches a maximum elevation of about 1,884 meters in the southern part of the Salt Lake City metropolitan area. The local relief between a prominent bench underlain by Bonneville shoreline deposits and the ridge crest reaches a maximum of about 311 meters and the average slope is relatively uniform, ranging between about 65 and 67 percent (33 to 34 degrees). Recent residential development has occurred at the base of the eastern part of the mountain (figure 12) despite the vulnerability to landsliding.

Steep Mountain is underlain by mostly fractured and weathered orthoquartzite of the Mississippian-Pennsylvanian Oquirrh Group. In general, the rock-mass quality of the Oquirrh Group rocks is poor and thus the rocks are easily eroded. Biek (2003a) describes the rocks as being “typically highly fractured, intensely brecciated, or locally pulverized.”

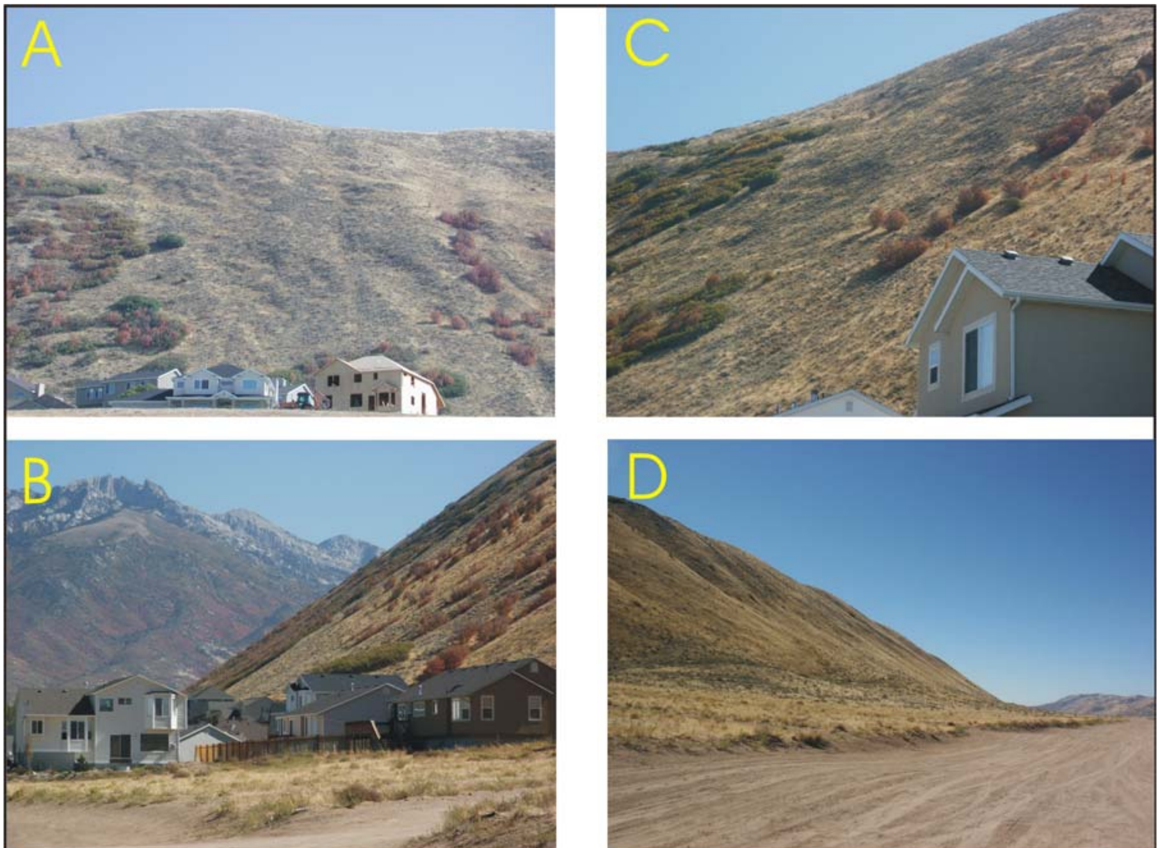


Figure 12. *Residential development along the base of Steep Mountain, Draper. Keaton and others (1987) mapped a high earthquake-induced landslide potential in the north slope prior to any development at the base of the mountain. (A) View of houses at the base of the north-facing slope in an area characterized by hummocks, and wavy ridges and swales. Biek (2003a, 2003b) interpreted the latter as evidence of creep (the extremely slow downslope movement) of variably thick colluvium on the slope. We infer that these areas may be near the threshold of failure and also extremely vulnerable to earthquake-induced landsliding. (B) View showing the proximity of houses to the north slope of Steep Mountain. Average slope is about 66 percent. (C) Detail showing proximity of houses to an area characterized by hummocks. Setback of houses from base of slope is inadequate to protect them from landsliding of the scale of the Draper Heights landslide. (D) View of the undeveloped western part of the Steep Mountain area showing the land that was (in the developed eastern part of Steep Mountain) available for building setback to reduce the risk from earthquake-induced landsliding.*

A variably thick veneer of colluvium and local alluvium overlies the Oquirrh Group rocks on most of the north slope of Steep Mountain. The colluvium is likely thickest in the lower slope, possibly including landslide debris from shallow disrupted slides, and in local broad swales. Due primarily to the poor rock-mass quality of the underlying Oquirrh Group rocks, the colluvium is generally well sorted in grain size consisting mostly of sand- and fine-gravel-sized particles. Cobble-sized fragments represent the maximum particle size in the colluvium. Based on this texture and the angular fragment shape, the colluvium is likely cohesionless, well drained, and has a relatively high friction angle.

The present north slope of Steep Mountain formed as the result of wave erosion by glacial Lake Bonneville as it reached its highest level. Oviatt and others (1992) estimated that the highest level of Lake Bonneville lasted about 1,000 years, between about 15,500 and 14,500 radiocarbon years ago (~18,000-16,800 cal yr B.P.). During this time, the north slope of Steep Mountain retreated southward due to erosion, resulting in the existing slope that is likely considerably steeper than the slope that existed prior to Lake Bonneville. A wave-cut bench in Oquirrh Group rocks extends as much as 518 meters north of the base of the north slope of Steep Mountain, indicating a maximum erosion rate of about 43 to 52 centimeters per year.

Following the catastrophic Bonneville flood at approximately 14,500 radiocarbon years ago (16,800 cal yr B.P.), the lake was lowered about 100 meters to the Provo shoreline, and sediments deposited at the highest (Bonneville shoreline) level at the base of Steep Mountain became subaerially exposed. Since that time, physical weathering of the slope rocks formed local colluvium and erosion occurred during intense rainstorms and rapid snowmelt forming local swales and gullies in the slope. Alluvial fans formed at the base of the slope below these swales and gullies. Biek (2003a) mapped a nearly continuous belt of alluvial-fan deposits at the base of the north slope along the western part of Steep Mountain.

Draper Heights Landslide

The Draper Heights landslide is a shallow, disrupted, complex debris slide-flow near the east end of Steep Mountain (figure 13). The landslide consists of a nearly perfect circular deposit at the base of the slope that overlies Lake Bonneville highstand shoreline sediments. The deposit is approximately 240 meters in diameter and about 6 to 9 meters thick near the base of the slope. The source area of the debris slide is a zone that locally exceeds 120 meters wide and extends about 270 meters between the base of the slope and the ridgeline. The local relief upslope of the deposit is about 190 meters or about 120 meters less than the maximum local relief farther to the west. The average slope directly west of the slide is about 65 percent.

Based solely on landslide type (disrupted slide), the Draper Heights landslide is a reasonable candidate for an earthquake-induced landslide. Harp and Jibson (1996) documented that this type of slide along with falls were the most common types of landslides triggered by the 1994 M 6.7 Northridge earthquake. Jibson (1996)

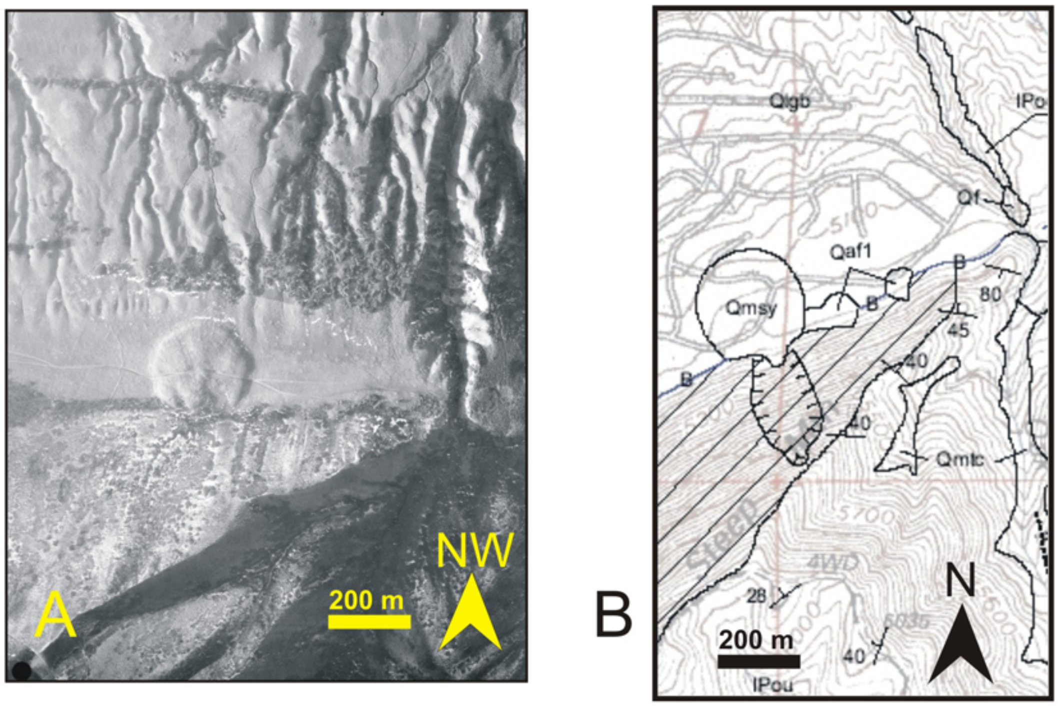


Figure 13. *Aerial photograph (A) and geologic map (B) of the Draper Heights landslide (Qmsy). Aerial photograph taken prior to residential development along the base of Steep Mountain. Geologic map from Biek (2003b).*

summarized the characteristics of slope materials that are particularly susceptible to earthquake-induced landsliding to include weathered, sheared, and intensely fractured and jointed rock, all of which describe the condition of the Oquirrh Group rocks that underlie the north slope of Steep Mountain (Biek, 2003a). The nearly circular shape and smoothness of the deposit suggest that the landslide occurred as a single event and that slide debris traveled relatively rapidly downslope as a flow.

Feasibility of Dating the Landslide

The Draper Heights landslide overlies Lake Bonneville highstand shoreline sediments that were deposited about 15,500 to 14,500 radiocarbon years ago (~18,000-16,800 cal yr B.P.). Thus, the landslide is latest Pleistocene or younger and overlaps in age with the documented chronology of the Salt Lake City segment of the Wasatch fault zone (McCalpin, 2002). Obtaining an age estimate of the landslide may be possible using either radiocarbon or cosmogenic dating, or both.

Radiocarbon dating of the landslide may be possible if a buried paleosol developed on Lake Bonneville highstand shoreline sediments underlies the deposit. Limited, if any, opportunities exist to obtain this sample from foundation excavations within the limits of the landslide deposit because most of the residential lots have already been developed. However, a borehole could be drilled on public property such as the street. Recovery of a buried paleosol could be attempted using continuous sampling methods near the estimated depth of the base of the deposit. However, preliminary evidence suggests that a buried paleosol may not be present atop the underlying Lake Bonneville highstand shoreline sediments. A trench in the toe of the nearby Potato Hill landslide did not encounter a buried paleosol in these sediments. We speculate that strong winds may strip organic sediments as rapidly as they form in the area.

Cosmogenic dating of either surface sediments on the deposit or in the source area may also be possible. Residential development over most of the deposit limits opportunity for cosmogenic dating because surface sediments are disturbed and buried. Cosmogenic dating of surface soils in the source area scar may be possible, but further reconnaissance of the area is necessary to determine if areas exist where colluvial processes have not buried or modified the original slide scar.

Other Possible Earthquake-Induced Shallow, Disrupted Slides

Based on the earthquake-induced-landslide-potential mapping of Keaton and others (1987), we evaluated the possibility of other shallow, disrupted slides in the vicinity of the Draper Heights landslide. Given the poor rock-mass condition of the Oquirrh Group rocks and the moderate to high earthquake-induced landslide potential of most of the nearby slopes, the Draper Heights landslide is likely not unique. Whereas Biek (2003a, 2003b) did not map any additional landslides in the vicinity of the Draper Heights landslide, AMEC Earth & Environmental (2003) mapped a shallow, disrupted rockslide/fall on the east side of a narrow spur underlain by shattered Oquirrh Group orthoquartzite about 1.8 kilometers to the east. In addition, we interpret four flat-bottomed scars and cone-shaped deposits as possible shallow, disrupted soil slides.

Three of the four scars occur in close proximity on slopes underlain by intensely fractured and faulted Oquirrh Group orthoquartzite (figure 14). The fourth is underlain by both Tertiary volcanic rocks and Oquirrh Group orthoquartzite. The scars are characteristically flat-bottomed and differ significantly from nearby V-shaped drainages formed by fluvial erosion that have alluvial fans at their base. The scars are occupied by short oak trees. The upslope part of each of the scars is characterized by an abrupt, step-like, downslope-facing scarp that suggests a landslide origin. At the base of the easternmost scar, a cone-shaped deposit has a local slope of 25 degrees. None of the deposits below the scars are incised by drainages, in contrast to the incised alluvial fan at the base of the V-shaped drainage directly to the east.

Dating of these possible landslides is feasible using the methods described for the Draper Heights landslides. The deposits at the base of the three closely spaced scars are undeveloped and accessible from a nearby road. We estimate that their thickness allows for excavation to their base with a backhoe, allowing the possibility of identifying landslide deposits and possibly finding a buried paleosol that dates the landslide(s). Cosmogenic dating of the landslide is also feasible, but some of the limitations discussed for cosmogenic dating of the Draper Heights landslide likely also apply at these slides.

Seismic Slope Stability of the North Slope of Steep Mountain

We re-evaluated the slope stability of the north slope of Steep Mountain using the most recent ground-motion estimates (Frankel and others, 1996) and the limit-equilibrium infinite-slope stability equation of Jibson and others (2000). Keaton and others (1987) used a fixed friction angle and concluded a high earthquake-induced potential where a calculated ground acceleration (0.13 g) with an exceedance probability of 50 percent in a 100-year time period exceeded the critical acceleration under dry conditions.

Keaton and others (1987) estimated the friction angles of geologic materials in the Wasatch Front because of the regional nature of their study and the lack of shear-strength data. However, we back-calculated a slope-specific minimum friction angle (34 degrees) for the north slope of Steep Mountain that is 4 degrees higher than the value assumed in the Keaton and others (1987) study. Our back-calculated minimum friction angle (34 degrees) falls near the mean for loose sands of Holtz and Kovacs (1981) and thus is representative, as a minimum value, of the cohesionless slope colluvium and intensely fractured Oquirrh Group orthoquartzite. We then calculated factors of safety using the limit-equilibrium infinite-slope stability equation of Jibson and others (2000) for each 4 degree interval for friction angles ranging between 34 and 46 degrees, the latter value being the upper bound reported in Holtz and Kovacs (1981) for cohesionless dense sand. Finally, we calculated critical accelerations and compared them to the estimated rock (site class B) ground motions for the site (Frankel and others, 1996).

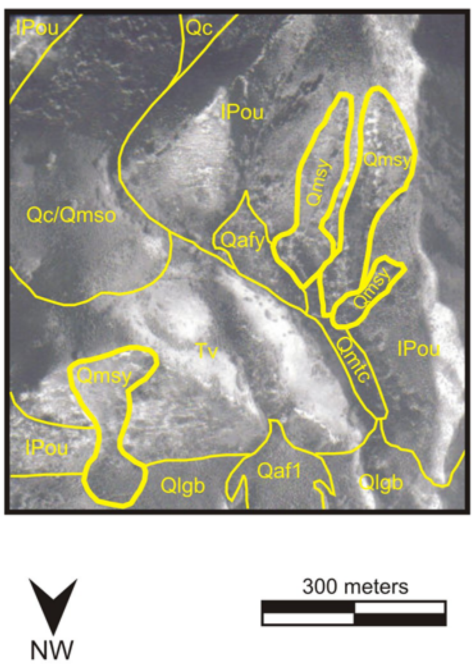


Figure 14. *Map showing four possible shallow, disrupted landslides (Qmsy) defined by shallow, flat-bottomed scars and cone-shaped deposits. Three of the landslides are in colluvium underlain by Oquirrh Group orthoquartzite. The fourth is underlain by both Tertiary volcanic rocks and Oquirhh Group orthoquartzite. Draper Heights landslide is about 1.2 kilometers west of these landslides.*

Figure 15 shows that depending on the actual friction angle of the slope material assuming dry conditions, that a potential for earthquake-induced landslides exists for ground motions less than the 5 percent in 50-year ground acceleration. If the friction angle is 42 degrees or less, then earthquake-induced landslides are possible for ground accelerations less than the 10 percent in 50-year ground acceleration. Thus, we can infer that the ground motions capable of triggering shallow, disrupted landslides in the north slope of Steep Mountain have a return period of less than 1,000 years and likely less than 500 years.

Summary

Based on the previously recognized potential for earthquake-induced landslides (Keaton and others, 1987), we evaluated the Steep Mountain area to determine whether landslides commonly triggered by major earthquakes exist in the area. We believe that the Draper Heights landslide is a possible candidate for an earthquake-induced landslide because it is a shallow, disrupted slide in a hillslope with a high earthquake-induced landslide potential. If such a landslide occurred today elsewhere on the north slope of Steep Mountain, it could be catastrophic, causing death and damage to houses, due to inadequate building setbacks at the base of the slope. We mapped other possible shallow, disrupted slides that suggest that earthquake-induced slides have been triggered in the area and are part of the geologic record that can be identified with careful mapping. We believe that opportunities exist, although somewhat limited ones, to date the Draper Heights landslide and other nearby slides. Correlation with documented surface-faulting earthquakes on the Wasatch fault zone could demonstrate that this type of earthquake-induced landsliding is characteristic of the surface-faulting earthquakes in the Wasatch Front. However, our analysis suggests that shallow, disrupted slides are possible in the Steep Mountain area for ground accelerations much less than those characteristic of a surface-faulting earthquake.

DISCUSSION

The possibility that the Grandview Peak rockslide is an earthquake-induced catastrophic event, although a rare occurrence, has implications for understanding this type of hazard in the canyons and mountain front areas of the Wasatch Range. Presently, the Madison Slide is the characteristic landslide triggered in mountainous terrain by a major Basin and Range earthquake. However, given the similarities of the Wasatch Range to other ranges including that at the Madison Slide, earthquake-induced catastrophic rockslides are likely part of the geologic record and pose a hazard in and near the Wasatch Range. In the Wasatch Front, Pashley and Wiggins (1972) identified at least three other prehistoric rockslides, which they inferred could have been triggered by major earthquakes. At least two of these would have devastated major urban areas if they occurred today. The youngest of these is the North Ogden rockslide, inferred to be latest Pleistocene in age by Nelson and Personius (1993) and predates the surface-faulting chronology of the Weber segment of the Wasatch fault zone (William Lund, Utah Geological Survey, written communication, 2003). Presently, no data preclude the

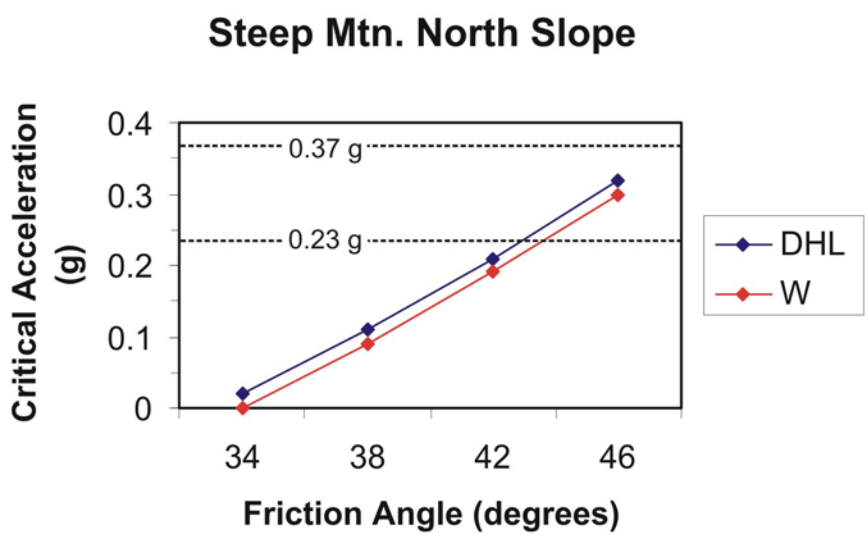


Figure 15. *Back-calculated critical accelerations for the north slope of Steep Mountain. Range in friction angle estimated for cohesionless colluvium and intensely fractured Oquirrh Group orthoquartzite. Lower bound friction angle (34 degrees) is minimum required for dry slope to remain stable. Most of the back-calculated critical accelerations are below the peak acceleration with a 10 percent probability of exceedance in 50 years (0.23 g) based on site class B conditions (Frankel and others, 1996). All back-calculated critical accelerations are below the peak acceleration with a 5 percent probability of exceedance in 50 years (0.37 g) based on site class B conditions (Frankel and others, 1996). Two profiles used for back-calculations: DHL - profile near Draper Heights landslide and W - profile in steepest part of slope west of slide.*

possibility that the Grandview Peak rockslide occurred within the time period bracketing the chronology of the two nearest segments (Weber and Salt Lake City) of the Wasatch fault zone. Thus, the rockslide is the best candidate for determining whether catastrophic rockslides may occur during surface-faulting earthquakes in the Wasatch Front.

The earthquake-induced reactivation of pre-existing landslides as deep, coherent slides is a significant threat in the Wasatch Front given the large number of landslides in the area and the increasing development on prehistoric landslides. Recent research (Ashland, 2003) suggests that many Wasatch Front landslides likely have low factors of safety as indicated by the reactivation of a number of pre-existing landslides during wet periods in the past 20 years. If many or most of the Wasatch Front landslides have marginal stability, then earthquake-induced reactivation likely has occurred in many slides. The demonstrated vulnerability of Wasatch Front landslides to movement triggered by a rise in ground-water levels associated with wet periods suggests that most movement episodes in recurrently moving slides are likely climatically controlled rather than earthquake induced. Separating out earthquake-induced movement episodes from the overall movement history of a landslide, i.e., demonstrating the seismic origin of a movement episode (Jibson, 1996), poses a significant challenge.

Our evaluation of the Little Valley landslide demonstrated the feasibility of determining, at least in part, the movement history of a landslide, using traditional paleoseismic methods and geomorphic analysis. However, the partial success of this study was due to the local presence of nearly ideal geomorphic conditions, including areas on the landslide such as sag ponds and structural troughs (Little Valley) with datable organic-rich sediments, which provided opportunities to date deformation and movement episodes. Whereas the preliminary evidence suggests that a mid-Holocene movement episode dated at about 4.7 ka was possibly earthquake-induced, the dating is not accurate enough to definitively correlate the movement episode with the surface-faulting event. The likelihood that the movement episode was earthquake triggered would increase if movement episodes of the same age were identified at other nearby landslides, although such evidence could also support a climatic cause. A seismic origin would be better supported where multiple landslides were identified as having occurred during a dry period (see figure 11), or other evidence of a seismic origin, such as contemporaneous liquefaction, was identified.

Characterizing the likelihood of deep, coherent landslides being triggered by major Wasatch Front earthquakes requires detailed study to determine the susceptibility and movement behavior of some representative slides. The susceptibility to earthquake-induced movement of an individual landslide could be better demonstrated if multiple episodes of movement correlated with surface-faulting events on the Wasatch fault zone. In addition, the dormancy of a particular landslide during a documented surface-faulting event on a nearby fault segment has implications for the control of other factors on whether earthquake-induced movement occurs. Such factors include ground-water levels, landslide boundary and geometry constraints (the geometric freedom of movement and available driving force under static conditions), temporal changes in shear strength (thixotropic hardening), and variations in ground accelerations generated by surface-faulting earthquakes on an individual fault segment.

Our evaluation of the Little Valley landslide was limited, and complete documentation of the movement history would require additional trenching of favorable structures such as the main scarp zone. Observations indicate that offset on the main scarp generally always occurs with movement of large landslides, except where the total movement is minimal (several centimeters or less). Thus, the main scarp zones likely document a more complete record of a landslide's movement history than internal deformation features in the landslide mass such as the antithetic fault exposed in the Intermountain GeoEnvironmental Services (2003) sag pond trench, particularly given the uncertainty of movement on any specific internal deformation feature during each movement episode (Ashland, 2002). With more complete documentation of the landslide's movement history, a better correlation with Wasatch fault zone surface-faulting earthquakes may become apparent, increasing our confidence that the 4.7 ka movement episode was earthquake induced.

Movement episodes that fall between the documented ages of Wasatch fault zone surface-faulting earthquakes do not necessarily preclude a seismic origin, but require other corroborating evidence to support one. Keefer (1984) indicates that the minimum magnitude to trigger soil and rock block slides and rotational slides (magnitude 4.5-5.0) is less than the magnitude estimated for a Wasatch fault zone surface-faulting earthquake. Thus, Wasatch Front landslides may have been triggered or reactivated by earthquakes of smaller magnitude than those of the documented surface-faulting events. Multiple lines of evidence that might support the conclusion that a landslide episode was triggered by a non-surface-faulting earthquake include similar-age movement episodes from several landslides, movement during prehistoric dry periods, and evidence for liquefaction coincident with landsliding.

CONCLUSIONS

Our preliminary studies evaluated the feasibility of recognizing earthquake-induced landslides in the geologic record in the Salt Lake City metropolitan area. Complimentary research includes ongoing efforts by the UGS to inventory and characterize Salt Lake County landslides and landslide investigations by consultants. In addition, the feasibility of recognizing a seismic origin for latest Pleistocene to present movement episodes in some landslides is increased by the documented surface-faulting chronology of the Salt Lake City segment of the Wasatch fault zone since the latest Pleistocene (McCalpin, 2002). With the exception of lateral spreads (Hylland and Lowe, 1998; Harty and Lowe, 2003), earthquake-induced landslides have not been recognized by previous researchers. However, the potential for earthquake-induced landslides has been mapped in the Wasatch Front (Keaton and others, 1987).

Our reconnaissance of the Grandview Peak rockslide revealed similarities to the Madison Slide triggered by the 1959 Hebgen Lake earthquake. Whereas these similarities are not conclusive evidence that the Grandview Peak rockslide was triggered by an earthquake, we identified opportunities to date the event and possibly correlate it with a documented surface-faulting earthquake on the nearby Salt Lake City or Weber segments of the Wasatch fault zone. The rockslide formed a landslide dam blocking City Creek and three tributary drainages and formed temporary ponds. The age of the landslide could be constrained by radiocarbon dating of basal pond sediments, or buried trees or paleosols in or beneath the pond sediments, but the backcountry setting of the rockslide and the likely depth of the upstream pond sediments makes this dating approach impractical. Cosmogenic dating of limestone and quartzite boulders on the surface of the deposit or of the exposed Paleozoic rock in the main scarp is likely the most feasible approach to obtain an age of the event. Recognition of the seismic origin of the slide would provide a model for characterizing the earthquake-induced catastrophic rockslide hazard elsewhere in the Wasatch Range and provide guidance for future earthquake-induced landslide studies, such as supplemental studies to that of Harp and Noble (1993).

We developed a partial movement history for the Little Valley landslide, one of the largest prehistoric slides in the Salt Lake City metropolitan area, using geomorphic analysis and radiocarbon ages obtained as part of a consultant's landslide investigation (Intermountain GeoEnvironmental Services, 2003). Our ability to create this movement history resulted from some ideal geomorphic characteristics of this particular landslide, including the presence of rotated blocks with deformed and faulted latest Pleistocene-Holocene sag pond sediments and local troughs on the landslide with Holocene alluvium, that allowed dating of movement episodes and periods of dormancy. Other areas of the slide were characterized by barren landslide debris with no opportunities for radiocarbon dating. A radiocarbon age obtained from the base of a colluvial wedge on the upslope side of an antithetic fault in the upper sag pond area in the head of the landslide indicated a movement episode about 4.7 ka. This age overlaps with the estimated age range of surface-faulting event W on the Salt Lake City segment of the Wasatch fault zone. Whereas the radiocarbon age alone is not conclusive proof of a seismic origin, the movement episode corresponds with a dry period in the Holocene (Murchison, 1989), suggesting movement was unlikely triggered by climatic conditions.

Given the inferred low factors of safety of many Wasatch Front landslides (Ashland, 2003), multiple lines of evidence are needed to confidently demonstrate a seismic origin for any specific movement episode. A combination of paleoliquefaction and landslide-movement-history studies may reveal the chronology of earthquakes in the magnitude range of 4.5 to 6.5.

We interpret the Draper Heights landslide on the north slope of Steep Mountain as a possible candidate for an earthquake-induced shallow, disrupted slide. Keaton and others (1987) had mapped the north slope as having a high earthquake-induced landslide potential. We interpret scars on similar nearby slopes as evidence of other possible earthquake-induced shallow, disrupted landslides, suggesting these types of slides, common in the 1994 Northridge earthquake, are likely part of the geologic record in the Salt Lake City metropolitan area. Dating of these events may provide some proof of their seismic origin; however, our analysis suggests that earthquakes of smaller magnitude than surface-faulting events may trigger landslides on the north slope of Steep Mountain. A better inventory may reveal more shallow, disrupted slides in the Steep Mountain area, but the absence of such slides may only indicate that most are too small to be preserved in the geologic record. Currently, building setbacks from the base of Steep Mountain are inadequate to protect houses from slides similar to the Draper Heights landslide.

FUTURE INVESTIGATIONS

Development of a movement history for a select subset of landslides in the Salt Lake City metropolitan area may reveal evidence that moderate earthquakes triggered landslide movement. A seismic origin of these events may be demonstrated if contemporaneous liquefaction episodes can be identified. By dating the age of contemporaneous prehistoric liquefaction and landslide movement episodes that occurred between documented surface-faulting earthquakes, a chronology for prehistoric earthquakes between a magnitude range of 4.5 to 6.5 may be developed, filling a gap in the current knowledge of earthquake frequency between historical earthquakes (M < 4.5) and prehistoric surface-faulting earthquakes (M > 6.5).

ACKNOWLEDGMENTS

Ben Everitt, Utah Division of Water Resources, shared his knowledge on the Grandview Peak rockslide. Justin Johnson, formerly with the UGS, prepared the initial draft of figure 1 of this report. We appreciate helpful reviews of the manuscript by Gary Christenson, Michael Hylland, and Kimm Harty (UGS).

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