EARTHQUAKE WORKING GROUPS, DATABASE UPDATES, AND PALEOSEISMIC FAULT STUDIES, UTAH

PART I: TECHNICAL AND NON-TECHNICAL SUMMARIES
PART II: EARTHQUAKE WORKING GROUPS AND DATABASE UPDATES
PART III: INTERIM SURFICIAL GEOLOGIC MAP OF THE FAYETTE SEGMENT OF THE WASATCH FAULT ZONE, JUAB AND SANPETE COUNTIES, UTAH
PART IV: PALEOSEISMIC RECONNAISSANCE OF THE SEVIER/TOROWEAP FAULT, WASHINGTON AND GARFIELD COUNTIES, UTAH

By

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Christopher B. DuRoss, and Greg N. McDonald

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P.O. Box 146100
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April 2005

Final Technical Report
National Earthquake Hazards Reduction Program
Effective date: January 1, 2004
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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 in 2003 and reconvened a series of working group meetings in 2004 to refine multi-year plans for developing earthquake ground shaking, liquefaction, and earthquake-induced landslide hazard maps. In support of the planning effort, the UGS updated interactive Quaternary fault and fold, 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 Fayette segment of the Wasatch fault zone (WFZ) and performed reconnaissance paleoseismic studies of the Sevier/Toroweap fault in southwestern Utah. Although listed in the original title of the proposal and maintained in the title of this Final Contract Report, the UGS did not perform any further studies of earthquake-induced landslides.

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 updates to the databases. Part III presents results of surficial geologic mapping of the Fayette segment of the WFZ, and Part IV summarizes the results of the initial paleoseismic studies of the Sevier/Toroweap fault.

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 express or implied, of the U.S. Government.

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PART I: TECHNICAL AND NON-TECHNICAL SUMMARIES

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CONTENTS

INTRODUCTION

The Utah Geological Survey (UGS), in cooperation with the U.S. Geological Survey (USGS) and Utah Seismic Safety Commission, convened a 2004 Earthquake Conference and second annual series of earthquake working group meetings in February 2004. In the working group meetings we revised the 2003 multi-year plans for developing the next generation of earthquake ground shaking, liquefaction, and earthquake-induced landslide maps for Utah, and held the final meeting of the Utah Quaternary Fault Parameters Working Group. In support of the working groups' effort, we updated our interactive Quaternary fault and fold, shallow shear-wave-velocity, deep-basin-structure, and geotechnical landslide shear-strength databases.

In addition, the UGS mapped the surficial geology of the Fayette segment of the Wasatch fault zone as a continuation of USGS and UGS surficial geologic mapping of segments of the Wasatch fault. 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 began paleoseismic studies on the Sevier/Toroweap fault in southwestern Utah to identify likely sites for detailed study to determine the timing of the most recent surface faulting, possible segmentation, recurrence intervals, and slip rates. Although the original proposal included earthquake-induced landslide studies, we did not perform any additional such studies.

TECHNICAL SUMMARY

Working Groups

The 2004 Utah Earthquake Conference was held on February 26, 2004, to present the latest results of mostly NEHRP-funded work over the previous year. Following the conference, one-day meetings of the Ground Shaking, Liquefaction, Earthquake-Induced Landslide, and Quaternary Fault Parameters Working Groups were held on February 27, 2004. Working groups discussed the previous year's work and revised 2003 long-term plans to identify partnerships and projects for future proposals. Final working group plans are available on the UGS Web site at geology.utah.gov. Over 150 people attended the Utah Earthquake Conference, and nearly 50 members attended the various working group meetings.

The Ground Shaking Working Group emphasized developing a "community velocity model" for use in developing detailed spectral-acceleration maps for ground motions at various periods that consider both shallow shear-wave velocities (Vs30) and deep-basin structure. The Liquefaction Working Group is coordinating an existing collaborative NEHRP-funded pilot project in northern Salt Lake Valley. The Earthquake-Induced Landslide Working Group did not arrive at a consensus regarding future work or identify interested researchers. Because of this, the working group may not continue. The Utah Quaternary Fault Parameters Working Group coordinated its final meeting with the Earthquake Conference and other working group meetings, and developed consensus recurrence intervals and slip rates for various trenched faults. In addition, they set priorities for future paleoseismic studies.

Databases

To help working groups develop earthquake-hazards-mapping plans, the UGS updated three databases compiled in 2003: 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). We also updated Utah's Quaternary fault and fold database.

The shallow shear-wave-velocity database was updated to include 2004 spectral analysis of shear wave (SASW) data collected under a NEHRP-funded project. No new data were available for the deep-basin-structure database. The geotechnical landslide shear-strength database was updated with laboratory soil-test data from various sources, principally from geotechnical consultants and the Utah Department of Transportation. The Quaternary fault and fold database was updated with trenching and mapping data collected since release of the database in 2003, and consensus values for recurrence intervals and slip rates for trenched faults determined by the Utah Quaternary Fault Parameters Working Group.

Fayette Segment Wasatch Fault Zone Mapping

We mapped the surficial geology of the Fayette segment, with an emphasis on the relations between Quaternary deposits and faults. The Fayette segment, the southernmost segment of the Wasatch fault zone, extends from 1.5 km north of Chriss Canyon in southern Juab County southward about 24 km to the town of Fayette in Sanpete County, Utah. Quaternary deposits along the Fayette segment are dominated by piedmont-slope alluvial fans of middle Pleistocene to late Holocene age. Other regionally important Quaternary deposits along the segment include unconsolidated to semiconsolidated fan alluvium of Quaternary-Tertiary age, and fine-grained lacustrine deposits of latest Pleistocene Lake Bonneville. Stream alluvium, landslide deposits, colluvium, and eolian deposits are also present locally.

The northern end of the Fayette segment overlaps with the southern end of the Levan segment in an area approximately 10 km long and 4 km wide. Subsidiary faults oblique and parallel to the Fayette and Levan segments appear to have accommodated transfer of displacement between the two segments at different times. We place the northern end of the Fayette segment about 1.5 km north of Chriss Creek, at the northern termination of a down-to-the-west normal fault in Tertiary bedrock. The southern end of the segment is placed at the southernmost late Quaternary fault scarp on fan alluvium east of the town of Fayette.

We observed no fault scarps on Quaternary deposits along the Fayette segment north of Hells Kitchen Canyon. However, we believe Quaternary faulting has occurred along this part of the segment, but not in late Quaternary time. South of Hells Kitchen Canyon, the Fayette segment comprises two late Quaternary fault strands. The western strand begins about 1 km south of Hells Kitchen Canyon and extends southward approximately 6 km. The eastern strand begins about 4 km south of Hells Kitchen Canyon and extends southward along the base of the San Pitch Mountains to the town of Fayette. Morphometric scarp data indicate that the most recent surface-faulting event on the western strand is younger (possibly Holocene) than the most recent event on the eastern strand (possibly latest Pleistocene).

We cannot calculate a Holocene slip rate for the Fayette segment because the timing of surface-faulting paleoearthquakes is unknown. However, our estimated long-term geologic vertical slip rate, determined from net vertical tectonic displacement and the estimated age of late to middle Pleistocene fan alluvium (100-250 ka), is about 0.01-0.03 mm/yr near the middle of the eastern strand of the Fayette segment. Higher long-term slip-rate values (0.06-0.1 mm/yr) calculated from a large (20-m-high) multiple-event scarp on the northern part of the western strand may result from spillover of Levan-segment ruptures onto the Fayette segment, or additive slip from separate eastern- and western-strand Fayette-segment ruptures that overlap on this part of the fault, or some combination of these two conditions. Additionally, the higher slip rate may reflect a component of localized diapirism or dissolution-induced subsidence associated with subsurface evaporite beds in the Arapien Shale.

We consider the Fayette and Levan segments to be good candidates for paleoseismic trenching studies that would likely provide data useful in testing models of partial- and multi-segment fault rupture.

Sevier/Toroweap Fault Zone Paleoseismic Reconnaissance

We conducted a reconnaissance of the Sevier fault in southwestern Utah to identify sites where future paleoseismic studies may provide information on earthquake timing, recurrence, displacement, and vertical slip rate. The reconnaissance included a literature review, aerial-photograph interpretation, field reconnaissance, and sampling of basalt flows for $^{40}Ar/^{39}Ar$ radiometric dating. Results of the reconnaissance showed no fault scarps formed on unconsolidated deposits along the main trace of the Sevier fault in Utah; however, Quaternary mafic volcanic rocks are displaced at two locations (Black Mountain and Red Canyon) on the Sevier (northern) section of the fault. Geologic relations at Black Mountain are complex and poorly exposed. Vertical slip rates calculated there based on displacement of 0.57 Ma volcanic rocks range from 0.04 to 0.40 mm/yr, depending on the amount of displacement in the volcanic rocks attributed to surface faulting. Detailed examination of the Red Canyon site identified a previously unknown source on the Sevier fault hanging wall for the displaced volcanic rocks, indicating that the 200 m difference in elevation of the volcanic rocks across the fault is due to surface faulting and is not the result of volcanic flows cascading from the fault footwall across a pre-existing fault escarpment. Based on an existing K-Ar age for the volcanic rocks of 0.56±0.07 Ma, this reconnaissance confirmed a vertical slip rate at Red Canyon of 0.36 mm/yr.

Scarps and folds formed on unconsolidated basin-fill deposits in the Sevier fault hanging wall include a zone of faults and folds that extends from the hills directly south of Panguitch northeastward across the Sevier River to east of Panguitch, and a short north-south-trending fault zone on the east side of the Sevier River north of Panguitch. The scarps displace deposits ranging in age from late Pleistocene to late Tertiary and vary in height from less than a meter to about 25 m high. The scarps in both areas may be genetically related to the main Sevier fault to the east, but the scarps in the northeast-trending fault and fold zone may have formed in response to aseismic folding. Scarps in both areas are suitable for trenching; however, what relation surface faulting on those scarps has to the timing of surface-faulting earthquakes on the main Sevier fault is unclear. Trenching of scarps within the fault and fold belt would reveal if those scarps formed in response to surface-faulting earthquakes or are due to aseismic folding (creep).

Recommendations for future paleoseismic study of the Sevier fault include:

(1) Detailed geologic mapping of Black Mountain and vicinity to determine (a) the net vertical displacement of the volcanic rocks across the Sevier fault, and (b) if a seismogenic segment boundary exists close to Black Mountain.

(2) If net vertical displacement is significantly different between Black Mountain and Red Canyon (results of 1a above), and no evidence of a seismogenic boundary is found near Black Mountain (results of 1b above), then prepare a detailed geologic map of the Sevier fault between Black Mountain and Red Canyon to determine if there is a segment boundary between those two locations.

(3) Trenching an alluvial scarp on the Northern Toroweap section of the Toroweap fault in Arizona to collect surface-faulting information that could be applied to the Utah portion of the Northern Toroweap section, which has no scarps.

(4) Trenching a minimum of one probable single-event and one multiple-event fault scarp in the fault and fold zone near Panguitch to determine if the fault scarps are the result of surface faulting or are a consequence of aseismic folding.

(5) Trenching a single-event and a multiple-event fault scarp in the short fault zone north of Panguitch to better constrain the timing and magnitude of paleoearthquakes on those faults.

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 and USGS entered into an agreement in 2003 for cooperative earthquake-hazards studies in Utah. In 2004, the second year of these cooperative studies, the UGS held meetings and performed a variety of earthquake-related studies.

The UGS held the 2004 Utah Earthquake Conference and working group meetings, co-sponsored by the USGS and Utah Seismic Safety Commission. Results of 2003 work were presented at the conference and discussed in working group meetings. The earthquake-hazard mapping plans developed in 2003 were revised and updated to define data needs and establish partnerships for proposed 2005 projects. In support of this effort, the UGS updated databases compiled in 2003.

We extended the surficial geologic mapping of the Wasatch fault to the south to include the Fayette segment in central Utah. We also performed reconnaissance paleoseismic studies of the Sevier/Toroweap fault in southwestern Utah to estimate slip rates and identify sites for future detailed studies.

EARTHQUAKE WORKING GROUPS, DATABASE UPDATES, AND PALEOSEISMIC FAULT STUDIES, UTAH

PART II: EARTHQUAKE WORKING GROUPS AND DATABASE UPDATES

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CONTENTS

DATABASES (on CD in pocket)

Updated final shallow shear-wave-velocity, deep-basin-structure, and geotechnical landslide shear-strength databases

ABSTRACT

The Utah Geological Survey (UGS), in cooperation with the U.S. Geological Survey (USGS) and Utah Seismic Safety Commission, held a general earthquake conference and again convened a series of earthquake working group meetings in 2004. The 2004 Utah Earthquake Conference provided a forum for researchers to present their results to the Utah technical community and other working group members prior to working group meetings the next day. The Ground Shaking, Liquefaction, and Earthquake-Induced Landslide Working Groups then met to re-evaluate long-term plans to produce maps and develop partnerships for investigations and topics for future proposals. The Utah Quaternary Fault Parameters Working Group (UQFPWG), funded under another NEHRP grant, held their final meeting in conjunction with these other three working groups and their final report is now complete.

The UGS maintains four GIS databases to accurately reflect the status of existing data on 1) shallow shear-wave velocities (Vs30), 2) deep-basin structure, 3) geotechnical landslide shear strengths, and 4) Quaternary faults and folds. The shallow shear-wave-velocity (Vs30), deep-basin-structure, and geotechnical landslide shear-strength databases were updated with new data from 2003 NEHRP-funded projects and other sources. The Quaternary fault and fold database was published in 2003 but completed in 2002 and many new studies have been completed since its publication that are now incorporated in this update, in addition to the results of the UQFPWG.

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 is to produce the next generation of earthquake-hazards maps, including: 1) large-scale ground-shaking maps incorporating the latest fault source parameters and site conditions, including shallow shear-wave velocity (Vs30) and deep basin structure, and 2) new liquefaction and earthquake-induced landslide maps depicting ground displacements or other parameters as appropriate. To initiate the process in 2003, the UGS established three technical working groups (Ground Shaking, Liquefaction, and Earthquake-Induced Landslide) and held meetings to develop plans for producing the maps. Meetings were again held in February 2004, co-sponsored by the UGS, USGS, and Utah Seismic Safety Commission, to update 2003 plans. To bring working group members up-to-date on current research results, we held a general earthquake conference preceding the working group meetings. The conference was open to the Utah technical community as well as working group members.

Each working group again discussed the types of maps needed, new data required, preferred data-collection and mapping techniques, and possible funding sources, and developed partnerships and identified projects for future proposals. One goal of timing the meetings in February was to define potential projects and partnerships for proposals in time to respond to the 2005 USGS National Earthquake Hazards Reduction Program

(NEHRP) Request for Proposals (RFP). Results of this program also 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.

The shear-wave-velocity, deep-basin-structure, geotechnical landslide shear-strength, and Quaternary fault and fold databases were updated in 2004. Most databases were originally distributed only in draft form in an interactive CD. The databases have now been checked and updated, and the final CD has been released and included in the pocket. Information needed to use and understand each database is included in the introductory material on the CD. Each database includes a description of the information contained, criteria used in compiling data, and comprehensiveness of the database. Updates for the Quaternary fault and fold database were submitted to the USGS to update the National Quaternary fault database, and will be incorporated into the UGS database on the UGS Web site. A new CD will not be produced at this time.

2004 UTAH EARTHQUAKE CONFERENCE

In preparation for the 2004 working group meetings, we held a general earthquake conference for researchers to present results of recent NEHRP-funded and other earthquake-related research. 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 to inform them of working group activities and research results. The conference included 21 speakers and attendance was about 150. The conference program is included in appendix A.

RESULTS OF EARTHQUAKE WORKING GROUP MEETINGS

Meetings of the Ground Shaking, Liquefaction, Earthquake-Induced Landslide, and Quaternary Fault Parameters Working Groups were held in Salt Lake City on February 27, 2004, following the conference. Working group members (appendix B) 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 various state agencies observed the proceedings and participated as desired (appendix B).

Under another NEHRP grant, the UGS established the Utah Quaternary Fault Parameters 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 B). The final meeting was held with other working group meetings on February 27, 2004. The final working group report was submitted separately in October 2004.

The Ground Shaking, Liquefaction, and Earthquake-Induced Landslide Working Groups updated their 2003 working group plans (appendices C, D, and E). The Ground Shaking Working Group concentrated on collecting data and developing 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 continued the long-term goal to produce maps showing annual probabilities of liquefaction and liquefaction-induced ground displacement, and keyed in on extending their pilot-project studies in the northern Salt Lake Valley to the southern Salt Lake Valley, particularly compilation of the comprehensive geotechnical database. See appendices C and D for 2004 updated Ground Shaking and Liquefaction Working Group plans.

The 2004 Earthquake-Induced Landslide Working Group meeting was not successful in achieving a consensus on future earthquake-induced landslide studies along the Wasatch Front. Support for preparing earthquake-induced landslide hazards maps is generally lacking, and no clear regulatory framework or interest among local governments for using such maps seems to exist. The work done by the UGS in year 1 of this cooperative agreement was presented at the 2004 Utah Earthquake Conference, and was discussed at the working group meeting. Support for additional similar work by the UGS, and interest in developing NEHRP proposals for other earthquake-induced landslide work for 2005, was also lacking. Therefore, the UGS will not continue earthquake-induced landslide studies until a consensus can be reached regarding what studies are needed. The 2003 plan is included in appendix E.

To determine the future of the Earthquake-Induced Landslide Working Group and related studies in Utah, we contacted working group members individually to get their opinions regarding their level of interest in continuing earthquake-induced landslide studies and maintaining the working group. Based on these discussions, we decided to at least temporarily postpone activities and not meet again in 2005. The funds for 2004 earthquake-induced landslide studies under this grant were redirected toward expanding the scope of priority projects identified by other working groups, principally fault characterization studies of the Fayette segment of the Wasatch fault and Sevier/Toroweap fault (Project 3 in 2004 proposal).

Initial planning for the 2005 working group meetings on March 2-4, 2005, was also completed under this grant. We do not plan to hold another earthquake conference, but will present the results of 2004 work in each individual working group meeting. Meetings will be held over three days, beginning with the Ground Shaking Working Group, followed by the Quaternary Fault Parameters and then the Liquefaction Working Groups. The Earthquake-Induced Landslide Working Group will not meet in 2005.

DATABASE UPDATES

Working groups are facilitating production of 1) large-scale ground-shaking maps, based on a community velocity model incorporating shallow shear-wave-velocity (Vs30) and deep-basin structure, and 2) new liquefaction maps. The UGS and others have compiled several databases to identify existing data on 1) shallow shear-wave velocities (Vs30), 2) deep basin structure, 3) geotechnical landslide shear strengths, and 4) Quaternary faults and folds. As part of another NEHRP-funded liquefaction study, geotechnical data from boreholes, cone-penetrometer soundings, and test pits have been compiled. The database covers only the northern Salt Lake Valley, and is available at a University of Utah Web site (http://www.civil.utah.edu/~bartlett/ulag.html).

We updated all UGS databases to include all data available through 2004. The 2003 databases were released in draft form only; the final databases including the 2004 updates are on the attached CD. A description of the data contained, criteria used in compiling data, and comprehensiveness of the database is included with each database. Information on the 2004 updates is given below.

Shallow Shear-Wave Velocities (Vs30)

New data became available on shallow (upper 30 m) shear-wave velocities (Vs), chiefly in Salt Lake Valley, from a NEHRP-funded study using spectral analysis of surface waves (SASW) methods at 44 sites. We also included additional data from the Utah Department of Transportation for the Bangerter Highway interchange with I-15 in southern Salt Lake Valley and the proposed Legacy Highway in Davis County. Additional cone-penetrometer data may be available from Conetec, Inc. We are presently evaluating the reliability of the data before including it in the database.

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Deep-Basin Structure

Few new data have been collected regarding the deep basin structure. The USGS performed a P-wave seismic imaging survey in the southwestern Salt Lake Valley and presented their preliminary results at the 2004 Earthquake Conference. We are awaiting their final report before including the data in the database. The USGS also performed five intermediate-depth (100-600 m) shear-wave-velocity imaging surveys in Salt Lake Valley and Utah Valley in summer 2004. These data are not yet available for addition to the database.

Geotechnical Landslide Shear Strengths

Several new studies, chiefly of landslides in the Salt Lake Valley area, have recently been completed and involved laboratory testing of soil and rock shear strengths for slope stability analysis. Sources of data are principally geotechnical consultant's reports and UDOT.

Quaternary Faults and Folds

Much new information became available for the Quaternary fault and fold database over the past year. We have updated entries for 95 faults and fault sections, and combined three faults into one for a revised total of 209 faults and fault sections in the database. The principal source of updated information was the final report of the Utah Quaternary Fault Parameters Working Group (Lund, 2004). This report tabulated consensus estimates of recurrence intervals and slip rates, where possible, for all faults that have been trenched in Utah. This report included recently published data on these faults, as well as results of the new analysis of existing data. In addition, new trenches had been excavated across several faults, generally in conjunction with dam safety studies.

The updated database was submitted to the USGS for incorporation into the National Quaternary Fault Database in March 2005, and the updated version will soon be available at the UGS Web site (geology.utah.gov). The original version is still available on CD (Black and others, 2003), but we will not publish an updated CD at this time.

ACKNOWLEDGMENTS

This work was partially funded under a continuation of USGS NEHRP grant 03HQAG0008. We thank Mark Petersen, USGS, for his support and in facilitating work in Utah 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, Francis Ashland, and William R. Lund for facilitating the Ground Shaking, Liquefaction, Earthquake-Induced Landslide, and Quaternary Fault Parameters Working Groups, 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 for assisting us in obtaining data for the databases.

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

Lund, W.R., 2004, Utah Quaternary Fault Parameters Working Group – Review of Utah paleoseismic-trenching data and determination of consensus recurrence-interval and slip-rate estimates: Salt Lake City, Utah Geological Survey Final Technical Report to the U.S. Geological Survey National Earthquake Hazards Reduction Program, contract number 03HQGR0033, variously paginated.

APPENDIX A

2004 UTAH EARTHQUAKE CONFERENCE

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

Moderator: Gary E. Christenson

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

Moderator: William R. Lund

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)

<u>Moderator: Ivan Wong</u>

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

<u>Moderator: Barry J. Solomon</u>

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

APPENDIX B

2004 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.

<u>Ground Shaking Working Group</u>
Ivan Wong, URS Corporation, Facilitator
Gary Christenson, UGS
Walter Arabasz, UUSS
Jim Pechmann, UUSS
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APPENDIX C

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
Developed March-April 2003; revised February 2004

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 UBC 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 and the Wasatch Front, including Tooele and Cache Valleys.

Research Needs

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: 2004-2006.

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: 2004-2007.

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: 2005-2007.

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, and will be published and distributed to individuals involved in earthquake hazard mitigation and the general public. Timing: 2007+.

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APPENDIX D

UTAH PLAN FOR DEVELOPING THE NEXT GENERATION OF LIQUEFACTION HAZARD MAPS

Developed by the Utah Liquefaction Advisory Group*
Adopted by the Utah Seismic Safety Commission and Utah Geological Survey
Developed March-April 2003; revised February 2004

(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 2003 site amplification coefficients to modify the strong motion estimates for soil effects. The proposed methods are being tested with a NEHRP grant for a pilot liquefaction-mapping project in north Salt Lake County during 2003 and 2004 (Federal FY 2004).

(2) Develop methods to perform uncertainty analyses and/or quantify the uncertainties associated with the liquefaction-hazard mapping.

(3) 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. Initial correlations will be developed during the pilot project and will continue in future projects (Federal FY 2005-2008) as data from additional geologic units and geographic areas are compiled.

(4) Compile the GIS database for other areas along the Wasatch Front using the pilot-project methods and complete liquefaction-hazard mapping for these areas. The preliminary priority of data compilation and mapping is: Salt Lake, Utah, Weber-Davis, and Cache Counties (Federal FY 2005-2008). Database compilation for south Salt Lake County may be proposed as a NEHRP project for Federal FY 2005.

(5) Develop probabilistic methods to map the amount of liquefaction-induced ground deformation (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 probabilistic liquefaction-hazard maps and will be completed during Federal FY 2005 to 2008. Liquefaction-induced ground deformation mapping in north Salt Lake Valley, the same area as the pilot project, may be proposed as a NEHRP project for Federal FY 2005.

(6) Study documented occurrences of deformed Quaternary soils to determine if deformation is liquefaction-induced or related to other mechanisms (for example, failure of underlying clay). Also, attempt to determine the age of failed soils to establish the liquefaction hazard posed by latest Pleistocene Lake Bonneville sands. Is the presence of these Pleistocene sands sufficient to indicate a high liquefaction hazard or, as suggested by criteria for liquefaction in California, does the Pleistocene age indicate a lower hazard? A limited study of documented occurrences may be proposed as a NEHRP project for Federal FY 2005.

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APPENDIX E

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

Utah Earthquake-Induced Landslide Working Group*
July-September 2003 (not updated in 2004)

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**

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EARTHQUAKE WORKING GROUPS, DATABASE UPDATES, AND PALEOSEISMIC FAULT STUDIES, UTAH

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

by

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April 2005

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Award number 03HQAG0008

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FIGURES

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PLATE

ABSTRACT

The Fayette segment, the southernmost segment of the Wasatch fault zone, extends from 1.5 km north of Chriss Canyon in southern Juab County southward about 24 km to the town of Fayette in Sanpete County, Utah. Quaternary deposits along the Fayette segment are dominated by piedmont-slope alluvial fans of middle Pleistocene to late Holocene age. Other regionally important Quaternary deposits along the segment include unconsolidated to semiconsolidated fan alluvium of Quaternary-Tertiary age, and fine-grained lacustrine deposits of latest Pleistocene Lake Bonneville. Stream alluvium, landslide deposits, colluvium, and eolian deposits are also present locally.

The northern end of the Fayette segment overlaps with the southern end of the Levan segment in an area approximately 10 km long and 4 km wide. Subsidiary faults oblique and parallel to the Fayette and Levan segments appear to have accommodated transfer of displacement between the two segments at different times. We place the northern end of the Fayette segment about 1.5 km north of Chriss Creek, at the northern termination of a down-to-the-west normal fault in Tertiary bedrock. The southern end of the segment is placed at the southernmost late Quaternary fault scarp on fan alluvium east of the town of Fayette.

We observed no fault scarps on Quaternary deposits along the Fayette segment north of Hells Kitchen Canyon. However, we believe Quaternary faulting has occurred along this part of the segment, but not in late Quaternary time. South of Hells Kitchen Canyon, the Fayette segment comprises two late Quaternary fault strands. The western strand begins about 1 km south of Hells Kitchen Canyon and extends southward approximately 6 km. The eastern strand begins about 4 km south of Hells Kitchen Canyon and extends southward along the base of the San Pitch Mountains to the town of Fayette. Morphometric scarp data indicate that the most recent surface-faulting event on the western strand is younger (possibly Holocene) than the most recent event on the eastern strand (possibly latest Pleistocene).

We cannot calculate a Holocene slip rate for the Fayette segment because the timing of surface-faulting paleoearthquakes is unknown. However, our estimated long-term geologic vertical slip rate, determined from net vertical tectonic displacement and the estimated age of late to middle Pleistocene fan alluvium (100-250 ka), is about 0.01-0.03 mm/yr near the middle of the eastern strand of the Fayette segment. Higher long-term slip-rate values (0.06-0.1 mm/yr) calculated from a large (20-m-high) multiple-event scarp on the northern part of the western strand may result from spillover of Levan-segment ruptures onto the Fayette segment, or additive slip from separate eastern- and western-strand Fayette-segment ruptures that overlap on this part of the fault, or some combination of these two conditions. Additionally, the higher slip rate may reflect a component of localized diapirism or dissolution-induced subsidence associated with subsurface evaporite beds in the Arapien Shale.

We consider the Fayette and Levan segments to be good candidates for paleoseismic trenching studies that would likely provide data useful in testing models of partial- and multi-segment fault rupture.

INTRODUCTION

Our mapping characterizes the surficial geology along the Fayette segment of the Wasatch fault zone in central Utah, with an emphasis on the relations between Quaternary deposits and faults. The Fayette segment is the southernmost segment 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 (plate 1) completes 1:50,000-scale surficial-geologic mapping of the fault zone south of the Collinston segment in northern Utah (figure 1). The Fayette segment extends through a rural area of low population density and therefore presents less of a seismic risk than segments to the north that trend through the heavily populated Wasatch Front area. Nevertheless, the Fayette segment shows evidence for latest Pleistocene and possibly Holocene surface faulting, and detailed mapping provides the basis for accurately characterizing the relative contribution of the fault segment to the overall seismic hazard of north-central Utah.

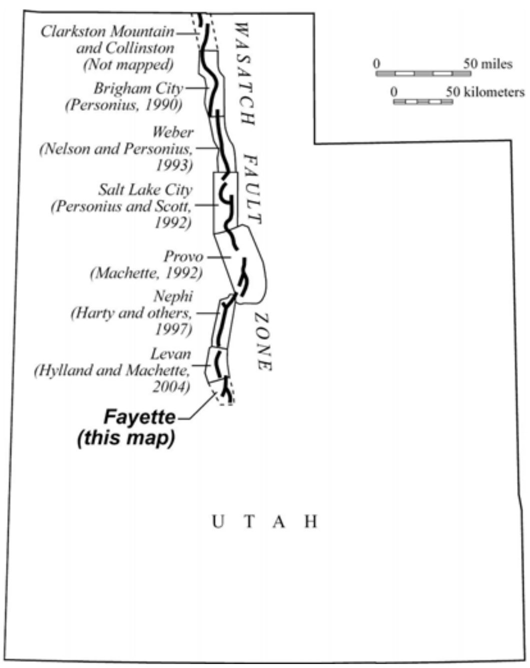

Figure 1. *Index map of Wasatch fault zone in Utah showing segments and published 1:50,000-scale strip maps.*

The Fayette segment lies at the base of the western slope of the San Pitch Mountains (Gunnison Plateau), forming the eastern margins of northern Sevier Valley and Flat Canyon (figure 2). The segment extends from 1.5 km north of Chriss Canyon in southern Juab County southward about 24 km to the town of Fayette in Sanpete County.

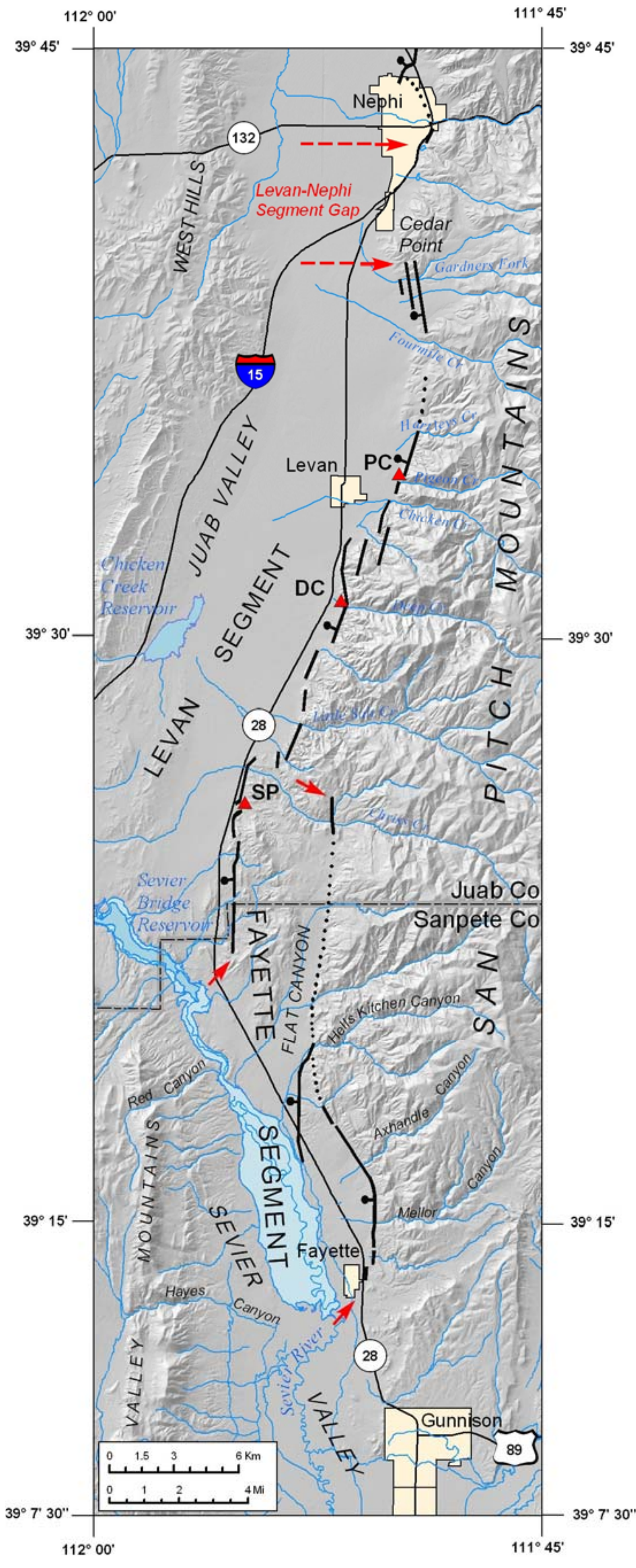

Figure 2. *Fayette and Levan segments of the Wasatch fault zone. Faults shown by heavy lines, dotted where concealed, bar and ball on downthrown side; arrows show ends of segments. Study sites on Levan segment shown by triangles: PC, Pigeon Creek (site of radiocarbon age of faulted fan alluvium reported by Schwartz and Coppersmith, 1984); DC, Deep Creek stream-cut exposure of fault; SP, Skinner Peaks trench of Jackson (1991).*

Utah Highway 28 closely parallels the fault along the southern part of the segment, and crosses the western strand of the segment. The Sevier River flows northward to the west of Highway 28. Sevier Bridge Dam (spillway elevation 1529 m; 5014 ft on base map), in southern Juab County, impounds water of the Sevier River to form Sevier Bridge Reservoir, which periodically inundates the valley as far south as Fayette. The Valley Mountains border northern Sevier Valley to the west.

This report includes descriptions of Quaternary geologic deposits and fault scarps along the fault zone, a discussion of estimated slip rates on the Fayette segment, and descriptions of the segment boundaries. Fault scarps have been profiled along the Fayette segment, but no paleoseismic trenching has been performed to date.

Geologic Setting

The Wasatch fault zone extends at least 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 Fayette segment is the southernmost segment of the fault zone, and its northern end forms an en echelon overlap with the Levan segment to the north (figures 1 and 2). The San Pitch Mountains are in the footwall of the fault and northern Sevier Valley is in the hanging wall.

Along the Fayette segment, bedrock exposed in the footwall consists of conglomerate and pebbly sandstone of the Upper Cretaceous Indianola Group; conglomerate and sandstone of the Paleocene-Upper Cretaceous North Horn Formation; limestone and sandstone of the Eocene-Paleocene Flagstaff Limestone; limestone, sandstone, and mudstone of the Eocene Colton and Green River Formations; and cherty sandstone of the Eocene Crazy Hollow Formation. Although not exposed along the Fayette segment, the Jurassic Arapien Shale is exposed in the San Pitch Mountains just a few kilometers north of Chriss Canyon, and is present in the subsurface along the Fayette segment. At the northern end of the Fayette segment, interbedded conglomerate, sandstone, and tuff of the Oligocene-Eocene Goldens Ranch and Moroni Formations are present in a structural block between the overlapping ends of the Fayette and Levan segments, as well as farther west in the hanging wall at the southern end of the Levan segment.

Quaternary-Tertiary alluvial-fan deposits are preserved locally along the fault as well as on the west side of the valley, where undifferentiated Quaternary-Tertiary basin-fill deposits are also present. The hanging wall of the Fayette segment is dominated by alluvial-fan deposits and basin fill ranging in age from Holocene to early Pleistocene. Fault scarps cut deposits of latest Pleistocene to early Holocene(?) age along the Fayette segment, but do not cut the youngest Holocene deposits of stream and fan alluvium at canyon mouths.

A shallow arm of late Pleistocene Lake Bonneville occupied the southern part of Juab Valley and the northern part of Sevier Valley during the Bonneville-level highstand between 16,800 and 18,000 cal yr B.P. (calendar-calibrated ages from D.R. Currey, University of Utah, written communication to Utah Geological Survey, 1996). Crittenden (1963) and Currey (1982) documented local erosional Bonneville shorelines in northern Sevier Valley at elevations of 1552 m (reported as 5090 ft) and 1556 m, respectively, and discontinuous deposits of fine-grained lacustrine sediment are present on the valley floor on either side of the Sevier River flood plain. A subtle fault scarp appears to be formed on Lake Bonneville deposits at the southern end of the western strand of the Fayette segment, thus indicating post-Bonneville faulting.

The principal geologic structure in the footwall of the Fayette segment is the north-trending West Gunnison monocline (Mattox, 1987, 1992; Weiss and others, 2003). Tertiary sedimentary strata unconformably overlie Upper Cretaceous rocks and dip relatively steeply to the west. Numerous normal faults, including those of the Fayette segment, cut the monocline; most of these faults are subparallel to the range front, but some trend at high angles to the predominant north-south structural grain. On the west side of the northern Sevier Valley, east-dipping Tertiary strata form the Valley Mountains monocline (Witkind and Page, 1984). This pair of monoclines has been variously attributed to extensional tectonism and (or) dissolution of salt beneath Sevier Valley (see, for example, Standlee, 1982; Witkind, 1983, 1994, 1999; Witkind and Page, 1984; Petersen, 1997).

The Flat Canyon graben (Felger, 1991) occupies most of the area of overlap between the northern part of the Fayette segment and southern part of the Levan segment. The down-to-the-west Fayette segment forms the eastern margin of the graben, and a down-to-the-east normal fault cutting Tertiary sedimentary and volcanic rocks forms the western margin. The valley of Flat Canyon, which is open to the south and terminates to the north at Chriss Canyon, occupies the eastern part of the graben. Felger (1991) interpreted the Flat Canyon graben as an extensional structure modified by diapiric collapse of the Jurassic Arapien Shale, which is present in the subsurface beneath Flat Canyon.

In the San Pitch Mountains, summit elevations are lower and the range front is less abrupt and steep than in the Wasatch Range to the north, suggesting lower rates of activity at the south end of the Wasatch fault. Wheeler and Krystinik (1988) noted that the general topographic relief is almost 2 km greater in the central part of the Wasatch Range than in the San Pitch Mountains. Some of this difference in relief may be the result of geologic factors, such as greater pre-Wasatch fault relief due to structural thickening associated with the Nebo-Charleston allochthon north of the San Pitch Mountains, and both pre- and post-Wasatch fault differential erosion. However, 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 is based on new geologic mapping and a compilation of previous geologic quadrangle mapping by Witkind and others (1987), Mattox (1987, 1992), Felger

(1991), Petersen (1997), and Weiss and others (2003) (figure 3). Because documentation of late Quaternary faulting was not the primary purpose of these geologic quadrangle maps, Hylland remapped the Quaternary deposits and fault scarps along the Fayette 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 valley-floor areas. 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 2004. In addition to new mapping of surficial geologic units along the fault zone, we extended our mapping to the west side of the Sevier River flood plain to encompass previously unmapped Lake Bonneville deposits, and some possible Quaternary faults.

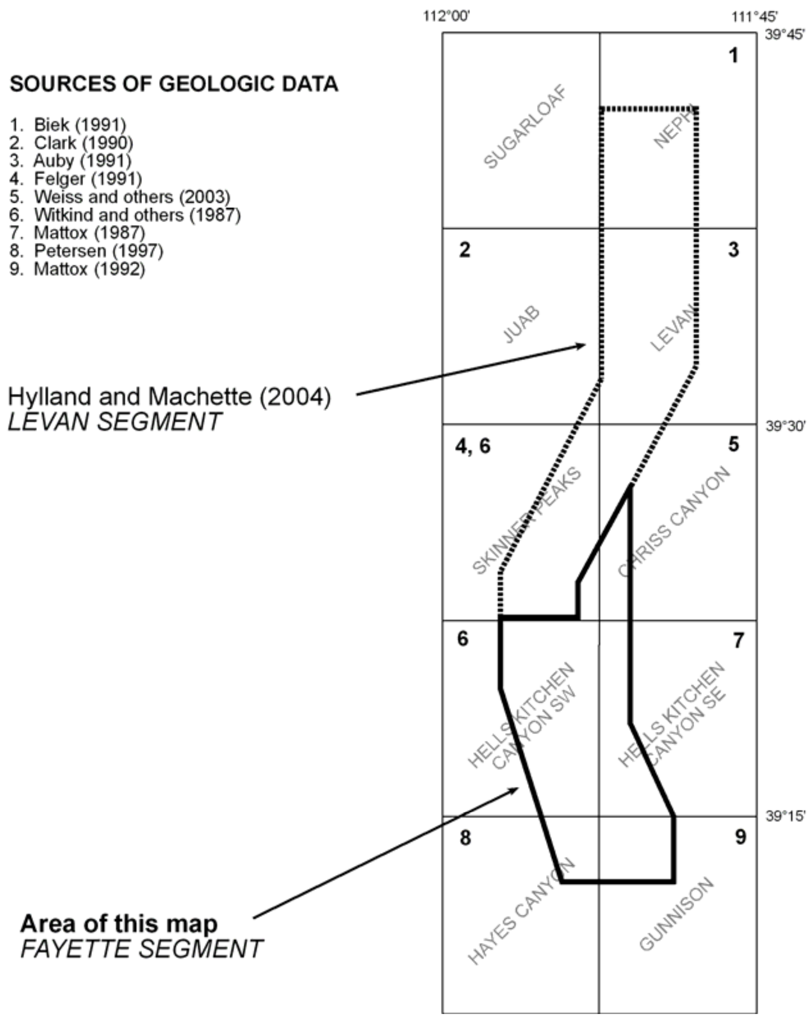

Figure 3. *Index of map coverage relative to USGS 7.5-minute quadrangles, and sources of geologic mapping used in compilation of this map.*

We differentiated Quaternary geologic units using standard relative-age criteria such as geomorphic expression, landform preservation, stratigraphic position, and soil development. For carbonate morphology in soils, we use the stage classification summarized in Machette (1985) and Birkeland and others (1991). The map-unit symbols used herein generally follow the conventions 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.

During his reconnaissance mapping in 1984, Machette measured 15 fault-scarp profiles along the Fayette segment using a stadia rod and Abney level. In 2004, Hylland and C.B. DuRoss (Utah Geological Survey) measured six additional scarp profiles along the segment using a laser range finder. Scarp heights, slope angles, and net vertical tectonic displacements were determined from computer plots of the scarp profiles, and we used these data to estimate single-event fault-scarp ages as described below under "Fault Scarp Age."

Results of Previous Paleoseismic Studies

Machette and others (1992a) concluded that morphometric scarp-profile data indicate that the most recent surface faulting on the Fayette segment occurred between 10 and 15 ka. Besides scarp-profile measurements, no other paleoseismic studies have been performed on the Fayette segment.

QUATERNARY DEPOSITS AND DEPOSITIONAL HISTORY

Relative uplift of the San Pitch and Valley Mountains since late Tertiary time has been accompanied by alluvial-fan deposition in northern Sevier Valley, and fan alluvium dominates Quaternary-age deposits along the Fayette segment. We divide the Quaternary fan alluvium along the Fayette 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). A fifth map unit, Quaternary-Tertiary alluvial-fan deposits (QTaf), consists of fan alluvium that may in part be as old as late Tertiary.

Along the range fronts, older fan alluvium (unit afo) is generally preserved in relatively small, isolated remnants whose surfaces are about 5-15 m above adjacent younger alluvial fans and modern stream channels. Relatively large and more continuous surfaces are preserved on a small structural block between the western and eastern strands of the Fayette segment. Soil carbonate development in the upper part of the alluvium ranges from continuous, thin to relatively thick coatings of secondary $CaCO_3$ on clasts (stage II) to a continuous horizon of completely cemented $CaCO_3$ having a weak platy structure (stage III+). Surfaces underlain by older fan alluvium are typically strewn with carbonate rubble derived from weathered pedogenic carbonate soil horizons. Comparison with soil carbonate morphology studied by Machette (1985a, 1985b) in the Beaver basin, about 110 km southwest of Fayette but in a similar climatic zone, indicates the older fan alluvium is probably late to middle Pleistocene in age. Intermediate-age fan alluvium (unit afi) underlies isolated surfaces that are as much as 5 m above adjacent younger alluvial fans and modern stream channels. West of the Sevier River, intermediate-age fan alluvium appears to have been deposited by streams graded to a transgressing Lake Bonneville (beginning around 32 ka elsewhere in the Bonneville basin) and its highest shoreline (16.8-18 ka). Thin, discontinuous to continuous $CaCO_3$ coatings are present on the undersides of clasts (stage I+) in deposits that probably range in age from latest Pleistocene to middle Holocene. Younger fan alluvium (unit afy) forms small, discrete alluvial fans where depositional processes are still active. Surface gradients of these younger 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 (unit afc) that fill the eastern part of Sevier Valley and Flat Canyon, 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. Locally, deposits of coalesced fan alluvium are probably at least as old as late Pleistocene.

Although we have correlated the various Quaternary alluvial-fan deposits of the Fayette segment with those of the Levan segment to the north, the actual ages of the fan surfaces likely differ between the two segments. Sediment in alluvial fans along the Levan segment is deposited by streams flowing into Juab Valley, which has no axial trunk stream. Also, with the exception of its extreme southern end, the valley was not inundated by Lake Bonneville. Base-level change for these streams, therefore, has been dominated by a slow rise associated with ongoing aggradation of valley fill, and fan incision and surface abandonment are governed by surface faulting and climatically controlled changes in stream flow. In contrast, sediment in alluvial fans along the Fayette segment is deposited by streams flowing into northern Sevier Valley, in which the Sevier River is the axial trunk stream. Furthermore, waters of Lake Bonneville filled the valley to a depth of at least 25 m. Therefore, in addition to the factors described above for the Levan segment, fan incision and surface abandonment along the Fayette segment have also been controlled by fluctuations in base level associated with changes in the longitudinal profile of the Sevier River and the presence or absence of Lake Bonneville.

Alluvial-fan deposits of Pleistocene to possibly Miocene age (unit QTaf) are preserved in several areas along and near the Fayette segment. We mapped Quaternary-Tertiary fan alluvium on the structural block between the overlapping northern end of the Fayette segment and southern end of the Levan segment, on the small structural block between the western and eastern strands of the Fayette segment, near the southern end of the Fayette segment, and at the foot of the Valley Mountains in the vicinity of Red Canyon. The surfaces of these deposits are as much as 150 m above the adjacent valley floor. About 1 km south of where the western strand of the Fayette segment splays off from the eastern strand, the surface of a small remnant of unit QTaf is tilted gently back to the east, toward the mountain front, presumably due to back-rotation of the hanging wall during fault movement on the eastern strand.

Along the base of the Valley Mountains south of Red Canyon, Quaternary-Tertiary basin fill deposits (unit QTb) underlie a relatively high-level, dissected, relatively planar surface. The deposits consist of weakly to strongly consolidated, typically gravelly sediment with clast composition that reflects nearby source areas in the Valley Mountains. Two parallel, north-trending normal faults cut these deposits and form a narrow horst, along which an electric transmission line right-of-way is located. A low cut along the service road in the NE1/4 section 16, T. 18 S., R. 1 W., Salt Lake Base Line and Meridian (SLBLM) exposes poorly indurated siltstone. The fault scarps on either side of the horst are fairly degraded, and no scarps are present on alluvium associated with antecedent steams that have eroded through the horst. The faulted deposits, which may correlate with the Axtell Formation (Spieker, 1949) and (or) Sevier River Formation (Callaghan, 1938; see also Anderson and Rowley, 1975), have previously been mapped as Quaternary pediment-mantle deposits (Witkind and others, 1987; Petersen, 1997).

Stream alluvium is present as channel deposits, as undifferentiated basin fill in interior valley-floor areas, and as flood-plain deposits along the modern Sevier River channel. Older stream alluvium (unit alo) along the Fayette segment typically forms terraces as much as 5 m above modern streams and has soils with stage I-II carbonate morphology; we interpret these deposits to be middle Holocene to late middle Pleistocene in age. Younger stream alluvium (unit aly) represents late Holocene deposition in the relatively larger modern stream channels. Minor, shallow drainages and basins contain stream alluvium mixed with a significant component of hillslope colluvium (unit ac). We map the valley-floor deposits in the interior part of Sevier Valley and western part of Flat Canyon, where alluvial fans are poorly developed or absent, as undifferentiated basin-fill alluvium (unit ab). Fine-grained, Holocene flood-plain alluvium of the Sevier River (unit alsr) is present in the middle of Sevier Valley. These deposits include reworked Lake Bonneville sediments as well as lacustrine silt and clay deposited during times when the valley floor is inundated by Sevier Bridge Reservoir.

Two aspects of the modern Sevier River channel and flood plain may have tectonic significance. First, the majority of abandoned channels and oxbow lakes lie west of the modern channel, indicating eastward channel migration during the Holocene. As noted by Keaton (1987), who observed a similar eastward migration of the Jordan River in Salt Lake Valley, this pattern could be the result either of migration away from the center of post-Lake Bonneville isostatic rebound (Crittenden, 1963), or tectonic subsidence associated with faulting, or both. Second, the modern flood plain narrows dramatically just south of the Red Canyon drainage. Here, the Sevier River cuts across the large Red Canyon alluvial fan (unit QTaf), isolating the toe of the fan on the east side of the river. The river must have followed a more eastern course, flowing around the toe of the fan, during the time when the fan was forming. Headward erosion by a distributary channel on the northern part of the alluvial fan during the early or middle Pleistocene, perhaps facilitated by normal faulting, apparently resulted in capture of the Sevier River, rerouting it through the alluvial-fan deposits.

A shallow arm of late Pleistocene Lake Bonneville occupied parts of southernmost Juab Valley and northern Sevier Valley during the Bonneville-level highstand, which culminated at about 16,800-18,000 cal yr B.P. (calendar-calibrated ages from D.R. Currey, University of Utah, written communication to Utah Geological

Survey, 1996). Assuming a valley-floor elevation at the onset of lacustrine sedimentation near the present mid-valley elevation, and using Currey's (1990) Lake Bonneville hydrograph, lake water was present in the map area for a period of about 3000 years leading up to the Bonneville flood at 16,800 cal yr B.P. A wave-cut shoreline bench at an elevation of about 1555 m (5100 ft) is present on the west side of the Painted Rocks, in the NW1/4 section 5, T. 17 S., R. 1 W., SLBLM. Lacustrine sediment is discontinuously exposed below this elevation along the margins of the Sevier River flood plain, and consists mostly of laminated to thin-bedded clay, silt, and fine sand (unit lbf). Some sand beds exhibit festoon cross-bedding. In the Hells Kitchen Canyon SE quadrangle, these deposits have been interpreted as an underflow fan, deposited mostly subaqueously by the cold, turbid water of tributary streams that flowed along the lake bottom as density currents (C.G. Oviatt, Kansas State University, 1984, personal communication cited in Mattox, 1987). Locally, the uppermost beds of the fine-grained deposits include thin beds of pebble gravel (unit lbfg), probably deposited in a shoreline environment by tributary streams flowing into the lake during its highstand. Elsewhere, the uppermost lacustrine sediments locally consist of well-sorted fine sand (unit lbs) that probably represents low-energy beach deposits.

Small, scattered deposits of mostly Holocene-age, well-sorted, fine-grained eolian sand (unit es) are present along the southern end of the Fayette segment. The sand probably consists largely of reworked Lake Bonneville sediment (Mattox, 1992). Some of these deposits form small dunes. Small dunes are also present to the west of the Painted Rocks, but here the dune sand is locally reworked lacustrine beach sand (unit lbs) and is not mapped as a separate unit.

Colluvial and mass-movement deposits along the Fayette segment include older landslide deposits (unit clso), younger landslide deposits (unit clsy), hillslope and fault-scarp colluvium (units chs and cfs, respectively), and deposits of mixed colluvium and alluvium (unit ca). The younger landslide deposits are Holocene in age, whereas the older landslide deposits may be as old as middle Pleistocene. However, the relative ages of landslide deposits are poorly constrained and are based primarily on their geomorphic expression. Thin, discontinuous deposits of hillslope colluvium of Holocene to possibly late Pleistocene age generally overlie bedrock throughout the map area. However, we mapped only deposits that are continuous over a relatively large area, and where relatively significant (thick or large) accumulations also include an alluvial component (unit ca). We mapped fault-scarp colluvium along large (>20 m high) scarps, primarily at the northern end of the western splay, where the colluvium forms a wedge up to about 2 m thick on the downdropped side of the fault.

QUATERNARY FAULTING

Quaternary fault scarps are concentrated on the southern half of the Fayette segment. The scarps are mostly on unconsolidated fan and stream alluvium, but locally are on bedrock. Lithologic characteristics of the faulted alluvium can generally be characterized as pebble gravel with scattered cobbles and boulders in a matrix of sand, silt, and clay. The scarps have relatively low maximum scarp angles (≤24º), and are in the wash-controlled stage of development of Wallace (1977).

In the discussion that follows, we give a general description of faulting along the Fayette segment, present morphometric data relative to the age of faulting, and address the issue of late Quaternary fault slip rates. Terminology used to describe fault-scarp morphology (figure 4) 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, and (3) comparison of scarp-height – slope-angle relationships with empirical regression lines for scarps of known age. The scarp-profile data are presented in table 1 and figure 5.

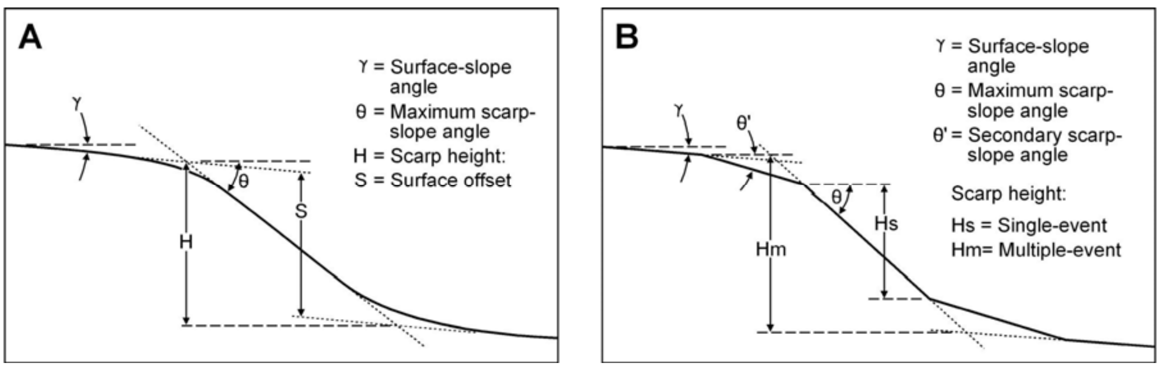

Figure 4. *Schematic diagrams illustrating fault-scarp nomenclature used in this report. A. Single-event scarp (modified from Bucknam and Anderson, 1979). B. Multiple-event scarp (modified from Machette, 1982).*

General Description of Fault Scarps

Late Quaternary fault scarps are relatively continuous along the southern half of the Fayette segment, south of Hells Kitchen Canyon, but we observed no fault scarps on Quaternary deposits along the range front north of Hells Kitchen Canyon. However, Machette and others (1992a) suspected that the range front in this area is fault controlled. Also, at the north end of Flat Canyon, Weiss and others (2003) mapped Quaternary-Tertiary fan alluvium faulted down-to-the-west against Tertiary sedimentary strata. We believe Quaternary faulting has occurred along the northern half of the Fayette segment, but not in late Quaternary time. South of Hells Kitchen Canyon, late Quaternary fault scarps comprise two strands. The western strand begins about 1 km south of Hells Kitchen Canyon and extends southward approximately 6 km, crossing Utah Highway 28 near its southern end. The eastern strand begins approximately 4 km south of Hells Kitchen Canyon and extends along the base of the San Pitch Mountains to the town of Fayette.

Table 1. *Fayette segment fault-scarp profile data. Profiles 85 to 92 are on the western strand of the fault, and profiles 93 to 99 are on the eastern strand.*

Scarp Profile[1]	Scarp Height (m)	Surface Offset[2] (m)	NVTD[3] (m)	Scarp Angle (θ)[4] (º)	Surface Slope Angle (γ) (º)	Comments
m85	-	-	-	-	-	Composite scarp on unit afo, unable to determine footwall γ
m86	2.1	0.9	0.9	16	8 (±1)	-
m87	2.6	1.6	1.6	24	8 (±1)	-
F87.1[5]	19.5	14	14	-	-	Composite scarp on unit afo, unable to determine footwall γ
m88L	1.1	0.6	0.6	17	7 (±1)	Doublet lower scarp
m88U	0.8	0.4	0.4	15	7 (±1)	Doublet upper scarp
m89	-	-	-	-	-	Composite scarp on unit QTaf, unable to determine γ
F89.1	2.0	1.6	1.6	7	2 (±1)	Scarp likely degraded by livestock
F89.2	1.5	1.0	1.0	8	3 (±1)	Scarp likely degraded by livestock
m90	1.9	1.2	0.8	24	9 (±2)	-
m91	2.3	1.4	1.3	20	5 (±1)	-
m92	1.8	1.4	1.1	17	3 (±1)	-
m93	-	-	-	-	-	Composite scarp on unit afo, unable to determine footwall γ
F93	4.9	2.8	2.8	-	-	Composite scarp on unit afo
m94	4.3	2.7	2.7	-	-	Composite scarp on unit afo
m95	2.4	1.0	1.0	11	6 (±1)	Uncertain location
F95	2.9	1.7	1.3	15	5 (±1)	-
F95.1	1.8	1.1	1.1	10	5 (±1)	-
m96	1.3	1.0	0.8	10	2 (±1)	-
m97	2.5	1.8	1.2	7	2 (±1)	-
m98	-	-	-	-	-	Unable to determine footwall γ
m99[5]	5.6	3.2	3.2	-	-	Composite scarp on unit afo

[1] Profiles designated as "m" measured by M.N. Machette (USGS), June 1984; profiles designated as "F" measured by M.D. Hylland and C.B. DuRoss (UGS), September 2004.
[2] Uncertainty is probably ±0.2 m.
[3] Net vertical tectonic displacement (= surface offset except where graben-forming antithetic fault is present).
[4] Uncertainty is probably ±1º.
[5] Scarp height, surface offset, and NVTD values are minima owing to post-faulting alluvial-fan deposition at base of scarp.

Fault scarps on the Fayette segment include low (probably single-event) scarps (table 1) cutting intermediate-age fan surfaces and stream terraces that range in age from latest Pleistocene to possibly middle Holocene. Geomorphically, these scarps appear to be older and more weathered than comparable scarps on the Levan segment, and post-faulting alluvial-fan deposits on the hanging wall partially bury the scarps in places. Measured scarp height ranges from 1.3 to 2.9 m, and net vertical tectonic displacement (NVTD) ranges from 0.8 to 1.6 m. Despite similar maximum scarp heights and NVTD on the eastern and western strands of the Fayette segment, maximum scarp-slope angles are generally lower on the eastern strand than on the western strand. Discounting two anomalously low scarp-slope angles on the western strand (scarps likely modified by livestock grazing), maximum scarp-slope angles on the western strand range from 15º to 24º, compared to a range of 7º to 15º on the eastern strand (table 1). Some fault scarps on the Fayette segment are high, multiple-event scarps on older (middle Pleistocene and older) alluvial-fan surfaces. Measured height of these scarps generally ranges from 4.3 to 5.6 m, and NVTD generally ranges from 2.7 to 3.2 m. However, the scarp at the northern end of the western strand locally reaches a height of 20 m, and its NVTD is at least 14 m. The actual NVTD is more, because the hanging wall has been buried to an unknown (but probably relatively shallow) depth by the southern margin of the Hells Kitchen Canyon alluvial fan.

Fault Scarp Age

Numerical ages are lacking for Quaternary deposits along the Fayette segment, so cross-cutting relationships provide only qualitative constraints on the timing of surface faulting. Along both strands of the fault, intermediate-age fan alluvium (unit afi) and older stream alluvium (unit alo) are extensively faulted, but younger fan alluvium (unit afy) is not. Also, Lake Bonneville deposits at the south end of the western trace appear to be faulted, although the suspect scarp is subtle. These relations indicate a post-Bonneville-highstand (<16.8 ka) time for the most recent surface-faulting event (MRE) on the Fayette segment.

Figure 5 shows our scarp profile data (scarp height and maximum scarp-slope angle) for both the Fayette and Levan segments, 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 and erosional Bonneville shoreline scarps. The late Holocene Fish Springs scarps are known from radiocarbon dating to have formed sometime after 2,280±70 ^{14}C yr B.P., perhaps about 2000 years ago (Bucknam and others, 1989); the early Holocene Drum Mountains scarps (Crone, 1983) are estimated from scarp diffusion modeling to be about 9000 years old (Pierce and Colman, 1986); and the latest Pleistocene Bonneville shoreline scarps are about 16,800 years old (calendar-calibrated age from D.R. Currey, University of Utah, written communication to Utah Geological Survey, 1996). In general, scarp-height – slope-angle data for single-event scarps on the western trace of the Fayette segment plot between the Fish Springs and Drum Mountains regression lines, and data for single-event scarps on the eastern trace plot closer to the Bonneville regression line, suggesting the western-trace scarps are considerably younger than the eastern-trace scarps. The two western-trace data points that plot below the Bonneville regression line represent scarps that likely have been modified by livestock grazing, and thus have greatly diminished maximum scarp-slope angles. Discounting these two data points, the scarp profile data indicate a Holocene MRE on the western strand and a latest Pleistocene MRE on the eastern strand.

Although Fayette-segment data points on figure 5 overlap with Levan-segment data points, several lines of evidence point to an older MRE on the Fayette segment than on the Levan segment. First, much of the Levan-segment scarp-profile data plots older than it should based on the 1 ka age of the scarp, probably due to differences in lithology, microclimate, or other fault-degradation factors that may exist between the Levan and Fish Springs scarps (Hylland and Machette, 2004). Second, differences in geomorphic

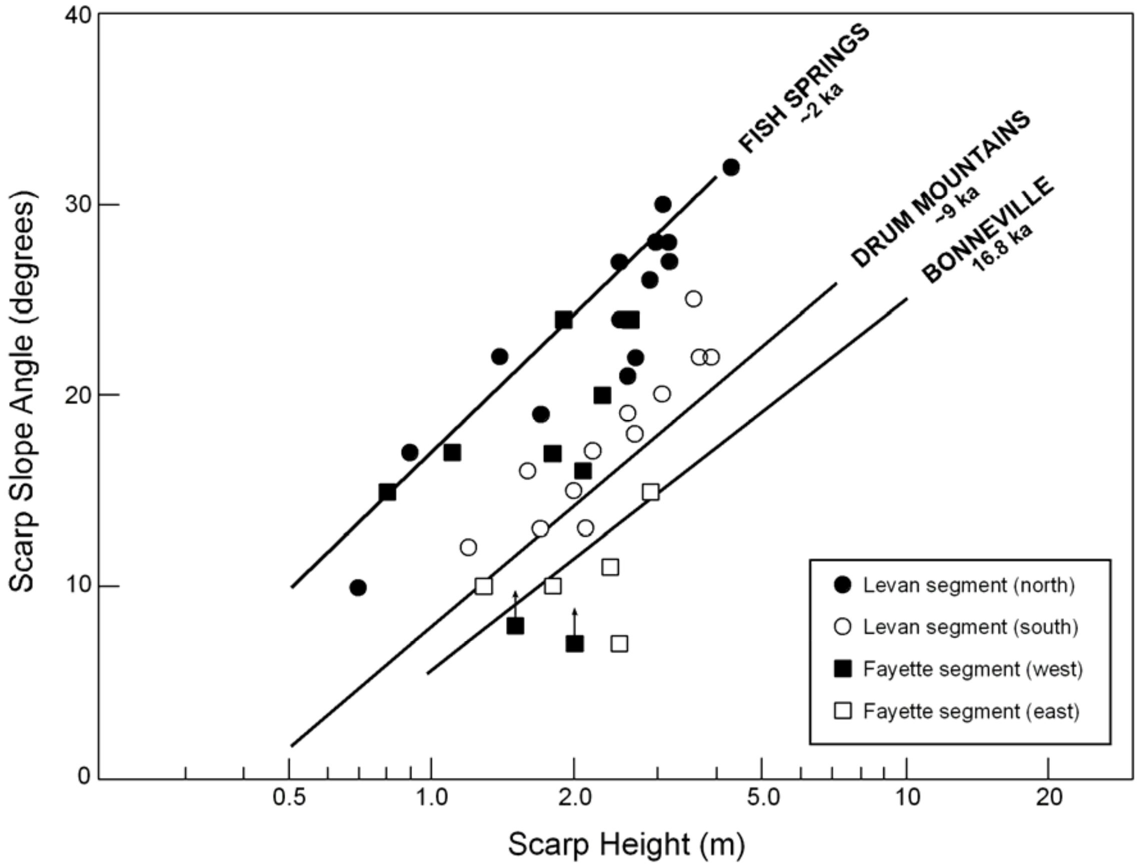

Figure 5. *Scarp-profile data for the Fayette and Levan segments. Also shown are best-fit empirical regression lines of Bucknam and Anderson (1979) for the Fish Springs and Drum Mountains fault scarps and Bonneville shoreline scarp. Data are omitted for scarps interpreted to likely be the result of multiple faulting events. Arrows indicate that scarp-slope angle may be greatly diminished by livestock. Fayette segment scarp-profile data are listed in table 1.*

appearance of the scarps, as well as the degree to which the scarps are partially buried by post-faulting alluvial-fan deposits, indicates the Fayette-segment scarps are older than the Levan-segment scarps. Third, unlike the Levan segment to the north, late Holocene alluvial fans along the Fayette segment are unfaulted. Although this could at least in part reflect a difference in fan-surface age between alluvial fans in Juab and northern Sevier Valleys due to nontectonic factors that have influenced fan development, it is consistent with the other evidence for a difference in the age of surface faulting.

The large scarps on the Fayette segment south of Hells Kitchen Canyon provide evidence for recurrent surface faulting during the late Quaternary. In the absence of paleoseismic trench data and numerical age constraints on fan surfaces, Holocene faulting cannot be precluded, particularly on the western strand.

Segment Boundaries

The Fayette segment was not identified as a segment of its own under the earliest segmentation models of the Wasatch fault zone. Schwartz and Coppersmith (1984) originally defined the Levan segment as extending 40 km from east of Levan southward to near Gunnison, thereby including the length of fault now known as the Fayette segment. Based on recency of faulting and fault geometry, Machette and others (1986, 1987) divided the original Levan segment into the Levan segment (restricted sense) and the Fayette segment to the south.

The northern segment boundary of the Fayette segment is a rather complex zone of overlap, about 10 km long and 4 km wide, between the Fayette and Levan segments. As described above under "General Description of Fault Scarps," we observed no scarps on Quaternary deposits along the range front of the San Pitch Mountains north of Hells Kitchen Canyon, but the range front in this area is likely fault controlled. At the north end of Flat Canyon, fault juxtaposition of Quaternary-Tertiary fan alluvium (unit QTaf) against Tertiary sedimentary strata indicates Quaternary fault movement. This fault terminates in Tertiary bedrock about 1.5 km north of Chriss Creek, and we interpret this to be the northern end of the Fayette segment. As such, Quaternary surface faulting has occurred on the northern half of the Fayette segment, but not in late Quaternary time.

Felger (1991) and Weiss and others (2003) mapped a concealed fault in northwest-trending Chriss Canyon that juxtaposes Quaternary-Tertiary alluvial-fan deposits in the downthrown southern block against Tertiary sedimentary strata in the upthrown northern block. Weiss and others (2003) interpreted this fault as an oblique connecting structure between the Levan and Fayette segments. Like the northern part of the Fayette segment, there are no scarps on Quaternary deposits along this fault; however, if the fault trace is along the floor of the narrow canyon, any scarp formed there would be quickly obliterated by stream flow and sediment deposition. We believe that this concealed fault, together with the northern end of the Fayette segment, was active in early or possibly middle Pleistocene time, but likely has been inactive since then. Given the presence of many northwest-trending normal faults in this part of the western San Pitch Mountains (Mattox, 1987; Weiss and others, 2003), it seems reasonable that this fault took advantage of a pre-existing Tertiary structure.

North- and north-northeast-trending fault scarps and lineaments on Quaternary-Tertiary alluvial-fan deposits (unit QTaf) and undifferentiated Quaternary basin fill (unit ab) are present at the southern end of the 4-km-wide area between the overlapping Fayette and Levan segments. These structures appear to accommodate a left-stepping transfer of displacement between the two segments. Although deposit ages in this area are poorly constrained, scarp morphology indicates an absence of Holocene movement on these faults. However, these scarps likely formed during surface faulting that was more recent than the surface faulting on the northern end of the Fayette segment.

At the southern end of the Fayette segment, fault scarps on late Quaternary deposits end east of the town of Fayette, near the Fayette Cemetery. We observed no evidence of Quaternary faulting on trend with the segment south of the town of Fayette. Cline and Bartley (2002) have proposed that fault displacement at the southern end of the Wasatch fault is transferred across the Sevier-Sanpete anticline (a north-northeast-trending fold beneath the Sevier and Sanpete Valleys, formed during the Sevier orogeny) to the Salina detachment, a low-angle, "rolling hinge"-style normal fault localized in the weak, evaporitic Arapien Shale.

Late Quaternary Slip Rates

Accurate determination of late Quaternary slip rates for the Fayette segment is presently not possible because the timing of surface-faulting paleoearthquakes is unknown. However, we can use NVTD and the estimated age of older (late to middle Pleistocene) fan alluvium to estimate a long-term geologic vertical slip rate, providing at the very least an order-of-magnitude slip rate for the Fayette segment. We estimate the age of the older fan alluvium (unit afo) from the secondary $CaCO_3$ morphology of its soil (stage II-III+) and comparison with soil data from the Beaver basin (Machette, 1985a, 1985b). From this comparison, we believe the older fan alluvium is probably no younger than about 100 ka and no older than about 250 ka. Dividing NVTD of 2.7-3.2 m by ages of 100 and 250 ka gives a range in estimated long-term vertical slip rate of about 0.01-0.03 mm/yr near the middle of the eastern strand (table 2). Using the minimum NVTD of 14 m calculated for the large scarp at the north end of the western strand gives an estimated minimum long-term geologic vertical slip rate of about 0.06-0.1 mm/yr. The higher slip rate on this part of the fault, near both the zone of overlap between the Fayette and Levan segments and the bifurcation of the two strands of the Fayette segment, may be the result of spillover of Levan-segment ruptures onto the Fayette segment, or additive slip from separate eastern- and western-strand ruptures that overlap on this part of the fault, or some combination of these two conditions. Additionally, the higher slip rate may reflect a component of localized diapirism or dissolution-induced subsidence associated with subsurface evaporite beds in the Arapien Shale.

Table 2. *Estimated long-term geologic vertical slip rates for the Fayette segment of the Wasatch fault zone, based on net vertical tectonic displacement (NVTD) calculated from profiles measured across multiple-event scarps on older alluvial-fan deposits (unit afo).*

Site	NVTD	Deposit Age	Slip Rate (mm/yr)	Comments
Hells Kitchen Canyon, profile F87.1	$\geq$14 m	100-250 ka	0.14-0.056	Hanging-wall surface younger than footwall surface; minimum NVTD and slip rate
Rough Canyon, profile F93	2.8 m	100-250 ka	0.028-0.011	Correlative surfaces across fault
Axhandle Canyon, profile m94	2.7 m	100-250 ka	0.027-0.011	Correlative surfaces across fault
Mellor Canyon, profile m99	$\geq$3.2 m	100-250 ka	0.032-0.013	Hanging-wall surface younger than footwall surface; minimum NVTD and slip rate

ISSUES FOR ADDITIONAL STUDY

Additional detailed studies of the Fayette and Levan segments could provide much-needed information regarding paleoearthquake timing and amount of displacement, data critical to meaningful estimates of recurrence intervals and slip rates, as well as insight into partial- and multi-segment fault rupture models presently being considered for various parts of the Wasatch fault. Both of these segments appear to have had no more than two post-Lake Bonneville surface-faulting earthquakes. Presently, only the timing of the MRE on the Levan segment is constrained by numerical ages. If the timing of the MRE on the Fayette segment and penultimate events (PE) on both segments could be determined, resolution of the late Pleistocene and Holocene paleoearthquake chronologies should be relatively straightforward. Paleoseismic trenching studies on the Levan and Fayette segments could address the following questions:

- Is the timing of the MRE on the eastern and western strands of the Fayette segment actually different, as the scarp-profile data indicate?
- When did the PE on the Fayette segment occur, and is the timing the same on both the eastern and western strands?
- When did the PE on the Levan segment occur? Does PE timing differ between the southern and northern ends of the segment?
- How does paleoearthquake timing on the southern end of the Levan segment compare with that on the Fayette segment (i.e., is there evidence for spillover of fault rupture onto the adjacent segment)?

SUMMARY AND CONCLUSIONS

The Fayette segment of the Wasatch fault zone extends from 1.5 km north of Chriss Canyon in southern Juab County southward about 24 km to the town of Fayette in Sanpete County. The northern segment boundary of the Fayette segment is a rather complex, 10-km-long and 4-km-wide area of overlap between the Fayette and Levan segments. At the northern end of the area of overlap, a concealed, northwest-trending, down-to-the-south normal fault coincident with Chriss Canyon is an oblique connecting structure between the Fayette and Levan segments, and was active in early or possibly middle Pleistocene time but likely has been inactive since then. North- and north-northeast-trending fault scarps and lineaments are present at the southern end of the area of overlap. These structures appear to accommodate a left-stepping transfer of displacement between the two segments. The southern segment boundary of the Fayette segment is marked by the southward termination of late Quaternary fault scarps east of the town of Fayette.

We observed no fault scarps on Quaternary deposits along the range front north of Hells Kitchen Canyon. Based on fault juxtaposition of Quaternary-Tertiary fan alluvium against Tertiary bedrock near the northern end of the segment, we believe Quaternary faulting has occurred on the northern half of the Fayette segment, but not in late Quaternary time. South of Hells Kitchen Canyon, late Quaternary fault scarps comprise two strands. The western strand of the Fayette segment begins about 1 km south of Hells Kitchen Canyon and extends southward approximately 6 km. The eastern strand begins about 4 km south of Hells Kitchen Canyon and extends along the base of the San Pitch Mountains to the town of Fayette.

Fault scarps on the Fayette segment include low (probably single-event) scarps on intermediate-age fan surfaces and stream terraces that range in age from latest Pleistocene to possibly middle Holocene, and high, multiple-event scarps on older (late Pleistocene and older) alluvial-fan surfaces. Along both the western and eastern strands of the fault, intermediate-age fan alluvium and older stream alluvium are faulted, but younger fan alluvium is not. Also, Lake Bonneville deposits at the south end of the western trace appear to be faulted. These relations indicate a post-Bonneville-highstand time for the most recent surface-faulting event (MRE) on the Fayette segment. Morphometric scarp data indicate that the MRE on the western strand is younger (possibly Holocene) than the MRE on the eastern strand (possibly latest Pleistocene).

The timing of surface-faulting paleoearthquakes on the Fayette segment is unknown, so late Quaternary slip rates cannot be accurately determined. Estimated long-term geologic vertical slip rate, determined from net vertical tectonic displacement and estimated age of older (late to middle Pleistocene) fan alluvium, is about 0.01-0.03 mm/yr near the middle of the eastern strand. Using minimum NVTD calculated for the large scarp at the north end of the western strand gives an estimated minimum long-term vertical slip rate of about 0.06-0.1 mm/yr. The higher slip rate on this part of the fault may be result from spillover of Levan-segment ruptures onto the Fayette segment, or additive slip from separate eastern- and western-strand Fayette-segment ruptures that overlap on this part of the fault, or some combination of these two conditions. Additionally, the higher slip rate may reflect a component of localized diapirism or dissolution-induced subsidence associated with subsurface evaporite beds in the Arapien Shale.

Paleoseismic trenching studies on the Fayette and Levan segments could provide data to constrain the timing of the MRE on the Fayette segment as well as the penultimate events on both segments. Additionally, strategically located trenches could provide data that would likely provide insights into partial- and multi-segment fault rupture models.

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APPENDIX

Description of Map Units

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

[Some units that are listed herein are present along the Levan segment (Hylland and Machette, 2004), but may not be present on this map.]

Quaternary Deposits

Stream Alluvium

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

alsr **Alluvium of Sevier River flood plain (Holocene)** – Mostly clay with silt and fine sand; comprises a mixture of fine-grained fluvial sediment and lacustrine deposits of the Bonneville highstand that were subsequently reworked by lateral channel migration. Episodic lacustrine deposition occurs below elevation 5014 ft when impounded water of Sevier Bridge Reservoir is present. Thickness unknown.

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 small alluvial fans, debris-flow deposits, and minor locally derived colluvium along steep stream embankments. Deposits generally form terraces less than 20 m above modern streams and have soils with stage I-II carbonate morphology; in the area of Old Pinery Canyon and Gardners Fork, deposits are incised as much as 40 m and have soils with stage II-III carbonate morphology. Exposed thickness about 2-40 m.

ab **Undifferentiated basin-fill alluvium (Holocene and Pleistocene)** – Variable mixtures of gravel, sand, silt, and clay; clasts well rounded to subangular; generally stratified. Deposited by intermittent streams in the southern Juab Valley and northern Sevier Valley where alluvial fans are poorly developed or absent. Highly variable clast composition and gradation, soil development, and thickness.

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, but generally <5 m.

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 original bar and swale topography. Local pedogenic soils have weak stage I carbonate morphology. Exposed thickness <5 m.

afc **Coalesced fan alluvium (upper Holocene to upper? Pleistocene)** – Pebble and cobble gravel, locally bouldery, in a matrix of sand, silt, and minor clay; clasts subangular to well rounded. Overall, deposits become finer grained away from valley margins. Deposited by perennial and intermittent streams, debris flows, and debris floods graded to or slightly above modern stream level; locally includes a significant component of eolian silt. Deposits form large, low-gradient fans that cover much of the floor of Flat Canyon and the eastern part of Sevier Valley. Includes local areas of active fan deposition (unit afy) too small to map separately. Thickness variable; maximum thickness unknown.

afi **Intermediate-age fan alluvium (middle Holocene to upper Pleistocene)** – 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; locally buried by younger fan alluvium (unit afy). West of the Sevier River, unit afi appears to be graded approximately to the upper surface of lacustrine deposits of the Bonneville highstand. Pedogenic soils have stage I-II 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 generally lack fan morphology. Deposits west of the Sevier River are locally overlain by, and therefore predate, lacustrine deposits of the Bonneville highstand. Pedogenic soils have stage II-III+ carbonate morphology. Locally includes exposures of unit QTaf too small to map separately. Exposed thickness <20 m.

Lacustrine Deposits

lbf **Fine-grained lacustrine deposits (upper Pleistocene)** – Lake-bottom clay with interbedded silt and fine sand; thin to thick bedded; contains small conispiral gastropod shells and bivalve shells as much as 5 cm across. Deposited during the Bonneville lake-cycle highstand. Ground surface locally displays polygonal pattern of shrinkage cracks, indicating expansive clay. Near the wave-cut Bonneville shoreline on the west side of the Painted Rocks, unit lbf locally contains abundant, angular gravel and cobbles of tuff eroded from the adjacent rock slope. Exposed thickness as much as 25 m.

lbfg **Fine-grained lacustrine deposits with gravel (upper Pleistocene)** – Lake-bottom and marginal clay with interbedded silt and fine sand, and thin beds of fine to medium-grained gravel in the upper part of the unit; clasts are subangular to rounded. Gravel probably deposited locally by tributary streams in a shoreline environment during lake-level oscillations associated with the Bonneville lake-cycle highstand.

lbs **Lacustrine sand (upper Pleistocene)** – Well-sorted fine sand; massive; unconsolidated. Generally forms a thin cap on fine-grained lacustrine deposits (unit lbf), and was probably deposited in a beach environment during the Bonneville lake-cycle highstand. Locally reworked by wind into small dunes now stabilized by vegetation. Exposed thickness about 2 m.

Eolian Deposits

es **Eolian sand (Holocene to uppermost Pleistocene)** – Well-sorted fine-grained sand; structureless and unconsolidated. Exposed thickness <3 m.

Colluvial and Mass-Movement Deposits

cd **Debris-flow deposits (upper Holocene)** – Primarily matrix-supported pebble and cobble gravel, locally bouldery; clasts angular; matrix consists of sand, silt, and clay; includes lesser beds of clast-supported (alluvial) gravel. Commonly have relatively fresh-appearing levees and channels. Generally 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.

chs **Hillslope colluvium (Holocene to upper Pleistocene)** – Pebble, cobble, and boulder gravel in a matrix of sand, silt, and clay; unsorted and poorly stratified. Deposited by slope-wash and mass-wasting processes on relatively steep slopes. Exposed thickness <5 m.

cfs **Fault-scarp colluvium (Holocene to upper Pleistocene)** – Gravel, cobbles, sand, and minor silt and clay; unsorted to poorly sorted. Present along most fault scarps, but mapped only on the lower part of large (>20 m high) scarps where the colluvium has accumulated in a wedge to a thickness of about 2 m on the downdropped side of the fault.

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 (about 35°). Exposed thickness <5 m.

clsy **Younger landslide deposits (Holocene)** – Unsorted, unstratified material that has moved downslope by rotational or translational gravity-induced slip. Relatively fresh main scarps and hummocky topography indicate young deposit age. Thickness highly variable.

clso **Older landslide deposits (Pleistocene)** – Unsorted, unstratified material that has moved downslope by rotational or translational gravity-induced slip. Main scarps and landslide surfaces are dissected and landslide morphology is subdued, suggesting relatively old deposit age. May include younger 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

fd **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 are shown.

Quaternary-Tertiary Deposits

QTaf **Quaternary-Tertiary alluvial-fan deposits (Pleistocene to Miocene?)** – Unconsolidated to semiconsolidated, poorly sorted fan alluvium generally preserved in high, isolated remnants; clasts include quartzite, sandstone, limestone, and volcanic rocks. Fan surfaces locally strewn with carbonate rubble weathered from soil horizon. Deposits at the northern end of the Levan segment previously mapped as Salt Creek Fanglomerate by Auby (1991) and Biek (1991); as much as 150 m thick; possibly as old as Pliocene. Deposits in the vicinity of the Fayette segment previously mapped as "rubble" by Witkind and others (1987) and as "older alluvial fans" by Felger (1991); as much as 90 m thick; possibly as old as Miocene.

QTb **Quaternary-Tertiary basin-fill deposits (lower Pleistocene to Miocene?)** – Unconsolidated to consolidated deposits of silt, sand, pebbles, cobbles, and boulders; poorly to relatively well stratified. Deposits underlie a relatively planar, gently sloping surface along the eastern base of the Valley Mountains. Previously mapped as Quaternary alluvial pediment-mantle deposits in the Hayes Canyon quadrangle by Petersen (1997). Possibly correlative to deposits mapped as Axtell Formation by Spieker (1949) and (or) Sevier River Formation by Callaghan (1938). Thickness unknown.

Bedrock

Bedrock units are not shown in detail on the map. For more information on the bedrock geology of the area, consult the geologic quadrangle maps listed in Sources of Geologic Data (figure 3 in the report). Bedrock areas may include thin, 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 to Upper Cretaceous)** – Includes the following bedrock formations: Eocene Crazy Hollow Formation (cherty sandstone), Eocene Green River Formation (limestone, sandstone, and mudstone), Eocene Colton Formation (mudstone, limestone, and sandstone), Eocene-Paleocene Flagstaff Limestone (limestone and sandstone), and Paleocene-Upper Cretaceous North Horn Formation (conglomerate and sandstone).

Mz **Mesozoic sedimentary rocks (Upper Cretaceous and Middle Jurassic)** – Conglomerate and pebbly sandstone of the Upper Cretaceous Indianola Group, and shaly limestone, sandstone, siltstone, mudstone, and gypsum of the Middle Jurassic Arapien Shale.

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

by

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and
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2005

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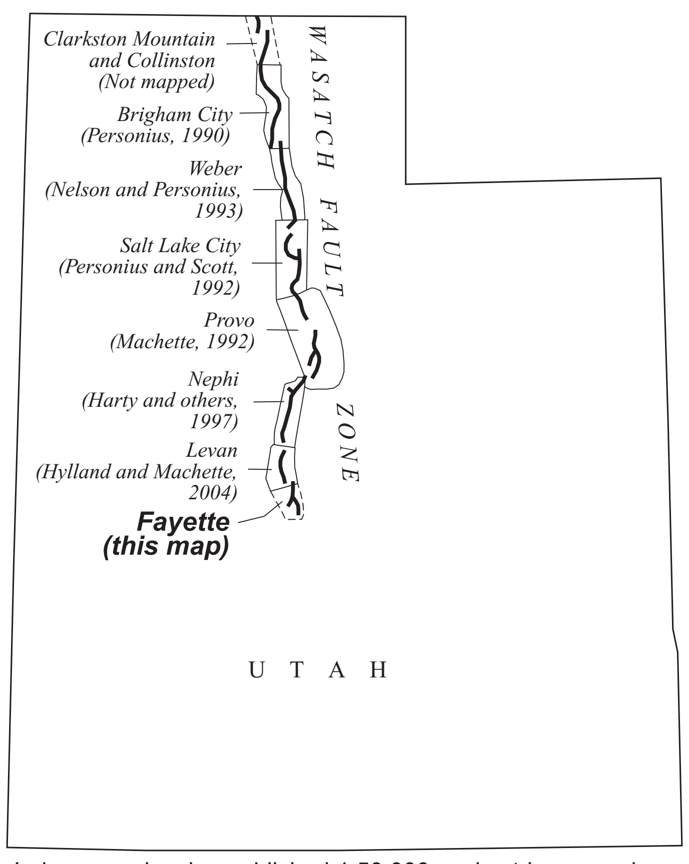
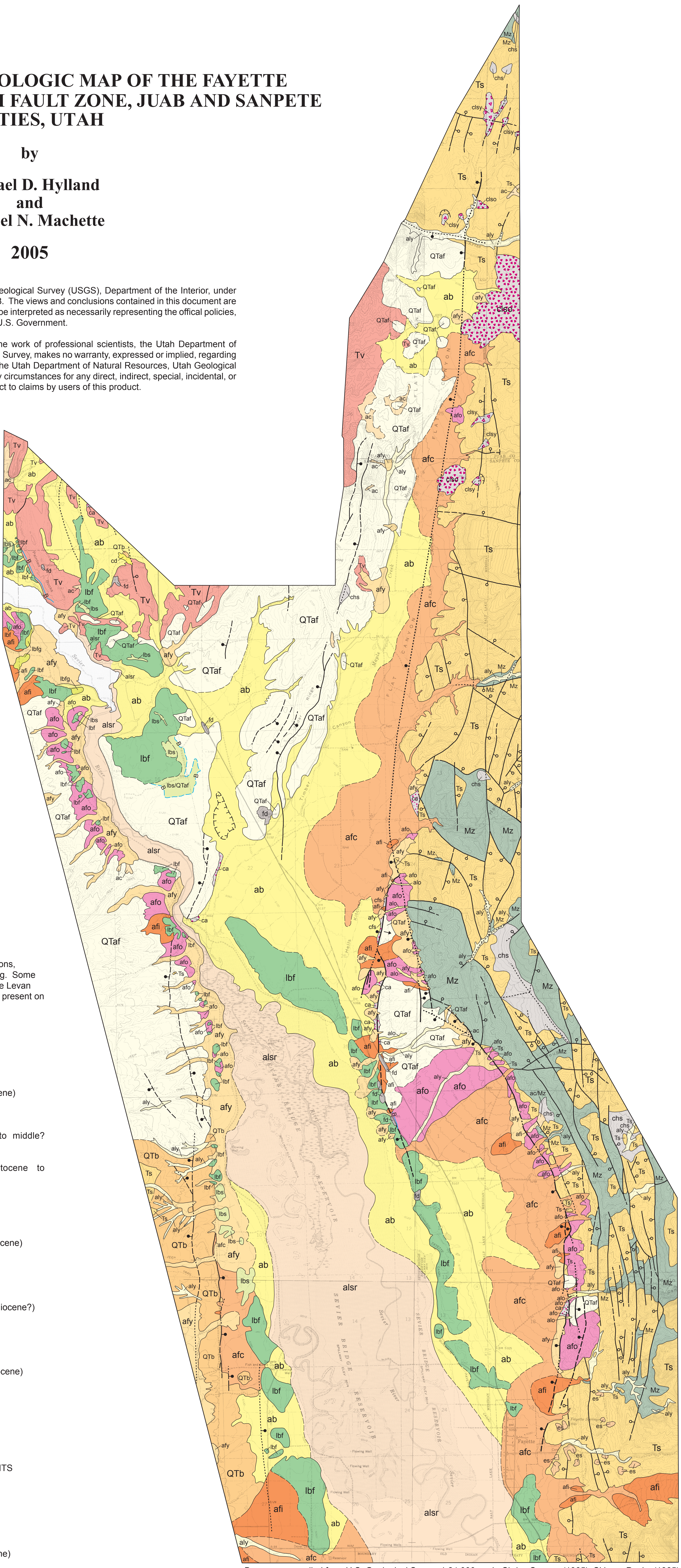
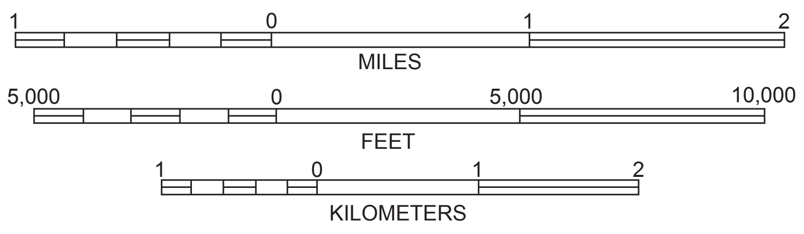


Index map showing published 1:50,000-scale strip maps along the Wasatch fault zone.



Base map compiled from U.S. Geological Survey 1:24,000-scale Chriss Canyon (1965), Skinner Peaks (1965), Hells Kitchen Canyon SW (1965), Hells Kitchen Canyon SE (1965), Hayes Canyon (1966), and Gunnison (1966) 7-1/2' quadrangles.



SCALE 1:50,000

DESCRIPTION OF MAP UNITS

(See text booklet appendix for detailed descriptions, and figure 3 for sources of compiled geologic mapping. Some units and symbols listed herein are present along the Levan segment (Hylland and Machette, 2004), but may not be present on this map)

STREAM ALLUVIUM

- aly — Younger stream alluvium (upper Holocene)
- alsr — Alluvium of Sevier River flood plain (Holocene)
- alo — Older stream alluvium (lower Holocene to middle Pleistocene)
- ac — Alluvium and colluvium, undivided (Holocene)
- ab — Undifferentiated basin-fill alluvium (upper Holocene to middle? Pleistocene)
- QTb — Quaternary-Tertiary basin-fill deposits (lower Pleistocene to Miocene?)

FAN 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 — Quaternary-Tertiary alluvial-fan deposits (Pleistocene to Miocene?)

LACUSTRINE DEPOSITS

- lbf — Fine-grained lacustrine deposits (upper Pleistocene)
- lbfg — Fine-grained lacustrine deposits with gravel (upper Pleistocene)
- lbs — Lacustrine sand (upper Pleistocene)

EOLIAN DEPOSITS

- es — Eolian sand (Holocene to uppermost Pleistocene)

COLLUVIAL AND MASS-MOVEMENT DEPOSITS

- cd — Debris-flow deposits (upper Holocene)
- chs — Hillslope colluvium (Holocene to upper Pleistocene)
- cfs — Fault-scarp colluvium (Holocene to upper Pleistocene)
- 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

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

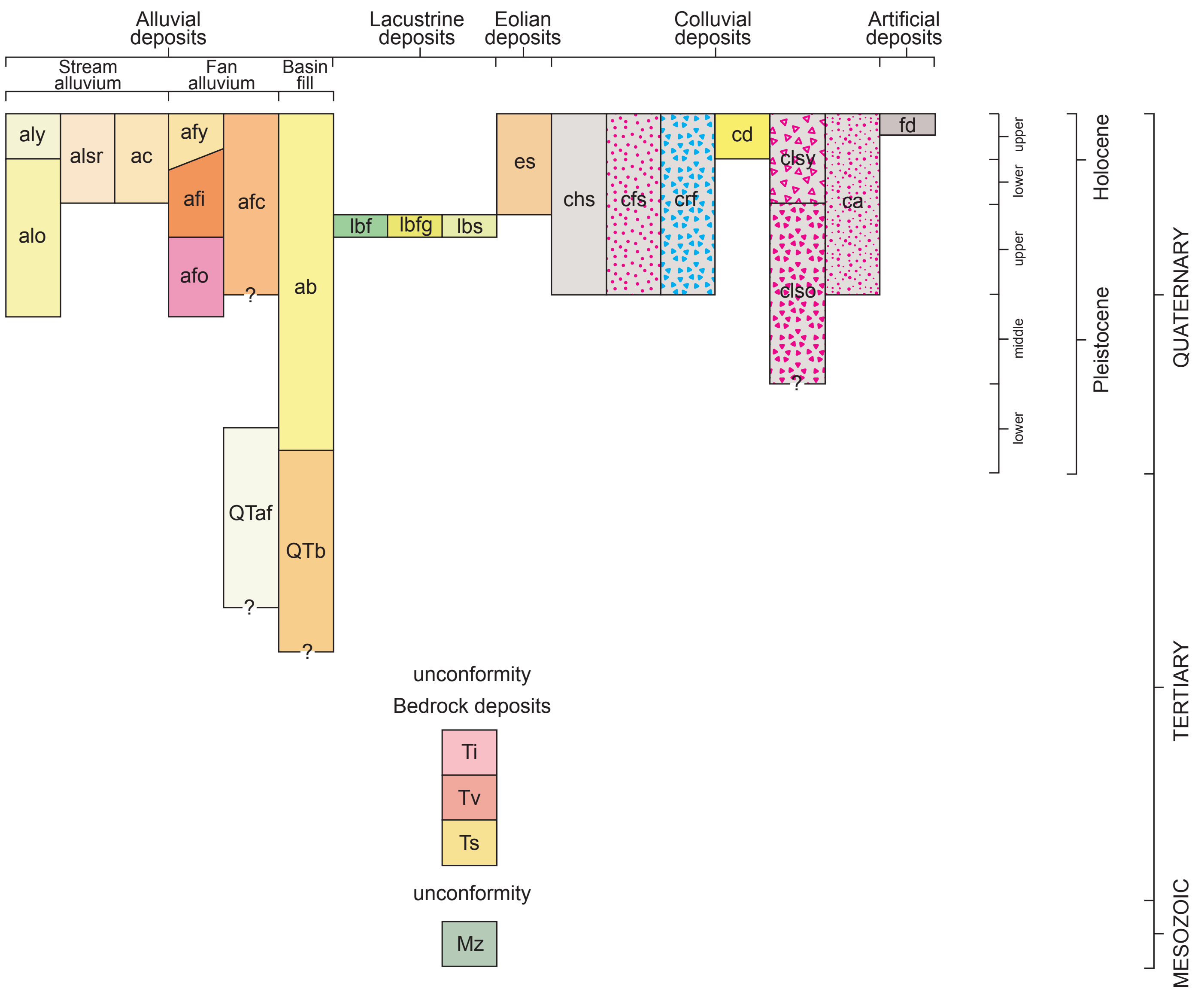
BEDROCK

- 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 (Quaternary). Bar and ball on downdropped side. Dashed where approximately located, dotted where concealed. Skinner Peaks (SP) trench location (Levan segement) shown with cross bar
- Normal fault - Other Quaternary faults. Bar and ball on downdropped side. Dashed where approximately located, dotted where concealed
- Normal fault - Bedrock faults (pre-Quaternary). Bar and ball on downdropped side (where sense of displacement is known). Dashed where approximately located, dotted where concealed
- Reverse fault - Bedrock faults (pre-Quaternary). Sawteeth on overriding plate or block in bedrock. Dotted where concealed
- B — Lake Bonneville highstand shoreline - Dashed where approximately located. Locally coincides with geologic contact
- Landslide escarpment - Main and internal scarps associated with mass-movement deposits; hachures face downslope
- Tilted geomorphic surface - Arrow points in general direction of downward tilt
- Sinkhole, other closed topographic depression
- x/y — Thin surficial unit x over older unit y

CORRELATION OF MAP UNITS



EARTHQUAKE WORKING GROUPS, DATABASE UPDATES, PALEOSEISMIC FAULT STUDIES, AND EARTHQUAKE-INDUCED LANDSLIDE HAZARD ASSESSMENT, UTAH

PART IV: PALEOSEISMIC RECONNAISSANCE OF THE SEVIER/TOROWEAP FAULT, WASHINGTON AND GARFIELD COUNTIES, UTAH

by

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CONTENTS

FIGURES

ABSTRACT

The Utah Geological Survey conducted a reconnaissance of the Sevier fault in southwestern Utah to identify sites where future paleoseismic studies may provide information on earthquake timing, recurrence, displacement, and vertical slip rate. The reconnaissance included a literature review, aerial-photograph interpretation, field reconnaissance, and sampling of basalt flows for ^{40}Ar/^{39}Ar radiometric dating. Results of the reconnaissance showed no fault scarps formed on unconsolidated deposits along the main trace of the Sevier fault in Utah; however, Quaternary mafic volcanic rocks are displaced at two locations (Black Mountain and Red Canyon) on the Sevier (northern) section of the fault. Geologic relations at Black Mountain are complex and poorly exposed. Vertical slip rates calculated there based on displacement of 0.57 Ma volcanic rocks range from 0.04 to 0.40 mm/yr, depending on the amount of displacement in the volcanic rocks attributed to surface faulting. Detailed examination of the Red Canyon site identified a previously unknown source on the Sevier fault hanging wall for the displaced volcanic rocks, indicating that the 200 m difference in elevation of the volcanic rocks across the fault is due to surface faulting and is not the result of volcanic flows cascading from the fault footwall across a pre-existing fault escarpment. Based on an existing K-Ar age for the volcanic rocks of 0.56±0.07 Ma, this reconnaissance confirmed a vertical slip rate at Red Canyon of 0.36 mm/yr.

Scarps and folds formed on unconsolidated basin-fill deposits in the Sevier fault hanging wall include a zone of faults and folds that extends from the hills directly south of Panguitch northeastward across the Sevier River to east of Panguitch, and a short north-south-trending fault zone on the east side of the Sevier River north of Panguitch. The scarps displace deposits ranging in age from late Pleistocene to late Tertiary and vary in height from less than a meter to about 25 m high. The scarps in both areas may be genetically related to the main Sevier fault to the east, but the scarps in the northeast-trending fault and fold zone may have formed in response to aseismic folding. Scarps in both areas are suitable for trenching; however, what relation surface faulting on those scarps has to the timing of surface-faulting earthquakes on the main Sevier fault is unclear. Trenching of scarps within the fault and fold belt would reveal if those scarps formed in response to surface-faulting earthquakes or are due to aseismic folding (creep).

Recommendations for future paleoseismic study of the Sevier fault include:

(1) Detailed geologic mapping of Black Mountain and vicinity to determine (a) the net vertical displacement of the volcanic rocks across the Sevier fault, and (b) if a seismogenic segment boundary exists close to Black Mountain.

(2) If net vertical displacement is significantly different between Black Mountain and Red Canyon (results of 1a above), and no evidence of a seismogenic boundary is found near Black Mountain (results of 1b above), then prepare a detailed geologic map of the Sevier fault between Black

Mountain and Red Canyon to determine if there is a segment boundary between those two locations.

(3) Trenching an alluvial scarp on the Northern Toroweap section of the Toroweap fault in Arizona to collect surface-faulting information that could be applied to the Utah portion of the Northern Toroweap section, which has no scarps.

(4) Trenching a minimum of one probable single-event and one multiple-event fault scarp in the fault and fold zone near Panguitch to determine if the fault scarps are the result of surface faulting or are a consequence of aseismic folding.

(5) Trenching a single-event and a multiple-event fault scarp in the short fault zone north of Panguitch to better constrain the timing and magnitude of paleoearthquakes on those faults.

INTRODUCTION

The Utah Geological Survey (UGS) has conducted a reconnaissance of the Sevier fault (SF) in southwestern Utah to identify sites where future paleoseismic investigations may provide information on earthquake timing, recurrence, displacement, and vertical slip rate. Determining these paleoseismic parameters will allow the UGS to more accurately characterize the SF's importance to the National Seismic Hazard Maps, to include these data in the UGS and U.S. Geological Survey Quaternary fault databases, and to determine the level of seismic hazard presented by the SF to southwestern Utah.

Our reconnaissance included a literature review, aerial-photograph interpretation (chiefly 1:40,000-scale with 1:20,000-scale stereoscopic photos of select areas), field verification of fault features and geologic units, and sampling of basalt flows for $^{40}Ar/^{39}Ar$ radiometric dating.

OVERVIEW

As defined by Black and others (2003), the SF is the Utah portion of the longer Sevier/Toroweap fault, a left-lateral oblique-slip fault that extends from south of the Grand Canyon in Arizona to north of Panguitch, Utah (figure 1). The Sevier/Toroweap fault is one of three major sub-parallel, generally north-trending faults (along with the Hurricane fault to the west and Paunsaugunt fault to the east) in northwestern Arizona and southwestern Utah that define the transition between the Basin and Range Province to the west and the Colorado Plateau to the east. Although a continuous structure that is almost 250 km long (Pearthree, 1998; Black and others, 2003), by convention the Sevier/Toroweap fault is named the Toroweap fault (TF) in Arizona

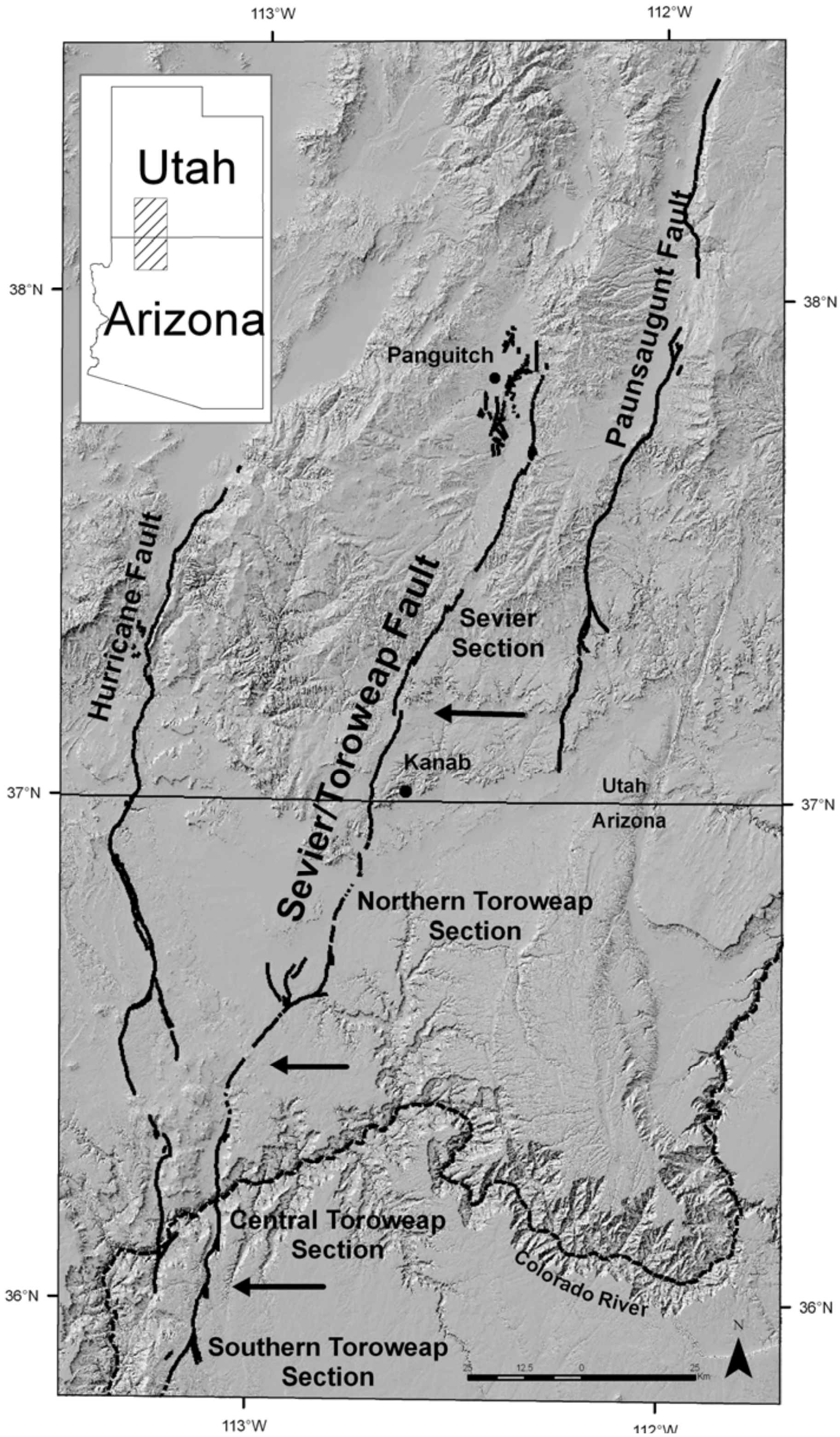

Figure 1. Index map of the Sevier/Toroweap fault and other major faults in the Basin and Range – Colorado Plateau transition zone; Sevier/Toroweap sections after Pearthree (1998) and Black and others (2003).

and the SF in Utah. The UGS follows that convention in this report.

Displacement across the Sevier/Toroweap fault is variable, but generally increases to the north. Near the Grand Canyon, Pearthree (1998) reports as much as 300 m of Cenozoic displacement, while Anderson and Christenson (1989) report displacements of 450 m near Mt. Carmel Junction and 900 m at Red Canyon in southwestern Utah. Along its length, the Sevier/Toroweap fault typically forms a west-facing bedrock scarp, the height and steepness of which depend on the resistance of the bedrock units displaced at the ground surface. Near the Utah/Arizona border and extending to Glendale, Utah (figure 2), the SF displaces the Navajo Sandstone and other well-indurated early and middle Mesozoic sedimentary rock units, and the resulting bedrock escarpment is typically several hundred feet high and commonly forms a near-vertical cliff. North of Glendale, the SF is exposed in softer Cretaceous and Cenozoic rock, and the escarpment is lower and less precipitous. At several locations along the fault, more resistant rock formations in the hanging wall are in contact with softer formations in the footwall and erosion has inverted the topography and produced obsequent fault-line scarps.   Obsequent fault-line scarps are particularly well developed near Pipe Springs National Monument in Arizona where the more resistant Kayenta Formation and Navajo Sandstone maintain the hanging wall at a high elevation compared to the softer Moenkopi Formation in the footwall.   A similar relation exists north of Alton, Utah where the resistant Eocene Claron Formation in the hanging wall forms the highest part of a ridge, while softer Cretaceous rocks in the footwall are at lower elevations.

In Arizona, Pearthree (1998) divided the TF into three sections, the northernmost of which (Northern Toroweap section [NTS]) he arbitrarily terminated at the Utah/Arizona border. Sargent and Philpott (1987) show uninterrupted faulting continuing northward across the border into Utah for an additional 20 km before making a 2.5 km left step at Clay Flat about 6.5 km south of Mt. Carmel Junction (figure 2). Based on the presence of the left step and the apparent pull-apart basin (Clay Flat) formed there by left oblique slip on the fault (Anderson and Christenson, 1989), Black and others (2003) subdivide the SF into two sections: (1) an extension of Pearthree's (1998) NTS continuing from the Utah/Arizona border north to Clay Flat, and (2) the Sevier section (SS) extending for an additional 88 km (end to end) from Clay Flat to north of Panguitch (figure 2). At its north end, the SF terminates within the thick Miocene Marysvale volcanic field.   An aerial-photograph study of this area by Anderson and Christenson (1989) showed that scarps are absent and that possible fault traces are expressed only as aligned drainages in bedrock.

In addition to the main SF, Anderson and Christenson (1989) and Black and others (2003) identify two other groups of faults/folds near Panguitch in the SF hanging wall. They are the "Sevier Valley [hills near Panguitch] faults and folds," and the "Sevier Valley [forth of Panguitch] faults" (figure 2).   Anderson and Christenson (1989) believe both groups of hanging-wall faults/folds are genetically related to the main SF. This reconnaissance study includes both sections of the main SF and both groups of

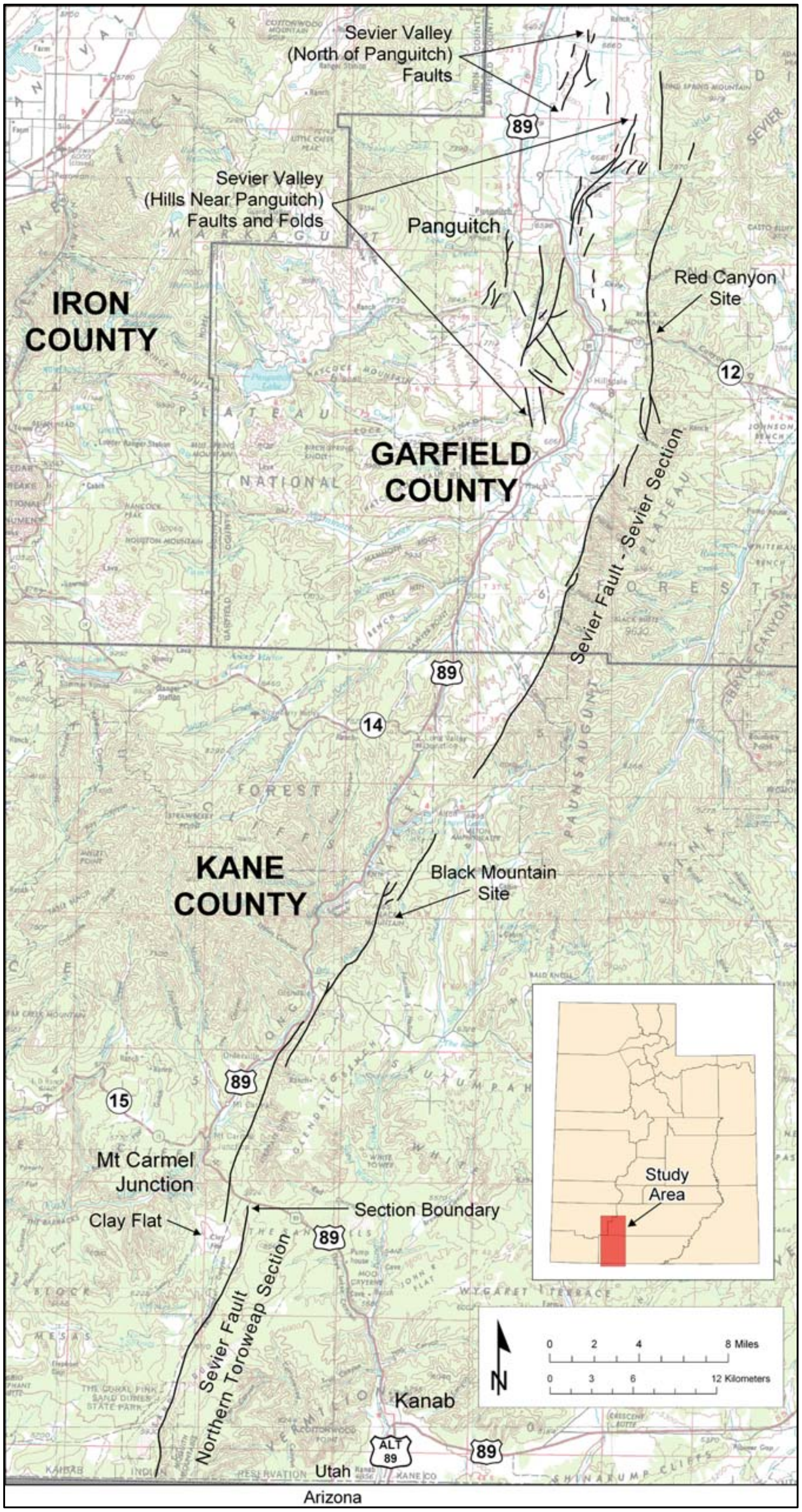

Figure 2. Map of the Sevier fault in Utah showing Clay Flat, the Black Mountain and Red Canyon sites, and hanging-wall faults near Panguitch; section boundaries after Black and others (2003).

faults/folds near Panguitch.

PREVIOUS WORK

The SF has long been recognized as a major block-bounding structural discontinuity in southwestern Utah that displaces near-horizontal Mesozoic and Cenozoic sedimentary formations and Cenozoic volcanic rocks down-to-the-west (Gilbert, 1875; Dutton, 1880). However, recognition by geologists that the SF is an active fault and a potential source of damaging earthquakes is a more recent phenomenon.

Gregory (1951) discusses the SF and states that earthquakes recorded at Tropic and Panguitch (east and west of the SF, respectively) in 1902, 1924, 1930, and 1931 may have had their foci on faults in the region, without indicating which fault or faults might have been involved. Cashion (1961, 1967) mapped a portion of the SF in the Glendale-Orderville area and reports that mafic volcanic rocks at Black Mountain in northern Kane County are displaced across the SF. He also notes the 1902 to 1931 Glendale earthquakes, and suggests that the SF may still be active.

Anderson and Rowley (1987) mapped the Panguitch NW quadrangle and show faults cutting late Pleistocene and Holocene deposits east of the Sevier River north of Panguitch (the Sevier Valley [north of Panguitch] faults of Black and others [2003]). Anderson and Rowley (1987) believe that the faults provide evidence of significant Quaternary, and possible ongoing Holocene tectonic activity. Doelling and Davis (1989) discuss earthquake hazards in Kane County, and ascribe 14 earthquakes with modified Mercalli intensities as high as III in the vicinity of Orderville, Utah between 1924 and 1927 to movement on the SF. They also note that the SF displaces Quaternary volcanic rocks at Black Mountain.

Anderson and Christenson (1989) discussed the SF and associated faults and folds near Panguitch. This report was the first to specifically address Quaternary tectonic features in southwestern Utah, and to evaluate their potential for generating large surface-faulting earthquakes. Covering an area of several thousand square miles, the Anderson and Christenson (1989) report is a reconnaissance study and includes numerous Quaternary tectonic and volcanic features in addition to the SF. The report documents displaced Quaternary mafic volcanic rocks at two locations along the SF, Black Mountain (see above) and Red Canyon in Garfield County; identifies Clay Flat as a possible pull-apart basin suggestive of possible Pleistocene fault movement; documents likely non-tectonic displacement on the SF along a short (6 km) obsequent fault scarp near Alton, Utah; and discusses the faults and folds in the SF hanging wall near Panguitch.

Moore and Staub (1995) and Kurlich and Anderson (1997) prepared geologic maps of the Panguitch and Hatch USGS 7.5 minute quadrangles, respectively. Both maps show faults thought to be genetically associated with the SF cutting Quaternary-age deposits.

Jorgenson Harbor (1998) studied changes in the morphology of the Sevier River where it crosses the fault and fold zone in the SF hanging wall east and south of Panguitch, and concluded that the area is one of active tectonic uplift. Davis (1999) and Reber and others (2001) studied structural details of the SF. Both report evidence of Quaternary movement, and based on historical seismicity Davis (1999) suggests that the SF is active. Schiefelbein (2002) addresses fault segmentation, fault linkage, and hazards along a 16-km-long section of the SF between Orderville and Black Mountain in Kane County, Utah. In addition to producing a detailed (1:12,000 scale) geologic map of her study area, she provides new information on displaced volcanic rocks at Black Mountain, and obtained $^{40}Ar/^{39}Ar$ radiometric ages on the volcanics from both the fault footwall and hanging wall.

Black and others (2003) summarize existing paleoseismic information available for the Sevier/Toroweap fault zone and nearby hanging-wall faults in Utah.

Geologists also recognize that the TF in Arizona is potentially active. Detailed geologic mapping and soils and geomorphologic analyses by Jackson (1990) indicate Holocene rupture along about 50 km of the Central Toroweap section (figure 1) centered on the Colorado River. Pearthree (1998) summarizes information regarding Quaternary fault activity on the Southern, Central, and Northern Toroweap sections of the TF through mid–1998. Fenton and others (2001a, 2001b) use cosmogenic isotope ages on displaced basalt flows to calculate vertical slip rates for the Central section (CS) of the TF at the Grand Canyon.

PALEOSEISMIC RECONNAISSANCE

This paleoseismic reconnaissance includes the main trace of the SF from the Utah/Arizona border to where the fault terminates north of Panguitch, Utah (figure 2). The end-to-end length of the SF main trace in Utah is approximately 108 km and includes the northern 20 km of the NTS and the 88-km-long SS (Pearthree, 1998; Black and others, 2003). This reconnaissance also includes two groups of faults and folds in the SF hanging wall near Panguitch. Black and others (2003) identify the groups as (1) the Sevier Valley (hills near Panguitch) faults and folds, and (2) the Sevier Valley (north of Panguitch) faults. The hanging-wall faults and folds are included because Anderson and Christenson (1989) believe they are genetically related to the main SF.

Sevier Fault Main Trace

Northern Toroweap Section

Pearthree (1998) defined the NTS as extending from the northern end of Toroweap Valley in Arizona to the Utah/Arizona border (figure 1), where he arbitrarily terminated the section because he was only compiling Quaternary fault data for Arizona. Sargent and Philpott (1987) mapped the Kanab 1:62,500-scale quadrangle in Kane County, Utah and Mohave and Coconino Counties, Arizona and demonstrate that the NTS extends as a single uninterrupted fault section from Arizona into Utah for an additional 20 km to Clay Flat about 6.5 km south of Mt. Carmel Junction (figures 1 and 2). Doelling and Davis (1989) mapped the geology of Kane County at 1:100,000-scale and included the Utah portion of the NTS on their geologic map.

Where exposed in bedrock, faults comprising the NTS in Utah define a zone up to a kilometer wide of overlapping and anastomosing fault strands. Sargent and Philpott (1987) identified several locations where Holocene alluvium, eolian, and mixed alluvium/eolian deposits bury portions of the NTS, and one location where the NTS is overlain by Pleistocene gravel. Sargent and Philpott (1987) do not show the NTS cutting Quaternary deposits. In contrast, Doelling and Davis (1989) show a strand of the NTS cutting a Holocene eolian dune deposit in section 24, T. 43 S., R. 8 W., SLB&M, and displacing the previously mentioned Pleistocene gravel deposit in section 17, T. 42 S., R. 7 W., SLB&M. The aerial-photograph analysis and field reconnaissance conducted for this study could neither verify the displaced deposits shown on the Doelling and Davis (1989) map, nor identify displaced Quaternary deposits elsewhere on the NTS in Utah. The Doelling and Davis (1989) map is chiefly a compilation of previously existing geologic mapping, of which the Sargent and Philpott (1987) map was a principal source. Therefore, the displaced Quaternary deposits shown on the Doelling and Davis (1989) map are most likely compilation errors.

While scarps formed on Quaternary deposits are absent on the NTS in Utah, Pearthree (1998) reports a gentle fault scarp on late Pleistocene alluvium on the NTS in Arizona near Pipe Springs National Monument.

Clay Flat

Clay Flat forms a small (1 km^2) closed basin where the SF makes a left en echelon step between the NTS on the east and the SS on the west (figure 2). Clay Flat receives sediment chiefly from the south via Yellowjacket and Sethys Canyons, and to a lesser extent from small, unnamed drainages to the east and north. The combined drainage area for Clay Flat is about 70 km^2 (Anderson and Christenson, 1989). The Clay Flat closed basin is superimposed upon Yellowjacket Canyon and divides the canyon into disconnected upper and lower reaches. The upper reach drains into Clay Flat, while the lower reach is tributary to the East Fork of the Virgin River. Headward erosion on the lower reach is presently within about 350 m of Clay Flat, and the drainage divide between the basin and the stream channel is only a few meters high, indicating geologically imminent stream capture, which will reconnect upper and lower Yellowjacket Canyon.

Anderson and Christenson (1989) document left-lateral oblique slip on the NTS south of Clay Flat, and point out that left-lateral slip combined with a left step in the fault trace would produce concentrated dilation and form a pull-apart basin at the step-over between the fault sections. They further speculate that maintaining a sediment depocenter virtually in the middle of a large active drainage such as Yellowjacket Canyon requires active late Pleistocene subsidence.

This reconnaissance documented the facts regarding Clay Flat as presented in Anderson and Christenson (1989), but could not identify relations between faults and sedimentary deposits in or near the basin that would allow Anderson and Christenson's (1989) hypothesis regarding Pleistocene subsidence to be tested. Undeformed Holocene basin-fill deposits overlie the faults in the immediate vicinity of Clay Flat indicating no Holocene deformation and masking possible evidence of Pleistocene tectonic activity.

Sevier Section

The SS extends for 88 km (straight line) from Clay Flat to northeast of Panguitch (figure 2). The section exhibits a complex pattern of right-stepping, overlapping faults that create a series of relay ramps and local folds between fault strands from Clay Flat to near Black Mountain, a distance of about 28 km (Sargent and Philpott, 1987; Doelling and Davis, 1989; Davis, 1999; Reber and others, 2001, Schiefelbein, 2002). North of Black Mountain the fault trace is less complex, and has been mapped as a single strand in many areas (Doelling, 1975; Doelling and Davis, 1989; Tilton, 2001). However, the SF has not been mapped in detail (1:24,000-scale) north of the Kane County/Garfield County boundary (figure 2), so complexities may exist along the fault, which are as yet unrecognized.

Doelling and Davis (1989) show strands of the SS cutting both Holocene and Pleistocene unconsolidated deposits at several locations between Clay Flat and Glendale, Utah. The aerial-photograph analysis and field reconnaissance conducted for this study could neither verify the displaced deposits shown on the Doelling and Davis (1989) map, nor identify displaced Quaternary deposits elsewhere on the SS in Utah. Additionally, examination of the original geologic mapping (Cashion, 1961, 1967; Sargent and Philpott, 1987) from which Doelling and Davis (1989) compiled their map showed no faults cutting unconsolidated Quaternary units.

The SS displaces Quaternary mafic volcanic rocks at two locations, Black Mountain in northern Kane County and Red Canyon in Garfield County (Gregory, 1951; Cashion, 1961, 1967; Anderson and Christenson, 1989; Davis and Doelling, 1989; Schiefelbein, 2002; figure 2). Because no scarps are formed on unconsolidated Quaternary deposits along the main trace of the SF in Utah, the displaced volcanic rocks at Black Mountain and Red Canyon provide the only opportunity to determine vertical slip rates for the SF; therefore, both locations are discussed in detail below.

Black Mountain: Mafic volcanic rocks cap a portion of the top and west flank of Black Mountain (sections 28, 29, 32, and 33, T. 39 S., R. 6 W., SLB&M.; figure 3), and are displaced across the SF (Cashion, 1961, 1967; Doelling and Davis, 1989; Schiefelbein, 2002). The source of the volcanic rocks has not been identified; however, it must be at

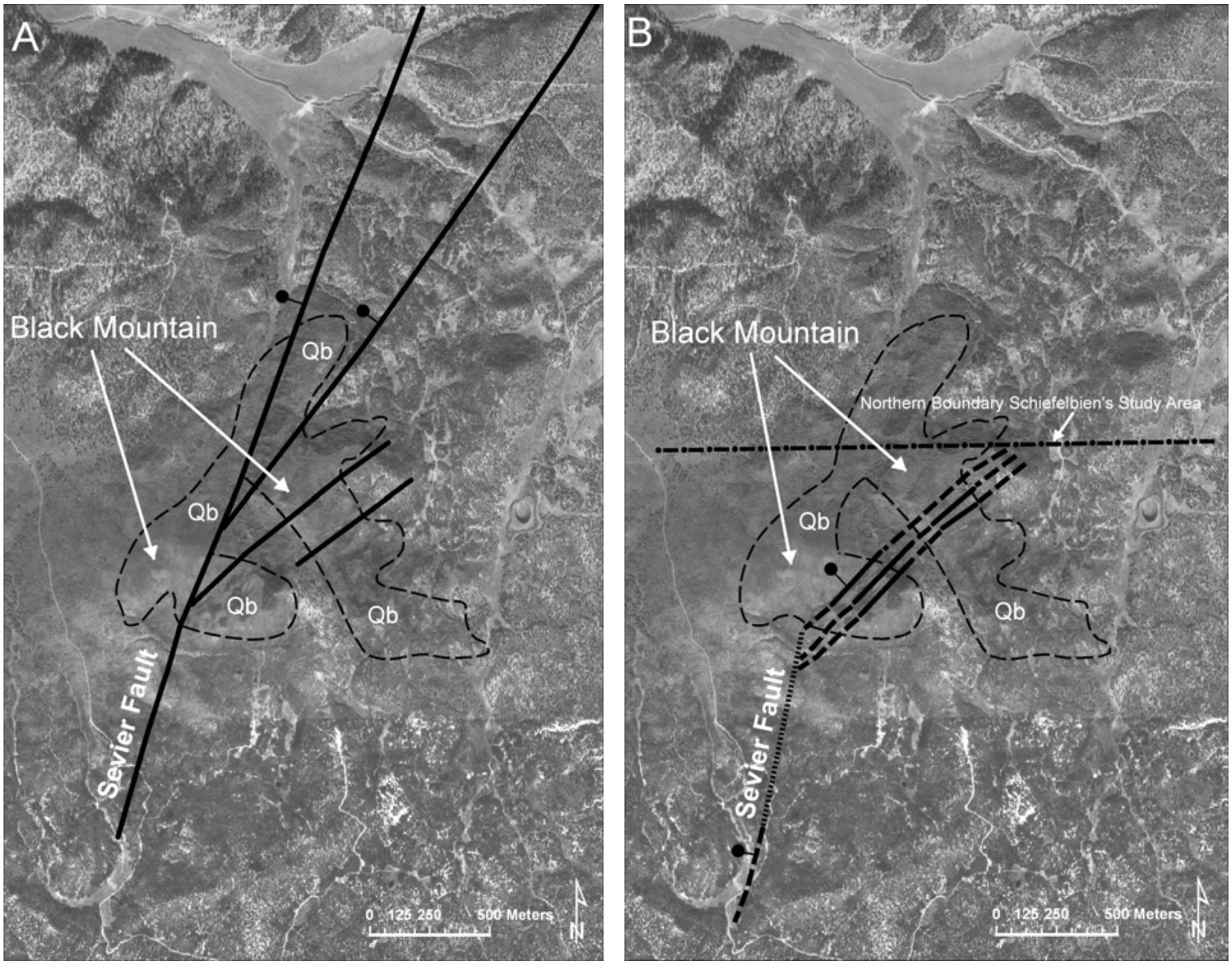

Figure 4. Aerial photograph of Black Mountain and vicinity showing the trace of the Sevier fault as mapped by (A) Cashion (1961, 1967) and (B) Schiefelbein (2002). Dashed line = approximately located, dotted line = concealed, bar and ball on the downthrown side of fault; Qb = mafic volcanic rocks.

or very close to Black Mountain because a lava flow(s) extends from the base of the mountain first westward to and then south along Spencer Bench parallel to the East Fork of the Virgin River for about 2.5 km (Cashion, 1961, 1967). At the time of its eruption, the lava flowed west down a small tributary to the East Fork of the Virgin River and then south down the ancestral river channel. Subsequent erosion by the river has left the flow capping Spencer Bench 30 m or more above the present river channel.

Cashion (1961) mapped the SF in the vicinity of Black Mountain (figure 3A), and reports 75 feet (23 m) of down-to-the-west displacement across the fault in the Quaternary volcanic rocks at Black Mountain. Best and others (1980) determined a K-

Ar age of 0.56±0.06 Ma for the Black Mountain volcanics. Anderson and Christenson (1989) examined the relation between the volcanic rocks and the SF at Black Mountain and found no definitive evidence that the flows are displaced by faulting despite the coincidence of the flows with the trace of the SF. They attribute other conspicuous scarps formed on the basalt to landslide head scarps. Anderson and Christenson (1989) state "Though it is probable that the basalt is displaced at the main [fault] trace, there is considerable uncertainty as to which scarps are related to landslides, pre-flow topography, or faults," and conclude "These uncertainties preclude estimating long-term displacement rates [at Black Mountain] from available data."

Schiefelbein (2002) mapped three fault strands of the SF cutting the Black Mountain volcanic rocks (figure 3B), and reports that the basalt is displaced ~ 21 m across the three strands (Schiefelbein, verbal communication, 2004). Schiefelbein (2002) obtained two ^{40}Ar/^{39}Ar radiometric ages at Black Mountain, one from volcanic rocks on Black Mountain (fault footwall), and one from the lava flow capping Spencer Bench (fault hanging wall). The two ages are 0.58±0.05 Ma and 0.564±0.02 Ma, respectively. Using a net vertical displacement of 10 m, Schiefelbein (2002) reported a vertical slip rate for the past 0.57 Ma of 0.0180 mm/yr for the westernmost of her three fault strands. Repeating the calculation using 21 m of total net vertical displacement (Schiefelbein, verbal communication, 2004) resulted in a vertical slip rate of 0.04 mm/yr since 0.57 Ma. Schiefelbein (2002) estimated a longer term vertical slip rate by assigning all SF displacement to post-Claron Formation time (past 30 myr). Using that time interval and the displacement on the SF measured on the top of the Jurassic Navajo Sandstone (~687 m) she reports a long-term slip rate of 0.0229 mm/yr. Schiefelbein (2002) acknowledged that if displacement on the SF initiated significantly later than the end of Claron Formation deposition at 30 Ma, the vertical slip rate would be higher.

The aerial-photograph analysis and field reconnaissance conducted for this study showed that geologic relations at Black Mountain are complicated by complex geology, poor exposures, heavy vegetative cover, pre-basalt topography, and mass wasting as indicated by Anderson and Christenson (1989). Cashion (1961) and Schiefelbein (verbal communication, 2004) report displacements of 23 and ~21 m, respectively, which are generally consistent with each other, and support a low late Quaternary vertical slip rate of about 0.04 mm/yr at Black Mountain. Conversely, if landsliding is discounted as a major cause of the prominent scarps formed on basalt at Black Mountain, and that displacement is instead attributed chiefly to surface faulting, and if the possibility of flows cascading over a pre-existing fault escarpment from a now unrecognizable volcanic source on the fault footwall is likewise discounted, the difference in elevation between the volcanic rocks on top of Black Mountain (fault footwall) and in the adjacent valley (fault hanging wall) is approximately 229 m. Assuming a maximum vertical displacement of 229 m and a basalt age of 0.57 Ma results in a vertical slip rate of 0.40 mm/yr, which is generally compatible with the 0.36 mm/yr vertical slip rate reported by Hecker (1993) in volcanic rocks of essentially the same age at Red Canyon (see below).

Red Canyon: The SF is well exposed at the mouth of Red Canyon immediately north of Utah SR-12 in section 22, T. 35 S., R. 4 1/2 W., SLB&M (figure 4). There, the SF places Quaternary mafic volcanic rocks in fault contact with red sandstone, siltstone,

Figure 4. Sevier fault at the mouth of Red Canyon; Qb = Quaternary basalt, Qt = basalt talus, and Tc= Claron Formation.

limestone, and conglomerate of the Eocene Claron Formation. Best and others (1980) obtained a K-Ar age of 0.56$\pm$0.07 Ma for the volcanic rocks, and Anderson and Christenson (1989) report that the basalt is displaced 200 m across the fault. Using those data, Hecker (1993) calculated a vertical slip rate of 0.36 mm/yr at Red Canyon.

Calculating a reliable vertical slip rate using displaced volcanic flows requires that the source of the flows be known. Flows erupting on the fault footwall may cascade over a pre-existing fault escarpment onto the hanging wall and create the impression of greater displacement than has actually occurred due to faulting. If cascading does occur and the flows are subsequently displaced by surface faulting, the vertical slip rate determined using the elevation difference between flows across the fault would be erroneously high.

A priority of this study was to identify the source and true tectonic displacement of the volcanic rocks at Red Canyon. The aerial-photograph analysis and field reconnaissance conducted at Red Canyon revealed:

(1) No discernable source for the volcanic flows in the fault footwall.

(2) The conspicuous white outcrop in the fault footwall beneath the basalt is not the 'White Claron" subunit of the Claron Formation (Gregory, 1951; Doelling and Davis, 1989), but more likely is an erosional remnant of the Boat Mesa conglomerate of Bowers (1990) from lower in the Claron section (Willis and Biek, UGS, verbal communication, 2004).

(3) The fine-grained white sandstone exposed in the fault hanging wall at the base of the fault escarpment contains flecks of biotite and is not the stratigraphic equivalent of the white, non-biotite-bearing unit (possible Boat Mesa conglomerate) in the fault footwall, and thus the difference in elevation between the two white units cannot be used to determine displacement across the SF.

(4) A previously unrecognized eroded cinder cone or possibly a string of small spatter cones is present on the SF hanging wall north of Utah SR-12 immediately adjacent to the Red Canyon site (figure 5).

Identification of a hanging-wall source for the volcanic rocks at Red Canyon indicates that lava from the cinder/spatter cone(s) likely flowed to and ponded against a pre-existing fault escarpment, and then flowed across the SF and a short distance up a drainage emanating from the escarpment. Subsequent surface faulting displaced the flow, leaving volcanic rocks stranded on the fault footwall. The 200 m difference in elevation between the volcanic rocks now on either side of the SF at Red Canyon is then a true measure of post-eruption surface-faulting displacement.

To further refine the vertical slip rate at Red Canyon, the UGS submitted samples of volcanic rock from the fault footwall and hanging wall to the Geochronology Research Laboratory at the New Mexico Institute of Mining and Technology for $^{40}Ar/^{39}Ar$ radiometric age analysis. The radiometric dating is not yet complete, and will be reported when the results become available in mid-2005. Until that time, the Hecker (1993) slip-rate estimate of 0.36 mm/yr appears reasonable and represents the currently best available vertical slip rate at Red Canyon.

Sevier Valley (Hills Near Panguitch) Faults and Folds

A diffuse zone of broad anticlines and synclines and generally fold-parallel fault scarps, many forming narrow grabens at anticlinal crests, extends for about 23 km from the hills south of Panguitch northeastward across the Sevier River to east of Panguitch (figure 2). The faults and folds are in the hanging wall of the SF and the deformed deposits range in age from late Tertiary to late Pleistocene (Kurlich and Anderson, 1987; Anderson and Christenson, 1989; Moore and Straub, 1995). The scarps are conspicuous on aerial photographs and range from less than a meter to more than 25 m high.

Figure 5. Preliminary photogeologic map of Red Canyon and vicinity.

EXPLANATION

Qal Stream alluvium
Qaf Alluvial-fan deposit
Qb Basalt
Qbc Basalt cinder/spatter cones
Qt Basalt talus
Tmds Mount Dutton volcanic sediments
Tc Claron Formation

Geologic unit contact

Dashed where approximately located, dotted where concealed

Fault trace

Dashed where approximately located, dotted where concealed

The northernmost northeast-trending anticline deforms fan surfaces extending eastward from the Sunset Cliffs (SF escarpment) that are probably as old as middle Pleistocene (Anderson and Christenson, 1989). The fold rotates the fan surfaces a few degrees away from a central graben (Race Hollow). North-trending anticlines to the south in the Panguitch Hills are also faulted, have limbs that dip an average of 5^{o}, and locally deform a 5.3 Ma basalt flow (Harald Mehnert, written communication, 1988, reported in Anderson and Christenson, 1989). Anderson and Christenson (1989) report that deformation resulting from folding far exceeds that due to faulting, and that the fault and fold zone is an area of net uplift. Two scarps on the east side of the Sevier River (sections 11 and 12, T. 35 S., R. 5 W., SLB&M) about 4 km north of the U.S. Hwy 89 and Utah SR-12 intersection each displace a probable late Pleistocene alluvial surface less than a meter, and appear to be the youngest faults in the zone. Several small closed basins that disrupt drainages in the Panguitch Hills (Anderson and Christenson, 1989) and an anomaly in the channel of the Sevier River (Jorgensen Harbor, 1998) indicate that deformation within the fault and fold zone is ongoing. Anderson and Christenson (1989) believe that the faults and folds formed aseismically, and are genetically related to the subparallel SF, which at its closest point lies 1 km to the east, but typically is 5 to 8 km distant from the fault and fold zone.

This reconnaissance identified numerous fault scarps formed on both Pleistocene alluvial surfaces east of the Sevier River and on older Tertiary gravels (Sevier River Formation of Gregory, 1951) in the Panguitch Hills. Many of the scarps and associated grabens have good access and are amenable to trenching. The age of the faults and folds is not known, but the wide range in scarp heights suggests a similar wide range in age and number of surface-faulting earthquakes. However, the origin of the scarps is uncertain; whether the scarps are the result of surface faulting, or formed in response to aseismic deformation, is unknown. In either case, trenching the scarps would reveal little information regarding surface faulting on the main SF to the east. If the scarps resulted from surface faulting, establishing a comprehensive surface-faulting chronology for the entire fault and fold zone would require trenching many scarps of different heights. In the absence of a viable trench site on the main SF (see above) for comparison, the relation between the timing of surface faulting within the fault and fold zone and the main SF would remain unresolved. Conversely, if the hanging-wall faults resulted from aseismic folding, subsequent scarp erosion would likely not have produced the kind of individual scarp-derived colluvial wedges typical of scarp erosion following surface faulting (Schwartz and Coppersmith, 1984; Machette and others, 1992; McCalpin, 1996). In that case, trenching would confirm only that the scarps did not result from surface faulting.

Sevier Valley (North of Panguitch) Faults

Anderson and Rowley (1987) mapped a short (6 km end to end) zone of northeast-trending normal faults in the floor of the Sevier Valley near Sanford Creek north of Panguitch (figure 2). The faults displace unconsolidated Quaternary deposits and form a conspicuous horst on the east side of the Sevier River. Scarps within the zone vary in height depending upon the age of the deposits displaced, and are as high as 12 m on surfaces thought to be as old as middle Pleistocene and less than a meter high on surfaces of probable late Pleistocene age (Anderson and Christenson, 1989).

Anderson and Christenson (1989) photo-logged a fault exposure in the wall of a commercial wood-chip disposal pit and report evidence for two surface-faulting earthquakes. Uncertainties regarding the relation between soil development and the most recent surface-faulting earthquake, and a lack of datable material (charcoal) in the fault exposure prevented determining either earthquake timing or the interval between the earthquakes. The most recent surface faulting displaced a middle to late Pleistocene alluvial surface about 80 cm, causing Anderson and Christenson (1989) to suggest a late Pleistocene age for that earthquake. The older earthquake produced about 60 cm of displacement and pre-dates formation of the middle to late Pleistocene alluvial surface. Anderson and Rowley (1989) report vegetation lineaments in Holocene stream-channel deposits as evidence of Holocene faulting. However, Anderson and Christenson (1989) disagree and believe that the lineaments are an expression of ground water concentrated along buried portions of late Pleistocene faults.

The faults in the Sanford Creek area appear to be related to tectonic surface faulting. The height of the scarps (12 m maximum) and short fault length (6 km end to end) are of concern. A fault exhibiting 12-m-high scarps should be considerably longer than 6 km (Wells and Coppersmith, 1994). However, Anderson and Rowley (1987) note that the northern Sevier Valley is an area of a “great amount of dissection” that probably exceeds 20 ft (6 m) in historical time. Erosion since the late Pleistocene may have removed evidence of a more extensive fault zone.

This reconnaissance showed that sites suitable for trenching exist on both multiple- and probable single-event fault scarps in the Sanford Creek area. However, it is unclear what relation surface faulting on this short fault zone has to faulting on the much larger SF several kilometers to the east. In the absence of a viable trench site on the main SF (see above) for comparison, the relation between the timing of surface faulting within this fault zone and the main SF would remain unresolved.

DISCUSSION

Earthquake Timing, Recurrence, and Displacement

The absence of scarps on unconsolidated deposits along the SF in Utah precludes using standard paleoseismic trenching techniques to determine the timing, recurrence, or displacement of individual paleoearthquakes. Trenching scarps on unconsolidated Quaternary deposits in the SF hanging wall near Panguitch is possible (assuming landowner permission is forthcoming), but what relation, if any, the surface-faulting parameters of those faults have to the main SF is unknown. Consequently, the only opportunity to develop paleoearthquake timing, recurrence, and displacement information relevant to the SF in Utah is by trenching scarps on unconsolidated deposits on the NTS in Arizona. No scarps are present on the SS, so individual paleoearthquake timing and displacement data will remain unavailable for that fault section.

Vertical Slip Rate

The possibility of a roughly ten-fold difference in late Quaternary vertical slip rates between Black Mountain (0.04 mm/yr) and Red Canyon (0.36 mm/yr) in volcanic rocks of essentially the same age implies that the rate of seismogenic activity at the two sites may be significantly different. Conversely, if the vertical slip rates at Red Canyon and Black Mountain are 0.36 and 0.40 mm/yr, respectively (see above), the difference between them is small and the two locations may have experienced similar surface-faulting histories.

Which of these two scenarios is the case cannot be determined with presently available data. Hecker's (1993) 0.36 mm/yr slip rate at Red Canyon may be revised once new $^{40}Ar/^{39}Ar$ radiometric ages become available for the volcanic rocks there, but any adjustment is expected to be minor, and the vertical slip rate at Red Canyon will likely continue to be measured in tenths of millimeters per year. Such certainty is not the case at Black Mountain, where Cashion (1961, 1967) and Schiefelbein (2002; written communication, 2004) report displacements in volcanic rocks that yield vertical slip rates that are measured in hundredths of a millimeter per year. Additionally, Anderson and Christenson (1989) concluded that uncertain geologic relations at Black Mountain precluded making a vertical slip-rate estimate there, and the results of this study show that if the total elevation difference between the volcanic rocks in the SF footwall at Black Mountain and the volcanic rocks immediately adjacent to Black Mountain in the fault hanging wall is due chiefly to surface faulting, then the vertical slip rates at Black Mountain and Red Canyon are similar.

By way of comparison, Fenton and others (2001a, 2001b) used cosmogenic isotope dating techniques to calculate vertical slip rates in basalt displaced on the CS of the TF near the Grand Canyon. The CS has scarps formed on lava flows, cinder cones, and alluvial deposits, and Fenton and others (2001a, 2001b) report slip rates ranging from 0.07 to 0.18 mm/yr. Pearthree (1998) estimates a long-term vertical slip rate for the CS of 0.05-0.075 mm/yr. Considering that the vertical slip rate at Red Canyon is 0.36 mm/yr, twice the highest estimated rate on the CS, the absence of fault scarps on unconsolidated deposits or other geomorphologic evidence of higher slip on the northern SF is puzzling. Possible reasons include rapid erosion that quickly destroys scarps, and/or the possibility that surface faulting occurs chiefly in bedrock or at the bedrock-alluvium interface rather than in unconsolidated deposits and therefore is difficult to recognize.

In the absence of scarps suitable for trenching, resolving an accurate vertical slip rate at Black Mountain is critical to gaining a better understanding of the SF's behavior in Utah. Whether ten times smaller than the slip rate at Red Canyon or essentially the same, the result has major implications for the seismogenic behavior and segmentation of the SF.

Segmentation

Long normal-slip faults in the Basin and Range Province typically rupture in shorter segments during surface-faulting earthquakes. Each segment is independently seismogenic (capable of generating its own surface-faulting earthquakes) and develops an independent surface-faulting history. Seismogenic segments are separated from adjoining segments by boundaries that may either be persistent (consistently stop surface rupture) or nonpersistent (sometimes allow rupture overlap between segments or multiple-segment ruptures). Machette and others (1992) compiled lengths of historical normal-slip earthquake surface ruptures in the Basin and Range Province. The ruptures ranged from as little as 11 km for the M_s 6.6 Hansel Valley, Utah earthquake, to as much as 62 km for the M_s 7.1 Fairview Peak and M_s 7.6 Pleasant Valley, Nevada earthquakes. The Wasatch fault in northern Utah is the longest and most extensively studied active fault in the Basin and Range Province. The results of numerous paleoseismic investigations show that the Wasatch fault is subdivided into 10 seismogenic segments with lengths ranging from 11 to almost 70 km, and that the average length of the six segments with surface faulting during the Holocene is 48 km (Machette and others, 1992). Machette and others (1992) also report segment lengths for six additional active normal faults in the western United States. The longest reported segment does not exceed 45 km, and average segment lengths for the faults range from 13 to 26 km. In comparison, Pearthree (1998) reports a length of 60 km for the NTS in Arizona and Black and others (2003) report that the section extends for an additional 20 km into Utah for a total length of 80 km. Similarly, Black and others (2003) report a length of 88 km for the SS in Utah. Considering the historical surface-faulting behavior of Basin and Range faults, it is questionable that the NTS and SS represent single seismogenic segments, and seems more likely that the SF ruptures in shorter increments in a manner similar to other Basin and Range normal faults.

Seismogenic segment boundaries may take the form of en echelon steps, salients, gaps in faulting, T-junctions, and intersections of cross structures with the active fault trace (Machette and others, 1992; Wheeler and Krystinik, 1992). Anderson and Christenson (1989) identified the 2.5-km-wide en echelon left step in the trace of the SF at Clay Flat (figure 2) as a possible seismogenic segment boundary. Black and others (2003) use the Clay Flat step-over as the boundary between the NTS and SS of the SF. Seismogenic segments by definition have different surface-faulting chronologies, and determining those chronologies typically requires detailed paleoseismic trenching investigations. No trenching studies have been conducted on either the NTS or SS, but the presence of scarps on unconsolidated Quaternary deposits on the NTS in Arizona, and the absence of scarps north of the en echelon step-over at Clay Flat, argues for a seismogenic segment boundary at Clay Flat.

From Clay Flat north to Black Mountain, a distance of 17 km, the SF exhibits a complex pattern of closely spaced overstepping fault strands that combine to form at least four relay ramps as slip is transferred between strands (Davis, 1999; Reber and others, 2001; Schiefelbein, 2002). Locally, folds have developed between the overstepping fault strands, particularly in conjunction with relay ramps (Schiefelbein, 2002). North from Black Mountain the trace of the SF is less complex (Gregory, 1951; Doelling, 1975; Doelling and Davis, 1989; Tilton, 2001). The transition to a less complicated fault structure may have significance for seismogenic segmentation, or it may simply reflect the manner in which the SF is expressed in the softer Cretaceous and Tertiary rocks that crop out north of Black Mountain as compared to the harder Mesozoic sedimentary rocks to the south. Because the SF has not been mapped in detail (1:24,000-scale) north of the Kane/Garfield County line (figure 2), fault complexities north of that point may be as yet unrecognized. One complexity that has been recognized even in regional-scale studies (Gregory, 1951; Doelling, 1975) is the intersection of the SF with the Ruby's Inn and Pine Hills thrust faults (Davis, 1999) near Hilldale Canyon south of Red Canyon. The SF truncates both thrust faults, and no difference in SF morphology was observed north or south of the fault intersections.

Key to gaining a better understanding of seismogenic segmentation of the SF in Utah is determining an accurate vertical slip rate at Black Mountain. Nelson and Personius (1993) document a decrease in vertical slip toward both ends of the Weber segment of the Wasatch fault. Chang and Smith (2002) employed a half-ellipse function, with greatest slip near the middle of the segment, to model long-term vertical slip distribution on the six central segments of the Wasatch fault with Holocene surface faulting. Crone and others (1985) showed that vertical slip distribution varied along strike during the 1983 Borah Peak earthquake. Likewise, Chang and Smith (2002) plotted the vertical slip distribution for nine historical Basin and Range earthquakes (including Borah Peak) and showed that slip varied along strike, but typically decreased gradually to zero at the rupture ends. Therefore, if the vertical slip rate at Black Mountain is only one-tenth as large as the vertical slip rate at Red Canyon, it is likely that either (1) Black Mountain is near the end of a seismogenic segment where slip is dying out (Crone and others, 1985; Nelson and Personius, 1993; Chang and Smith, 2002; Nelson, in press), or (2) Black Mountain and Red Canyon are on different seismogenic segments and are separated by a persistent seismogenic boundary. Regardless of which option is correct, determining the location of a seismogenic segment boundary would require detailed geologic mapping of the SF in the vicinity of Black Mountain and possibly as far north as Red Canyon. Conversely, if the vertical slip rate at Black Mountain and Red Canyon are roughly equivalent, and no potential seismogenic segment boundary can be identified between the two locations, then the two sites are likely on the same seismogenic segment and have experienced similar surface-faulting histories. In that case, a seismogenic boundary likely lies to the south of Black Mountain.

RECOMMENDATIONS FOR FUTURE PALEOSEISMIC STUDY

Based on the results of this paleoseismic reconnaissance, the UGS recommends the following paleoseismic studies be conducted on the Sevier and related faults. The recommendations are in order of decreasing priority:

1. Detailed geologic mapping of Black Mountain and vicinity to determine (a) the net vertical displacement of the volcanic rocks across the Sevier fault, and (b) if a seismogenic segment boundary exists close to Black Mountain.

2. If net vertical displacement is significantly different between Black Mountain and Red Canyon (results of [a] above), and no evidence of a seismogenic boundary is found near Black Mountain (results of [b] above), then prepare a detailed geologic map of the Sevier fault between Black Mountain and Red Canyon to determine if there is a segment boundary between those two locations.

3. Trench an alluvial scarp on the NTS of the TF in Arizona to collect surface-faulting information that could be applied to the NTS in Utah, which has no scarps.

4. Trench a minimum of one probable single-event and one multiple-event fault scarp in the Sevier Valley (hills near Panguitch) faults and folds to determine if the fault scarps are the result of surface faulting or are a consequence of aseismic folding. Although the relation of surface faulting in the SF hanging wall to the main SF will likely remain unresolved, determining whether or not the scarps are of seismogenic origin will better characterize the seismic hazard to Panguitch and the surrounding Sevier Valley.

5. Trench a single-event and a multiple-event fault scarp in the Sevier Valley (north of Panguitch) faults to better constrain the timing and magnitude of paleoearthquakes on those faults. Again, the relation between surface faulting there and on the main SF will likely remain unresolved, but the data will better characterize the seismic hazard to Panguitch and the surrounding Sevier Valley.

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