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
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PART V: BASIN AND RANGE PROVINCE EARTHQUAKE WORKING GROUP SEISMIC-HAZARD RECOMMENDATIONS

By

Gary E. Christenson, Christopher B. DuRoss, Michael D. Hylland,
William R. Lund, and Greg N. McDonald

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

August 2006

Final Technical Report
National Earthquake Hazards Reduction Program
Effective date: January 1, 2005
Expiration date: December 31, 2005
No-Cost Extension date: June 30, 2006
Cooperative Agreement number 03HQAG0008

PREFACE

The Utah Geological Survey (UGS) and U.S. Geological Survey (USGS) entered into a multi-year agreement in 2003 for cooperative earthquake-hazards studies in Utah. This report presents the results of studies performed during the third year (2005) of this cooperative agreement, which are presented in a series of self-contained reports. Part I includes both a technical and non-technical summary of the entire project. The remaining parts of the report cover the following topics: Part II - 2005 working group meetings and database updates, Part III - paleoseismic studies of the Collinston and Clarkston Mountain segments of the Wasatch fault zone (WFZ), Part IV – the potential for multi-segment ruptures on the central segments of the WFZ, and Part V - results of the Basin and Range Province Earthquake Working Group meeting.

DISCLAIMER

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

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PART I: TECHNICAL AND NON-TECHNICAL SUMMARIES

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TECHNICAL SUMMARY

Working Group Meetings and Database Updates

The Utah Geological Survey (UGS), in cooperation with the U.S. Geological Survey (USGS) and Utah Seismic Safety Commission, convened the 2005 earthquake working group meetings March 2-4. The Ground Shaking, Liquefaction, and Quaternary Fault Parameters Working Groups met to re-evaluate long-term plans to produce maps and develop partnerships for investigations and topics for future proposals. Priorities for future studies include better characterization of deep shear-wave-velocity structure and final development of the community velocity model for the Wasatch Front, additional paleoseismic investigations of critical faults in northern and southwestern Utah, and preparation of probabilistic liquefaction- and lateral-spread-hazard maps for Salt Lake Valley. The Earthquake-Induced Landslide Working Group did not meet in 2005.

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 2004 NEHRP-funded projects and other sources. Updates to the Quaternary fault and fold database and map were submitted to the USGS for inclusion in the national database, including the results of the Utah Quaternary Fault Parameters Working Group.

Collinston and Clarkston Mountain Segments, Wasatch Fault Zone Studies

The Collinston and Clarkston Mountain segments, the northernmost two segments of the WFZ in Utah, have been active during the Quaternary Period but show no evidence of Holocene surface faulting. The only fault scarps on Quaternary deposits along the Collinston segment are in the area of the Coldwater Canyon reentrant, which is at the segment boundary with the Brigham City segment to the south and includes numerous scarps that resulted at least in part from Holocene Brigham City-segment ruptures. Empirical analysis of scarp-profile data obtained in this study indicates that the timing of the late Holocene most recent surface-faulting earthquake (MRE) in the segment boundary area predates the MRE timing determined in trench studies by others farther south on the Brigham City segment; this suggests the Brigham City-segment MRE identified in the trench studies did not rupture the northernmost part of the Brigham City segment.

The only fault scarp on Quaternary deposits along the Clarkston Mountain segment is at Elgrove Canyon, in a reentrant near the south end of the main trace of the segment. Profiles indicate the scarp resulted from two or possibly three surface-faulting earthquakes, each producing approximately 2 m of vertical surface offset. Empirical analysis of the profile data, as well as geologic evidence, indicates the MRE probably occurred shortly prior to the Bonneville highstand of the Bonneville lake cycle. The surface-offset and timing data yield a maximum geologic (open-ended) slip rate of about 0.1 mm/yr for the past 18,000+ years. Empirical relationships between vertical displacement and surface rupture length predict a 30-km-long rupture during a large earthquake on the Clarkston Mountain segment, based on 2 m of per-event vertical displacement at Elgrove Canyon. Surface rupture beyond the mapped main trace during an earthquake could occur on the Short Divide fault or parallel, concealed fault to the south (and possibly both); any concealed southern extension of the main trace of the fault in the valley south of the Short Divide fault; and parts of adjacent segments. Calculations based on displacement and surface rupture length produce an expected earthquake moment magnitude in the range of **M** = 6.8-6.9.

Two profiles across the Bonneville-highstand shoreline scarp in the Coldwater Canyon reentrant provide data for use in calibrating diffusion-equation age determinations of nearby fault scarps. However, several complicating issues exist related to the application of these data to diffusion-equation modeling of fault-scarp age, and work to resolve these issues is ongoing.

Potential for Multi-Segment Ruptures, Wasatch Fault Zone

The WFZ is one of the best-studied normal faults in the Basin and Range Province, but the potential for multi-segment ruptures (MSRs) among its segments is poorly understood. Understanding the rupture behavior of the WFZ, including the possibility of MSRs between adjacent segments, is an important step in understanding normal-fault hazards and improving national, regional, and local earthquake-probability studies. This investigation considered the potential for two-segment ruptures from a dataset of 16 earthquakes occurring after ~6500 cal yr B.P. on the Brigham City, Weber, Salt Lake City, and Provo segments (BCS, WS, SLCS, and PS) of the WFZ.

Vertical-displacement (VD) data for these segments as well as the Nephi segment (NS) and Levan segment indicate a tendency toward single-segment ruptures (SSRs), but do not preclude the possibility of MSRs. For example, the largest VDs observed along the central WFZ correspond well with the maximum displacements predicted from a maximum-displacement – surface-rupture-length (SRL) regression for normal faults; however, 86-90% of the observed VD estimates are larger than the average displacements predicted by the segment lengths using average-displacement – SRL regressions for normal- and all-fault types. Also, when normalized by segment length, the majority (~68%) of the VD data fit within a half-ellipse-shaped slip envelope, which shows VD decreasing from a maximum of ~1.8-3.4 m near the segment centers to ~0.8-2.1 m near the segment ends, though several anomalously large VD estimates near the ends of the fault segments suggest the possibility of surface fault ruptures at least 20 km longer than the mapped segment lengths.

This MSR analysis includes a preferred set of six MSRs among the last 16 earthquakes on the BCS to PS. However, the paleoseismic data necessary to have confidence in such MSRs are limited. MSR potential is based on a comparison of timing information for earthquakes on adjacent segments having overlapping time ranges, and paleoseismic-event confidence based on the quality of available paleoseismic data. Among the possible MSRs, there is a prevalence of low- to medium-MSR-potential earthquake pairs and low to medium paleoseismic-event confidence, and a lack of high-potential MSRs based on high-confidence paleoseismic data, which preclude development of well-constrained MSR models. As the oldest paleoearthquakes are combined in three separate high-potential MSR pairs, additional investigations into the middle and early Holocene paleoearthquake histories on these segments are needed.

Four MSR scenarios (different combinations of SSRs and MSRs for one earthquake cycle) are generated for the central WFZ (e.g., scenario 2 includes a BCS-WS MSR and SSRs on the SLCS and PS) and new methods are developed to quantify the relative occurrence of the scenarios using MSR potential and paleoseismic-event confidence. Weights for two generalized fault-rupture models (weighted combination of different scenarios) and a quantitative model, based on the MSR analysis, are provided. The quantitative model indicates the more frequent occurrence of BCS-WS and SLCS-PS MSRs to WS-SLCS MSRs. A preferred MSR model (with relative weights for different fault-rupture models) is not provided due to the limits of available WFZ paleoseismic data. A simple, time-independent MSR model (e.g., a low-probability, large-SRL floating earthquake) should be used to account for WFZ MSRs in the 2007 update of the National Seismic Hazard Maps (NSHMs). Prior to finalizing a preferred model for use in the NSHMs, continued work is necessary to 1) extend these analyses to include possible MSRs between the PS and NS, 2) improve the paleoseismic-data density and quality, and include new paleoseismic data for the WS, PS, and NS, 3) moment balance the models, and 4) reach working-group consensus as to the preferred method of generating models and assigning relative weights.

Results of the Basin and Range Province Earthquake Working Group Meeting

The Basin and Range Province Earthquake Working Group (BRPEWG) convened to develop a consensus on five seismic-hazard issues in the Basin and Range Province (BRP) important to the USGS 2007 update of the National Seismic Hazard Maps (NSHMs). Scientists attending the Western States Seismic Policy Council (WSSPC)-sponsored Basin and Range Province Seismic Hazard Summit II (BRPSHSII) held in Reno, Nevada, in May 2004, first identified the five issues. Following BRPSHSII, WSSPC incorporated the issues into their Policy Recommendation (PR) 04-5, which advocated convening a broad-based group of technical experts to evaluate each of the issues and advise the USGS regarding the 2007 NSHM update. In response to PR 04-5, the WSSPC Basin and Range Province Committee (BRPC) and the UGS convened the BRPEWG under the auspices of WSSPC and the USGS NSHM Project. The BRPEWG was charged with reviewing information regarding the five issues, and developing consensus recommendations for the 2007 NSHM update. The BRPEWG drew its members from several BRP state geological surveys, federal government agencies, academic institutions and seismological laboratories, and geotechnical consulting firms. The BRPEWG met on March 8-10, 2006, in Salt Lake City, Utah.

The five seismic-hazard issues in the BRP that the BRPEWG considered are:

1. Use and relative weighting of time-dependent, Poisson, and clustering models in characterizing fault behavior.

2. Proper magnitude-frequency distributions (Gutenberg-Richter versus characteristic earthquake models) for BRP faults.
3. Use of length versus displacement relations to estimate earthquake magnitude.
4. Probabilities and magnitudes of multi-segment ruptures.
5. Resolving discrepancies between geodetic extension rates and geologic slip rates.

The BRPEWG recommendations are published in UGS Open-File Report 477, and appear in Part V of this report. The short-term recommendations reflect the BRPEWG's consensus on best professional practice at this time for the 2007 NSHM update. Recognizing that these critical issues can only be accommodated, not resolved, in the 2007 NSHMs, the BRPEWG also made recommendations for long-term research priorities and goals that will help both the USGS and other research institutions eventually resolve the issues to better refine the NSHMs in the future.

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, IV, and V reports.

NON-TECHNICAL SUMMARY

The Utah Geological Survey (UGS) and U.S. Geological Survey (USGS) entered into an agreement in 2003 for a multi-year program of cooperative earthquake-hazards studies in Utah. In 2005, the third year of these cooperative studies, the UGS held working group meetings and performed a variety of earthquake-related studies.

At the 2005 Utah Earthquake Working Group meetings, co-sponsored by the USGS and Utah Seismic Safety Commission, results of 2004 work were presented and discussed, plans for on-going and future work were developed, and the long-term earthquake-hazard mapping plans developed in 2003 were revised. Also, the UGS updated its earthquake databases originally compiled in 2003.

We performed non-trenching paleoseismic studies of the Collinston and Clarkston Mountain segments of the Wasatch fault zone (WFZ) in northern Utah, and assessed the potential for multi-segment ruptures and resulting larger earthquakes on the central segments of the WFZ. The UGS also organized the Basin and Range Province Earthquake Working Group which met in March 2006 to develop recommendations for the 2007 update of the USGS National Seismic Hazard Maps with respect to fault behavior and earthquake hazards in the Basin and Range Province.

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

<u>PART II</u>: EARTHQUAKE WORKING GROUPS AND DATABASE UPDATES

By

Gary E. Christenson, Christopher B. DuRoss, Michael D. Hylland,
and Greg N. McDonald

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

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ABSTRACT

The Utah Geological Survey (UGS), in cooperation with the U.S. Geological Survey (USGS) and Utah Seismic Safety Commission, convened the 2005 earthquake working group meetings March 2-4. The Ground Shaking, Liquefaction, and Quaternary Fault Parameters Working Groups met to re-evaluate long-term plans to produce maps and develop partnerships for investigations and topics for future proposals. The Earthquake-Induced Landslide Working Group did not meet this year.

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 2004 NEHRP-funded projects and other sources. Updates to the Quaternary fault and fold database and map were submitted to the USGS for inclusion in the national database, including the results of the Utah Quaternary Fault Parameters Working Group.

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 velocities (Vs30) and deep basin structure, and 2) new liquefaction potential and ground displacement maps. 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 and March 2005, co-sponsored by the UGS, USGS, and Utah Seismic Safety Commission, to update 2003 plans. Initial planning for the 2006 working group meetings on February 14-16, 2006, was also completed under this grant.

To bring working group members up-to-date on current research results in 2005, the first part of each of the working group meetings was devoted to presentations by researchers of their results. Each working group then 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 March is to define potential projects and partnerships for proposals in time to respond to the 2006 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, and geotechnical landslide shear-strength databases were formally updated and a final CD was included in the 2004 report. Information needed to use and understand each database is included in the introductory material on the CD. These databases have not yet been published and made available to the public, but have been distributed to researchers as needed. Each database includes a description of the information contained, criteria used in compiling data, and comprehensiveness of the database. The formal 2004 update for the Utah Quaternary fault and fold database and map was submitted to the USGS in March 2005 for inclusion in the national Quaternary fault and fold database.

RESULTS OF EARTHQUAKE WORKING GROUP MEETINGS

Meetings of the Ground Shaking, Liquefaction, and Quaternary Fault Parameters Working Groups were held in Salt Lake City on March 2-4, 2005. The results of the 2005 meetings are shown in appendix A. 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).

The Ground Shaking and Liquefaction Working Groups reviewed the 2004 update of their 2003 working group plans (appendices C, D) and determined that no 2005 updates were needed. 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 northern Salt Lake Valley to 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 Quaternary Fault Parameters Working Group revised their list of priorities for paleoseismic fault studies from Lund (2005) (appendix E), and listed the highest priority faults (appendix A). The Earthquake-Induced Landslide Working Group did not meet in 2005; their plan from 2003 in shown in Appendix F.

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. We updated all UGS databases to include all data available through 2005. Information on the 2005 updates is given below.

As part of a NEHRP-funded liquefaction study, geotechnical data from boreholes and cone-penetrometer tests have been compiled. The database covers Salt Lake Valley, and is at a University of Utah Web site (http://www.civil.utah.edu/~bartlett/ulag.html).

Shallow Shear-Wave Velocities (Vs30)

Relatively few new shallow (upper 30 m) shear-wave-velocity (Vs30) data became available in 2005. New data were collected on shallow shear-wave velocities outside of Salt Lake Valley in a NEHRP-funded study using spectral analysis of surface waves (SASW) methods at approximately 40 sites. These data were collected over the summer of 2005 and are being analyzed by Utah State University (USU). We will include them in the database once the analysis is complete and the data are submitted to the UGS. The USGS collected intermediate-depth shear-wave-velocity imaging surveys at several sites in Salt Lake and Utah Counties, but data are not yet available for inclusion in the database. We also funded a USU student to compile additional cone-penetrometer data available from Conetec, Inc. He completed a final report (Bischoff, 2005), and the new data are input into the database.

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Deep-Basin Structure

Few new data have been collected pertaining to deep-basin structure. The USGS performed a P wave seismic imaging survey in the southwestern Salt Lake Valley in 2003 and five intermediate-depth (100-300 m) shear-wave-velocity imaging surveys in Salt Lake Valley and Utah Valley in summer 2004. The USGS collected additional intermediate depth shear-wave-velocity data at five sites in northwestern Salt Lake Valley and the Spanish Fork area of southern Utah Valley in summer 2005. These data are not yet available for addition to the database. The intermediate-depth shear-wave-velocity imaging surveys collected by the USGS should provide data of use in modeling deep-basin structure.

Geotechnical Landslide Shear Strengths

Several new studies, chiefly of landslides in the Salt Lake Valley area, have recently been completed involving laboratory testing of soil and rock shear strengths for slope stability analysis. Laboratory test results have been incorporated into the database. Sources of data are principally geotechnical consultant's reports and the Utah Department of Transportation (UDOT).

Quaternary Faults and Folds

We completed a formal update in 2004 and submitted it to the USGS in March 2005 for incorporation into the national Quaternary fault and fold database. This update included a systematic revision of the database to better conform to the format of the national database, new trenching studies for various faults, and the results of the Utah Quaternary Fault Parameters Working Group review of fault trenching studies (Lund, 2005). The now-outdated version of the Utah Quaternary fault and fold database on the UGS Web site will be replaced with a link to the USGS national Quaternary fault and fold database Web site. The original version of the *Utah Quaternary Fault and Fold Database and Map* 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 cooperative agreement 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, and William R. Lund for facilitating the Ground Shaking, Liquefaction, 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 disk.

Lund, W.R., 2005, Utah Quaternary Fault Parameters Working Group – Review of Utah paleoseismic-trenching data and determination of consensus recurrence-interval and slip-rate estimates: Utah Geological Survey Bulletin 134, compact disk.

APPENDIX A

PRIORITIES FOR 2006 EARTHQUAKE RESEARCH IN UTAH

Utah Ground Shaking, Quaternary Fault Parameters, and Liquefaction Working Groups

Developed at the Salt Lake City meetings:
March 2-4, 2005

The Utah Geological Survey, Utah Seismic Safety Commission, and U.S. Geological Survey convened Utah's Earthquake Working Groups on March 2-4, 2005 to update priorities for earthquake research in Utah. Priorities evolve as work is completed, and the priorities for 2006 are listed below for each working group.

Ground Shaking Working Group:

- Collect data to better characterize the deep shear-wave velocity structure (greater than 150 m) along the Wasatch Front.
- Finalize development and testing of the Wasatch Front community velocity model.
- Continue laboratory testing of dynamic soil properties of Bonneville clays.

Quaternary Fault Parameters Working Group (perform detailed paleoseismic studies for the following fault zones, listed in order of priority):

- West Valley fault zone (Salt Lake County).
- Weber segment of the Wasatch fault zone (Weber and Davis Counties).
- Faults and folds beneath Utah Lake (Utah County).
- Washington fault (St. George area).
- East Cache fault zone (Cache Valley).

Liquefaction Working Group:

- Produce probabilistic liquefaction hazard map for southern Salt Lake County.
- Produce probabilistic lateral spread hazard map for northern Salt Lake County.
- Continue gathering subsurface data in Salt Lake County.
- Develop CPT-SPT correlations to allow lateral spread analysis from SPT data.
- Investigate the mapped prehistoric ground displacements in Salt Lake City using CPT.

Utah's Earthquake Working Groups include over 50 geologists, seismologists, and engineers from state and federal agencies, local governments, universities, and private consulting companies. The working groups are tasked with setting earthquake research goals for the State of Utah, and each has developed a plan for developing the next generation of hazard maps for the state. These plans can be viewed at the UGS Web site: http://ugs.utah.gov/ghp/workgroups/index.htm.

APPENDIX B
2005 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
Kris Pankow, UUSS
Bob Smith, UUSS
Gerard Schuster, UUGG
Kim Olsen, SDSU
Harold Magistrale, SDSU
Mark Petersen, USGS
Jim Bay, USUCEE
Marv Halling, USUCEE
Francis Ashland, UGS
Steve Bartlett, UUCE
Kyle Rollins, BYUCE
Ken Stokoe, UT
WuLung Chang, UUGG

<u>Liquefaction Working Group</u>
Steve Bartlett, UUCE, Facilitator
Barry Solomon, UGS
Bill Turner, Earthtec
Les Youd, BYUCE
Kyle Rollins, BYUCE
Loren Anderson, USUCEE
David Simon, SBI
Mark Petersen, USGS

<u>Earthquake-Induced Landslide Working Group (inactive)</u>
Francis Ashland, UGS, Facilitator
Randy Jibson, USGS
Tim McCrink, CGS
Robert Pack, USUCEE

Barry Solomon, UGS
Leslie Heppler, UDOT
Loren Anderson, USUCEE
Fulvio Tonon, UUGG
Jim Nordquist, AGEC
Jim Higbee, UDOT
Danny Horns, UVSC

<u>Invited Observers (all Working Groups)</u>
Bob Carey, DES
Barry Welliver, USSC Chair
Joergen Pilz, USSC Geoscience Committee Chair and Chair, Utah Geotechnical Group, ASCE
Darlene Batatian, Salt Lake County Geologist; Chair, Utah Section, AEG
David Marble, Utah Dam Safety

Quaternary Fault Parameters Working Group

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

APPENDIX 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.

<u>Research Needs</u>

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

***Ground-Shaking Working Group**

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

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.

*** Advisory Group Members**

Loren Anderson, Utah State University
Steve Bartlett, University of Utah
Clifton Farnsworth, UDOT
Travis Gerber, Brigham Young University
Dave Simon, Simon-Bymaster, Inc.
Barry Solomon, Utah Geological Survey
Bill Turner, Kleinfelder, Inc.
Les Youd, Brigham Young University

APPENDIX E

PRIORITIES FOR PALEOSEISMIC FAULT STUDIES

Utah Quaternary Fault Parameters Working Group
March 2005 (modified from Lund, 2005)

(1) Nephi segment WFZ
(2) West Valley fault zone
(3) Weber segment WFZ – MRE
(4) Weber segment WFZ - megatrench
(5) Faults beneath Utah Lake
(6) Great Salt Lake fault zone (Promontory section)
(7) Collinston and Clarkston Mountain segments WFZ
(8) Sevier/Toroweap fault
(9) Washington fault zone
(10) Cedar City-Parowan monocline/Paragonah fault
(11) Enoch graben
(12) East Cache fault zone (northern and southern sections)
(13) Clarkston fault
(14) Wasatch Range back-valley fault
(15) Hurricane fault zone (Cedar City section)
(16) Levan segment WFZ
(17) Gunnison fault
(18) Scipio Valley faults
(19) Faults beneath Bear Lake
(20) Eastern Bear Lake fault

APPENDIX F

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**

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

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

PART III: PALEOSEISMIC (NON-TRENCHING) INVESTIGATION OF THE COLLINSTON AND CLARKSTON MOUNTAIN SEGMENTS OF THE WASATCH FAULT ZONE, BOX ELDER COUNTY, UTAH

By

Michael D. Hylland

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

August 2006

Effective date: January 1, 2005
Expiration date: December 31, 2005
No-Cost Extension date: June 30, 2006
Cooperative Agreement number 03HQAG0008

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FIGURES

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ABSTRACT

The Collinston and Clarkston Mountain segments, the northernmost two segments of the Wasatch fault zone in Utah, have been active during the Quaternary Period but show no evidence of Holocene surface faulting. The only fault scarps on Quaternary deposits along the Collinston segment are in the area of the Coldwater Canyon reentrant, which is at the segment boundary with the Brigham City segment to the south and includes numerous scarps that resulted at least in part from Holocene Brigham City-segment ruptures. Empirical analysis of scarp-profile data obtained in this study indicates that the timing of the late Holocene most recent surface-faulting earthquake (MRE) in the segment boundary area predates the MRE timing determined in trench studies by others farther south on the Brigham City segment; this suggests the Brigham City-segment MRE identified in the trench studies did not rupture the northernmost part of the Brigham City segment.

The only fault scarp on Quaternary deposits along the Clarkston Mountain segment is at Elgrove Canyon, in a reentrant near the south end of the main trace of the segment. Profiles indicate the scarp resulted from two or possibly three surface-faulting earthquakes, each producing approximately 2 m of vertical surface offset. Empirical analysis of the profile data, as well as geologic evidence, indicates the MRE probably occurred shortly prior to the Bonneville highstand of the Bonneville lake cycle. The surface-offset and timing data yield a maximum geologic (open-ended) slip rate of about 0.1 mm/yr for the past 18,000+ years. Empirical relationships between vertical displacement and surface rupture length predict a 30-km-long rupture during a large earthquake on the Clarkston Mountain segment, based on 2 m of per-event vertical displacement at Elgrove Canyon. Surface rupture beyond the mapped main trace during an earthquake could occur on the Short Divide fault or parallel, concealed fault to the south (and possibly both); any concealed southern extension of the main trace of the fault in the valley south of the Short Divide fault; and parts of adjacent segments. Calculations based on displacement and surface rupture length produce an expected earthquake moment magnitude in the range of $\mathbf{M}$ = 6.8-6.9.

Two profiles across the Bonneville-highstand shoreline scarp in the Coldwater Canyon reentrant provide data for use in calibrating diffusion-equation age determinations of nearby fault scarps. However, several complicating issues exist related to the application of these data to diffusion-equation modeling of fault-scarp age, and work to resolve these issues is ongoing.

INTRODUCTION

This report summarizes a non-trenching paleoseismic investigation of the Collinston and Clarkston Mountain segments of the Wasatch fault zone (figure 1). These are the northernmost two segments of the Wasatch fault zone in Utah, and along with the Malad City segment in Idaho, are substantially less active than the more central segments of the fault zone to the south. Whereas the Collinston and Clarkston Mountain segments

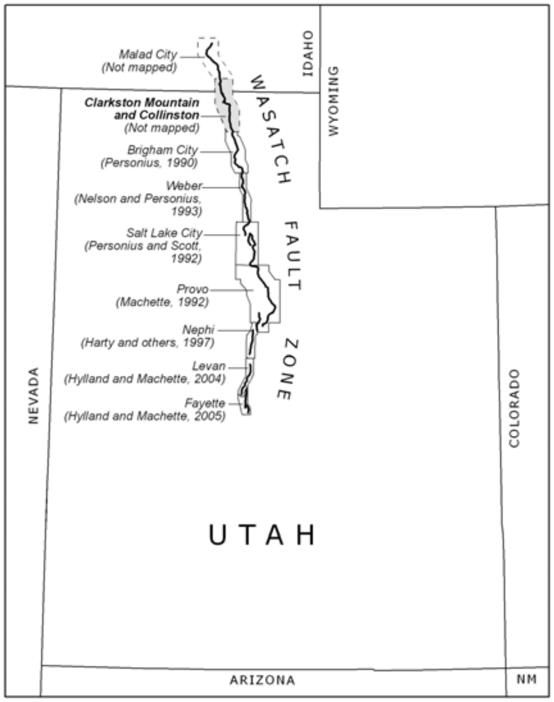


Figure 1. *Index map of Wasatch fault zone showing segments and published 1:50,000-scale strip maps.*

have been the subject of reconnaissance paleoseismic studies in the past (summarized in Machette and others, 1992a) and have been mapped in the context of 1:24,000-scale geologic quadrangle mapping (Oviatt, 1986a, 1986b; Biek and others, 2003), they have not had any detailed paleoseismic study, primarily owing to the scarcity of Holocene fault scarps and distance from large population centers. The purpose of this investigation is to confirm the presence/absence of fault scarps as determined by previous workers, verify mapped surficial geology in areas where scarps are present, and evaluate the timing of scarp formation using scarp-profile data.

This investigation consisted of a review of published and unpublished geologic mapping along the segments; aerial-photo and field reconnaissance to verify the existing geologic mapping, particularly map relations among Tertiary and Quaternary deposits, fault scarps, and shoreline scarps formed during stillstands of the latest Pleistocene Bonneville lake cycle; and measurement of 14 profiles across fault and shoreline scarps to obtain data for empirical and diffusion-equation age determinations. The scarp profiles were measured using an Abney level and telescoping stadia rod; scarp heights, slope angles, and net surface offsets were determined from computer plots of the scarp profiles. Terminology used to describe fault-scarp morphology, summarized in figure 2, follows that established by Bucknam and Anderson (1979), Machette (1982), and Hanks and others (1984). Metric (SI) units are used throughout this report except for elevations of map features (such as shorelines), which are reported using English units (feet) to be consistent with the base maps.

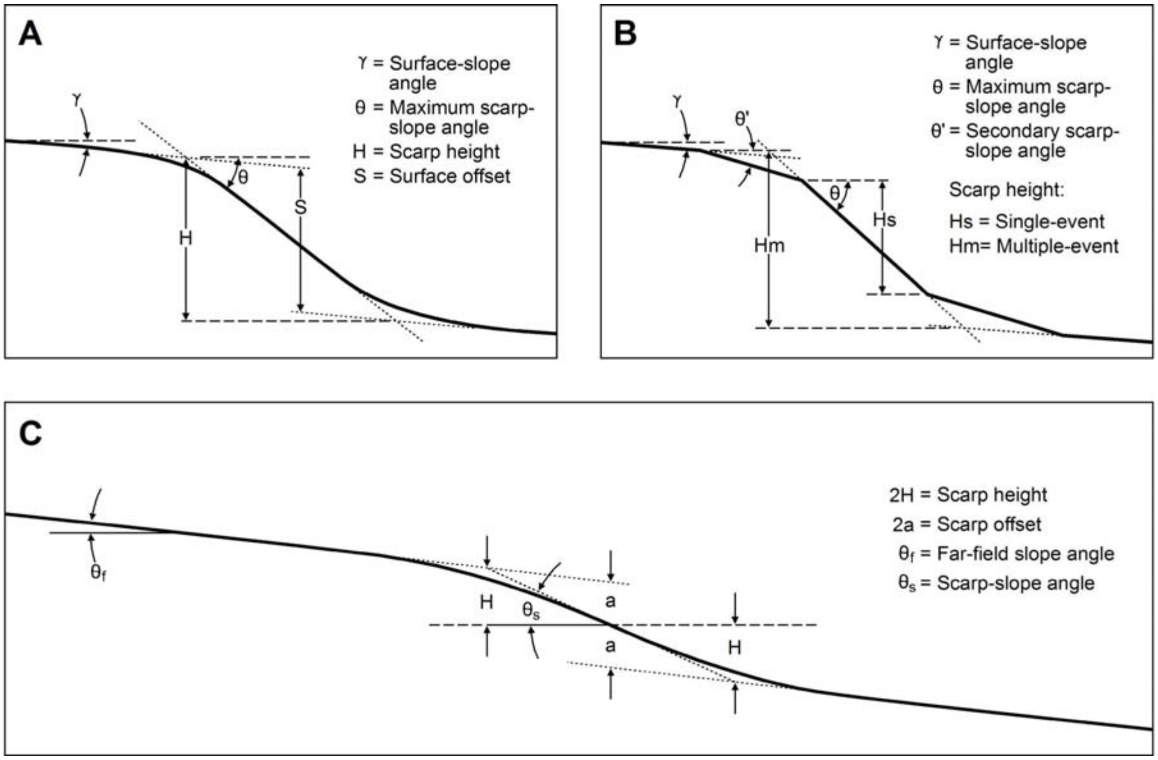


Figure 2. *Schematic diagrams illustrating fault-scarp nomenclature used in this report. A. Single-event scarp profile and measurements used in empirical scarp-age modeling (modified from Bucknam and Anderson, 1979). B. Multiple-event scarp profile and measurements used in empirical scarp-age modeling (modified from Machette, 1982). C. Generalized scarp profile and measurements used in diffusion-equation scarp-age modeling (after Hanks and others, 1984).*

PREVIOUS WORK

Cluff and others (1974) used low-sun-angle aerial photography and limited field reconnaissance to map lineaments, including fault scarps, along the Wasatch fault zone from Brigham City, Utah, to 4 km northeast of Malad City, Idaho. This part of the Wasatch fault zone was subsequently divided into three segments, primarily on the basis of geomorphic and structural relations: from south to north, the Collinston, Clarkston Mountain, and Malad City segments (figure 3). Reconnaissance mapping and limited paleoseismic data to the south led Schwartz and Coppersmith (1984) to initially define the Collinston segment as extending approximately 30 km between Brigham City and the town of Collinston. Personius (1990) redefined the south end of the Collinston segment as being located near Honeyville, 12 km north of Brigham City; he included the southern approximately 10 km of the Collinston segment on his 1:50,000-scale surficial-geologic strip map of the Brigham City segment, and measured several scarp profiles in the segment-boundary area. Machette and others (1991, 1992a) subdivided the remaining northern 36 km of the Wasatch fault zone into the Clarkston Mountain segment (19 km) and Malad City segment (17 km), placing the segment boundary at the Woodruff spur in southern Idaho.

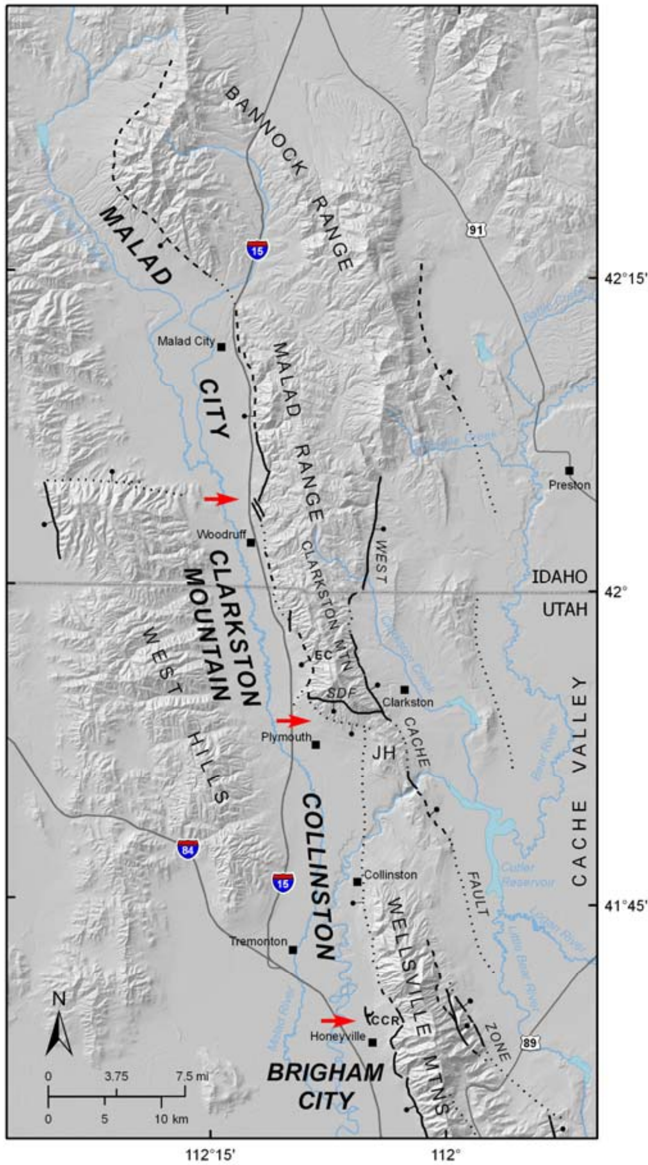


Figure 3. *Northern segments of the Wasatch fault zone (large, bold type), including the Collinston and Clarkston Mountain segments, and other nearby faults having Quaternary movement. Faults shown by heavy lines, dashed where approximately located, dotted where concealed; bar and ball on downthrown side; red arrows show segment boundaries. CCR, Coldwater Canyon reentrant; EC, Elgrove Canyon; JH, Junction Hills; SDF, Short Divide fault. Fault traces after Black and others (2003; Utah), and U.S. Geological Survey and Idaho Geological Survey (2006; Idaho).*

Doelling's (1980) 1:125,000-scale geologic map of Box Elder County shows generalized geology along the Collinston and Clarkston Mountain segments. More detailed (1:24,000 scale) geologic maps include those of Oviatt (1986a, 1986b) in the area of the Collinston segment and Biek and others (2003) in the area of the Clarkston Mountain segment.

GEOLOGIC SETTING

The Collinston and Clarkston Mountain segments of the Wasatch fault zone lie along the base of the steep western slopes of the Wellsville Mountains and southern Malad Range (Clarkston Mountain), respectively (figure 3). Bedrock in both ranges consists primarily of Paleozoic sedimentary rocks. A major topographic saddle exists between the northern end of the Wellsville Mountains and southern end of Clarkston Mountain, through which the Bear River flows westward out of Cache Valley into the Great Salt Lake basin. Bedrock in this area, exposed in and adjacent to the Junction Hills, consists of Paleozoic sedimentary rocks and Tertiary basin-fill deposits, the latter of which are typically assigned to the Salt Lake Formation. Outcrops of Salt Lake Formation are also present in the reentrant in the vicinity of Elgrove Canyon near the southern end of Clarkston Mountain. Quaternary deposits along the fault zone include nearshore lacustrine sediments deposited in Lake Bonneville, fan alluvium, talus and colluvium, and mass-movement deposits.

Latest Pleistocene Lake Bonneville had a pronounced effect on the surficial geology of the area. Lacustrine sediments and the lake's two highest shoreline complexes are preserved along both the Collinston and Clarkston Mountain segments. As summarized by Currey (1990) and Oviatt and others (1992), the Bonneville lake cycle began around 30 ka. Over time, the lake rose and eventually reached its highest level at the Bonneville shoreline around 18,000 cal yr B.P. (calendar-calibrated radiocarbon ages in this discussion from D.R. Currey, University of Utah, written communication to Utah Geological Survey, 1996). At the Bonneville level, lake water overflowed the low point on the basin rim at Zenda in southeastern Idaho, spilling into the Snake-Colombia River drainage basin. Around 16,800 cal yr B.P., the alluvial-fan deposits at the Zenda outlet failed catastrophically, resulting in a rapid drop in lake level of approximately 100 m associated with the Bonneville Flood. The lake level stabilized when further erosional downcutting was essentially stopped by the bedrock-controlled Red Rock Pass threshold. The lake remained at this level for possibly over 2500 years (Godsey and Chan, 2005), forming the Provo shoreline. A change in climate to warmer and drier conditions caused the lake to regress rapidly from the Provo shoreline to near modern Great Salt Lake levels by around the beginning of the Holocene.

COLLINSTON SEGMENT

General Description

The extent of the Collinston segment is poorly defined because of the absence of post-Lake Bonneville fault scarps along most of its length (Schwartz and Coppersmith, 1984; Oviatt, 1986a, 1986b; Personius, 1990; Machette and others, 1992a; this study). The southern end of the segment is in a reentrant in the mountain front 2 km northeast of Honeyville (Coldwater Canyon reentrant of Oviatt, 1986a) (figure 3). Here, the trend of the fault changes abruptly, the amount of net surface offset of similar-aged deposits changes substantially, and Holocene fault scarps characteristic of the Brigham City segment to the south are absent to the north (Personius, 1990; Machette and others, 1992a). The northern end of the Collinston segment is generally considered to be in the vicinity of Short Divide at the southern end of Clarkston Mountain (Machette and others, 1992a; Biek and others, 2003) (figure 3), where two down-to-the-south normal faults extend east-west between the Collinston and Clarkston Mountain segments (see "Clarkston Mountain Segment" discussion below).

The topography of the area between the Wellsville Mountains and Clarkston Mountain suggests a south-to-north decrease in total throw on the Collinston segment (Machette and others, 1992a). Machette and others (1992a) proposed the presence of the West Cache fault zone, which lies within 10 km east of the Collinston and Clarkston Mountain segments (figure 3), as a possible explanation for the decrease in throw. The West Cache fault zone has undergone movement in the Holocene (Solomon, 1999; Black and others, 2000), indicating an apparent eastward transfer of extension, or strain partitioning, from the Wasatch fault zone to the West Cache fault zone in the late Quaternary.

A northwest-trending, down-to-the-southwest, low-angle normal fault (Beaver Dam fault; Goessel, 1999; Goessel and others, 1999) is present in the area between the Wellsville Mountains and Clarkston Mountain. This fault extends along the west side of the Junction Hills from the southern end of Clarkston Mountain to the West Cache fault zone at the northeastern end of the Wellsville Mountains, diagonally crossing the topographic divide between Cache Valley and the Great Salt Lake basin. Sprinkel (1976) first described the fault, and cited the apparent juxtaposition of Salt Lake Formation against Lake Bonneville sediments near the south end of the fault as evidence for late Pleistocene movement. However, Quaternary fault scarps are absent along the entire length of the fault, the inferred trace being concealed beneath lacustrine, landslide, and colluvial deposits (Sprinkel, 1976; Oviatt, 1986b; Biek and others, 2003). If Quaternary movement has occurred along this fault, it may have been subsidiary to primary rupture on the Collinston segment or West Cache fault zone. The Beaver Dam fault has been tentatively proposed as a new segment of the Wasatch fault zone (Goessel, 1999; Goessel and others, 1999). Given the structural uncertainties associated with this fault and the lack of compelling geologic evidence, I do not treat it herein as an independent segment of the Wasatch fault zone, but rather follow the traditional segmentation scheme of Schwartz and Coppersmith (1984) and Machette and others (1992a).

Bonneville-lake-cycle and younger deposits conceal the trace of the Collinston segment along nearly its entire length (Oviatt, 1986a, 1986b; Personius, 1990; Machette and others, 1992a; this study). The only fault scarps on Quaternary deposits that have been reported by previous workers are in the area of the Coldwater Canyon reentrant. Personius (1990) interpreted the northernmost of these fault scarps—an indistinct, eroded, 2-km-long scarp on Bonneville-lake-cycle lacustrine deposits and Provo-aged fan alluvium—as the north end of a Brigham City-segment rupture, and I concur. North of this scarp, isolated outcrops of Paleozoic and Tertiary bedrock west of the main mountain front help to constrain the location of the concealed trace of the Collinston segment, and indicate that the fault lies between the Bonneville and Provo shorelines in several places

(Oviatt, 1986a, 1986b). Therefore, the most recent Collinston-segment surface faulting occurred sometime before the Bonneville highstand at 18-16.8 ka. Scarps on Quaternary deposits along the Collinston segment north of the Coldwater Canyon reentrant all appear to be associated with Lake Bonneville shorelines or mass movements. The steep bedrock escarpments along the Wellsville Mountains and Junction Hills to the north suggest that the Collinston segment may have been relatively active in late Pleistocene time (Machette and others, 1992a).

Surficial Geology of the Coldwater Canyon Reentrant

Quaternary deposits in the general area of the Coldwater Canyon reentrant consist of fan alluvium, lacustrine sediment of the Bonneville lake cycle, hillslope colluvium, and mass-movement deposits (figure 4). As mapped by Personius (1990), the fan alluvium includes two pre-Bonneville units, one Bonneville-aged unit graded to the Provo shoreline, and three post-Bonneville units. The two pre-Bonneville alluvial-fan units (af5 and af4) form high, remnant surfaces at the mouths of Coldwater, Jim May, and Two Jump Canyons. The af5 and af4 surfaces are as high as about 40 m and 20 m, respectively, above adjacent modern stream channels. Soil developed on the af5 deposits is characterized by a strong argillic B horizon and stage III carbonate morphology, and soil developed on the af4 deposits is characterized by a moderate argillic B horizon and stage II-III carbonate morphology; both units are probably of middle Pleistocene age (Personius, 1990). The Bonneville shoreline, at an altitude of 5200 ft in this area, cuts and forms large scarps on both of these units. At the mouth of Jim May Canyon, two parallel fault scarps form a relatively large graben on the af5 deposits. The main, west-facing scarp is 39 m high, and the net surface offset across the graben is 12 m (Personius, 1990).

The Provo shoreline (figure 4) is at an altitude of about 4800 ft in this area. Alluvial-fan deposits graded to the Provo shoreline (afp) are present in isolated exposures where they have not been buried by younger fan alluvium. Fault scarps on the order of about 10 m high are present on afp deposits at two locations: about 1 km southwest of the mouth of Two Jump Canyon, and midway between the Provo and Bonneville shorelines west of Two Jump Canyon. Most of the ground surface between the Provo and Bonneville shorelines, as well as much of the surface below the Provo shoreline, is covered by unfaulted post-Provo fan alluvium (af2, af1, afy).

Lake Bonneville nearshore sand and gravel deposits are present immediately below the Bonneville (lbg) and Provo (lpg) shorelines (figure 4). Two short, parallel scarps are present on a small exposure of lacustrine sediment, mapped by Oviatt (1986a) and Personius (1990) as shoreline sand and gravel (unit lbg on figure 4), immediately south of the mouth of Coldwater Canyon (figures 4 and 5). Neither Oviatt (1986a) nor Personius (1990) delineated these scarps on their maps. The lower (western) scarp is about 7-9 m high and the upper (eastern) scarp is about 13-15 m high. The scarps are truncated at both ends by Holocene fan alluvium. Given that these scarps are at an elevation between the Bonneville and Provo shorelines, trend slightly oblique to topographic contours, and are on-trend with the 10-m-high fault scarp to the south, I interpret them to be fault scarps rather than lacustrine depositional features such as beach berms. Also, the very coarse (bouldery) nature of the deposits suggests that they may comprise pre-Bonneville-shoreline fan alluvium, possibly correlative with late Pleistocene fan alluvium (af3) mapped elsewhere along the Wasatch fault zone (see, for example, Nelson and Personius, 1993). The Bonneville sand and gravel deposits appear to form a discontinuous veneer over the older, bouldery deposits.

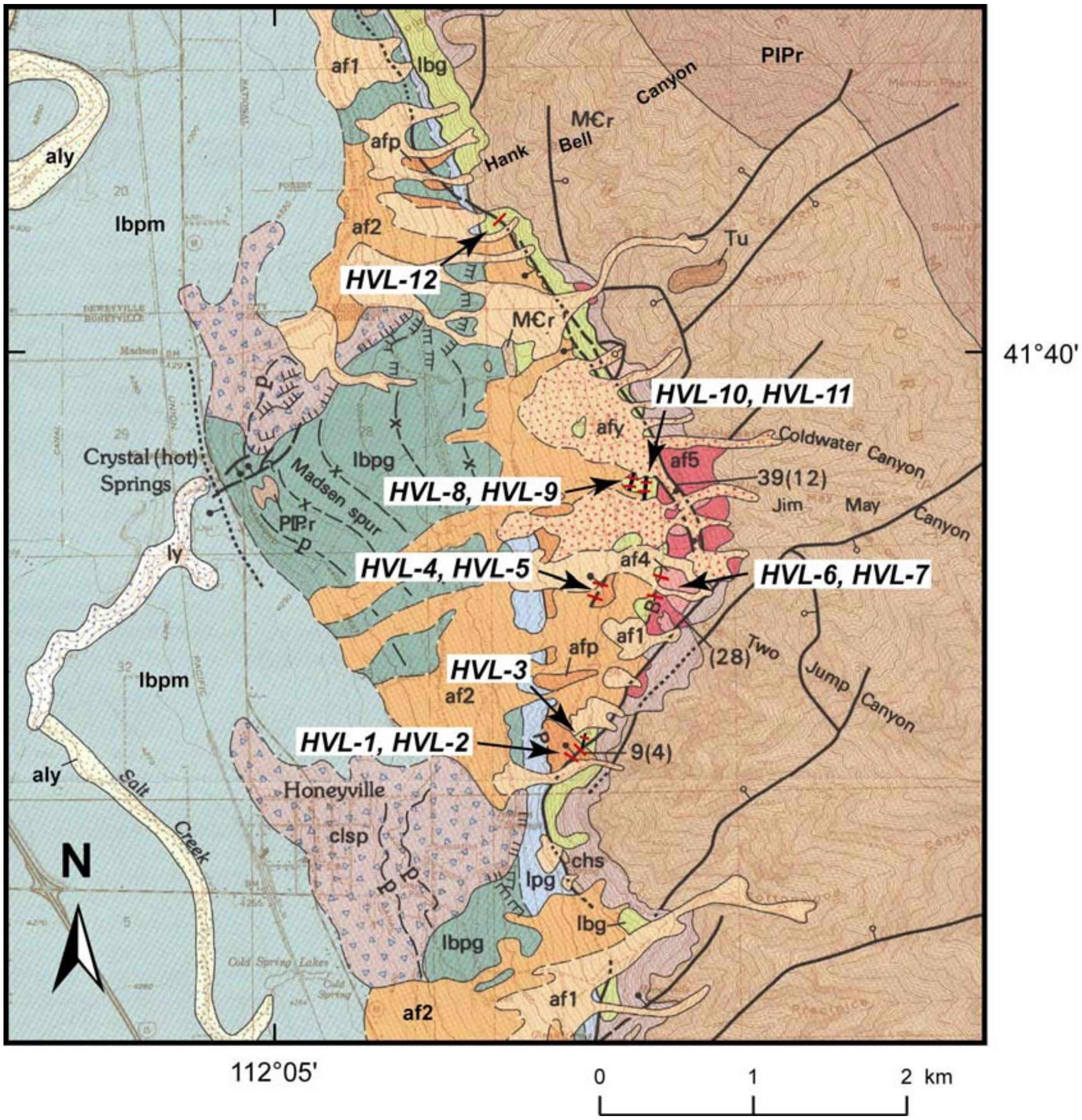
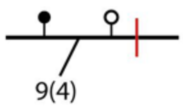


Figure 4a. *Surficial-geologic map of the segment boundary between the Collinston and Brigham City segments (Coldwater Canyon reentrant), showing locations of scarp profiles measured in this study (modified from Personius, 1990). Explanation given on figure 4b.*

EXPLANATION

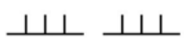
aly	Younger stream alluvium (Holocene - uppermost Pleistocene)
ly	Marsh and lacustrine deposits (Holocene - uppermost Pleistocene)
af1	Fan alluvium (upper Holocene)
af2	Fan alluvium (middle Holocene - uppermost Pleistocene)
afy	Younger fan alluvium (Holocene - uppermost Pleistocene)
afp	Fan alluvium related to Provo shorelines (uppermost Pleistocene)
af4	Fan alluvium (upper middle Pleistocene)
af5	Fan alluvium (middle Pleistocene)
lpg	Lacustrine sand and gravel related to Provo shorelines (uppermost Pleistocene)
lbg	Lacustrine sand and gravel related to Bonneville shorelines (upper Pleistocene)
lbpg	Lacustrine sand and gravel related to Provo and Bonneville shorelines (upper Pleistocene)
lbpm	Lacustrine silt and clay related to Provo and Bonneville shorelines (upper Pleistocene)
chs	Hillslope colluvium (Holocene to upper Pleistocene)
clsp	Lateral spread deposits (Holocene to upper Pleistocene) (reinterpreted by Harty and Lowe [2003] as mass-movement deposits not associated with liquefaction-induced lateral spread)
PIPr	Lower Permian to Pennsylvanian sedimentary rocks
MCr	Mississippian to Cambrian sedimentary rocks



Normal fault - Bar and solid ball on downdropped side along Wasatch fault zone; bar and hollow ball along other faults. Dashed where approximately located, dotted where concealed. Height of fault scarp and amount of geomorphic surface offset (in parentheses) shown in meters (from Personius, 1990). Red line shows location of scarp profile measured in this study

– – –B– – – Major shorelines related to levels of the Bonneville lake cycle - May coincide with geologic contact

B - Highest shoreline of the Bonneville level
P - Highest shoreline of the Provo level
p - Other shorelines of the Provo level (mostly regressive)
x - Undesignated shorelines of the Bonneville lake cycle



Landslide escarpment - Main scarps and fissures; may coincide with geologic contacts

Figure 4b. *Explanation for surficial-geologic map of the segment boundary between the Collinston and Brigham City segments (Coldwater Canyon reentrant), shown on figure 4a.*

Scarp Profiles

Fault Scarps

I measured a total of 10 profiles across fault scarps in the Coldwater Canyon/Honeyville area (figure 4): two profiles (HVL-1 and HVL-2) across the main scarp southwest of Two Jump Canyon and a third profile (HVL-3) across a small splay off of the main scarp; two profiles (HVL-4 and HVL-5) across the scarp west of Two

Jump Canyon; two profiles across each of the lower (HVL-8 and HVL-9) and upper (HVL-10 and HVL-11) scarps near the mouth of Coldwater Canyon; and one profile (HVL-12) across the northernmost scarp on Quaternary deposits, south of Hank Bell Canyon. Table 1 summarizes the scarp morphometry data. These profiles are intended to provide data, using empirical and diffusion-equation models, to evaluate along-strike temporal variation in rupture patterns by comparing the timing of Brigham City-segment surface faulting in the segment boundary area with that developed from paleoseismic trenching studies to the south (Personius, 1991; McCalpin and Forman, 2002).

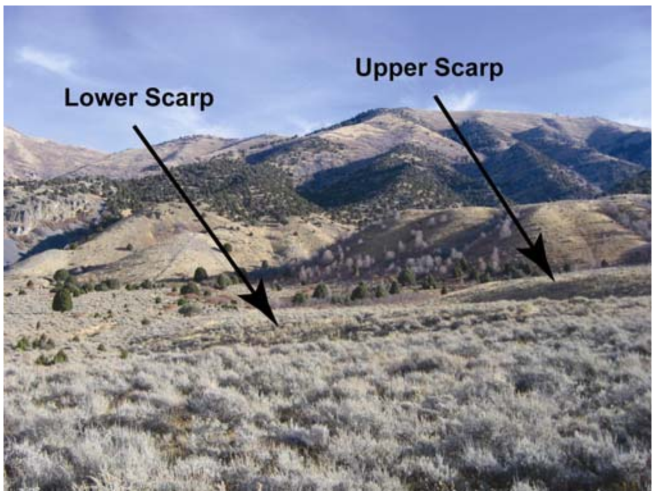


Figure 5. *Fault scarps near the mouth of Coldwater Canyon (view to the northeast). Lower (western) scarp is 7-9 m high and upper (eastern) scarp is 13-15 m high. See scarp profiles HVL-8 through HVL-11 (figures 9 and 10). Elevated surface in mid-ground above upper scarp is underlain by middle Pleistocene fan alluvium (af5), and surface in foreground is underlain by younger fan alluvium (afy); refer to figure 4.*

Profiles HVL-1 and HVL-2 indicate that the main fault scarp on Provo-aged fan alluvium at the south end of the Coldwater Canyon reentrant likely resulted from two surface-faulting earthquakes (figure 6). The cumulative surface offset of 3.4-3.7 m (table 1) is larger than would be expected from a single faulting event near the end of a segment (mid-segment Holocene surface displacements have averaged about 2-3 m on the central segments of the Wasatch fault zone; Machette and others, 1992a, 1992b; Lund, 2005), and the composite form of profile HVL-2 is consistent with two events. Personius (1990) also profiled this scarp and, based on a calculated 4 m of surface offset, concluded that the scarp resulted from at least two surface-faulting earthquakes. I determined scarp height and maximum scarp-slope angle associated with the most recent event (MRE) and penultimate event (PE) using the two straight-line segments of the scarp face on profile HVL-2, and geologic observations of textural changes in the scarp-face deposits at profile HVL-1 that correspond to the two scarp-face segments of profile HVL-2. Empirical analysis (after Bucknam and Anderson, 1979) of the scarp heights and maximum scarp-slope angles associated with the MRE, as well as those of the single-event splay scarp (profile HVL-3), indicates a mid-Holocene surface-faulting earthquake based on the position of the data points between regression lines for the Fish Springs and Drum Mountains fault scarps (figure 7). Interestingly, the data points plot well below the regression line for the Fish Springs fault scarp, which is known from radiocarbon dating to have formed sometime after 2280±70 ^{14}C yr B.P., perhaps about 2000 years ago

(Bucknam and others, 1989). The scarp-height – slope-angle data therefore indicate that the timing of the MRE in the segment-boundary area predates the timing determined for the MRE at the Brigham City trench site 15 km to the south (event Z; 2100±800 cal yr B.P.) (McCalpin and Forman, 2002; Lund, 2005). Apparently the MRE surface rupture documented at the Brigham City trench site did not propagate all the way to the north end of the Brigham City segment.

Table 1. *Scarp-profile data from the Coldwater Canyon/Honeyville (HVL) and Elgrove Canyon (EC) areas.*

Profile	H_s (m)	H_m (m)	S (m)	θ (º)	θ' (º)	γ (º)	Comments
HVL-1 (full scarp)	-	9.0	3.4	24.5	24.5	16.0	MES (simple morphology)
HVL-1 (MRE)	4.3	-	1.6	24.5	-	16.0	H_s based on field observations
HVL-1 (PE)	4.7	-	1.8	-	24.5	16.0	-
HVL-2 (full scarp)	-	11.7	3.7	27.0	20.0	16.0	MES (pronounced bevel)
HVL-2 (MRE)	5.2	-	1.7	27.0	-	16.0	-
HVL-2 (PE)	6.5	-	2.0	-	20.0	16.0	-
HVL-3	3.0	-	1.0	22.0	-	15.5	SES
HVL-4	-	9.4	5.3	24.0	20.0	10.0	MES (slight bevel)
HVL-5	-	10.5	6.6	24.0	19.0	8.0	MES (slight bevel)
HVL-6	26.5	-	17.0	32.0	-	13.0	Bonneville shoreline scarp
HVL-7	23.0	-	15.8	30.0	-	10.5	Bonneville shoreline scarp
HVL-8	-	8.9	6.6	24.5	21.5, 15.5	4.0	MES (pronounced bevel); min. *S*
HVL-9	-	7.3	5.7	22.0	15.0	5.0	MES (pronounced bevel); min. *S*
HVL-10	-	13.4	9.9	25.0	17.5	6.0	MES (pronounced bevel)
HVL-11	-	14.8	11.2	26.0	23.0, 15.5	5.0	MES (pronounced bevel)
HVL-12	3.0	-	1.0	16.0	-	11.5	SES
EC-1 (full scarp)	-	6.2	2.9±1.1	17.5	10.0	4.5 (u), 9.0 (l)	MES (pronounced bevel); min. *S*
EC-1 (MRE)	2.8	-	~2.1	17.5	-	4.5 (u), 9.0 (l)	Min. *S*
EC-1 (PE)	3.4	-	~1.9	-	10.0	4.5 (u), 9.0 (l)	May be min. *S*
EC-2 (full scarp)	-	6.7	3.3±0.8	16.5	13.5	5.5 (u), 9.0 (l)	MES (slight bevel); min. *S*
EC-2 (MRE)	2.9	-	~1.9	16.5	-	5.5 (u), 9.0 (l)	Min. *S*
EC-2 (PE)	3.8	-	~2.2	-	13.5	5.5 (u), 9.0 (l)	May be min. *S*

Symbols and abbreviations:

H_s, scarp height (single-event)
H_m, scarp height (multiple-event)
S, surface offset
θ, maximum scarp-slope angle
θ', secondary scarp-slope angle
γ, ambient (far-field, fan) slope angle

MES, multiple-event scarp
SES, single-event scarp
MRE, most recent event
PE, penultimate event
l, lower fan surface
u, upper fan surface

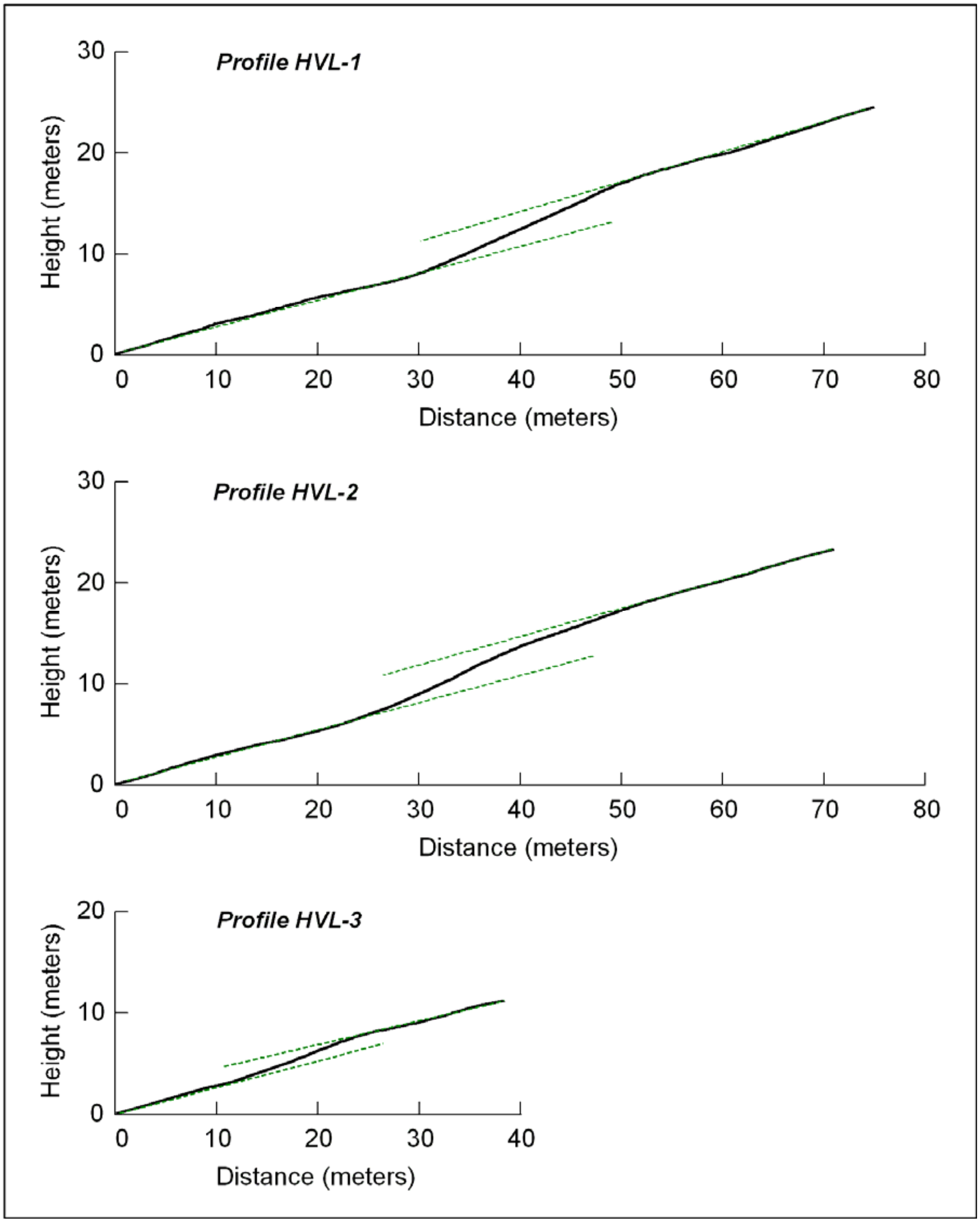


Figure 6. *Scarp profiles in Coldwater Canyon reentrant area near Honeyville, southwest of Two Jump Canyon. Profiles HVL-1 and HVL-2 are on main-trace scarp, and HVL-3 is on splay scarp. Dashed lines show averaged ambient (far-field) surface slope. Profile locations are shown on figure 4, and data are summarized in table 1.*

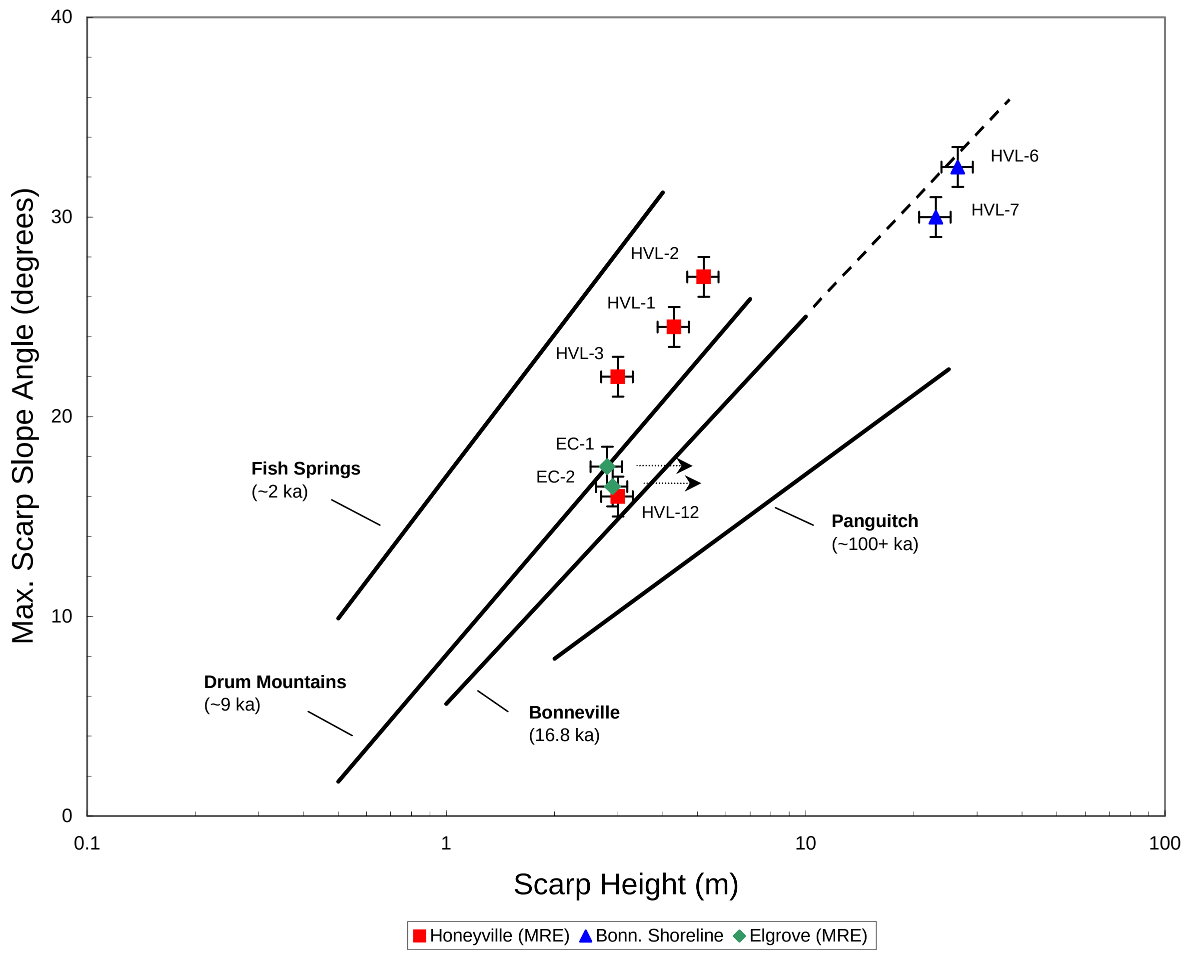


Figure 7. *Scarp-height – slope-angle relationships for fault scarps and the Bonneville shoreline scarp near Honeyville (Coldwater Canyon reentrant), and the fault scarp at Elgrove Canyon (Clarkston Mountain segment). Also shown are best-fit empirical regression lines of Bucknam and Anderson (1979; solid lines) for fault scarps at Fish Springs, Drum Mountains, and Panguitch, Utah, and for shoreline scarps of the Bonneville highstand. Fault-scarp age estimates from Bucknam and others (1989; Fish Springs), Pierce and Colman (1986; Drum Mountains), and Bucknam and Anderson (1979; Panguitch). Dashed part of Bonneville regression line is projected from the Bucknam and Anderson (1979) data. Arrows indicate that scarp height is a minimum value due to partial burial by post-faulting deposition of fan alluvium on the hanging wall. Scarp-profile data are summarized in table 1.*

Profiles HVL-4 and HVL-5 (figure 8) indicate that the scarp on Provo-aged fan alluvium west of Two Jump Canyon likely resulted from at least three surface-faulting earthquakes. Both profiles show composite form, and indicate cumulative surface offset of 5.3-6.6 m (table 1). Scarp heights and maximum scarp-slope angles associated with

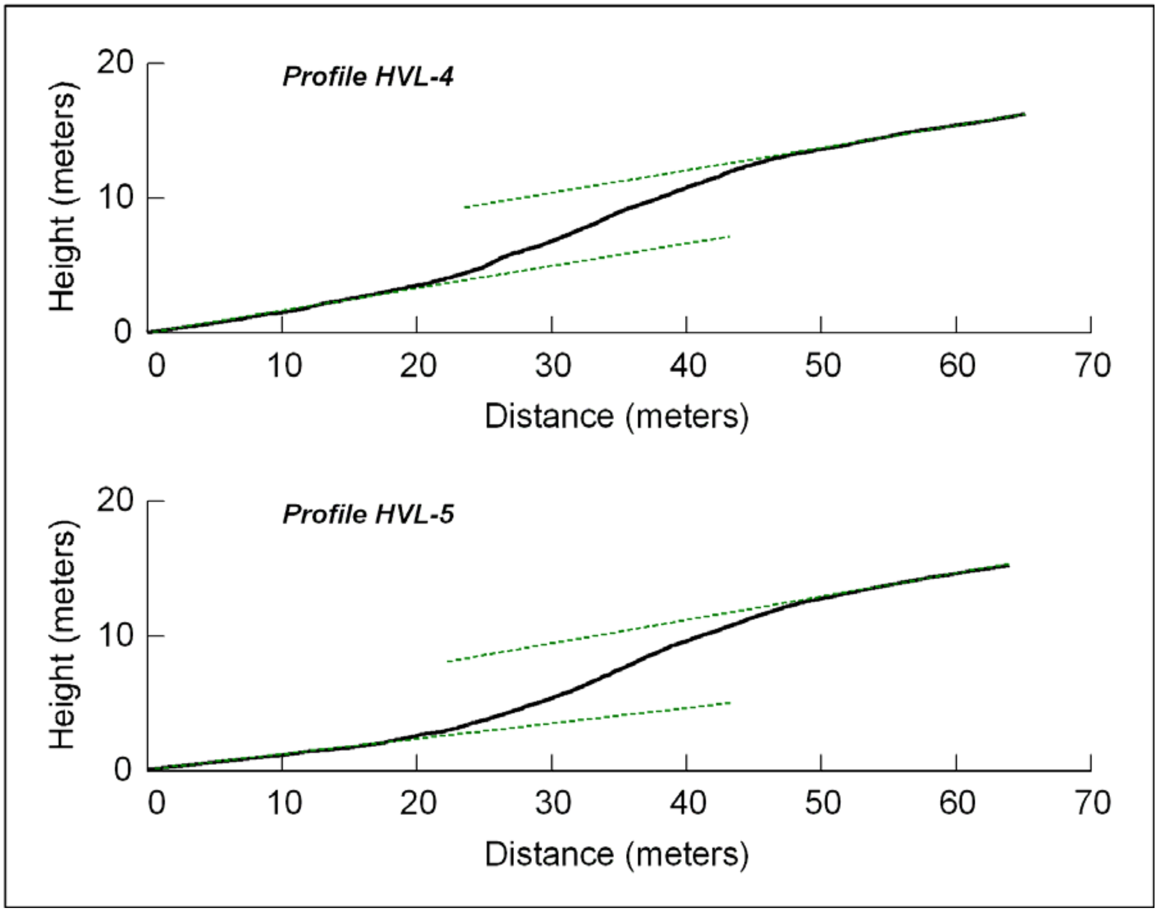


Figure 8. *Scarp profiles HVL-4 and HVL-5 in Coldwater Canyon reentrant area near Honeyville, west of Two Jump Canyon. Dashed lines show averaged ambient (far-field) surface slope. Profile locations are shown on figure 4, and data are summarized in table 1.*

individual faulting events cannot be distinguished from these profiles with any reasonable degree of confidence, so no empirical analysis was performed using these data.

Profiles HVL-8 and HVL-9 (lower scarp; figure 9) and HVL-10 and HVL-11 (upper scarp; figure 10) indicate that the two parallel scarps on pre-Bonneville fan alluvium (see "Description" discussion above, and figure 5) near the mouth of Coldwater Canyon resulted from numerous surface-faulting earthquakes. The surfaces above and below the upper scarp appear to be correlative, consisting of pre-Bonneville fan alluvium with a veneer of Lake Bonneville sand and gravel. This is not the case for the lower scarp, where the footwall deposits are pre-Bonneville fan alluvium/Bonneville sand and gravel, but the hanging-wall deposits are Holocene fan alluvium. Therefore, the cumulative surface offset of 9.9-11.2 m determined for the upper scarp is representative of total offset, whereas the cumulative surface offset of 5.7-6.6 m determined for the lower scarp is a minimum value of total offset (table 1). The minimum net cumulative

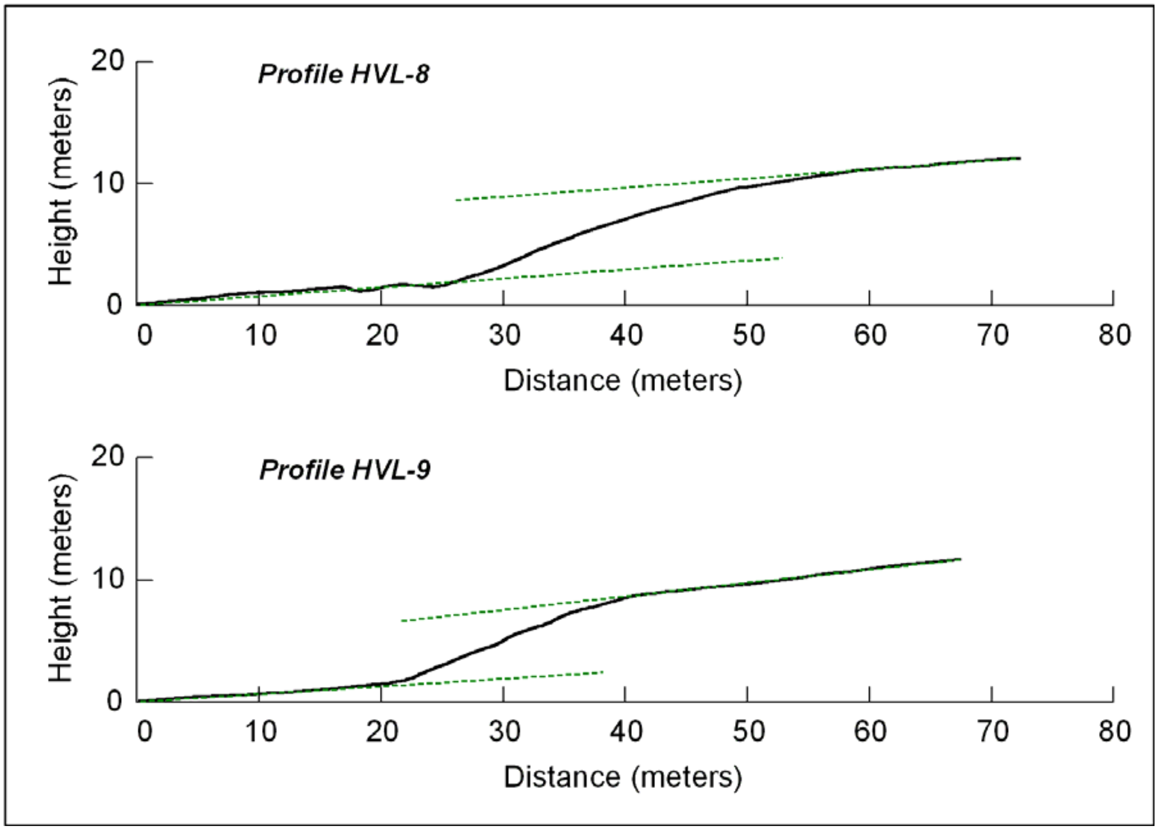


Figure 9. *Scarp profiles HVL-8 and HVL-9 in Coldwater Canyon reentrant area near Honeyville, on lower (western) of two scarps near mouth of Coldwater Canyon. Dashed lines show averaged ambient (far-field) surface slope. Note that deposits underlying footwall and hanging-wall surfaces are not correlative. Profile locations are shown on figure 4, and data are summarized in table 1.*

surface offset across both faults is approximately 16.7 m. Assuming offset per event is ≤ 2 m, these two scarps represent at least eight surface-faulting earthquakes. For the same reasons given for HVL-4 and HVL-5 in the preceding paragraph, no empirical analysis was performed using the profile data for these scarps. Also, if the faulted deposits are pre-Bonneville in age, and if some of the surface faulting occurred prior to Lake Bonneville reaching this elevation, then transgressional and nearshore lacustrine erosion of the scarp during the Bonneville highstand might have compromised the suitability of the profile data for meaningful diffusion-equation modeling.

Profile HVL-12 (figure 11) is across the relatively obscure fault scarp in the northern part of the Coldwater Canyon reentrant, originally identified by Personius (1990) with the aid of low-sun-angle aerial photos. Although the scarp can be traced over a distance of about 2 km, it is unsuitable for profiling along much of its length due to stream incision, erosion associated with spring discharge, and spatial coincidence with a minor lacustrine shoreline. Where the scarp is relatively well preserved, its height and

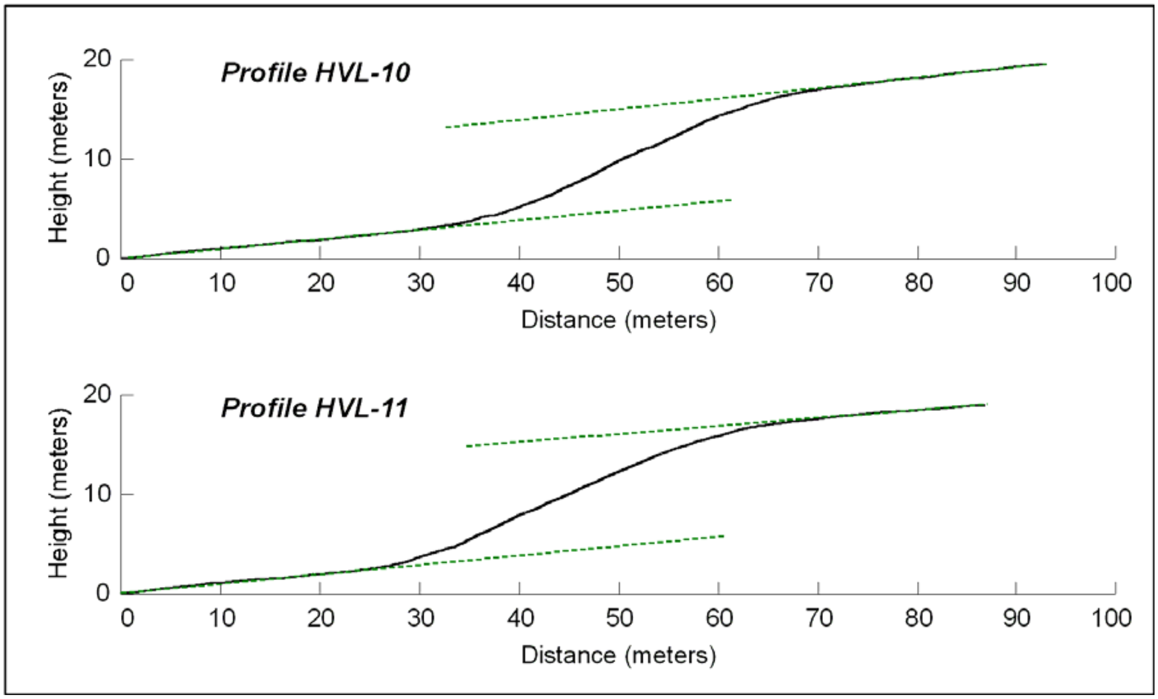


Figure 10. *Scarp profiles HVL-10 and HVL-11 in Coldwater Canyon reentrant area near Honeyville, on upper (eastern) of two scarps near mouth of Coldwater Canyon. Dashed lines show averaged ambient (far-field) surface slope. Profile locations are shown on figure 4, and data are summarized in table 1.*

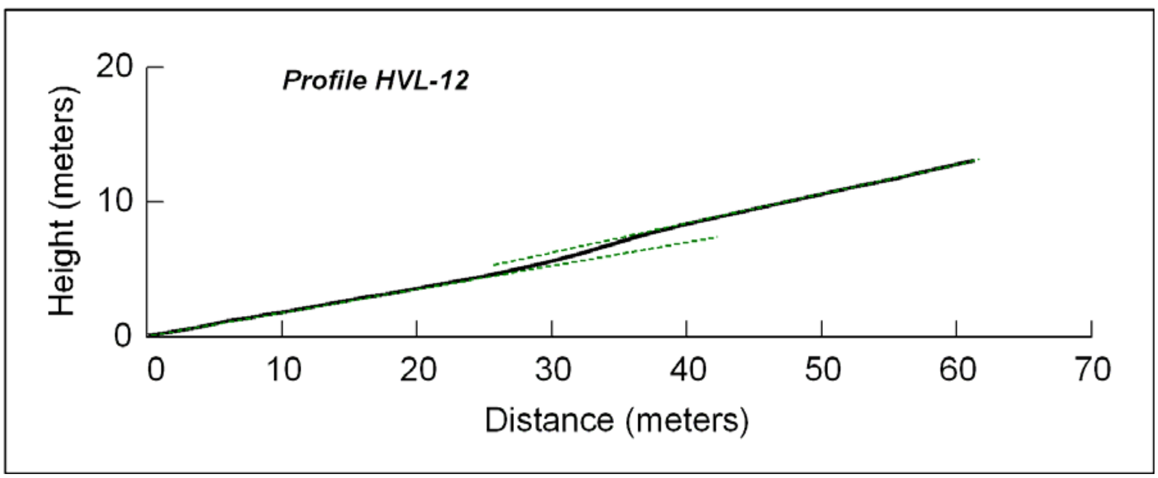


Figure 11. *Scarp profile HVL-12 in Coldwater Canyon reentrant area near Honeyville, south of Hank Bell Canyon. Dashed lines show averaged ambient (far-field) surface slope. Profile locations are shown on figure 4, and data are summarized in table 1.*

surface offset (table 1), as well as its simple morphology, indicate it formed as the result of a single surface-faulting earthquake. Empirical analysis of the scarp height and maximum scarp-slope angle indicates latest Pleistocene timing for this earthquake (figure 7); the scarp may represent the northern end of rupture associated with event T on the Brigham City segment, which occurred sometime between 17,000 and 14,800±1200 cal yr B.P. (McCalpin and Forman, 2002; Lund, 2005).

In summary, numerous fault scarps are present in the Coldwater Canyon reentrant, but none can be shown to have formed solely as the result of surface faulting on the Collinston segment. Previous scarp profiling (Personius, 1990) documented a substantial difference in the amount of net surface offset of similar-aged deposits (12 vs. 28 m on scarps on unit af5; see figure 4a), indicating the segment boundary between the Collinston and Brigham City segments is likely at the change in fault trend from northeast (Brigham City) to northwest (Collinston). Scarps in the segment-boundary area on deposits associated with latest Pleistocene Lake Bonneville formed from surface-faulting earthquakes on the Brigham City segment, including the 2-km-long scarp at the southern end of the Collinston segment that has been interpreted as resulting from a Brigham City-segment rupture that spilled over onto the Collinston segment (Personius, 1990). Empirical analysis of scarp-profile data obtained during this study indicates a difference in timing between the Brigham City-segment MRE in the vicinity of the segment boundary and that documented in trench studies 15 km to the south.

Lake Bonneville Shoreline Scarps

A well-developed, erosional, Bonneville-highstand shoreline scarp is present on middle Pleistocene fan alluvium in the Coldwater Canyon reentrant. I measured two profiles (HVL-6 and HVL-7; figure 12, table 1) across the scarp in the vicinity of Two Jump Canyon to provide data for use in calibrating diffusion-equation age determinations of the nearby fault scarps. Several complicating issues exist, however, and work to resolve these issues is ongoing. A discussion of these issues, and preliminary results of the data analysis performed thus far, are presented below under "Bonneville Shoreline Scarp-Profile Data."

CLARKSTON MOUNTAIN SEGMENT

General Description

The Clarkston Mountain segment extends between the southern end of Clarkston Mountain and the Woodruff spur in southern Idaho (Machette and others, 1991, 1992a) (figure 3). The segment boundary between the Clarkston Mountain and Collinston segments is a zone of east-west-trending, down-to-the-south normal faulting that includes the Short Divide fault, which juxtaposes Tertiary Salt Lake Formation strata against lower Paleozoic sedimentary rock. A linear, high (up to 120 m) escarpment subparallel to and about 1 km south of the Short Divide fault is likely a wave-modified fault-line

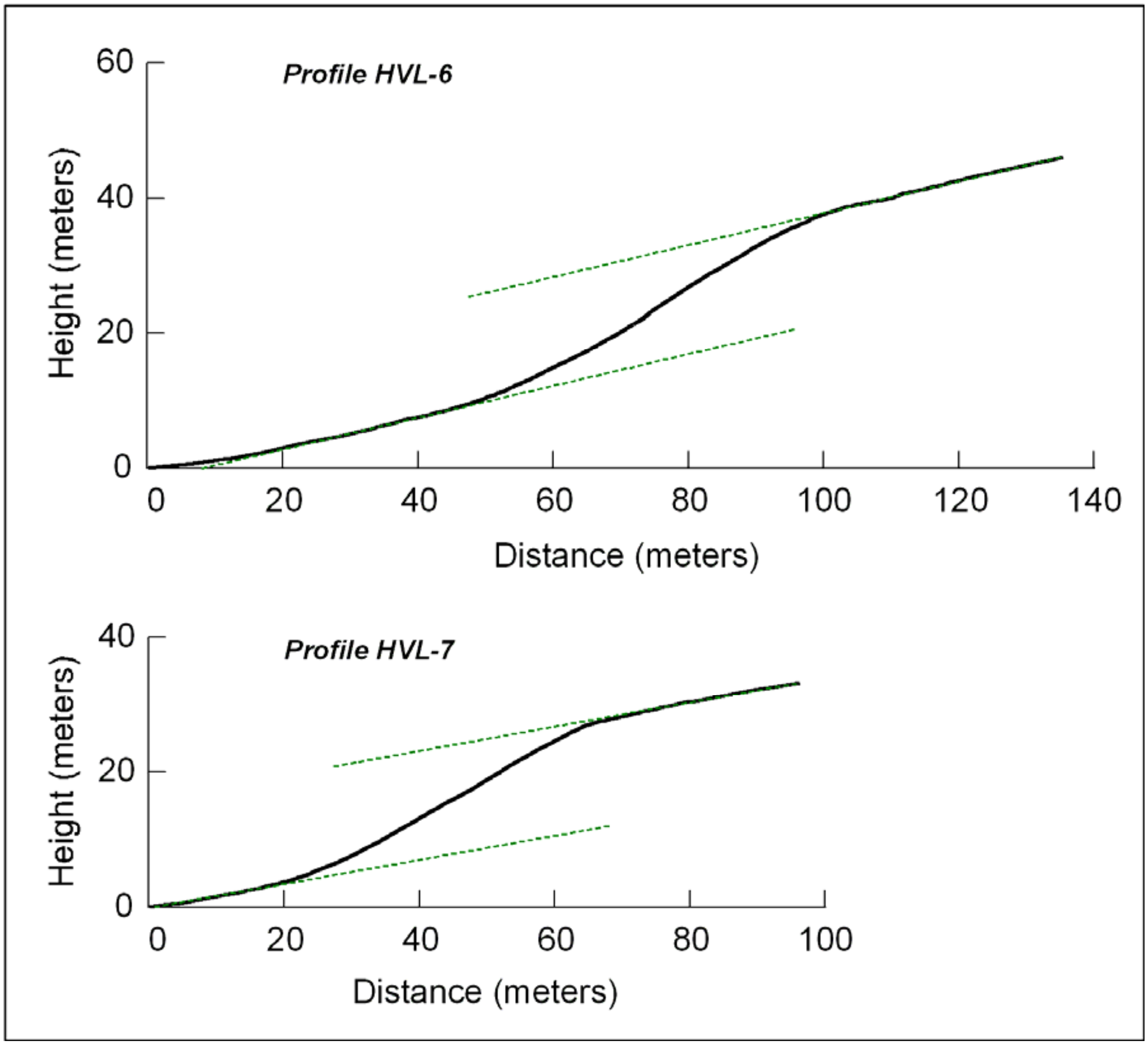


Figure 12. *Scarp profiles HVL-6 and HVL-7 in Coldwater Canyon reentrant area near Honeyville, on Bonneville shoreline scarp near Two Jump Canyon. Dashed lines show averaged ambient (far-field) surface slope. Profile locations are shown on figure 4, and data are summarized in table 1.*

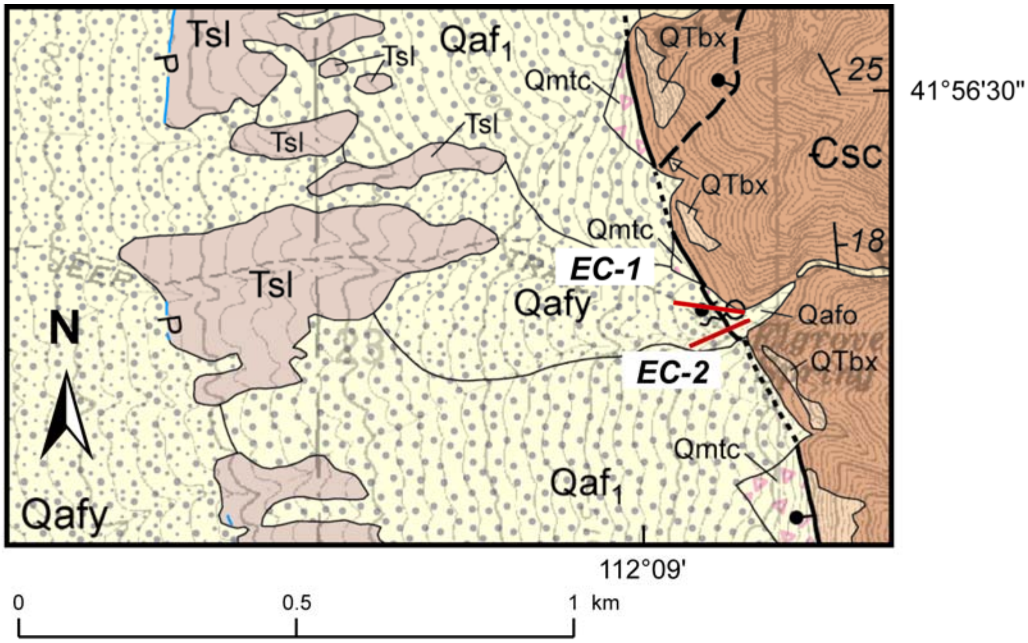
scarp associated with a fault concealed by Bonneville-phase lacustrine sediments, post-Bonneville fan alluvium, and landslide deposits (Biek and others, 2003). The structural block between the Short Divide and concealed faults preserves Salt Lake Formation strata at an intermediate structural level; the youngest faulted unit (tephra subunit of Junction Hills) tephrochronologically correlates with a 7.9±0.5 Ma ash (Biek and others, 2003). Machette and others (1992a) noted that the Short Divide fault appears to have been active as recently as Quaternary time, but post-Salt Lake Formation deposits preserving fault scarps are absent along the fault.

The Woodruff spur is a faulted bedrock spur that extends 6 km along the range front northeast of the town of Woodruff (figure 3). Machette and others (1992a) considered the Woodruff spur to mark the segment boundary between the Clarkston Mountain and Malad City segments based on the complex nature of the fault zone in this area, and coincidence with a transverse structural ridge/gravity saddle (Peterson, 1974; Zoback, 1983).

Bonneville-lake-cycle and younger deposits conceal the trace of the Clarkston Mountain segment along nearly its entire length (Biek and others, 2003; Machette and others, 1992a; this study). The only fault scarp on Quaternary deposits that has been reported by previous workers is at the mouth of Elgrove Canyon near the southern end of the segment (SE1/4NE1/4 section 23, T. 14 N., R. 3 W.). Here, the canyon mouth is above the elevation of the Bonneville shoreline, which in this area is approximately 5150-5180 ft, and the scarp cuts pre-shoreline fan alluvium (Biek and others, 2003). The incised stream channel at the south end of the scarp lacks any apparent knickpoint, suggesting a relatively long period of time since scarp formation. The absence of fault scarps on Bonneville-aged or younger deposits elsewhere along the segment indicates the most recent Clarkston Mountain-segment surface faulting occurred sometime before the Bonneville highstand at 18-16.8 ka (Machette and others, 1992a; Biek and others, 2003; this study). Similar to the Wellsville Mountains to the south, the abrupt, linear bedrock escarpment along Clarkston Mountain suggests that the Clarkston Mountain segment may have been relatively active in late Pleistocene time.

Surficial Geology of the Elgrove Canyon Area

Elgrove Canyon is within a reentrant that is of remarkably similar size and shape to the Coldwater Canyon reentrant described above in the discussion of the Collinston segment. Tertiary and younger deposits in the vicinity of Elgrove Canyon consist of the Salt Lake Formation, fan alluvium, and unmapped deposits of hillslope colluvium and talus (figure 13). As mapped by Biek and others (2003), the fan alluvium includes one unit deposited before and during the Bonneville lake cycle, and two post-Bonneville units. The Bonneville-and-older fan alluvium (Qafo) is preserved as small remnants along the mountain front, including at the mouth of Elgrove Canyon in the footwall of the fault. At Elgrove Canyon, the fan surface is about 5 m above the adjacent modern stream channel. Although I observed no exposures of soil developed on these deposits (and none are reported by Biek and others, 2003), substantial carbonate coatings on clasts at the ground surface indicate the presence of a calcic paleosol of possibly stage II carbonate morphology. Undifferentiated Holocene (post-Bonneville) fan alluvium (Qafy) is present immediately west of the mouth of Elgrove Canyon, and appears to be deposited up against the fault scarp. Late Holocene fan alluvium (Qaf1) bounds the exposure of Qafy on the north and south. The absence of expression of the Bonneville shoreline, either erosionally or depositionally, attests to these deposits being Holocene in age. Steep aprons of talus and colluvium (Qmtc) generally cover the upper parts of these fan deposits adjacent to the bedrock escarpment (Biek and others, 2003).



EXPLANATION

Qaf_1	Modern alluvial-fan deposits (upper Holocene)
Qafy	Younger undifferentiated alluvial-fan deposits (Holocene - uppermost Pleistocene)
Qafo	Older alluvial-fan deposits (upper Pleistocene)
Qmtc	Talus and colluvium (Holocene - upper Pleistocene)
QTbx	Fault breccia (Pleistocene to Pliocene?)
Tsl	Salt Lake Formation (Pliocene - Miocene)
Ꞓsc	St. Charles Formation (Lower Ordovician - Upper Cambrian)

Normal fault - Bar and ball on downdropped side. Dashed where approximately located, dotted where concealed. Red line shows location of scarp profile

P — Highest level of the Provo shoreline of the Bonneville lake cycle - May coincide with geologic contact

25 — Strike and dip of inclined bedding

Figure 13. *Surficial-geologic map of the Elgrove Canyon area near the south end of the Clarkston Mountain segment, showing locations of scarp profiles measured in this study (modified from Biek and others, 2003).*

Although abundant to the north and south, Lake Bonneville deposits are absent in the immediate vicinity of Elgrove Canyon. The Bonneville shoreline has been buried by Holocene alluvial fans across much of the reentrant, and where the shoreline is above the basin-fill/bedrock contact, only small deposits of shoreline sand and gravel remain perched on the steep escarpment. The Provo shoreline, at an altitude of about 4780-4800 ft in this area, is cut on Tertiary Salt Lake Formation, which forms a narrow outcrop belt approximately 0.3 to 1 km west of the mountain front. These exposures of Salt Lake Formation are similar to those south of the Short Divide fault, and indicate the likely presence of a concealed, down-to-the-west normal fault west of the Tertiary outcrops. Biek and others (2003) reported no scarps associated with this fault, and I likewise observed none.

Finally, outcrops of fault breccia are present along the base of the mountain front (figure 13). The well-cemented dolomite breccia forms resistant flatirons and allows direct measurement of fault dip. Biek and others (2003) reported a fault dip of about 45º W. for the Clarkston Mountain segment, and I measured a dip of 44º W. on several flatirons in the vicinity of Elgrove Canyon.

Scarp Profiles and Slip Rate

I measured two profiles across the fault scarp that cuts pre-Bonneville-shoreline fan alluvium at the mouth of Elgrove Canyon (figures 13 and 14). The scarp extends approximately 40 m between the incised stream channel at its south end and the steep colluvial apron with which it merges at its north end. Table 1 summarizes the scarp morphometry data. Several factors make this scarp less-than-ideal for providing reliable data to determine the timing of scarp formation. First, the geomorphic surfaces on the footwall and hanging wall are not correlative; the hanging-wall fan alluvium is younger than that of the footwall. Second, the scarp is at a U.S. Forest Service trailhead, and while there is no evidence of grading, there has undoubtedly been some localized ground disturbance on the hanging wall associated with vehicle parking. Third, a stock-watering tank has been installed at the base of the scarp to make use of a small spring, and there was probably some ground disturbance on the hanging wall as a result of establishing a level base for the tank. Finally, at least four remains of stone building foundations and other structures are present along the margins of the stream channel near the scarp. These are believed to be pioneer-era (late 1800s) structures used for water storage (Ollie Abusaidi, Caribou National Forest, verbal communication, 2006), and indicate a relatively long period of human activity in the general vicinity of the scarp. Despite these limitations and given the lack of alternative sites, I measured the two profiles across the scarp where ground disturbance appears to be minor to nonexistent.

The profiles (EC-1 and EC-2; figure 15) show a composite scarp morphology resulting from multiple (at least two) surface-faulting events. The profile data indicate a total scarp height of 6.2-6.7 m and a maximum scarp-slope angle of about 17º (table 1). The steepest slope angle is at the base of the scarp, so either the MRE ruptured near the base of the pre-existing scarp, or the ruptures were near the middle of the scarp and the lower part of the scarp associated with the earlier rupture(s) is completely buried. I determined scarp height and maximum scarp-slope angle associated with the MRE and PE (assuming the upper part of the scarp represents a single earlier event) using the two straight-line segments of each profile. Empirical analysis (after Bucknam and Anderson, 1979) of the scarp height and maximum scarp-slope angle associated with the MRE indicates early Holocene timing for this surface-faulting earthquake (figure 7), but this

Figure 14. *Fault scarp at the mouth of Elgrove Canyon, directly behind green stock-watering tank (view to the southeast). Several factors complicate the use of profile data for determining the timing of scarp formation, including ground disturbance of unknown extent associated with use of the site as a trailhead, and installation of the stock-watering tank. Profile EC-1 crosses the scarp to the left of the stock-watering tank, and EC-2 crosses the scarp to the right of the U.S. Forest Service sign, which is approximately 2 m high.*

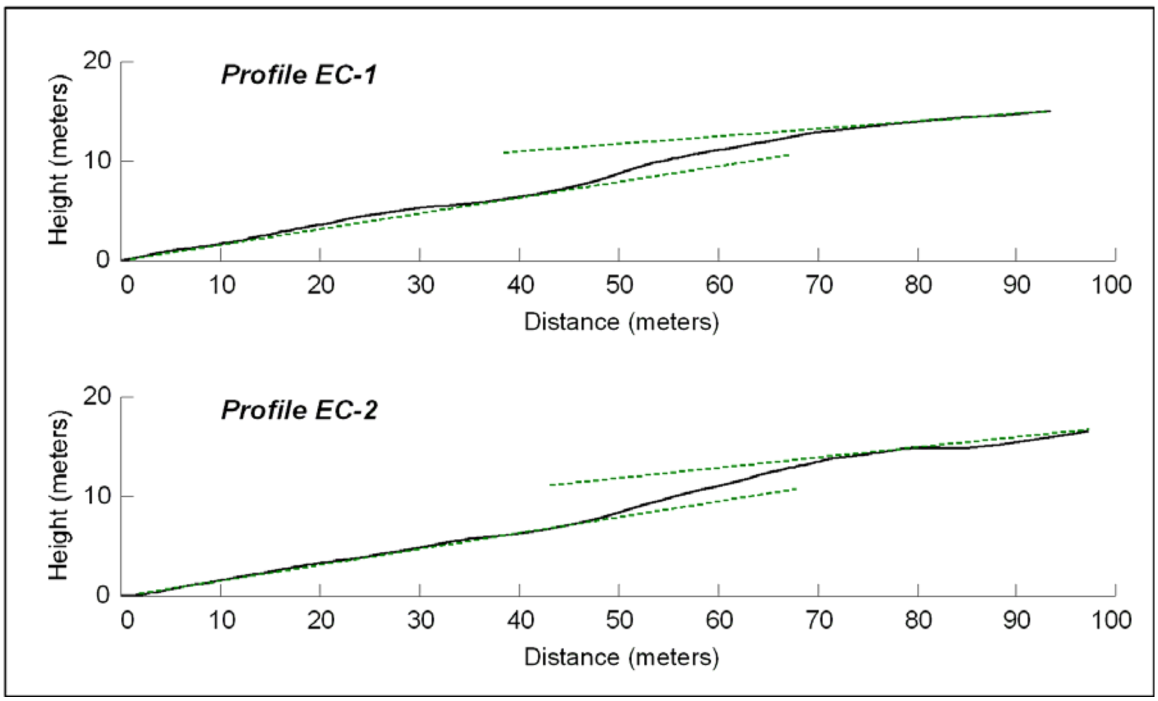


Figure 15. *Scarp profiles EC-1 (northern) and EC-2 (southern) on fault scarp at mouth of Elgrove Canyon. Dashed lines show averaged ambient (far-field) surface slope. Note that deposits underlying footwall and hanging-wall surfaces are not correlative. Profile locations are shown on figure 4, and data are summarized in table 1.*

timing estimate is likely a minimum. Part of the total MRE scarp height is likely beneath the surface of the fan alluvium on the hanging wall, so the position of the two data points on figure 7 would shift to the right to represent the true scarp height formed during the surface-faulting earthquake. Timing of the MRE shortly prior to the Bonneville highstand of the Bonneville lake cycle (18-16.8 ka) would be consistent with geologic evidence suggesting that the most recent scarp-forming event predates the end of the Bonneville lake cycle (Machette and others, 1992a; Biek and others, 2003).

Minimum net surface offset across the scarp is between 1.8 and 4.1 m; the large uncertainty is due to the average slope of the fan surface on the hanging wall (~9º) being significantly steeper than that on the footwall (~5º), perhaps associated with footwall erosion. I estimated surface offsets for the MRE and PE (again, assuming the upper part of the scarp represents a single earlier event) by projecting lines from the base and top of the MRE scarp slope, the lines being parallel to the footwall ground surface. This indicates a surface offset of about 2 m for both the MRE and PE (table 1). If the upper part of the scarp is actually the result of two earlier events instead of just one, and an equivalent amount of vertical offset at the base of the scarp is buried beneath post-faulting alluvium, the per-event surface offset would still be about 2 m.

The lack of any numerical ages to constrain the timing of surface faulting precludes calculation of an accurate slip rate. A maximum geologic (open-ended) slip rate, however, can be estimated using the 2 m of vertical displacement that occurred sometime shortly prior to the Bonneville highstand. This results in an estimated maximum slip rate of about 0.1 mm/yr for the past 18,000+ years.

Length-Displacement Relations and Earthquake Magnitude

The straight-line, end-to-end, surface rupture length (SRL) of the Clarkston Mountain segment is approximately 20 km. This length does not include the Short Divide fault or the parallel, concealed fault to the south. Assuming surface offset measured at Elgrove Canyon provides a reasonably close approximation of vertical fault displacement (throw on fault underestimated by <15%; see, for example, Caskey, 1995), empirical relationships between SRL and displacement (Wells and Coppersmith, 1994) provide insight into the extent of rupture during a surface-faulting earthquake on the segment.

Because of the absence of displacement data from anywhere on the segment other than Elgrove Canyon, it is unclear whether the displacements there are more representative of average or maximum values. The location of Elgrove Canyon near the southern end of the mapped rupture trace (not including the Short Divide fault or parallel, concealed fault) may be justification for considering the inferred 2-m displacements to be more representative of average values; however, given the along-strike variability of vertical displacement typically observed on normal faults, the possibility of the measured displacements representing maximum values cannot be precluded. Table 2 summarizes estimates of SRL predicted from considering 2 m as both an average (AD) and maximum (MD) vertical displacement. Considering 2 m as AD produces a very long SRL relative

Table 2. *Estimated surface rupture length (SRL) for the Clarkston Mountain segment predicted from 2 m vertical displacement, considered as average (AD) and maximum (MD) displacements, based on empirical relationships of Wells and Coppersmith (1994).*

Displacement	Fault Type[1]	SRL (km)
AD	Normal	40
	All	60
MD	Normal	29
	All	40

[1] *Normal faults in Wells and Coppersmith database:*

$$log\ (SRL) = 1.52 + 0.28 * log\ (AD)$$

$$log\ (SRL) = 1.36 + 0.35 * log\ (MD)$$

All faults in Wells and Coppersmith database:

$$log\ (SRL) = 1.61 + 0.57 * log\ (AD)$$

$$log\ (SRL) = 1.43 + 0.56 * log\ (MD)$$

to the 20-km length of the main trace of the segment. Considering 2 m as MD also produces a long SRL for the segment, but one that is more compatible with the vertical displacement. These results suggest the displacements at Elgrove Canyon may be more representative of MD for the segment than AD. However, these results could also indicate that surface rupture during a large earthquake on the segment may exceed a length of 20 km.

Table 3 summarizes estimates of AD and MD predicted from SRLs of 20 km (approximate length of mapped main trace), 30 km (approximate length predicted from 2-m MD, normal-fault regression), and 40 km (length predicted from 2-m AD, normal-fault regression). The largest estimates of AD, associated with a 40-km SRL, are roughly half of the per-event vertical displacement inferred from the scarp profile data at Elgrove Canyon, whereas the estimated MD for a 30-km SRL (normal-fault regression) is very similar to the inferred per-event vertical displacement. These results further support the hypothesis that vertical displacement at Elgrove Canyon is more representative of MD than AD for the segment. These results also suggest that rupture of just the 20-km main trace of the Clarkston Mountain segment is insufficient to produce the displacements inferred at Elgrove Canyon, and that SRL during a large earthquake may be closer to 30 km. Several possibilities exist where surface rupture could occur beyond the mapped main trace during an earthquake, including the Short Divide fault or parallel, concealed fault (and possibly both); any concealed southern extension of the main trace of the fault in the valley south of the Short Divide fault (e.g., see Biek and others, 2003); and parts of adjacent segments.

In summary, empirical regressions indicate SRL of about 30 km during a large earthquake on the Clarkston Mountain segment, based on 2 m of per-event vertical displacement at Elgrove Canyon. An earthquake associated with 30 km of surface

Table 3. *Estimated average (AD) and maximum (MD) vertical displacements for the Clarkston Mountain segment predicted from surface rupture length (SRL), based on empirical relationships of Wells and Coppersmith (1994).*

SRL (km)	Fault Type[1]	AD (m)	MD (m)
20	Normal	0.42	0.96
	All	0.52	0.88
30	Normal	0.69	1.8
	All	0.74	1.3
40	Normal	0.99	2.7
	All	0.95	1.8

[1] *Normal faults in Wells and Coppersmith database:*

$\log(AD) = -1.99 + 1.24 * \log(SRL)$

$\log(MD) = -1.98 + 1.51 * \log(SRL)$

All faults in Wells and Coppersmith database:

$\log(AD) = -1.43 + 0.88 * \log(SRL)$

$\log(MD) = -1.38 + 1.02 * \log(SRL)$

rupture would have an estimated moment magnitude of **M** = 6.8, based on the equations of Wells and Coppersmith (1994) using SRL. Equations using MD = 2 m indicate **M** = 6.8-6.9. These magnitudes compare with **M** = 6.6 resulting from calculations using SRL = 20 km.

BONNEVILLE SHORELINE SCARP-PROFILE DATA

The two profiles (HVL-6 and HVL-7; figure 12) across the Bonneville-highstand shoreline scarp in the Coldwater Canyon/Honeyville area were measured to obtain data for use in calibrating diffusion-equation age determinations of the nearby fault scarps. Applied to landform evolution, the diffusion equation returns the product κt, where the constant of proportionality κ (κ in linear models, κ_o in nonlinear models) is mass diffusivity, and t is time or age (10^3 yr B.P.). If the scarp age is known (e.g., in the case of the Bonneville shoreline scarp), κ or κ_o can be determined. Conversely, if κ or κ_o is known, the timing of scarp formation can be determined. For the shoreline scarp in the Coldwater Canyon/Honeyville area, three issues have emerged that complicate use of the shoreline-scarp profile data in diffusion-equation modeling: (1) the scarp is very high, and has a correspondingly large surface offset, (2) the scarp slope is relatively steep, and (3) the ambient slope (far-field or fan slope) is relatively steep.

Where the Bonneville shoreline scarp is well developed in the Coldwater Canyon/Honeyville area, it is large (23-26 m high, "surface offset" of 16-17 m), roughly two to four times larger than the profiled fault scarps (table 1). Figures 7 and 16 show the Bonneville shoreline profile data from the Coldwater Canyon/Honeyville area in

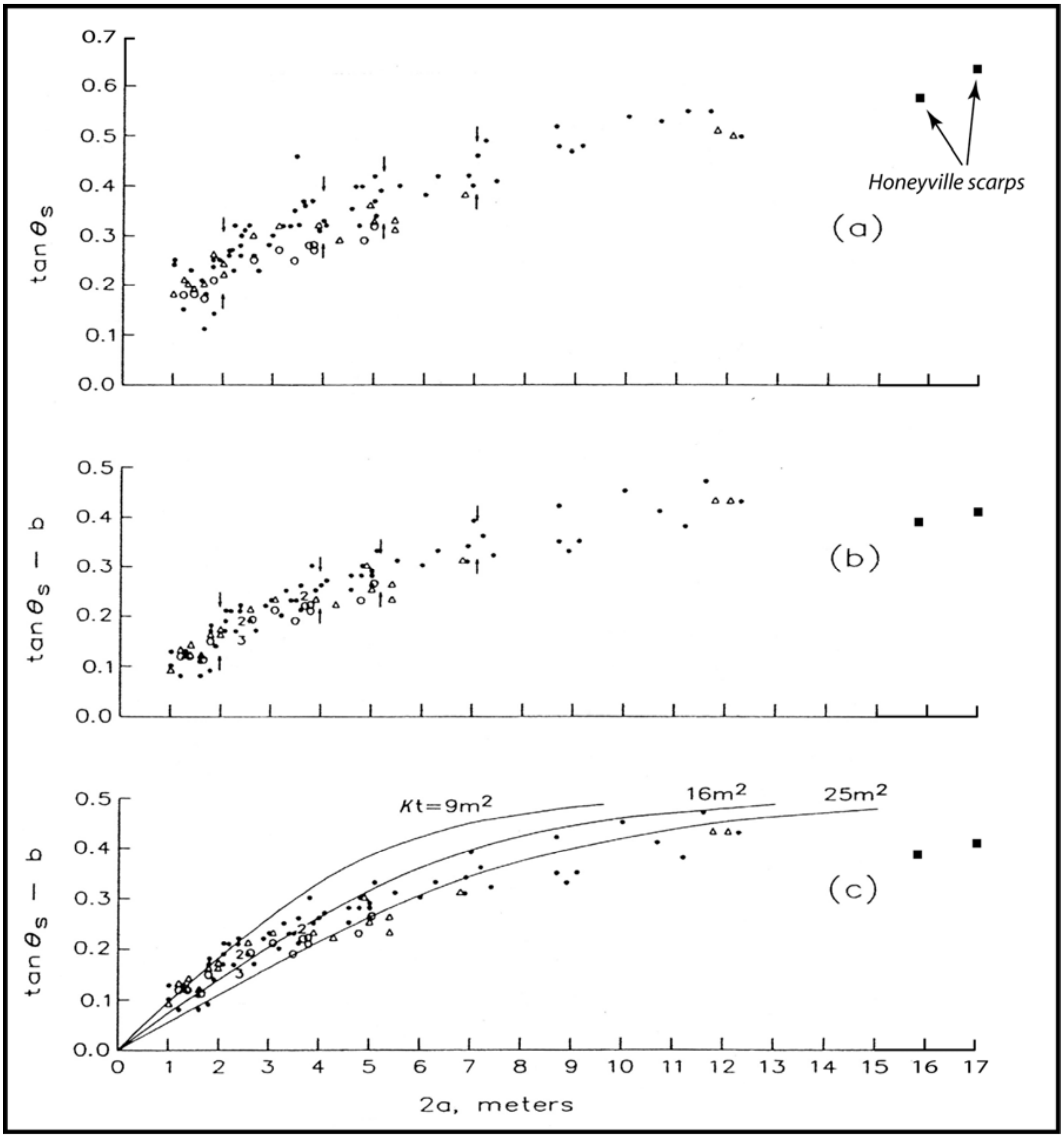


Figure 16. *Slope-offset plots showing Lake Bonneville (solid circles) and Lake Lahontan (open symbols) shoreline-scarp data used by Hanks and Andrews (1989). Solid squares are data obtained in this study from Bonneville shoreline in Coldwater Canyon reentrant near Honeyville. (a) tan θ_s versus 2a, and (b) tan $\theta_s - b$ (reduced scarp slope) versus 2a. Arrows on (a) and (b) indicate "full-range" scatter in θ_s for several values of 2a. (c) The data of (b) are shown with three indicated values of κt and (α – b) = 0.5. α, tangent of the angle of repose; b, far-field or fan slope. After Hanks and Andrews (1989).*

comparison with previously published Bonneville shoreline datasets. On figure 7, the two Honeyville-scarp data points plot very near the projection (dashed line) of the scarp-height – slope-angle regression line developed for the Bonneville shoreline by Bucknam and Anderson (1979), but are well to the right of the highest scarps used to develop the regression (solid line). Similarly, figure 16 shows that the Honeyville-scarp data points plot well to the right of the Bonneville shoreline scarps having the greatest surface offset ($2a$) in the dataset used to develop the slope-offset plots of Hanks and Andrews (1989). So, with respect to these two Bonneville shoreline datasets, the Honeyville data are outliers. A correction for scarp height will undoubtedly need to be made before the data can be used to calibrate diffusion-equation models for the nearby fault scarps (see, for example, Pierce and Colman, 1986), if they can be used at all (see Nash, 1998).

Hanks and others (1984) showed a dependence of κ on surface offset; in other words, larger values of $2a$ require larger model values of κt (see also Andrews and Bucknam, 1987; Hanks and Andrews, 1989; Hanks, 2000; Mattson and Bruhn, 2001). This dependence is what led to the nonlinear models proposed by Andrews and Bucknam (1987) and Hanks and Andrews (1989). The Andrews and Bucknam (1987) model results in the equation $t = t' (2a)^2/\kappa_o$. The dimensionless age value t' relates maximum scarp slope angle (θ) to ambient (far-field) slope angle (γ) (see discussion in Hanks and Andrews, 1989), and values of t' have been tabulated for a range of θ and γ (Andrews and Bucknam, 1987, table 2). However, the range of θ assumes an initial scarp slope angle of 31º, and the range of γ has a maximum value of 9º. Also, Andrews and Bucknam (1987) recommended using the tabulated values only for dating scarps with θ = 10º-24º, the range for which their model is well calibrated against data from Bonneville shoreline scarps. These limitations present challenges in using their model to determine the Bonneville shoreline κ_o in the Coldwater Canyon/Honeyville area. In the case of profile HVL-7 (θ = 30º), t' can be extrapolated, as only γ (10º) falls outside the range of tabulated values. For profile HVL-6, however, both θ (32º) and γ (13º) are outside the range of tabulated values.

Another important consideration related to the Andrews and Bucknam (1987) model is that it is appropriate only for dating single-event scarps. Most of the fault scarps in the Coldwater Canyon/Honeyville area are multiple-event scarps. Mattson and Bruhn (2001) have developed a "constant slip rate" (CSR) solution to diffusion-equation models that can be applied to multiple-event scarps having an unknown rupture history. The CSR solution returns a scarp "initiation age," or time elapsed since slip initiated, as well as an estimate of slip rate that is independent of the age of the offset geomorphic surface (Mattson and Bruhn, 2001; see also DuRoss, 2004, and DuRoss and Bruhn, 2005). Mattson and Bruhn's approach appears to hold promise for quantitative analysis of the fault scarps in the Coldwater Canyon/Honeyville area, but further work is needed to develop appropriate values of κ and κ_o for use in the model.

Table 4 summarizes published κ and κ_o values determined for Bonneville shoreline scarps, as well as preliminary values determined in this study. Hanks and others (1984) and Andrews and Bucknam (1987) used a dataset consisting of 61 Bonneville shoreline triplets ($2a$, θ, and γ), with $2a$ ranging from 1 to 12 m. Their κ and

κ_o values were obtained using the radiocarbon age of the Bonneville shoreline (14,500 ^{14}C yr B.P.); I recalculated their values using the calendar-calibrated shoreline age (16,800 cal yr B.P.). Mattson and Bruhn (2001) measured 12 profiles across Bonneville shoreline scarps at four locations, and 2*a* at two of these sites is ≥ 23 m. The value of κ that I determined for the Honeyville scarp is similar to that determined by Mattson and Bruhn (2001) for the Bonneville shoreline at Tooele, and my κ_o value is similar to that determined by Andrews and Bucknam (1987). Again, the applicability of diffusivity values derived from the large Bonneville shoreline scarp at Honeyville to dating nearby but smaller, multiple-event fault scarps remains uncertain, and the subject of ongoing evaluation and testing.

Table 4. *Comparison of preliminary κ (linear) and κ_o (nonlinear) values for Bonneville shoreline scarps determined in this study with previously published values. N, number of scarp profiles; 2a, scarp "offset" (see figure 2).*

Site	N	2*a* (m)	κ (m^2/kyr)	κ_o (m^2/kyr)	Reference
W. Utah	61	1-12	1.1 [0.95][1]	-	Hanks and others (1984)
W. Utah	61	1-12	-	0.46 [0.39][1]	Andrews and Bucknam (1987)
North Ogden	3	29±3	12.9±1.7	5.9±0.1	Mattson and Bruhn (2001)
South Willow Canyon	4	10±4	1.9±0.5	1.2±0.3	Mattson and Bruhn (2001)
Tooele	2	23	4.7	1.4	Mattson and Bruhn (2001)
Stansbury Mountains	3	4±3	1.8±0.9	1.1±0.4	Mattson and Bruhn (2001)
Honeyville	2	16±1	4.5±0.3[2]	0.55[3]	This study

[1] Recalculated using calendar-calibrated Bonneville shoreline age.
[2] Calculated using equations in Hanks (2000); assumes initial scarp-slope angle of 35°.
[3] Calculated using equation in Andrews and Bucknam (1987); data from profile HVL-7.

SUMMARY AND CONCLUSIONS

The Collinston and Clarkston Mountain segments, the northernmost two segments of the Wasatch fault zone in Utah, are substantially less active than the more central segments of the fault zone to the south. Although apparently relatively more active in late Pleistocene time, the Collinston and Clarkston Mountain segments show no evidence of Holocene surface faulting. As suggested by Machette and others (1992a), the absence of Holocene movement on the Collinston segment may be related to strain partitioning as reflected by activity on the West Cache fault zone, and the absence of Holocene movement on the Clarkston Mountain segment may be similarly attributed to activity on the West Cache fault zone.

The only fault scarps on Quaternary deposits along the Collinston segment are in the area of the Coldwater Canyon reentrant, which is at the segment boundary with the Brigham City segment to the south. The northernmost of these scarps, an indistinct scarp on Bonneville-lake-cycle lacustrine deposits and Provo-aged fan alluvium, appears to be the northern end of a Brigham City-segment rupture. I measured 10 profiles across fault scarps in the Coldwater Canyon reentrant to develop data to evaluate along-strike temporal variation in rupture patterns of the Brigham City segment. All but two of these scarps resulted from multiple surface-faulting earthquakes. Empirical analysis indicates that the timing of the late Holocene most recent event (MRE) in the segment-boundary area predates the timing determined for the MRE at the Brigham City trench site 15 km to the south, suggesting the Brigham City-segment MRE identified in the trench studies did not rupture the northernmost part of the Brigham City segment.

The only fault scarp on Quaternary deposits that has been identified on the Clarkston Mountain segment is at Elgrove Canyon, in a reentrant near the south end of the main trace of the segment. Profiles indicate the scarp on late Pleistocene fan alluvium is the result of two or possibly three surface-faulting earthquakes, each producing approximately 2 m of vertical surface offset. Empirical analysis indicates the MRE probably occurred shortly prior to the Bonneville highstand of the Bonneville lake cycle (18-16.8 ka), consistent with geologic evidence suggesting that the most recent scarp-forming event predates the end of the Bonneville lake cycle. These data indicate a maximum geologic (open-ended) slip rate of about 0.1 mm/yr for the past 18,000+ years.

Empirical relationships between surface rupture length and vertical displacement provide insight into the extent of rupture during a surface-faulting earthquake on the Clarkston Mountain segment. First, the 2-m-per-event displacements inferred from the scarp-profile data at Elgrove Canyon are more likely representative of maximum displacement than average displacement for the segment. Second, more than just the 20-km main trace likely ruptures during a surface-faulting earthquake on the segment. A modeled maximum displacement of 2 m yields a surface rupture length on the order of 30 km. Surface rupture beyond the mapped main trace during an earthquake could occur on the Short Divide fault or parallel, concealed fault to the south (and possibly both); any concealed southern extension of the main trace of the fault in the valley south of the Short Divide fault; and parts of adjacent segments. The difference in rupture length from 20 to 30 km results in an increase in calculated earthquake moment magnitude from **M** = 6.6 to **M** = 6.8. Earthquake magnitude calculated from 2 m maximum vertical displacement is in the range of **M** = 6.8-6.9.

I measured two profiles across the Bonneville-highstand shoreline scarp in the Coldwater Canyon reentrant to obtain data for use in calibrating diffusion-equation age determinations of nearby fault scarps. Application of the shoreline-scarp profile data to diffusion-equation modeling is complicated, however, by the height of the scarp and correspondingly large "surface offset," the steepness of the scarp slope, and the steepness of the far-field (fan) slope. Preliminary determinations of diffusivity (κ and κ_o) are similar to some published values, but these results will undoubtedly need to be corrected for scarp height before they can be used to calibrate diffusion-equation models for nearby fault scarps, if they can be used at all. The applicability of these preliminary results to diffusion-equation modeling remains the subject of ongoing evaluation and testing.

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

PART IV: THE POTENTIAL FOR MULTI-SEGMENT RUPTURE ON THE CENTRAL SEGMENTS OF THE WASATCH FAULT ZONE, UTAH

By

Christopher B. DuRoss

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

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ABSTRACT

The Wasatch fault zone (WFZ) is one of the best-studied normal faults in the Basin and Range Province, but the potential for multi-segment ruptures (MSRs) among its segments is poorly understood. Understanding the rupture behavior of the WFZ, including the possibility of MSRs between adjacent segments, is an important step in understanding normal-fault hazards and improving national, regional, and local earthquake-probability studies. In this investigation, I consider the potential for two-segment ruptures from a dataset of 16 earthquakes occurring after ~6500 cal yr B.P. on the Brigham City, Weber, Salt Lake City, and Provo segments (BCS, WS, SLCS, and PS) of the WFZ.

Vertical-displacement (VD) data for these segments as well as the Nephi segment (NS) and Levan segment indicate a tendency toward single-segment ruptures (SSRs), but do not preclude the possibility of MSRs. For example, the largest VDs observed along the central WFZ correspond well with the maximum displacements predicted from a maximum-displacement – surface-rupture-length (SRL) regression for normal faults; however, 86-90% of the observed VD estimates are larger than the average displacements predicted by the segment lengths using average-displacement – SRL regressions for normal- and all-fault types. Also, when normalized by segment length, the majority (~68%) of the VD data fit within a half-ellipse-shaped slip envelope, which shows VD decreasing from a maximum of ~1.8-3.4 m near the segment centers to ~0.8-2.1 m near the segment ends, though several anomalously large VD estimates near the ends of the fault segments suggest the possibility of surface fault ruptures at least 20 km longer than the mapped segment lengths.

This MSR analysis includes a preferred set of six MSRs among the last 16 earthquakes on the BCS to PS. However, the paleoseismic data necessary to have confidence in such MSRs are limited. I report MSR potential based on a comparison of timing information for earthquakes on adjacent segments having overlapping time ranges, and paleoseismic-event confidence based on the quality of available paleoseismic data. Among the possible MSRs, there is a prevalence of low- to medium-MSR-potential earthquake pairs and low to medium paleoseismic-event confidence, and a lack of high-potential MSRs based on high-confidence paleoseismic data, which preclude development of well-constrained MSR models. As the oldest paleoearthquakes are combined in three separate high-potential MSR pairs, I recommend additional investigations into the middle and early Holocene paleoearthquake histories on these segments.

I generated four MSR scenarios (different combinations of SSRs and MSRs for one earthquake cycle) for the central WFZ (e.g., scenario 2 includes a BCS-WS MSR and SSRs on the SLCS and PS) and developed new methods to quantify the relative occurrence of the scenarios using MSR potential and paleoseismic-event confidence. I provide weights for two generalized fault-rupture models (weighted combination of different scenarios) and a quantitative model, based on the MSR analysis. The quantitative model indicates the more frequent occurrence of BCS-WS and SLCS-PS

MSRs to WS-SLCS MSRs. I do not include a preferred MSR model (with relative weights for different fault-rupture models) due to the limits of available WFZ paleoseismic data, and recommend that a simple, time-independent MSR model (e.g., a low-probability, large-SRL floating earthquake) be used to account for WFZ MSRs in the 2007 update of the National Seismic Hazard Maps (NSHMs). Prior to finalizing a preferred model for use in the NSHMs, continued work is necessary to 1) extend these analyses to include possible MSRs between the PS and NS, 2) improve the paleoseismic-data density and quality, and include new paleoseismic data for the WS, PS, and NS, 3) moment balance the models, and 4) reach working-group consensus as to the preferred method of generating models and assigning relative weights.

INTRODUCTION

Background

Along-strike variations in the physical and temporal characteristics of a fault zone, including changes in fault-zone structure, geomorphology, rates of activity, and paleoseismic history, provide the basis for defining individually rupturing fault segments (Sibson, 1987; Crone and Haller, 1991; dePolo and others, 1991; Machette and others, 1992). Segment boundaries may act as barriers to earthquake surface faulting propagating along individual segments, as rupture energy is dissipated over diffuse or complex fault zones or halted by relative increases in the physical strength of the fault zone (King and Nabelek, 1985; Bruhn and others, 1987; Wheeler and Krystinik, 1992; Ward, 1997). However, a nonzero probability of segment-boundary rupture is generally accepted (Andrews and Schwerer, 2000), as surface faulting may propagate toward and across segment boundaries (e.g., 1992 M 7.3 Landers, California earthquake; Sieh and others, 1993) or initiate at a segment boundary and rupture bilaterally onto the adjacent segments (e.g., 1995 M 6.9 Kobe earthquake; Working Group on California Earthquake Probabilities [WGCEP], 2003).

Developing methods to correlate paleoearthquakes revealed from paleoseismic investigations into either single-segment or multi-segment ruptures (SSRs or MSRs) is a current challenge in paleoseismology (Weldon and others, 2005). The possibility of MSRs on strike-slip faults is well established (WGCEP, 1995; Andrews and Schwerer, 2000; Frankel and others, 2002; WGCEP, 2003; Weldon and others, 2004, 2005), but less understood for normal faults. For example, Jackson and White (1989) suggest a likely maximum normal-fault-segment length of ~20 km, based on the continuous ruptures (lacking rupture gaps or changes in strike) of historical normal-faulting earthquakes, but several historical, Basin and Range Province (BRP) earthquakes have end-to-end rupture lengths up to 2-3 times greater than this estimate. These BRP earthquakes are characterized by complex and extensive surface faulting consistent with MSR processes (dePolo and others, 1991; Zhang and others, 1999; Chang and Smith, 2002; Slemmons and DePolo, 2004). Examples of possible historical multi-segment, normal-faulting earthquakes include the 1887 M 7.4 Pitaychachi, Mexico earthquake, which ruptured three fault segments over a 101-km distance (Suter and Contreras, 2002), and the 1915 M 7.3 Pleasant Valley earthquake, which had a complex, 60-km-long rupture trace (Wallace, 1984; dePolo and others, 1991).

Segmentation of the Wasatch Fault Zone

The 350-km-long Wasatch fault zone (WFZ) forms the structural eastern boundary of the BRP in north-central Utah and is important in understanding earthquake behavior and surface faulting in the province. The central, Holocene-active part of the WFZ is composed of six segments, including the Brigham City segment (BCS), Weber segment (WS), Salt Lake City segment (SLCS), Provo segment (PS), Nephi segment (NS), and Levan segment (LS) (figure 1). The segments range from 26 to 59 km long (Machette and others, 1992) and are thought to be individually capable of generating large-magnitude (M ~7) surface-faulting earthquakes (Swan and others, 1980; Schwartz and Coppersmith, 1984; Machette and others, 1992). Segment boundaries are based on well-expressed geometric and structural discontinuities along the fault (Wheeler and Krystinik, 1992), as well as preferred segment-specific earthquake chronologies (e.g., Machette and others, 1992; McCalpin and Nishenko, 1996). However, a recent review of available paleoseismic data for the WFZ by the Utah Quaternary Fault Parameters Working Group (UQFPWG; Lund, 2005) has highlighted broad uncertainties in paleoearthquake timing and displacement, and raised questions regarding the possibility of partial-segment, spill-over, and multi-segment rupture on the WFZ.

The possibility of MSRs on the central WFZ segments has been discussed, but with the exception of Chang and Smith (2002), quantified models are lacking. McCalpin and Nishenko (1996) suggested the possibility of MSRs on the central WFZ segments, and recommended that hazard analyses include an end-member MSR hypothesis. Frankel and others (2002) considered MSRs on the SLCS and PS when constructing the 2002 National Seismic Hazard Maps (NSHMs), but reported insignificant changes in the peak ground acceleration. Wong and others (2002) included an unsegmented WFZ (MSR) model in their probabilistic ground-shaking maps for the Salt Lake valley, which was given 20% weight, compared to 80% weight for their segmented model. Most recently, Chang and Smith (2002) formulated a scenario of 8 MSRs and 2 SSRs occurring after ~6500 years on the BCS to LS, which they preferred over a simple model of 17 SSRs. Their model is based on qualitative comparisons of earthquake timing, but also incorporates per-event vertical displacement to estimate MSR distribution of slip, average displacement, and magnitude.

Purpose and Scope

This work represents my most recent investigation into the potential for MSRs along the four central, most active segments of the WFZ. I consider the BCS, WS, SLCS, and PS (figure 1), excluding the LS, due to its reduced rate of paleoearthquake activity, and the NS, because of ongoing paleoseismic investigations (DuRoss and others, 2006). To avoid overly complex MSR models, only the potential for ruptures spanning two adjacent segments is considered. The purpose of this investigation is to analyze the potential for MSRs on the central WFZ, evaluate methods for the development of a preferred MSR model, and provide a basis for additional paleoseismic research on the WFZ. Ultimately, an improved understanding of MSRs on the WFZ and the methods to quantify them is important for updating and refining both regional (e.g., the NSHMs; Frankel and others, 2002) and local (e.g., Salt Lake City, Utah area; Wong and others, 2002) earthquake-probability studies. I present an updated and revised WFZ paleoearthquake space-time diagram (figure 1), which incorporates the UQFPWG consensus earthquake-timing estimates (Lund, 2005). I also compile and analyze per-earthquake displacement estimates for the WFZ, formulate criteria to quantify the potential for MSRs and the quality of paleoseismic data along the WFZ, and discuss possible methods of developing preferred MSR models for the WFZ.

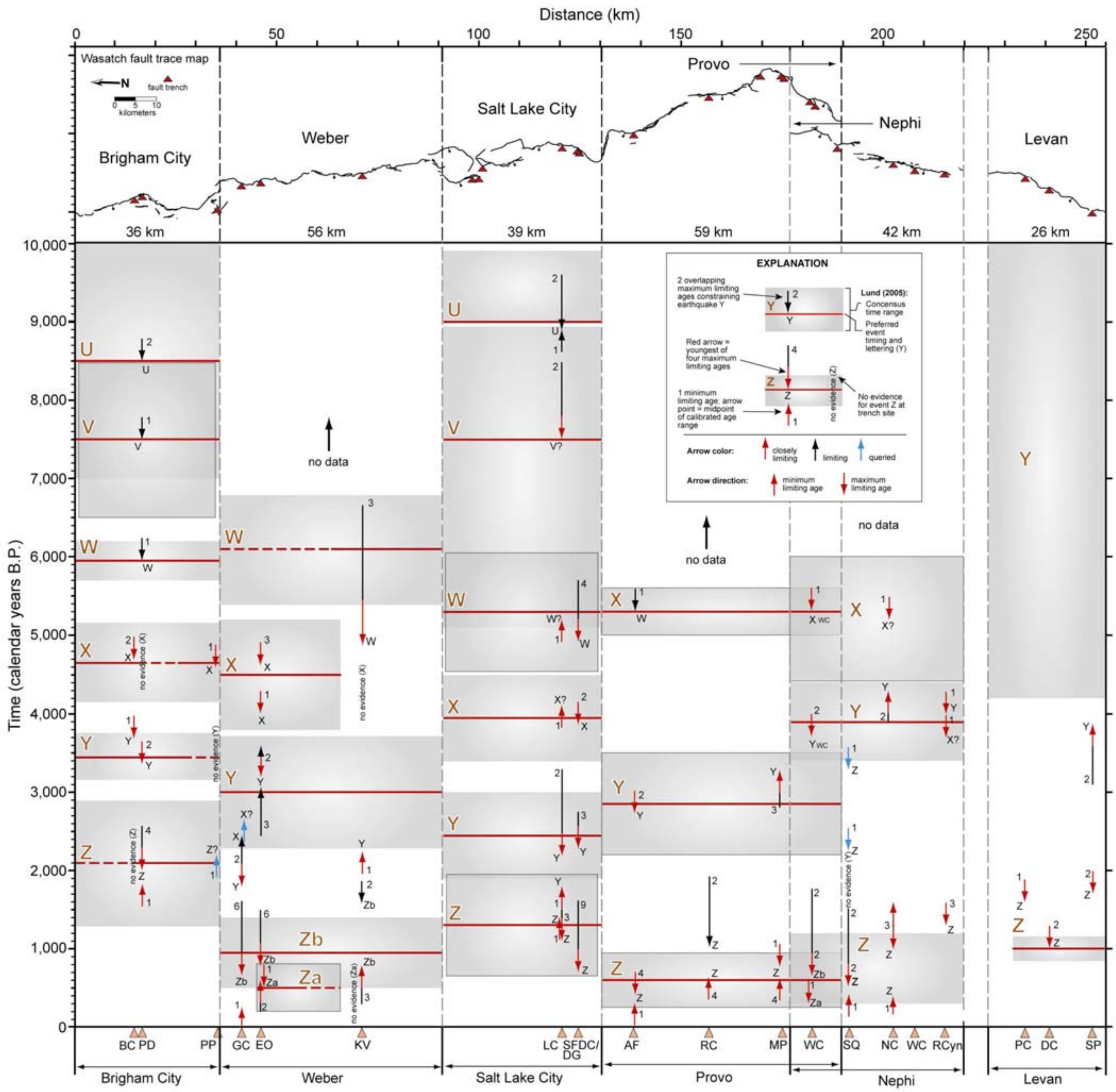

Figure 1. Wasatch fault zone paleoearthquake space-time diagram, showing UQFPWG timing estimates (Lund, 2005) and timing data from paleoseismic sites. Trench-site abbreviations (north to south): BC - Brigham City, PD - Provo delta (Box Elder Canyon), PP - Pole Patch, GC - Garner Canyon (construction-related excavation), EO - East Ogden, KV - Kaysville, LC - Little Cottonwood Canyon (megatrench), SFDC/DG - South Fork Dry Creek/Dry Gulch, AF - American Fork, RC - Rock Creek (stream cut)/Rock Canyon, MP - Mapleton north and south, WC - Water Canyon, SQ - Santaquin Canyon, NC - North Creek, WC - Willow Creek (results pending), RCyn - Red Canyon, PC - Pigeon Creek (stream cut), DC - Deep Creek (stream cut), and SP - Skinner Peaks. See table 1 for source information.

CHARACTERISTICS OF SURFACE FAULTING ALONG THE CENTRAL WASATCH FAULT ZONE

Vertical Displacement

To investigate whether WFZ per-earthquake vertical-displacement (VD) measurements are indicative of SSRs or MSRs, I compiled 35 preferred VD estimates for Holocene surface-faulting events revealed from 16 paleoseismic sites (including fault-trench sites and natural exposures) on the WFZ between the BCS and LS (table 1). The VDs range from a minimum of 0.5-0.8 m for WS event Za (Nelson and others, in press) to a maximum of 4.7 m for PS event Z (Olig, verbal communication, 2006); the mean displacement (± one sigma) is 2.1 ± 0.97 m.

Distribution of Slip

The distribution of slip along the length of a single fault segment is important for understanding SSRs versus MSRs. For example, a symmetrical, half-ellipse-shaped displacement profile (with many points near the maximum value and slip decreasing rapidly toward the segment ends in a concave-down shape) may suggest a SSR, where characteristic slip is bound by strong segment boundaries (Ward, 1997). Additionally, an asymmetric displacement profile (with relatively large values near the segment ends) may suggest mechanical interaction between neighboring segments (Willemse, 1997), for example, by rupture continuity onto an adjacent segment during a MSR. In contrast, a concave-up profile shape near the segment ends may indicate non-characteristic slip, where displacement decreases slowly along a fault, coming to a halt at a random location (Willemse, 1997), for example, during a partial-segment rupture.

Sparse VD measurements along the WFZ segments preclude generating detailed slip profiles for each segment. However, I generated a composite slip distribution for the six central segments by normalizing the locations of the 35 VD estimates along each segment (figure 2a). The composite profile has a complex shape, with several low- and high-valued outliers. However, disregarding the outliers, ~68% of the VD data fit within a weakly symmetrical half-ellipse-shaped slip envelope (blue dashed line, figure 2a), indicating a tendency towards characteristic SSRs on the central WFZ. Based on the shape of the slip envelope, displacements between 1.8 m and 3.4 m are likely for locations near the fault-segment centers, decreasing to between about 0.8 m and 2.1 m near the segment ends (for locations 10% of the segment length from the segment end) (figure 2a). Several relatively large VD estimates exist near the ends of the composite profile, possibly indicating slip interaction between adjacent segments. The most obvious of these (WS events X and Y [4.2 m] from the East Ogden site [Nelson and others, in press], and PS event Z [4.7 m] from the Mapleton site [Olig, verbal communication, 2006]; table 1) are more than double the mean VD value (~2.1 m) and located <25% of the segment length from the segment end, suggesting that the possibility of MSRs, although likely rare, cannot be ignored when developing WFZ segmentation models. The low-valued outliers reflect either minimum or poorly constrained VD

Table 1. Vertical displacement per earthquake for the Wasatch fault zone

Segment (length)[1]	Event	Paleoseismic site[2]	Preferred VD[3]	Notes[4]
BCS	W	Provo Delta[a]	0.9-1.2*	CWT, AD
(36)	W	Bowden Canyon[b]	2.5	RD
	X	Bowden Canyon	2.5	CWT, RD
	X	Pole Patch[b]	1.5-1.8	CWT, TR
	Y	Bowden Canyon	1.0	CWT, RD
	Y	Provo Delta	1.1*	CWT, AD, TR
	Z	Provo Delta	0.5-1.2*	CWT, AD, TR
	Z	Pole Patch	0.7-1.3	CWT, RD
WS	W	Kaysville[c]	1.4	SD, TR
(56)	X	East Ogden[d]	4.2	ASD
	X	Garner Canyon[d]	0.9-1.1	CWT, AD
	Y	Garner Canyon	0.8-2.1	CWT, AD
	Y	East Ogden	4.2	ASD
	Y	Kaysville	2.3-3.4	SD, TR
	Zb	Garner Canyon	1.0-1.3	CWT, AD
	Zb	East Ogden	2.6	ASD
	Zb	Kaysville	1.7-1.9	SD, TR
	Za	East Ogden	0.5-0.8	SD
SLCS	X	South Fork Dry Creek[e]	1.5-2.5	SPD, AD
(39)	Y	South Fork Dry Creek	1.5-2.5	SPD, AD
	Z	South Fork Dry Creek	1.5-2.5	SPD, AD
PS	X	American Fork[f]	2.2-2.7	ASD
(59)	Y	American Fork	2.2-2.7	ASD
	Z	American Fork	2.2-2.7	ASD
	Z	Rock Creek Trench[g]	3.3	SD
	Z	Mapleton[h]	1.4-3.0	CWT, SPD, TR
	Z	Mapleton megatrench[i]	4.7	CWT, SD, TR
NS	X	Red Canyon[j]	1.4-2.0	CWT, SD
(42)	Y	North Creek[k]	2.0-2.5	RD
	Y	Red Canyon	1.3-1.7	CWT
	Z	Santaquin[l]	2.8-3.2	SD, SPD
	Z	North Creek	2.0-2.2	CWT, SD, SPD
	Z	Red Canyon	1.1-1.7	CWT
LS	Z	Deep Creek[j]	1.8	SD
(26)	Z	Skinner Peaks[j]	1.8-3.0	SD, CWT

[1] Length is straight-line distance in kilometers.
[2] Paleoseismic-site source information: [a]McCalpin and Forman (2002), [b]Personius (1991), [c]McCalpin and others (1994), [d]Nelson and others (in press), [e]Black and others (1996), [f]Machette and others (1992), [g]Lund and Black (1998), [h]Lund and others (1991), [i]Olig, verbal communication (2006), [j]Jackson (1991), [k]Hanson and others (1981), [l]DuRoss and others (2006).
[3] VD - Vertical displacement from paleoseismic reports. *indicates minimum VD estimate; not all synthetic scarps trenched at site.
[4] Vertical displacement based on: AD – average displacement (site displacement/# events), ASD – apportioned stratigraphic displacement, using relative colluvial wedge thickness, RD – relative displacement between events (e.g., if event Y displacement is 2 m, event Z must be 1 m), CWT – colluvial wedge thickness, SD – stratigraphic displacement (e.g., stratigraphic units correlated across the fault zone), SPD – scarp-profile displacement, TR – trench retrodeformation/reconstruction.

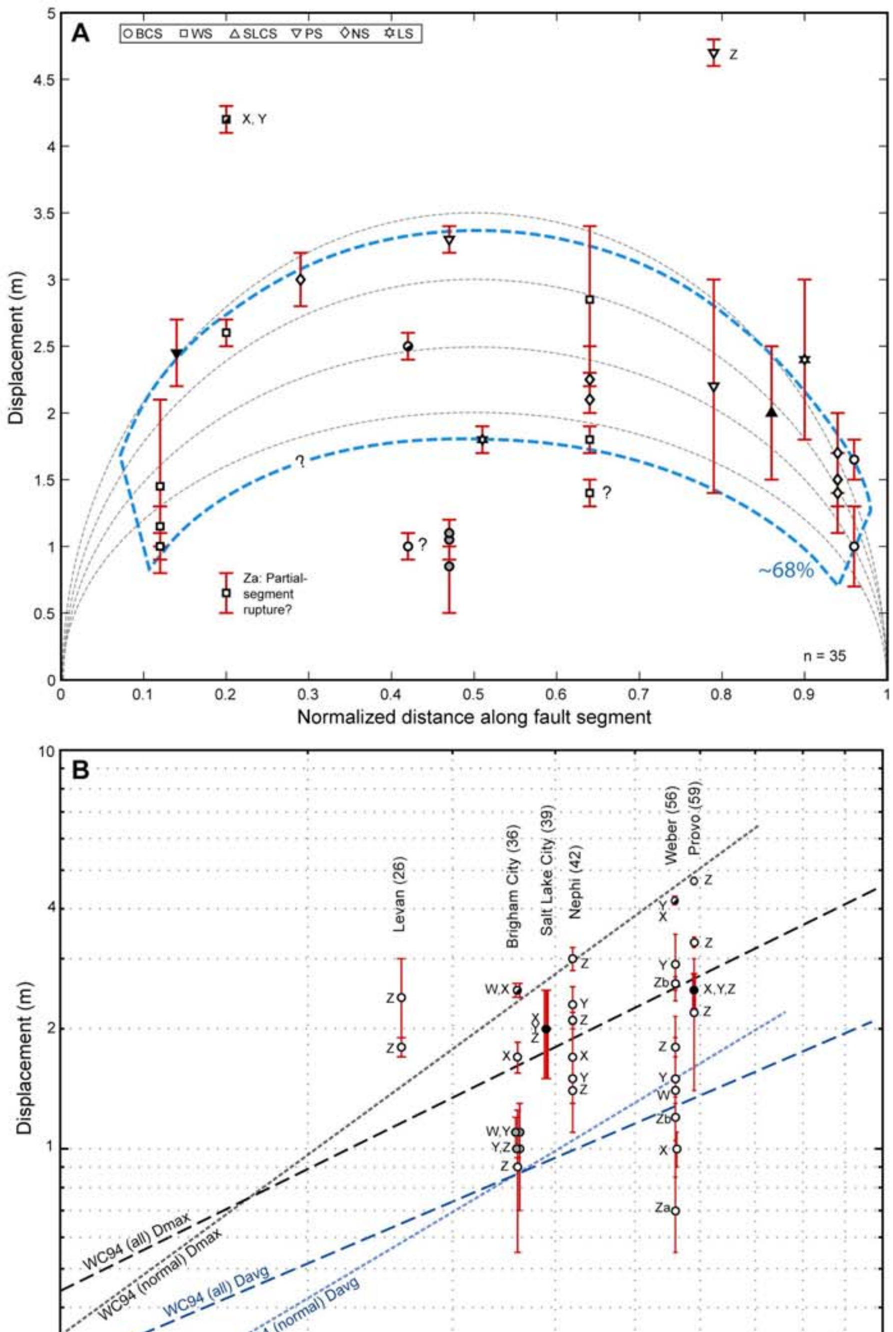

Figure 2. Per-event vertical displacement (VD) from Wasatch fault zone paleoseismic sites, plotted as A) VD versus normalized distance along fault segment (north to south: 0 to 1), showing possible modeled slip distributions (short-dashed half ellipses), and a slip envelope (blue dashed line) including ~68% of the VD data; and B) VD vs. surface rupture length (SRL), showing 'all-fault-type' (long- dashed lines) and 'normal-fault-type' (short-dashed lines) average and maximum VD-SRL regressions from Wells and Coppersmith (1994). See table 1 for displacement values, measurement type, and source. Red bars indicate data range (± 0.1 m if none reported; table 1); gray-filled shapes indicate minimum estimates; half-filled indicate two identical VD estimates; black-filled indicate three identical VD estimates.

estimates (e.g., BCS events Y and Z from the Provo Delta site [McCalpin and Forman, 2002]; table 1), or in the case of WS event Za, relatively small VD associated with a possible partial-segment rupture (Nelson and others, in press).

Vertical Displacement and Surface Rupture Length

Per-earthquake VD is positively correlated with surface rupture length (SRL) for most historical surface-faulting earthquakes (Wells and Coppersmith, 1994). Thus, VD estimates may be used to infer paleoearthquake SRL and magnitude (Hemphill-Haley and Weldon, 1999; Chang and Smith, 2002), as well as the probability that a paleoearthquake of given displacement at a point on the fault ruptured at an additional location on the fault some distance away (Biasi and Weldon, in press). I compared the VD and SRL (using single-segment length) estimates to average- and maximum-displacement regressions (for all- and normal-fault types) from Wells and Coppersmith (1994) (figure 2b). Using the all-fault-type regressions, about 49% of individual paleoearthquake displacements for the WFZ segments are larger than the maximum displacements predicted by the segment lengths, and over 90% are greater than the average displacements predicted by the segment lengths. When compared with the normal-fault-type regressions, about 86% of the observed WFZ displacements are greater than the average displacements predicted by the segment lengths. However, the largest observed displacements from each WFZ segment fit remarkably well with the maximum displacements predicted by the segment lengths (using the normal-fault-type regressions), and only ~14% of the WFZ displacements are greater than the regression-predicted maximum displacements.

These comparisons indicate that for the WFZ segments, the largest observed displacements closely match the maximum displacements predicted by the Wells and Coppersmith (1994) normal-fault-type maximum-displacement regression. However, 86-90% of the observed WFZ displacements are larger than those predicted by the normal- and all-fault average-displacement regressions, indicating anomalously large displacements along the WFZ, or possibly a bias toward locating paleoseismic sites on the largest and best-preserved scarps along each segment. In particular, anomalously large displacements (>4 m) for the WS and PS support the possibility of MSRs on the WFZ. The large VDs, if considered to be random measurements of displacement along the fault, suggest ruptures that have a 95% likelihood of being at least ~20 km longer than the segment lengths, based on the method of Biasi and Weldon (in press).

Fault-Trace Complexity

I investigated along-strike changes in the complexity of the Quaternary Wasatch fault trace to identify areas that may impede or accommodate MSRs. I delineated areas along the fault where 1) the width of the mapped fault zone is ≥ 5 km, 2) the fault orientation changes by ≥ 45° over ≥ 2 km, and/or 3) three or more fault strands are mapped (figure 3). The most complex zones along the WFZ correspond well with mapped segment boundaries as reported by Wheeler and Krystinik (1992) and Machette and others (1992). Using the fault-zone-complexity criteria, the WS-SLCS boundary is most complex, meeting all three criteria and having the longest and widest zones of

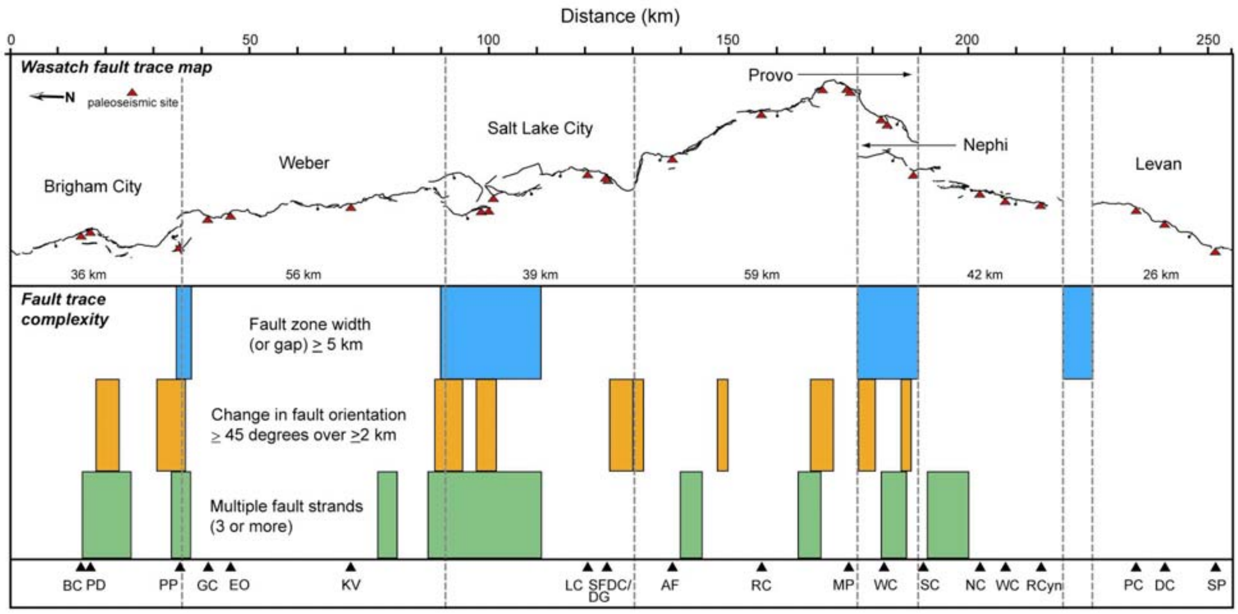

Figure 3. Fault-trace complexity of the central segments of the Wasatch fault zone, showing areas along the fault having a width ≥ 5 km (blue boxes), change in fault orientation of ≥ 45 degrees over 2 km (orange boxes), and multiple (three or more) fault strands (green boxes). Fault trace from Black and others (2003). Trench-site abbreviations as per figure 1.

complex faulting, followed by the PS-NS and BCS-WS boundaries, which also meet all three criteria. The SLCS-PS and NS-LS boundaries are the least complex, composed of relatively simple traces that respectively have a significant change in orientation and a ~5 km gap in Quaternary surface faulting.

WFZ MULTI-SEGMENT-RUPTURE ANALYSES

In evaluating the potential for MSR on the WFZ, I considered only middle to late Holocene earthquakes on the four central segments (BCS, WS, SLCS, and PS). Sixteen events occurred after ~6500 cal yr B.P. on these segments, resulting in 16 possible earthquake pairs (of adjacent segments) that have overlapping time ranges (figure 4). I assigned a low, medium, or high MSR-potential value (table 2) to each earthquake pair, based on the similarity of the consensus preferred earthquake times from the UQFPWG (Lund, 2005). I also analyzed the chronological control for each earthquake, ranking the quality of the paleoseismic data for each event (paleoseismic-event confidence) as low to high based on the number of paleoseismic sites having evidence for the earthquake and number and type of limiting numerical ages that constrain the timing of the event (table 3). In discussing possible MSRs, the following notation of segments and earthquakes is used: BCS-WS[X] – possible MSR during BCS event X and WS event X, or SLCS[W]-PS[X] – possible MSR between SLCS event W and PS event X.

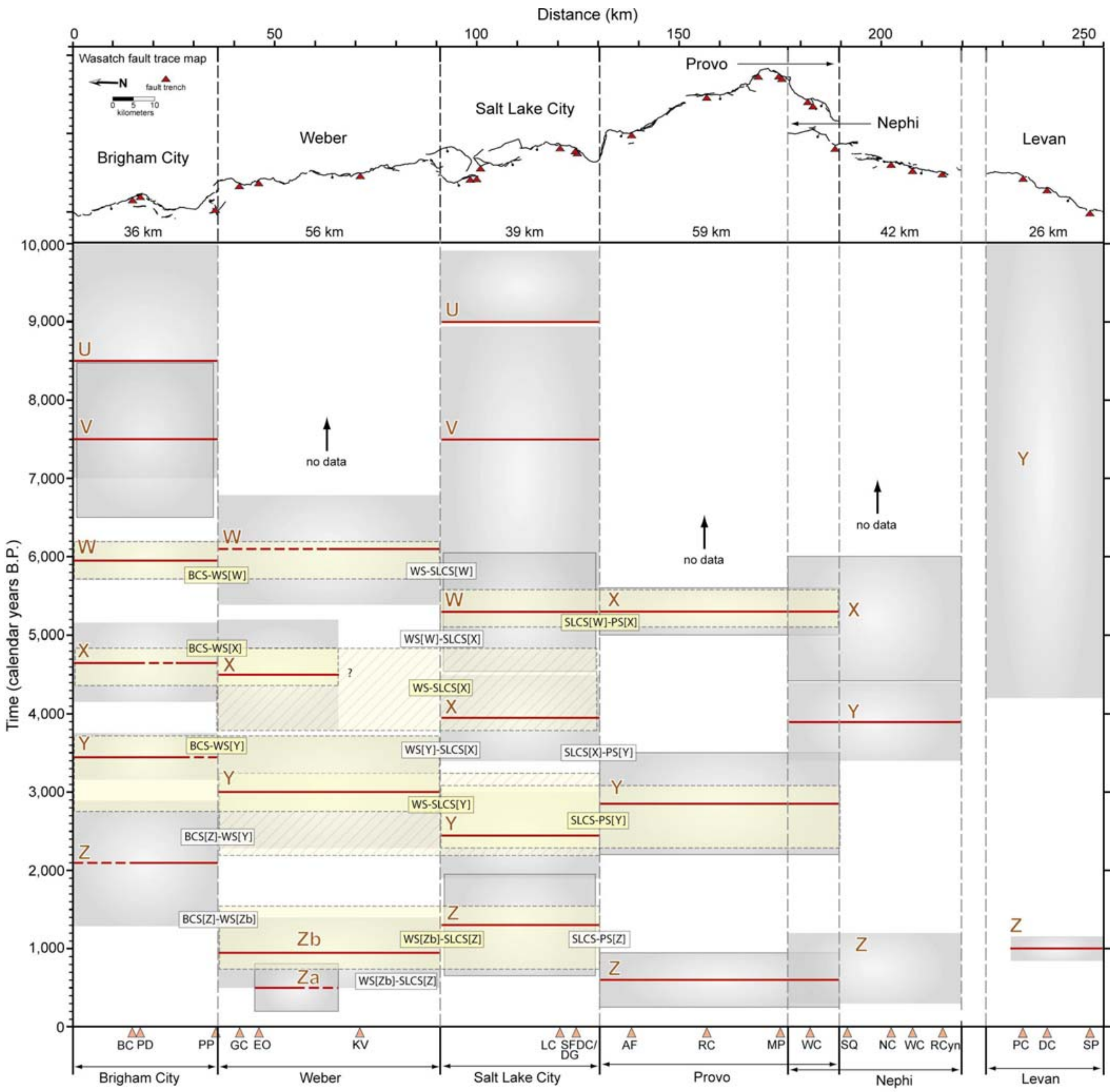

Figure 4. Possible earthquake pairs (of adjacent segments) having overlapping time ranges among the 16 earthquakes occurring after ~6500 cal yr B.P. on the Brigham City, Weber, Salt Lake City, and Provo segments. Earthquake pairs that meet the MSR criteria are highlighted in yellow and discussed in the text. Cross-hatched earthquake pairs indicate those conflicting with adjacent pairs and not included in the preferred set (figure 5). UQFPWG earthquake timing estimates from Lund (2005).

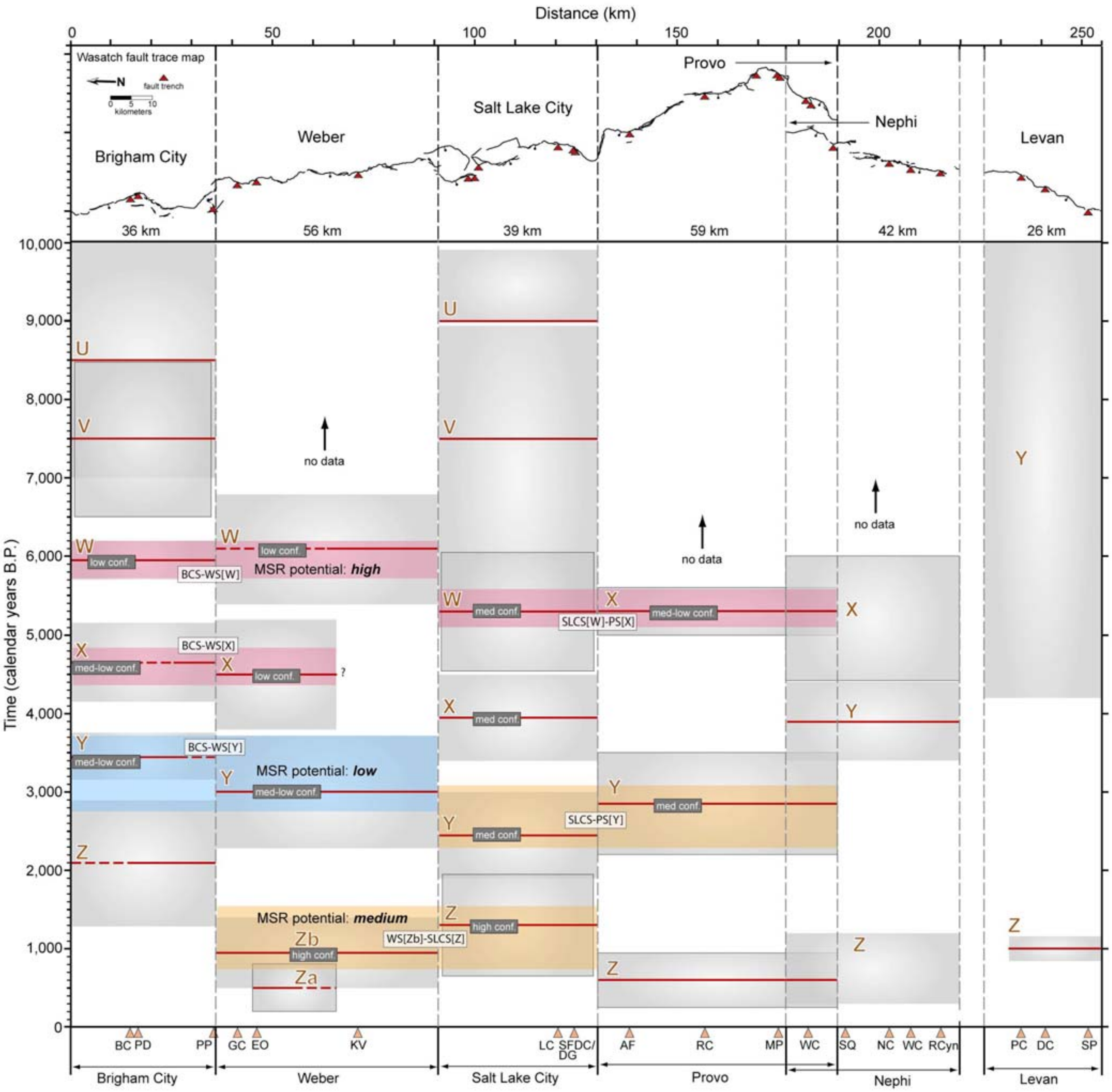

Figure 5. Preferred set of possible multi-segment ruptures (MSRs) on the Brigham City, Weber, Salt Lake City, and Provo segments of the Wasatch fault zone, showing MSR potential (low to high: blue, orange, and pink) and paleoseismic-event confidence.

Multi-Segment-Rupture Potential

Of the 16 possible earthquake pairs, eight MSRs are possible: three have a high potential for representing a MSR, two have medium MSR potential, and three have low potential (figures 4, 5; tables 2, 4). The eight remaining pairs do not meet the MSR-potential criteria or do not have rupture lengths supporting a two-segment rupture (e.g., WS event Za). I identified two high-potential earthquake pairs on the BCS-WS and one high-potential pair between the SLCS-PS, but none between the WS-SLCS. Also, medium-potential earthquake pairs exist between the WS-SLCS and SLCS-PS, but not the BCS-WS. Low-potential pairs include events on the BCS-WS and WS-SLS, but none on the SLCS-PS. Multiple combinations of the MSR pairs are possible because of earthquakes that have been used to generate more than one MSR. For example, the WS[Y] earthquake is used to form both the BCS-WS[Y] and WS-SLCS[Y] MSRs. A preferred set of MSR pairs excludes the conflicting low-potential MSRs. WS-SLCS[Y] is removed due to a preference for the higher potential SLCS-PS[Y] MSR, and WS-SLCS[X] is disregarded because of a lack evidence for the WS[X] rupture along the entire length of the fault (McCalpin and others, 1994; Nelson and others, in press). Thus, the preferred set of possible WFZ MSRs includes six rather than eight possible two-segment MSRs among the 16 post-6500-yr earthquakes identified on the BCS to PS (figure 5).

Paleoseismic-Event Confidence

Paleoseismic data constraining the timing of earthquakes on the central segments of the WFZ varies from low to high between sites and through time (figure 5, tables 3, 4), presenting a significant challenge in the quantification of MSR potential along the WFZ. As expected, the paleoseismic-event confidence level is highest for the youngest earthquakes on each segment, and generally decreases with increasing earthquake age. Where paleoearthquake timing is constrained by multiple numerical ages from multiple paleoseismic sites, the relation between adjacent segments is clarified (e.g., SLCS[Z] and PS[Z], figures 1 and 4). However, about 38% of paleoearthquakes (6 of 16) in the past ~6500 years on the BCS to PS have poor chronological control (low to med-low confidence; table 3): two (BCS[W] and WS[Za]) are based on a single numerical age from a single paleoseismic site, three (WS[W], WS[X], and BCS[Z]) are based on two or more ages from a single paleoseismic site, and one (PS[X]) is based on a total of two samples from two paleoseismic sites (figure 1). Unexpectedly, the six oldest and most poorly dated earthquakes are combined in three instances to form high-potential MSRs (figure 5, table 4). These high-potential, but low-paleoseismic-quality MSRs warrant additional investigations of the middle and early Holocene paleoearthquake histories of the central four WFZ segments.

Table 2. Multi-segment rupture potential

High potential	• Estimated 2-sigma time ranges for separate earthquakes overlap in time. • Preferred time of earthquake "A" is within time range of earthquake "B." • Preferred time of earthquake "A" minus preferred time of earthquake "B" is 0-200 yrs.
Medium potential	• Estimated 2-sigma time ranges for separate earthquakes overlap in time. • Preferred time of earthquake "A" is within time range of earthquake "B." • Preferred time of earthquake "A" minus preferred time of earthquake "B" is 201-400 yrs.
Low potential	• Estimated 2-sigma time ranges for separate earthquakes overlap in time. • Preferred time of earthquake "A" is within time range of earthquake "B." • Preferred time of earthquake "A" minus preferred time of earthquake "B" is >400 yrs.

The MSR-potential criteria above assume two hypothetical earthquake ruptures A and B on adjacent segments. No MSR potential is given when the time ranges do not overlap.

Table 3. Criteria for defining paleoseismic-event confidence

Number of paleoseismic sites[1]	Number of limiting ages[2]	Min & max ages?[3]	Paleoseismic-event confidence	Example	Min & max ages? [3]	Paleoseismic-event confidence	Example
3+	6+	Y*/N	**High**	PS[Z]	-	-	-
3+	5	Y*	**High**	-	N	**Med-high**	-
3+	4	Y/N	**Med-high**	-	-	-	-
3+	3	Y/N	**Med**	-	-	-	-
2	6+	Y*	**High**	SLCS[Z]	N	**Med-high**	-
2	5	Y*	**Med-high**	SLCS[W]*	N	**Med**	SLCS[Y]
2	4	Y/N	**Med**	-	-	-	-
2	3	Y	**Med**	SLCS[X]	N	**Med-low**	BCS[Y]
2	2	Y/N	**Med-low**	PS[X]	-	-	-
1	6+	Y/N	**Med-low**	-	-	-	-
1	5	Y/N	**Med-low**	BCS[Z]	-	-	-
1	4	Y/N	**Med-low**	-	-	-	-
1	3	Y	**Med-low**	WS[Za]	N	**Low**	WS[X]
1	2	Y	**Med-low**	-	N	**Low**	BCS[U]
1	1	NA	**Low**	BCS[W]	-	-	-

[1] Number of paleoseismic sites having overlapping minimum (min) or maximum (max) limiting ages. For example, if three sites exist, but only two have numerical limiting ages that are similar (overlapping) at their 2-sigma age ranges, then two sites are counted.
[2] Total number of min and max limiting ages between all paleoseismic sites (overlapping at 2 sigma).
[3] Y – yes, min and max ages present; N – no, only min or max ages present. *indicates that if minimum ages are from one paleoseismic site and maximum limiting ages are from a separate site, then confidence is decreased by one level (e.g., SLCS[W] is reduced from med-high to medium).

Table 4. Multi-segment rupture potential and confidence

Paleoearthquake pair[1]	**MSR potential**	**Paleoseismic-event confidence**
BCS-WS[W]	High	Low
BCS-WS[X]	High	Low to medium-low
SLCS[W]-PS[X]	High	Med-low to medium
WS[Zb]-SLCS[Z]	Medium	High
SLCS-PS[Y]	Medium	Medium
BCS-WS[Y]	Low	Med-low
WS-SLCS[X]	Low	Low to medium
WS-SLCS[Y]	Low	Medium-low to medium

[1] Notation: BCS-W[X] – possible MSR between events X on BCS and WS, SLCS[W]-PS[X] – possible MSR between event W on SLCS and event X on PS.

WFZ MULTI-SEGMENT RUPTURE MODELS

Several methods have been employed to generate MSR models for strike-slip faults, including those based on “cascading” ruptures (WGCEP, 1995, 2003; Field and others, 1999; Andrews and Schwerer, 2000), weighted combinations of SSR and MSR sources (fault-rupture scenarios) using expert opinion (Frankel and others, 2002; WGCEP, 2003), and probabilistically “stringing” ruptures between paleoseismic sites into moment-balanced models using earthquake-age distributions and displacement information (Weldon and others, 2005; Biasi and Weldon, in press). I have considered the application of each method to the WFZ, but herein discuss only the scenario/expert-opinion method. Through discussions of this research at meetings of the UQFPWG and Basin and Range Province Earthquake Working Group, I recognize the need to apply the moment-balanced “string” models of Weldon and others (2005), which may be the focus of continued research. Although I generally follow the methods of WGCEP (2003), a preferred MSR model is not quantified, due to (1) the complexity of determining the relative occurrence of MSR pairs on the WFZ and balancing the modeled occurrence with the geologic occurrence, (2) significant, pending paleoseismic reports for the WS, PS, and NS, and (3) a lack of a working-group consensus as to the preferred method of determining MSR probabilities for BRP normal faults.

WFZ Preliminary Fault-Rupture Scenarios and Models

I generated MSR models for the WFZ by defining five fault-rupture scenarios for the BCS, WS, SLCS, and PS (table 5), each representing one possible mode of failure of the fault during one earthquake cycle (WGCEP, 2003). For example, rupture scenario 1 includes separate rupturing of all four segments, whereas scenario 2 accounts for a MSR between the BCS-WS, and separate SSRs on the SLCS and PS (table 5). I then created preliminary fault-rupture models (e.g., model A, table 5), each having weighted combinations of the different rupture scenarios. Models A and B (table 5) are simplified and qualitative, whereas model C is based on the relative occurrence of each scenario using the preferred set of six MSRs (figure 5). Each fault-rupture model represents one possible long-term mode of earthquake rupturing on the central part of the WFZ, whereas a preferred model specifies relative weights for the individual fault-rupture models (WGCEP, 2003).

Table 5. Examples of possible MSR models for the central WFZ

Rupture scenarios[1]		Fault-rupture models		
		Model **A**[2]	Model **B**[2]	Model **C**[3]
1	BCS, WS, SLCS, PS	100%	20%	0%
2	***BCS+WS***, SLCS, PS	0%	20%	34%
3	BCS, ***WS+SLCS***, PS	0%	20%	15%
4	BCS, WS, ***SLCS+PS***	0%	20%	27%
5	***BCS+WS***, ***SLCS+PS***	0%	20%	24%
Preferred model [4]:		%	%	%

[1] Commas between segments indicate separate rupturing, pluses and bold-italic text indicate MSRs between segments. Terminology from WGCEP (2003).
[2] Models A and B are simplified examples.
[3] Model C is based on the relative occurrence of the four rupture scenarios (2 through 5) that include MSR pairs, using the preferred set of MSR pairs and the MSR potential and paleoseismic-event confidence to define the relative weights; see text for discussion.
[4] A preferred MSR model is not included, but would give relative weights to models A to C.

MSRs on the BCS-WS and SLC-PS (scenarios 2, 4, and 5) may occur more frequently than those on the WS-SLCS, based on the preferred set of MSRs and a qualitative evaluation of vertical displacement and fault-zone complexity. Although a possible medium-potential WS-SLCS MSR is associated with high-confidence paleoseismic data, the majority of the possible MSRs are on the BCS-WS and SLCS-PS segments. Vertical-displacement data for the central segments roughly support BCS-WS and SLCS-PS MSRs (indicating large amounts of slip near the segment boundaries), but are lacking for the southern part of the WS and northern part of the SLCS segments. Additionally, the WS-SLCS segment boundary is relatively more complex than the BCS-WS and SLCS-PS boundaries, possibly indicating a more persistent boundary to rupture propagation.

Fault-rupture model C (table 5) is based on the relative occurrence of scenarios 2-5, using the preferred set of six MSRs. Calculated relative weights for the scenarios indicate more frequent BCS-WS and SLCS-PS MSRs than WS-SLCS MSRs. As model C is a “worst-case” model and I was only interested in the relative occurrence of the MSR scenarios (2 to 5), scenario 1 received zero weight. Prior to determining scenario weights, I gave MSR-potential values (increasing for higher potential) to each MSR pair, and then adjusted those values using the paleoseismic-event confidence – by a factor of 0.7 for low confidence to 1.0 for high confidence. Thus, each MSR pair had a numeric value (MSR-potential value), higher for higher potential and greater paleoseismic-event confidence, which I used to determine the relative weights for each scenario over the 6500-yr time span. Where a particular MSR pair could be part of two different scenarios, I divided the MSR-potential value equally between them. For example, MSR pair SLCS[W]-PS[X] counts toward scenario 4, but if BCS-WS[W] also occurred, then both MSR pairs would count towards scenario 5 (table 5). Additionally, BCS-WS[Y] would contribute to the relative occurrence of scenario 2, but if combined with SLCS-PS[Y], would apply to scenario 5. An additional fault-rupture model excludes the possibility of scenario 5, but is not included here.

To compute the relative weights for scenarios 2 to 5, I amassed the maximum number of scenario combinations (e.g., for MSR pairs BCS-WS[X] and SLCS[W]-PS[X], scenarios 2, 4, and 5 are possible [table 5]), determined the MSR-potential value for each scenario based on the average value of the MSR pairs used (for a MSR pair used in multiple scenarios, the value is divided equally between the scenarios), summed the scenario values, and divided the MSR-potential value for each scenario by the sum for all scenarios. Using this method, scenarios having MSR pairs with higher MSR-potential values draw more weight and have a higher relative occurrence. Thus, based on the MSR pairs, scenario 2 could occur a maximum of three times, scenario 3 – once, scenario 4 – twice, and scenario 5 – twice. Using the sums of the average adjusted MSR-potential values for each possible scenario and the method described above, I determined relative weights of 0.34, 0.15, 0.27, and 0.24 for scenarios 2 to 5, respectively (table 5).

Preferred Fault-Rupture Model

The product of the multiple-scenario method is a preferred fault-rupture model, which specifies individual weights for the separate fault-rupture models, generally through a working-group consensus process (e.g., WGCEP, 2003). The preferred model can then be used to determine the relative occurrence of each rupture source (e.g., a SSR or MSR source), which may be compared and balanced with geologic occurrence rates (using the seismic moment and moment rate), though the process is arduous (appendix G in WGCEP, 2003).

I do not specify a preferred fault-rupture model for the WFZ, as the individual model weights are not balanced with the geologic moment (long-term slip rate). Additionally, through the process of creating and weighting the scenarios and models, I recognize the importance of a methods review by a working-group process before formalizing model weights, also through a consensus process. Prior to finalizing a preferred model, it is necessary to incorporate new paleoseismic data for the WS, PS, and NS, and to analyze the potential for MSRs between the PS and NS, which may be the best "case study" of a potential MSR on the WFZ, in which the earthquake timing, vertical displacement, and geologic moment can be considered.

RECOMMENDATIONS FOR THE NATIONAL SEISMIC HAZARD MAPS

The current use of epistemic uncertainty in characteristic magnitude in the NSHMs for a SSR on the WFZ (± 0.2 M; Frankel and others, 2002) accounts for an additional 15-20 km of rupture beyond the single-segment length (Lund, 2006), but does not include the possibility of a full two-segment earthquake on the WFZ. For example, in the NSHMs, the BCS, WS, SLCS, and PS are given characteristic magnitudes (± 0.2) of 7.0, 7.2, 7.1, and 7.4, respectively (U.S. Geological Survey, 2006); however, moment-magnitude estimates for MSRs between these segments are between 7.4 and 7.5, using magnitude-SRL regressions for all-fault and normal-fault types in Wells and Coppersmith (1994) (table 6). Although applying a two-segment MSR model to the WFZ results in small changes (between -4% and +7% g) in the 2% in 50-year peak ground accelerations when compared with the NSHM SSR model, the MSR model is important from an emergency-response standpoint because of the potential for longer period and longer duration ground shaking and a significantly larger extent of damage (Lund, 2006).

Table 6. Moment-magnitude estimates for MSRs on the central WFZ

MSR	**SRL (km)**[1]	**Moment magnitude (Mw)**[2]	
		All-fault type	Normal-fault type
BCS-WS	91	7.4	7.4
WS-SLCS	95	7.4	7.5
SLCS-PS	98	7.4	7.5

[1] SRL – surface rupture length (straight-line distance).
[2] Moment-magnitude estimate based on Wells and Coppersmith (1994) magnitude-SRL regressions: for all-fault type, Mw = 1.16 log SRL + 5.08; for normal-fault type, Mw = 1.32 log SRL + 4.86.

Considering the long-term requirements in developing a well-constrained MSR model for the central segments of the WFZ, including additional paleoseismic data; continued work developing, reviewing, and testing the models; and working-group consensus on relative model weights, I do not recommend that a time-dependent or paleoearthquake-based MSR model be incorporated into the 2007 update of the NSHMs. Rather, I recommend that a simple, time-independent MSR model be used. For example, MSRs on the central WFZ could be accounted for by 1) including a low-probability two-segment rupture, 2) including a low-probability large-SRL floating earthquake (e.g., Wong and others, 2002; WGCEP, 2003), or 3) appropriately increasing epistemic uncertainty in magnitude (Lund, 2006).

CONCLUSIONS

The WFZ is one of the best-studied normal faults in the BRP, but the potential for MSRs among its segments is poorly understood. Understanding the rupture behavior of the WFZ, and developing methods to investigate and quantify the possibility of MSRs is an important step in understanding normal-fault hazards and improving national, regional (e.g., BRP), and local (e.g., Salt Lake City area) earthquake-hazard studies.

The largest VDs observed along the central WFZ correspond well with the maximum displacements predicted by the segment lengths using the Wells and Coppersmith (1994) maximum-displacement-SRL regression for normal faults. However, 86-90% of the observed VD estimates from the central WFZ are larger than the average displacements predicted by the segment lengths using the Wells and Coppersmith (1994) average-displacement-SRL regressions for normal- and all-fault types, suggesting SRLs longer than the mapped segment lengths. Additionally, when normalized for segment length, the VD data indicate a tendency toward SSRs, but do not preclude the potential for MSRs. Although the majority (~68%) of the VD data fit within a half-ellipse-shaped slip envelope, which shows VD decreasing from a maximum of ~1.8-3.4 m near the segment centers to ~0.8-2.1 m near the segment ends, several anomalously large VD estimates near the ends of the fault segments suggest the possibility of surface fault ruptures at least 20 km longer than the mapped segment lengths. Thus, the paleoseismic data support a simple model of Holocene SSRs along the central WFZ, but do not preclude the possibility of infrequent MSRs, which should be addressed in fault-segmentation models.

This investigation shows that eight of the 16 different post-6500-yr earthquake pairs on the central four segments of the WFZ (BCS, WS, SLCS, and PS) have the potential to represent MSRs, with a preferred set including six possible MSRs among the last 16 earthquakes. However, the paleoseismic data necessary to have confidence in such MSRs are limited. I report a prevalence of low- to medium-MSR-potential earthquake pairs and low to medium data confidence, and a lack of high-potential MSRs based on high-confidence paleoseismic data, which preclude development of well-constrained MSR models. As the oldest paleoearthquakes on the BCS to PS are combined in three separate high-potential MSR pairs, I recommend additional investigations into the middle and early Holocene paleoearthquake histories on these segments.

I followed the multiple-scenario method of WGCEP (2003), considering SSRs and MSRs in fault-rupture scenarios and models, and developed new methods to quantify the relative occurrence of the scenarios using MSR potential and paleoseismic-event confidence. I provide weights for two generalized fault-rupture models (A and B, table 5) and a quantitative model (C, table 5), based on the above MSR analysis, which indicates the more frequent occurrence of BCS-WS and SLCS-PS MSRs to WS-SLCS MSRs. I do not include a preferred model (with relative weights for different fault-rupture models) due to the limits of available WFZ paleoseismic data, and recommend that a simple, time-independent MSR model (e.g., a low-probability, large-SRL floating earthquake) be used to account for WFZ MSRs in the 2007 update of the National Seismic Hazard Maps (NSHMs). Prior to finalizing a preferred model for use in the NSHMs, continued work is necessary to 1) extend these analyses to include possible MSRs between the PS and NS, 2) improve the paleoseismic-data density and quality (e.g., by incorporating new paleoseismic data for the WS, PS, and NS), 3) moment balance the models and consider the “string” method of Weldon and others (2005), and 4) reach working-group consensus as to the preferred method of generating models and assigning relative weights.

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

PART V: BASIN AND RANGE PROVINCE EARTHQUAKE WORKING GROUP SEISMIC-HAZARD RECOMMENDATIONS to the U.S. GEOLOGICAL SURVEY NATIONAL SEISMIC HAZARD MAPPING PROGRAM*

By

Basin and Range Province Earthquake Working Group
in cooperation with the
Basin and Range Province Committee
of the
Western States Seismic Policy Council

Edited by
William R. Lund, Utah Geological Survey

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

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SESSION SUMMARIES

INTRODUCTION

This report presents consensus recommendations of the Basin and Range Province Earthquake Working Group (BRPEWG) on five seismic-hazard issues in the Basin and Range Province (BRP) important to the U.S. Geological Survey's (USGS) 2007 update of the National Seismic Hazard Maps (NSHMs). Scientists attending the Western States Seismic Policy Council (WSSPC)-sponsored Basin and Range Province Seismic Hazard Summit II (BRPSHSII) held in Reno, Nevada, in May 2004 first identified the five issues. Following BRPSHSII, WSSPC incorporated the issues into their Policy Recommendation (PR) 04-5, which advocated convening a broad-based group of technical experts to evaluate each of the issues and advise the USGS regarding the 2007 NSHM update. In response to PR 04-5, the WSSPC Basin and Range Province Committee (BRPC) and the Utah Geological Survey (UGS) convened the BRPEWG under the auspices of WSSPC and the USGS NSHM Project. The BRPEWG was charged with reviewing information regarding the five issues, and developing consensus recommendations for the 2007 NSHM update. The BRPEWG drew its members from several BRP state geological surveys, federal government agencies, academic institutions and seismological laboratories, and geotechnical consulting firms. The BRPEWG met on March 8-10, 2006, in Salt Lake City, Utah.

BRPEWG RECOMMENDATIONS

The BRPEWG arrived at the following consensus recommendations through a deliberative process. The Working Group relied on the broad technical expertise and experience of its members when considering how the issues should be accommodated in the 2007 update of the NSHMs. Where appropriate, the Working Group also made recommendations for long-term research that will permit further refinement of the NSHMs beyond the 2007 update.

Issue 1
Use and Relative Weighting of Time-Dependent, Poisson, and Clustering Models in Characterizing Fault Behavior

Short-Term Recommendation for the 2007 NSHMs

1. The USGS should incorporate uncertainties in slip rates and recurrence intervals for the more significant BRP faults.
    a. Most studies giving slip rates and recurrence intervals identify the range of uncertainties.
    b. In Utah, use the slip-rate/recurrence distributions developed by the Utah Quaternary Fault Parameters Working Group (Lund, 2005a).

Long-Term Recommendations

1. Regional working groups are needed to develop consensus slip-rate and/or recurrence-interval distributions for significant faults.
    a. These rate distributions should represent temporal variation of the rates, if any, and other uncertainties.
    b. A high-level working group needs to recommend guidelines for establishing these distributions.
    c. Each regional group needs a “champion” who will take “ownership” to lead the group and secure results.
    d. Regions will not necessarily be by state. Some organizations (e.g., USGS or WSSPC) need to take responsibility to assure complete geographic coverage.

2. The USGS should continue to develop time-dependent maps as a research product.
    a. In general, research needs to focus more on the timing of the most recent earthquake, average recurrence, and determining coefficients of variation for recurrence.

Issue 2
Proper Magnitude-Frequency Distributions (Gutenberg-Richter versus Characteristic Earthquake Models) for BRP Faults

Short-Term Recommendations for the 2007 NSHMs

1. The USGS “floating exponential” model should be validated to the extent possible, or at least made consistent with the paleoseismic and historical earthquake record in the BRP. The USGS model should also be compared with traditional magnitude-frequency models currently used in state-of-the-practice PSHAs.

2. The USGS should use the same recurrence model and weights for all BRP faults unless there is a technical basis for deviating from this characterization.

3. Weights assigned to the maximum magnitude and “floating exponential” models used for the 2007 NSHMs should, at a minimum, have the same weights as those used in California (2/3 - 1/3) unless there is a technical basis for deviating from this characterization.

4. To avoid double-counting earthquakes in the range of M 6.5 to the characteristic earthquake magnitude, zones surrounding BRP faults should be removed from the areas included in the Gaussian smoothing of background seismicity.

5. The methodology used for constructing the NSHMs must be fully transparent. The USGS is urged to publish, if only as a short note, how recurrence modeling is performed for the NSHMs, especially for fault-specific sources.

Issue 3
Use of Length versus Displacement Relations to Estimate Earthquake Magnitude

Short-Term Recommendations for the 2007 NSHMs

Estimating Displacement and Length:

1. Include uncertainty in surface rupture length (SRL) and its consequences for magnitude.

2. Constrain the minimum magnitude assigned to surface-faulting earthquakes to M 6.5 to be consistent with the hazard set by background seismicity.

3. Use magnitude-displacement regressions to improve magnitude estimates where the magnitude from SRL appears inconsistent.

4. Have a working group look at the faults for which displacement data are available (thought to be ~20 in Nevada), and suggest a weighting between displacement and SRL estimates of magnitude to achieve a combined fault magnitude estimate.

Long-Term Recommendations

Regressions:

1. Revisit the Wells and Coppersmith (1994) regressions to update the database and evaluate the need to censor short rupture lengths and small magnitudes.

2. Develop a M_w versus SRL$*$displacement scaling as a tool for improving use of displacement in making magnitude estimates.

3. Develop a multivariate regression for magnitude, given SRL and displacement, to improve magnitude estimates on faults for which both are available.

4. Invest in determining whether regional regressions materially improve ground motion predictions; for long strike-slip faults (western BRP) consider using the Hanks and Bakun (2002) M_w versus area regression relation.

5. For short faults, consider whether Wells and Coppersmith (1994) is appropriate considering the results of Stirling and others (2002).

6. Evaluate whether an estimate of magnitude based on area (with an assumed width) is more appropriate than magnitude based on SRL.

Displacement:

1. There should be a concerted effort to assess:
   a. the variability of displacement along rupture strike for historical surface ruptures for the entire range of magnitude (e.g., a follow up to McCalpin and Slemmons, 1998), and
   b. whether surface-faulting data for the BRP support regional (BRP-specific) regressions.

Issue 4
Probabilities and Magnitudes of Multi-Segment Ruptures

Short-Term Recommendations for the 2007 NSHMs

1. Hazard calculations for the NSHMs should consider the possibility of multi-segment ruptures on BRP faults.

2. For BRP faults for which single-segment-rupture models are being used to compute the hazard, the 2007 NSHMs should also use an unsegmented rupture model which accounts for the possibility of ruptures extending beyond segment boundaries. The unsegmented model should be given a relatively low weight.

3. The two faults that ruptured together in the 1959 Hebgen Lake earthquake should be treated as a single seismic source for the purpose of the 2007 NSHM hazard calculations.

Short-Term/Long-Term Recommendation

1. Where available, displacement data should be used to provide a consistency check for segmentation models – especially to identify segments on which ruptures longer than the mapped length could occur.

Long-Term Recommendations

1. Newly developed methods for probabilistically constructing rupture scenarios from paleoearthquake timing and displacements should be applied to the Wasatch fault.

2. Research needs to be conducted on the following topics to facilitate segmentation modeling in the BRP:
   a. how to recognize and characterize fault-rupture segments,
   b. the quality and quantity of paleoseismic data needed to support segmented earthquake models along BRP faults, and
   c. construction of earthquake-segmentation models for important BRP faults.

Issue 5
Resolving Discrepancies between Geodetic Extension Rates and Geologic Slip Rates

Short-Term Recommendations for the 2007 NSHMs

1. Convert vertical slip rates to extensional rates for consistency with GPS data. This involves resolving the question of dip of normal faults. The NSHMs currently use a dip of 60°; the BRPEWG recommends using a dip of 50°±10°.

2. For the BRP, use the province-wide kinematic (GPS) boundary condition (12-14 mm/yr) as a constraint on the sum of geologic slip rates. Enhance the fault catalog used in the NSHMs if necessary to achieve the far-field rates.

3. Modify the boundaries of the geodetic zones in the western Great Basin used in the 1996 NSHMs to better reflect the areas of high strain depicted on the GPS-based strain-rate map.

4. Use the geodetic data as the total strain budget. Ideally, the moment rates from the faults, areal source zones, and GPS zones should add up to the full geodetic budget. This total should be comparable to the seismicity, which is a separate estimate of moment rate. Differences that exist between these individual moment sources should be fully accounted for in the 2007 NSHMs.

5. The USGS should test models to evaluate the effect of releasing geodetic strain as 80% coseismic and 20% aseismic.

6. The USGS should evaluate the impact on the NSHMs of partitioning geodetic strain on individual faults within a zone (assigning default slip rates) versus distributing the geodetic strain uniformly across the zone.

Long-Term Recommendations

1. Move toward assigning minimum slip rates to specific faults. To this end, develop a strategy of how to assign slip rates based on combined geodetic and geologic criteria; this could be a charge for a future working group.

2. Develop a consistent-resolution fault map for the western margin of the Great Basin as a first step toward an integrated geodetic/geologic model.

3. Develop robust, geologically based (paleoseismic) slip rates in the source zones where geodesy shows significant strain accumulation, giving priority to urban and rapidly urbanizing areas.

4. The geoscience community should work toward the goal of determining if geodesy can identify specific faults where strain is being localized (i.e., indicator of higher hazard).

5. Where adequate data exist, develop an integrated model that incorporates geodetic, seismicity, and fault data.

6. The USGS should fully explain in an easily accessible publication or Web page the methodology behind the NSHMs, including the properties of each version of the maps so that changes in the maps over time can be completely understood.

BACKGROUND

The BRPEWG and the recommendations presented here are the outcome of a process begun in May 1997, when WSSPC, the USGS, the Federal Emergency Management Agency, and several BRP state geological surveys jointly sponsored the Basin and Range Province Seismic-Hazard Summit (BRPSHS) in Reno, Nevada. The purpose of BRPSHS was to bring together technical experts, emergency planners, and policy makers to review important technical issues in characterizing seismic hazards in the BRP and to consider their public-policy implications (Lund, 1998). Seven years later in May 2004, the same organizations sponsored a second seismic-hazard summit, BRPSHSII, in Sparks, Nevada. The purpose of BRPSHSII was to convene a group similar to that in 1997, to present and discuss advances in BRP earthquake-hazard research since the first summit, and to evaluate the implications of the new research for hazard reduction and public policy in the BRP (Lund, 2005b).

Seismic-Hazard Issues

The scientists attending BRPSHSII identified six seismic-hazard issues in the BRP that they considered important to the 2007 NSHM update. The six issues are:

1. Use and relative weighting of time-dependent, Poisson, and clustering models in characterizing fault behavior.
2. Appropriate attenuation relations, stress drop, and kappa in modeling ground motions, including consideration of evidence from precarious rock studies.
3. Proper magnitude-frequency distributions (Gutenberg-Richter versus characteristic earthquake models) for BRP faults.
4. Use of length versus displacement relations to estimate earthquake magnitude.
5. Probabilities and magnitudes of multi-segment ruptures.
6. Resolving discrepancies between geodetic extension rates and geologic slip rates.

WSSPC Policy Recommendation

The BRPC reviewed the above issues following BRPSHSII, and prepared a draft WSSPC policy statement that recommended convening a broad-based technical working group to develop scientific consensus regarding fault behavior, ground shaking, ground-failure modeling, and research priorities relevant to seismic policy and the USGS NSHMs in the BRP. After review and discussion by the WSSPC Board, the draft policy was adopted as *WSSPC Policy Recommendation 04-5: Basin and Range Province Earthquake Working Group* (the full text of the policy may be viewed at http://www.wsspc.org/PublicPolicy/PolicyRecs/2004/policy04-5.html). The BRPC and the UGS took responsibility for implementing PR 04-5 under the auspices of the USGS NSHM Project.

BASIN AND RANGE PROVINCE EARTHQUAKE WORKING GROUP

Various seismic-hazard-evaluation initiatives in California (Working Groups on California Earthquake Probabilities, 1988, 1990, 1995, 1999, 2003), as well as the Utah Quaternary Fault Parameters Working Group (Lund, 2005a) have successfully employed working groups composed of technical experts to critically evaluate datasets or issues and arrive at consensus decisions regarding data values/reliability and seismic-policy recommendations/decisions. The BRPC and the UGS employed a similar strategy when convening the BRPEWG, which consisted of subject-matter experts in the fields of geology, paleoseismology, seismology, and geodetics with experience in the BRP (table 1).

Table 1. Members of the BRPEWG

John Anderson	University of Nevada Reno Seismological Laboratory
Walter Arabasz	University of Utah Seismograph Stations
Glenn Biasi	University of Nevada Reno Seismological Laboratory
Tony Crone	U.S. Geological Survey, Denver
Craig dePolo	Nevada Bureau of Mines & Geology
Chris DuRoss	Utah Geological Survey
Kathy Haller	U.S. Geological Survey, Denver
Bill Hammond	Nevada Bureau of Mines & Geology
Suzanne Hecker	U.S. Geological Survey, Menlo Park
Mark Hemphill-Haley	Humboldt State University
David Love	New Mexico Bureau of Geology & Mineral Resources
William Lund	Utah Geological Survey
Vince Matthews	Colorado Geological Survey
Jim McCalpin	GEOHAZ, Inc.
Susan Olig	URS Corp.
Dean Ostenaa	U.S. Bureau of Reclamation, Denver
Phil Pearthree	Arizona Geological Survey
Jim Pechmann	University of Utah Seismograph Stations
Mark Petersen	U.S. Geological Survey, Denver
Robert Smith	University of Utah Department of Geology and Geophysics
Bill Phillips	Idaho Geological Survey
David Schwartz	U.S. Geological Survey, Menlo Park
Burt Slemmons	University of Nevada Reno, emeritus

Mike Stickney	Montana Bureau of Mines & Geology
Wayne Thatcher	U.S. Geological Survey, Menlo Park
Chris Wills	California Geological Survey
Ivan Wong	URS Corp.

BRPEWG Process

The BRPEWG met for three days (March 8-10, 2006) in Salt Lake City to consider five of the six seismic-policy issues identified at BRPSHSII and incorporated in WSSPC PR 04-5. The sixth issue (number 2 above), "*Appropriate attenuation relations, stress drop, and kappa in modeling ground motions, including consideration of evidence from precarious rock studies*," is being addressed through a separate USGS-sponsored process (Next Generation of Attenuation Models), and therefore was not considered by the BRPEWG. The three-day meeting was divided into six four-hour sessions. The BRPEWG devoted the first five sessions to considering the five seismic-policy issues. The Working Group used the sixth session, on the afternoon of the final day, to review the recommendations generated during the meeting.

For each session, the BRPC and UGS identified two subject-matter experts to serve as session leaders (table 2). Session leaders were charged with framing their issue succinctly for the BRPEWG as a whole, facilitating discussion during their session, and guiding the BRPEWG toward consensus recommendations to the USGS for the 2007 NSHMs. Where appropriate, the BRPEWG also made longer term recommendations that the USGS could use to set research priorities for both their own internal studies and for their National Earthquake Hazards Reduction Program (NEHRP) external grants to better resolve these issues for future (beyond 2007) NSHM updates.

Table 2. BRPEWG session leaders.

Session Leader	Seismic-Policy Issue
John Anderson Susan Olig	Use and relative weighting of time-dependent, Poisson, and clustering models in characterizing fault behavior
David Schwartz Ivan Wong	Proper magnitude-frequency distributions (Gutenberg-Richter versus characteristic earthquake models) for BRP faults
Glenn Biasi Mark Hemphill-Haley	Use of length versus displacement relations to estimate earthquake magnitude
Craig dePolo Jim Pechmann	Probabilities and magnitudes of multi-segment ruptures
Robert Smith Wayne Thatcher	Resolving discrepancies between geodetic extension rates and geologic slip rates

Each pair of leaders organized their session as they thought appropriate; the BRPC and UGS did not mandate a consistent session format. However, all of the meeting sessions followed a generally similar pattern, with the session leaders and invited speakers making a series of technical presentations to help define and provide information about the issue under consideration. The presentations were followed by open discussion to elicit consensus recommendations from the BRPEWG. The UGS took careful notes during the sessions, and prepared draft summaries of the sessions and the resulting recommendations. The UGS distributed the draft summaries to the BRPEWG members for review and comment. The members commented directly to the session leaders, who then revised the UGS drafts and created a final session summary (see “Session Summaries” below) and set of recommendations for their session.

SUMMARY

The BRPEWG recommendations contained in this document provide guidance to the USGS regarding five critical seismic-hazard issues in the BRP that are relevant to the next update of the NSHMs. The short-term recommendations reflect the BRPEWG’s consensus on best professional practice at this time for the 2007 NSHM update. Recognizing that these critical issues can only be accommodated, not resolved, in the 2007 NSHMs, the BRPEWG also made recommendations for long-term research priorities and goals that will help both the USGS and other research institutions eventually resolve the issues to better refine the NSHMs in the future. The BRPEWG hopes that the USGS will find their recommendations both timely and useful, and that the BRPEWG process will result in improvements to the NSHMs and a reduction in seismic risk in the BRP.

ACKNOWLEDGEMENTS

William Lund (UGS) organized and convened the meeting with assistance from the BRPC BRPEWG Organizing Committee (Ivan Wong [URS Corp.], Gary Christenson [UGS], Craig dePolo [NBM&G], and Bill Phillips [IGS]). On behalf of WSSPC and the UGS, we thank all of the members of the BRPEWG who gave generously of their time to make this effort a success. We especially thank the session leaders who organized and conducted their sessions, the members of BRPEWG who made presentations during the meeting, and the UGS (William Lund, Gary Christenson, Chris DuRoss, and Mike Hylland) for preparing the session summaries. William Lund compiled and edited the final report. Funding for the BRPEWG was provided by the UGS and through USGS NEHRP grant 03HQAG0008.

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SESSION SUMMARIES

SESSION 1
USE AND RELATIVE WEIGHTING OF TIME-DEPENDENT, POISSON, AND CLUSTERING MODELS IN CHARACTERIZING FAULT BEHAVIOR

Session Leaders

John Anderson, University of Nevada Reno Seismological Laboratory, Reno, Nevada
Susan Olig, URS Corporation, Oakland, California

Presentations

BRPEWG morning session, March 8, 2006

Olig	Earthquake clustering and time-dependent models
dePolo	Behavior of the Genoa fault, Monte Cristo fault, and Warm Springs fault system, Nevada
Schwartz	Time dependence and historical earthquakes – Hebgen Lake faults
Petersen	Process for the 2007 maps and time-dependent hazard analysis
Olig	Time-dependent probabilistic seismic hazard analyses along the Wasatch Front, Utah: The need for longer and more complete paleoseismic records

Session Summary

Susan Olig began the session by noting that slip rates drive seismic hazard, and then centered initial discussions on temporal clustering and slip variability. She and Craig dePolo gave examples of paleoseismic data indicating clustering behavior on several Basin and Range Province (BRP) faults. Important points regarding clustering behavior included:

- BRP faults, particularly those for which we've obtained long paleoseismic records, commonly demonstrate clustering behavior (e.g., Canyon Ferry fault, Montana; Lost River fault, Idaho; Pajarito fault, New Mexico).
- The National Seismic Hazards Maps (NSHMs) presently use long-term average slip rates, and do not consider clustering behavior.
- Where temporal clusters occur, slip-rate distributions incorporating slip-rate variability (e.g., including inter- and intra-cluster rates) and uncertainty would be an improvement over just considering long-term average slip rates.
- We need to understand why clustering occurs if we wish to use only an intra- or inter-cluster slip rate in a probabilistic seismic hazard analysis (PSHA).

- Paleoseismic records for BRP faults should be compiled and compared/contrasted to understand the timing and causes of clustering.
- Lower slip-rate faults seem to have less regular recurrence and are more subject to clustering than are high slip-rate faults.
- Weighted mean slip rates for slip-rate distributions that consider clusters are generally higher (increasing the hazard) than long-term average slip rates, but are needed to better incorporate uncertainty.
- Slip-rate distributions typically are not symmetrical.

Discussion turned to the use of time-dependent models in PSHAs. David Schwartz highlighted the Hebgen Lake fault paleoseismic record and issues related to time-dependent models for faults with historical earthquakes. Mark Petersen indicated that time-dependent models are a research product of the NSHM Project, but outside of California, are not being considered for incorporation into the 2007 NSHM update. He then discussed the various time-dependent models (Poisson, time-predictable, Brownian passage time, empirical). Important points from the discussion of time-dependent models included:

- We need complete paleoseismic records with well-established average recurrence (2-3 intervals), coefficients of variation for recurrence, and elapsed time since the most recent earthquake before applying a time-dependent model. Only a few faults in the BRP have been studied well enough for time dependence to be applied.
- To determine recurrence, we need to include variability in slip rates and recurrence intervals and not just rely on long-term average slip rates.
- Time dependence should theoretically raise the probabilities of earthquakes on some faults.
- Faults will yield different long-term slip rates depending on how far back (how many earthquakes) we are able to extend the paleoseismic record.
- BRP faults having low slip rates (and long recurrence) may not be suitable for time-dependent modeling due to the difficulty in determining average recurrence over multiple earthquake cycles.
- Faults with historical earthquakes pose a challenge because time-dependent models yield a greatly reduced hazard (depending on stress drop, a potential for subsequent rupture in the near-term may remain), whereas the hazard is unchanged following a historical earthquake using a Poisson model.
- We need to collect/analyze data on recurrence for faults with historical earthquakes to look for time-dependent behavior.
- It is difficult to use Coulomb stress changes caused by historical earthquakes in time-dependent models because, although a historical earthquake may cause stresses to increase on certain neighboring faults, we do not know each fault’s state of stress prior to the historical event.

Recommendations

The BRPEWG reached consensus on the following recommendations regarding the NSHMs:

Short-term Recommendation for the 2007 NSHMs

1. The USGS should incorporate uncertainties in slip rates and recurrence intervals for the more significant BRP faults.
    a. Most studies giving slip rates and recurrence intervals identify the range of uncertainties.
    b. In Utah, use the slip-rate/recurrence distributions developed by the Utah Quaternary Fault Parameters Working Group (Lund, 2005).

Long-term Recommendations

1 Regional working groups are needed to develop consensus slip-rate and/or recurrence-interval distributions for significant faults.
    a. These rate distributions should represent temporal variation of the rates, if any, and other uncertainties.
    b. A high-level working group needs to recommend guidelines for establishing these distributions.
    c. Each regional group needs a "champion" who will take "ownership" to lead the group and secure results.
    d. Regions will not necessarily be by state. Some organizations (e.g., USGS or WSSPC) need to take responsibility to assure complete geographic coverage.

2. USGS should continue to develop time-dependent maps as a research product.
    a. In general, research needs to focus more on the timing of the most recent earthquake, average recurrence, and determining coefficients of variation for recurrence.

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SESSION 2
PROPER MAGNITUDE-FREQUENCY DISTRIBUTIONS (GUTENBERG-RICHTER VERSUS CHARACTERISTIC EARTHQUAKE MODELS) FOR BASIN AND RANGE PROVINCE FAULTS

Session Leaders

David Schwartz, U.S. Geological Survey, Menlo Park, California
Ivan Wong, URS Corporation, Oakland, California

Presentations

BRPEWG afternoon session, March 8, 2006

Wong and Schwartz	Introduction of issue and specific questions
Schwartz	Recurrence models and their physical and observational basis
Wong	Impact on hazard from choice of recurrence model
Petersen	Models and weights used in USGS National Seismic Hazard Maps
Hecker	Analysis of paleoseismic displacements and implications to recurrence models
Olig	Example of non-characteristic behavior in the Rio Grande Rift: Hubbell Spring fault, New Mexico
Arabasz	Analysis of Wasatch Front historical seismicity
Wong	Models and their weights considered in other PSHAs and rationale

Session Summary

Ivan Wong began the session by outlining outstanding issues and questions related to the proper magnitude-frequency (recurrence) distribution for Basin and Range Province (BRP) faults. David Schwartz then characterized the three magnitude-frequency distributions (characteristic, maximum magnitude, and truncated exponential [modified Gutenberg-Richter]) currently used to model the recurrence (size and frequency) of earthquakes on faults.

Ivan then discussed how the choice of a recurrence model can impact hazard. The highest probabilistic hazard results from use of the truncated exponential model because it allows for frequent moderate-sized earthquakes. The limited exponential portion of the recurrence in the characteristic model and the lack of an exponential portion in the maximum magnitude model results in lower to lowest hazard, respectively.

Mark Petersen presented the recurrence models used for the 2002 National Seismic Hazard Maps (NSHMs). The NSHMs employ a weighted combination of maximum magnitude (referred to as characteristic in Frankel and others, 2002), and “floating exponential” (referred to as truncated Gutenberg-Richter in Frankel and others, 2002) models weighted at 50/50 for all BRP faults except for the Wasatch fault, which is weighted at 80/20. A discussion ensued during which Mark Petersen described in greater detail the 2002 NSHM recurrence model: the maximum magnitude model is similar to that developed by Wesnousky (1986), but includes a distribution of possible magnitudes based on epistemic and aleatory uncertainties, whereas the floating exponential model essentially “floats” a M 6.5 to ~M_{max} earthquake along the fault. Additional discussion focused on whether or not large faults in the BRP are a major source of moderate-size (M ≤ 6.5) earthquakes, and the effect on the NSHMs of modifying the current USGS magnitude-frequency models.

Suzanne Hecker reported on the work that she and Norm Abrahamson are doing to evaluate slip-at-a-point variability on active faults and the resulting implications for earthquake-size distributions. Results to date, which incorporate thresholds of detection for earthquake displacements, do not support a truncated exponential model for earthquake distributions on large faults. The variability in displacements from multiple events on a fault at a given location indicates a relatively narrow range suggesting the characteristic model best fits the paleoseismic data.

Conversely, the next presentation by Susan Olig on the Hubbell Springs fault in New Mexico reported on large variability in displacement among the four to five surface-faulting earthquakes on that fault since about 84 ± 6 ka. Her conclusion was that at least in the case of the Hubbell Springs fault, neither the characteristic nor maximum-magnitude earthquake models seem to apply. During the follow-up discussion, it was pointed out that the characteristic-earthquake model does not require that all earthquakes be of the same magnitude (there is a bell-shaped distribution around the mean characteristic magnitude), that a complex upward propagation of the rupture through thick unconsolidated sediments may help account for the variability, and that not all traces of the very complex Hubbell Springs fault were trenched, allowing for additional, as-yet unrecognized displacement during the apparent low-slip earthquakes.

Walter Arabasz discussed observed seismicity and recurrence modeling for the Wasatch fault (WF). He concluded that observed historical seismicity is consistent with a characteristic model, but that the association of sampled seismicity with the WF is uncertain (if the instrumental seismicity is not on the WF, then its behavior is even more likely to be characteristic). With regard to a magnitude-frequency model, a maximum-magnitude model is viable for the WF provided that smaller earthquakes are incorporated in a background seismic zone.

Ivan Wong discussed the rationale for the various recurrence models and their weights used in current state-of-the-practice probabilistic seismic hazard analyses (PSHAs) in the BRP such as that done for Yucca Mountain. In all these analyses, the characteristic model was heavily favored.

The discussion following the presentations was wide ranging and covered differences in the 2002 NSHM frequency-magnitude model compared to those used in most PSHAs, whether or not the WF is a suitable analogue for other BRP faults, and whether the current 50/50 application of maximum magnitude and floating exponential models used for BRP faults on the 2002 NSHMs is appropriate. Of particular concern was the 80/20 weighting for the WF in the 2002 NSHMs, which drives the hazard down (fewer moderate-size earthquakes) relative to other BRP faults weighted at 50/50. The BRPEWG discussed the possibility of using a single distribution (for example, the current California 67/33 model for unsegmented faults) for the entire BRP, and acknowledged that whatever magnitude-frequency model is adopted for the BRP, it must account for historical seismicity (i.e., a lack of small- and moderate-size earthquakes on most BRP faults) and be consistent with the paleoseismic record.

Short-Term Recommendations for the 2007 NSHMs

The BRPEWG reached consensus on five recommendations regarding the magnitude-frequency relations used for the NSHMs:

1. The USGS “floating exponential” model should be validated to the extent possible, or at least made consistent with the paleoseismic and historical earthquake record in the BRP. The USGS model should also be compared with traditional magnitude-frequency models currently used in state-of-the-practice PSHAs.

2. The USGS should use the same recurrence model and weights for all BRP faults unless there is a technical basis for deviating from this characterization.

3. Weights assigned to the maximum magnitude and “floating exponential” models used for the 2007 NSHMs should, at a minimum, have the same weights as those used in California (2/3 - 1/3) unless there is a technical basis for deviating from this characterization.

4. To avoid double-counting earthquakes in the range of M 6.5 to the characteristic earthquake magnitude, zones surrounding BRP faults should be removed from the areas included in the Gaussian smoothing of background seismicity.

5. The methodology used for constructing the NSHMs must be fully transparent. The USGS is urged to publish, if only as a short note, how recurrence modeling is performed for the NSHMs, especially for fault-specific sources.

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SESSION 3
USE OF LENGTH VERSUS DISPLACEMENT RELATIONS TO ESTIMATE EARTHQUAKE MAGNITUDE

Session Leaders

Glenn Biasi, University of Nevada Reno Seismological Laboratory, Reno, Nevada
Mark Hemphill-Haley, Department of Geology, Humboldt State University, Arcata, California

Presentations

BRPEWG morning session, March 9, 2006

Hemphill-Haley	Length and displacement inferences about magnitude
Hemphill-Haley	Using prehistoric coseismic surface displacements to estimate earthquake magnitude: Hemphill-Haley and Weldon (1999)
Biasi and Hemphill-Haley	Average displacement estimation in “Integrated hazard analysis of the Wasatch Front, Utah:” Chang and Smith (2002)
Biasi	Probabilities of magnitude and surface rupture length from a displacement observation: Biasi and Weldon (in development)
Slemmons	Linear regressions of magnitude and the Denali earthquake
Biasi and Hemphill-Haley	Wells and Coppersmith (1994) magnitude regressions
Hemphill-Haley and Biasi	Instrumental versus preinstrumental earthquake scaling relations: Stirling and others (2002)
Biasi and Hemphill-Haley	Bilinear source scaling: Hanks and Bakun (2002)
Anderson	Moment magnitude equations

Session Summary

Glenn Biasi and Mark Hemphill-Haley structured the magnitude-regression session around the estimation of seismic moment (M_o), where M_o = shear modulus $*$average displacement$*$ rupture length $*$down-dip rupture width. The session leaders posed two questions regarding updating the National Seismic Hazard Maps (NSHMs) for the Basin and Range Province (BRP):

1. What primary data are needed to improve estimates of average displacement and length?

2. What data are needed to reliably infer magnitude from displacement and/or length?

Estimating Fault Displacement, Surface Rupture Length, and Width

Mark Hemphill-Haley started the session by outlining the advantages and disadvantages of using surface rupture length (SRL) and displacement to estimate earthquake magnitude, citing both historic and prehistoric examples of anomalous displacement and SRL measurements (e.g., the 1959 M 7.5 Hebgen Lake earthquake, which had a short SRL but large displacement and magnitude). Mark and Glenn Biasi then summarized methods developed by Hemphill-Haley and Weldon (1999), Chang and Smith (2002), and Biasi and Weldon (in development) to estimate average displacement and paleoearthquake magnitude given observed point displacements. The Hemphill-Haley and Weldon (1999) work shows how average displacement estimates improve when multiple measurements are made of a rupture, and using the Landers example, how even a single displacement measurement can improve the magnitude estimate. The Chang and Smith (2002) method develops an average displacement estimate by assuming segment bounds and an elliptical rupture shape, then using paleoseismic displacements to adjust the height of the rupture. For short segments their method tends to predict large average and maximum displacements. For multi-segment ruptures, average rupture displacements can be smaller than for the individual contributing segments, but the lower displacement estimates brought paleomagnitude estimates more in line with expectations. The Biasi and Weldon (in development) method uses individual displacement measurements to develop a probability distribution for magnitude and length. Burt Slemmons presented information from the Alaska pipeline, which accommodated 4.9 meters of right-lateral displacement on the Denali fault during the 2002 M 7.9 Denali earthquake. The Denali fault rupture is a good analog for strike-slip surface faulting in the Walker Lane fault zone in the western BRP.

Working Group members discussed issues related to displacement measurements, including (1) differences in average, maximum, and modal displacement values, (2) estimating displacement uncertainties (related to the number of measurements and difficulties in obtaining accurate measurements), and (3) measurement (and geologic) biases due to paleoseismic site selection, scarp preservation, and the difficulty in recognizing single- versus multiple-event displacements. Discussions regarding SRL estimates focused on (1) the importance of including length uncertainties, (2) the effect of segmentation, multi-segment rupture (e.g., 1915 M 7.3 Pleasant Valley), multi-fault rupture (e.g., 1992 M 7.4 Landers), and spatial clustering (e.g., Central Nevada seismic belt) on SRL estimates, and (3) measurement biases due to fault-scarp preservation. Working Group members also discussed estimates of fault width (as a function of fault geometry and dip angle) and considered potential scaling relations between width, displacement, and length for BRP faults. The BRPEWG considered potential variations in shear modulus, but agreed that a lack of data precluded defining regional shear-modulus boundaries, and that incorporating estimated uncertainties (e.g., ±10%) into the NSHMs was not appropriate due to the resulting insignificant changes in hazard. A better understanding of the values and uncertainties in shear modulus in the BRP is needed.

Magnitude Regressions

Glenn and Mark organized a review and discussion of early magnitude-SRL regressions (e.g., Slemmons, 1977; Bonilla and others, 1984), and recent SRL, displacement, width, and area regressions in Wells and Coppersmith (1994). Wells and Coppersmith regressions show that SRL tends to systematically underestimate the subsurface rupture length. They then presented and discussed the results of Hanks and Bakun (2002), who included improved (bilinear) regressions for large-magnitude (M >7) strike-slip earthquakes, and Stirling and others (2002), who relied on a censored instrumental dataset (i.e., removing earthquakes with SRL <10 km, area <200 km^2, average displacement <2 m, and moment magnitude [M_w] <6.5) to form SRL and area regressions that fit preinstrumental large earthquakes. John Anderson presented three equations for determining moment magnitude from seismic moment, static stress drop, and a constant defined by fault type, and discussed the application of each equation to short versus long SRL faults.

Mark Petersen stated that the NSHMs cap the magnitude of BRP earthquakes at 7.5. Craig dePolo noted that the longest historical surface ruptures (of about 100 km) in the BRP occurred during the 1872 M 7.4 Owens Valley and 1887 M 7.4 Pitaychachi earthquakes. Working Group members discussed the current practice of using a single SRL regression (from Wells and Coppersmith, 1994) to determine earthquake magnitudes for the 2002 NSHMs, which likely underestimates the hazard (as suggested by short faults having large displacements). Working Group members agreed that displacement information should be used with SRL to estimate magnitude for faults having anomalously short ruptures and large displacements. Working Group members also discussed the use of a minimum magnitude estimate (e.g., M ~6.5) for faults having surface rupture, a short SRL, but poor displacement-per-event information. Discussions also considered (1) using additional fault-parameter regressions (e.g., based on displacement*SRL, width, or area), (2) the possibility of developing multivariate regressions using SRL and displacement, and (3) the method of predicting SRL given observed displacement (Biasi and Weldon, in development). The BRPEWG considered the suitability of global, all-fault-type magnitude regressions for BRP faults and the prospect of developing BRP-specific regressions (after Dowrick and Rhoades, 2004), but most agreed that limited historical surface faulting in the BRP precluded developing region-specific regressions.

Recommendations

The BRPEWG reached consensus on the following recommendations regarding the magnitude-frequency relations used for the NSHMs:

Short-Term Recommendations for the 2007 NSHMs

Estimating Displacement and Length:

1. Include uncertainty in SRL and its consequences for magnitude.

2. Constrain the minimum magnitude assigned to surface-faulting earthquakes to M 6.5 to be consistent with the hazard set by background seismicity.

3. Use magnitude-displacement regressions to improve magnitude estimates where the magnitude from SRL appears inconsistent.

4. Have a working group look at the faults for which displacement data are available (thought to be ~20 in Nevada), and suggest a weighting between displacement and SRL estimates of magnitude to achieve a combined fault magnitude estimate.

Long-Term Recommendations

Regressions:

1. Revisit the Wells and Coppersmith (1994) regressions to update the database and evaluate the need to censor short rupture lengths and small magnitudes.

2. Develop a M_w versus SRL$*$displacement scaling as a tool for improving use of displacement in making magnitude estimates.

3. Develop a multivariate regression for magnitude, given SRL and displacement, to improve magnitude estimates on faults for which both are available.

4. Invest in determining whether regional regressions materially improve ground motion predictions; for long strike-slip faults (western BRP) consider using the Hanks and Bakun (2002) M_w versus area regression relation.

5. For short faults, consider whether Wells and Coppersmith (1994) is appropriate considering the results of Stirling and others (2002).

6. Evaluate whether an estimate of magnitude based on area (with an assumed width) is more appropriate than a magnitude based on SRL.

Displacement:

1. There should be a concerted effort to assess:
    a. the variability of displacement along rupture strike for historical surface ruptures for the entire range of magnitude (e.g., a follow-up to McCalpin and Slemmons, 1998), and

b. whether surface-faulting data for the BRP support regional (BRP-specific) regressions.

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SESSION 4
PROBABILITIES AND MAGNITUDES OF MULTI-SEGMENT RUPTURES

Session Leaders

Craig dePolo, Nevada Bureau of Mines and Geology, Reno, Nevada
James Pechmann, University of Utah Seismograph Stations, Salt Lake City, Utah

Presentations

BRPEWG afternoon session, March 9, 2006

Pechmann	Probabilities and magnitudes of multi-segment ruptures: specific questions
Haller	Fault segmentation models in probabilistic seismic hazard analyses and an example for the Wasatch fault
dePolo	The fault segmentation model and maximum earthquake magnitudes for the Basin and Range Province
DuRoss	Addressing the potential for multi-segment ruptures on the Wasatch fault
Pechmann	Use of multi-segment rupture models in the National Seismic Hazard Maps: options and effects

Session Summary

Jim Pechmann began the session by pointing out that the 2002 National Seismic Hazard Maps (NSHMs) use multi-segment rupture (MSR) models for the San Andreas and Hayward faults in California. He then posed three fundamental questions regarding the use of MSR models for Basin and Range Province (BRP) faults:

1. Should the NSHMs use MSR models for BRP faults?

2. If so, what general types of models should be used, and how should they be weighted relative to single-segment rupture (SSR) models?

3. Should rupture “spill-over” and triggered earthquakes be considered in the models as well?

Kathy Haller stated that characteristic earthquake magnitudes for faults on the NSHMs are determined from surface rupture length only. She presented examples of three comparatively well-studied BRP faults (Lost River, Hebgen Lake, and Pleasant Valley) where the use of magnitudes from segmentation (fault length) models, plus slip rates, to calculate the average rate of surface-faulting earthquakes results in a significant over-estimation of the expected number of such earthquakes compared to the paleoseismic record. Kathy noted that the two fault strands that ruptured together during the 1959 Hebgen Lake earthquake are modeled separately on the 2002 NSHMs. She then discussed the Ruby Mountain fault, which is one of only three segmented BRP faults on the NSHMs (the others being the Wasatch fault [WF] and the Hurricane fault). Earthquake occurrence for individual segments of the Ruby Mountains fault is in general agreement with the observed paleoseismic record. Finally, Kathy discussed the WF. For the segments of the WF, the NSHMs use average rates of surface-faulting earthquakes, which are estimated directly from paleoearthquake timing instead of from slip rates. Kathy pointed out that the treatment of characteristic magnitude uncertainty in the NSHMs effectively gives some weight to MSRs along the WF because the assumed epistemic uncertainty of ±0.2 M produces rupture lengths which are up to 15-20 kilometers longer than the single-segment rupture (SSR) lengths. Application of a simple two-segment rupture model to the WF showed that the differences in the 2% in 50 years peak ground accelerations calculated using this model and the NSHM SSR model are small (between -4% and +7% *g*). Lessons learned from Kathy's presentation include:

- The need to carefully evaluate both the quality and quantity of data supporting segmentation prior to constructing a segmentation model for a fault.

- The need to define a minimum data standard (type, quantity, and quality) for fault segmentation in the BRP.

- The need to be aware of possible outcomes when choosing a segmentation model.

Craig dePolo then discussed the history and present practice of defining fault segments on long faults. He defined earthquake segmentation as "using physical features of a fault, including historical and paleoseismic data, to define potential earthquake segments for approximating future earthquake ruptures." The basis for earthquake segmentation includes (1) historical surface ruptures, (2) paleoseismic information (trenching data), and (3) tectonic geomorphology (chiefly young fault scarps). However, Craig noted that earthquake segmentation theory only predicted about half of the end points of historical BRP surface-faulting ruptures. Regarding a threshold for MSRs, Craig believes that overall fault lengths must exceed 15-20 kilometers. Craig concluded by saying that the division of long faults into earthquake segments makes physical sense and likely does model future earthquakes; however, echoing Kathy, he stated that the process of determining defensible segmentation models and likelihoods is difficult, especially where good paleoearthquake data are lacking.

Chris DuRoss presented the results of his recent work on evaluating the potential for MSRs on the WF. To examine that possibility, Chris updated and revised the WF paleoearthquake space-time diagram, evaluated paleoseismic data quality/confidence, and generated a variety of MSR models for the fault. His work is ongoing, but preliminary results for the central four (Brigham City to Provo) segments indicate that six to eight two-segment ruptures, combined from 16 single-segment paleoearthquakes in the past 6000 years, are possible. Chris displayed a displacement versus rupture-length diagram for the WF, which shows that 47% of individual paleoearthquake displacements for the WF segments are larger than the maximum displacements predicted by the segment lengths (using Wells and Coppersmith [1994] all-fault regression), thus again indicating that MSRs are a possibility on the WF.

Jim Pechmann concluded the session presentations by reviewing the five principal types of MSR models presently in use, and the effects of MSR models on seismic-hazard analyses. The MSR models include an unsegmented model (e.g., Youngs and others, 2000; Wong and others, 2002), weighted sets of MSR scenarios based on expert judgment (e.g., Frankel and others, 2002), weighted sets of MSR scenarios based on "stringing" ruptures together probabilistically using paleoearthquake timing and displacements (Biasi and Weldon, in development), and two versions of cascade models (e.g., WGCEP, 1995; Field and others, 1999; Andrews and Schwerer, 2000). Jim concluded that "overall, MSR models give lower probabilistic seismic hazard than SSR models if the models are moment balanced," (i.e., the slip rate is the same for both). The hazard is lower because MSRs produce larger earthquakes, which result in longer recurrence intervals, which translate into fewer earthquakes over a given time period, and consequently, lower seismic hazard. Jim also commented on Kathy Haller's two-segment rupture model for the WF, which was not moment balanced, but showed only a small change in hazard compared to a SSR model. Jim finished by stating that while MSRs may have only a small effect on overall hazard, MSR scenarios, where credible, are important for emergency planning purposes due to the potential for longer period and duration ground shaking and greater geographical extent of damage (along two segments rather than one).

Discussion following the presentations considered whether or not long faults on the NSHMs should be segmented (the BRPEWG consensus was yes), and whether or not current information for most BRP faults is sufficient to allow them to be segmented (the consensus was generally no). Working Group members agreed that acquiring the new data necessary to permit fault segmentation would be a long-term undertaking. A suggestion was made to focus data-gathering activities on urban faults where the risk is the greatest. An objection to this suggestion was raised on the grounds that most opportunities to study urban faults have been lost to development, while more remote faults are still largely available for study and may teach us important lessons. Discussion then moved on to whether or not a MSR model should be applied to BRP faults once they are segmented, and if so what kind of model it should be. Working Group members agreed that the method of probabilistically using earthquake timing and displacement to create MSR scenarios should be applied to the WF. They also agreed that cascade models are not appropriate for the BRP because these models assume that MSRs occur on two or more complete segments, but even two-segment ruptures along the WF were considered unlikely. The BRPEWG concluded that it is important to consider the possibility of MSRs on presently segmented BRP faults when doing the NSHM hazard calculations. Given our present understanding of fault segmentation in the BRP, it was decided that the best way to account for MSRs is by using an unsegmented model with a maximum rupture length greater than the average segment length.

Recommendations

The Working Group reached consensus on six recommendations regarding SSR versus MSR models for BRP faults. Three are short-term recommendations and should be included in the 2007 NSHMs update. One recommendation is both short- and long-term, and the final two recommendations are long-term and are intended to guide future research.

Short-Term Recommendations for the 2007 NSHMs

1. Hazard calculations for the NSHMs should consider the possibility of MSRs on BRP faults.

2. For BRP faults for which SSR models are being used to compute the hazard, the 2007 NSHMs should also use an unsegmented rupture model which accounts for the possibility of ruptures extending beyond segment boundaries. The unsegmented model should be given a relatively low weight.

3. The two faults that ruptured together in the 1959 Hebgen Lake earthquake should be treated as a single seismic source for the purpose of the 2007 NSHM hazard calculations.

Short-Term/Long-Term Recommendation

1. Where available, displacement data should be used to provide a consistency check for segmentation models – especially to identify segments on which ruptures longer than the mapped length could occur.

Long-Term Recommendations

1. Newly developed methods for probabilistically constructing rupture scenarios from paleoearthquake timing and displacements should be applied to the WF.

2. Research needs to be conducted on the following topics to facilitate segmentation modeling in the BRP:
    a. how to recognize and characterize fault-rupture segments,
    b. the quality and quantity of paleoseismic data needed to support segmented earthquake models along BRP faults, and
    c. construction of earthquake-segmentation models for important BRP faults.

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SESSION 5
RESOLVING DISCREPANCIES BETWEEN GEODETIC EXTENSION RATES AND GEOLOGIC SLIP RATES

Session Leaders

Robert Smith, University of Utah, Salt Lake City, Utah
Wayne Thatcher, U.S. Geological Survey, Menlo Park, California

Presentations

BRPEWG morning session, March 10, 2006

Thatcher	Introduction and objectives
Crone	Geological perspective on contemporary deformation in the Basin and Range Province
Hammond	Kinematic overview of active Basin and Range deformation measured with GPS
Smith and Chang	Integrated earthquake hazard assessment, eastern Basin and Range
Thatcher	Summary and discussion

Session Summary

Wayne Thatcher began the session by summarizing the issues related to integrating geodetic extension rates and geologic slip rates in models of seismic hazard. The geodetic data indicate a total strain budget of 12-14 mm/yr across the Basin and Range Province (BRP), of which modern seismicity and paleoseismically determined fault slip rates are individual components. Tony Crone then summarized the spatial and temporal patterns of Quaternary faulting across the BRP using the geologically determined earthquake-timing and slip-rate data compiled in the Quaternary Fault and Fold Database of the United States, and highlighted the limitations of geologic data (both from a regional perspective and from site-specific trench studies) in determining the timing of surface-faulting earthquakes. Tony also noted that historical earthquake activity in the Central Nevada seismic belt (CNSB) (six surface-faulting earthquakes since 1915) is anomalous in the BRP paleoseismic record, and raised the question as to whether the locations and rates of GPS-determined deformation might fluctuate greatly over time spans that are relevant to seismic-hazard assessment.

The next two presentations dealt with geodetic constraints on horizontal strain. Bill Hammond discussed province-wide data and issues, and Robert Smith and WuLung Chang focused on the eastern margin of the BRP, in particular the Yellowstone-Snake River Plain and Wasatch Front regions. Bill illustrated the spatial variability of GPS-measured extension across the BRP (with respect to stable North America), ranging from ~3 mm/yr across western Utah and central Nevada to ~10 mm/yr across western Nevada and eastern California. He noted the concentration of contemporary deformation at the province margins, the large component of dextral shear at the western margin, and the anomalously high GPS-measured rates of dilatation across the CNSB, where the geodetic moment rate is nearly six times higher than the moment rate inferred from paleoseismic studies. According to Bill, recent modeling by several groups strongly suggests that the geodetic velocities across the CNSB are temporarily enhanced by post-seismic relaxation following the historical surface-faulting earthquakes. Bob Smith discussed data from campaign and continuous GPS networks in the Yellowstone-Snake River Plain region, models of post-rupture stress contagion on adjacent segments of the Wasatch fault (WF), and use of GPS-measured interseismic loading rates as proxies for geologically determined fault slip rates. As part of this discussion, WuLung presented models he has been developing, using data from the WF, for strain loading, converting geologic (vertical) displacement to geodetic (horizontal) extension, multi-segment ruptures, and integrated probabilistic seismic-hazard assessment.

Prior to ending the session with open discussion of the issues, Mark Petersen summarized how geodetic data were used in the 1996 and 2002 NSHMs. Mark said that GPS-measured relative velocities were applied in zones in the high-strain-rate region of western Nevada and eastern California. In each zone, 50% of the geodetic rate is accounted for by coseismic strain release, and deformation is distributed uniformly across the zone rather than partitioned on individual faults. The BRPEWG recommended that, in the future, the rates in these zones need to be increased (e.g., by increasing the percentage of coseismic strain release), and the eastern limit of the zones needs to extend farther east to include the Walker Lane fault zone. Mark also indicated that geodetic data could be used in other areas where there is little geologic slip-rate data. Finally, John Anderson reiterated that models of strain rate need to faithfully account for seismic moment, and that for the BRP as a whole, the geologic moment rate is less than the seismicity- and geodesy-based rates by a factor of 2 to 3.

The closing discussion revisited the issues raised during the presentations that are important in incorporating geodetic data in the NSHMs. Key issues include the following:

- Uncertainty in fault dip; the dip of normal faults is critical in relating vertical slip rates and horizontal extension rates.
- Model-dependency of slip rates (e.g., corrections for post-seismic relaxation effects).
- Coseismic versus aseismic strain release; although evidence is generally lacking for aseismic creep, its existence cannot be completely dismissed. However,

should the 50% weight presently given to aseismic strain release be lowered to 20%, or even 10%?

- Geodetic moment rate applied such that the rate of faults is not double-counted.
- How best to assign the geodetic slip-rate "residual" (i.e., the rate remaining after historical seismicity and paleoseismic data are accounted for): to known faults individually, or as a smoothed rate across a broad area?
- Areas having a large component of strike-slip faulting where accurate measurement of fault slip is difficult.
- The relatively short geodetic record; is it representative of the total long-term moment rate?
- Strain-rate gradients need to be preserved at the higher strain-rate eastern and western margins of the BRP.

Recommendations

The BRPEWG reached consensus on a number of both short-term and long-term recommendations related to geodetic extension rates/geologic slip rates in the BRP. In general, the BRPEWG believes that the geodetic and geologic data need to be combined into a single integrated model, rather than used separately, for effective incorporation in the NSHMs.

Short-Term Recommendations for the 2007 NSHMs

1. Convert vertical slip rates to extensional rates for consistency with GPS data. This involves resolving the question of dip of normal faults. The NSHMs currently use a dip of 60°; the Working Group recommends using a dip of 50°±10°.

2. For the BRP, use the province-wide kinematic (GPS) boundary condition (12-14 mm/yr) as a constraint on the sum of geologic slip rates. Enhance the fault catalog used in the NSHMs as necessary to achieve the far-field rates.

3. Modify the boundaries of the geodetic zones in the western Great Basin used in the 1996 NSHMs to better reflect the areas of high strain depicted on the GPS-based strain-rate map.

4. Use the geodetic data as the total strain budget. Ideally, the moment rates from the faults, areal source zones, and GPS zones should add up to the full geodetic budget. This total should be comparable to the seismicity, which is a separate estimate of moment rate. Differences that exist between these individual moment sources should be fully accounted for in the 2007 NSHMs.

5. The USGS should test models to evaluate the effect of releasing geodetic strain as 80% coseismic and 20% aseismic.

6. The USGS should evaluate the impact on the NSHMs of partitioning geodetic strain on individual faults within a zone (assigning default slip rates) versus distributing the geodetic strain uniformly across the zone.

Long-Term Recommendations

1. Move toward assigning minimum slip rates to specific faults. To this end, develop a strategy of how to assign slip rates based on combined geodetic and geologic criteria; this could be a charge for a future working group.

2. Develop a consistent-resolution fault map for the western margin of the Great Basin as a first step toward an integrated geodetic/geologic model.

3. Develop robust, geologically based (paleoseismic) slip rates in the source zones where geodesy shows significant strain accumulation, giving priority to urban and rapidly urbanizing areas.

4. The geoscience community should work toward the goal of determining if geodesy can identify specific faults where strain is being localized (i.e., indicator of higher hazard).

5. Where adequate data exist, develop an integrated model that incorporates geodetic, seismicity, and fault data.

6. The USGS should fully explain in an easily accessible publication or Web page the methodology behind the NSHMs, including the properties of each version of the maps so that changes in the maps over time can be completely understood.